A perceptually-driven account of onset-sensitive stress[1]

Matthew Gordon
University of California, Santa Barbara

This paper explores onset-sensitive stress from a typological, phonetic and phonological perspective. A phonetic study of three onset-sensitive stress systems suggests a close match between onset weight distinctions and a phonetic measure of perceptual energy, such that phonological weight criteria are the phonetically most effective ones. Perceptual considerations also offer an explanation for other typological observations, including the relative rarity of onset-sensitive stress, the greater weight of low sonority onsets, and the subordination of onset-sensitive weight distinctions to rimal based ones in languages with both types of weight distinctions. Onset-based weight criteria are effectively modelled using a skeletal slot model of the syllable referenced by a family of prominence constraints requiring that heavy syllables be stressed and that light syllables be unstressed.

1. Introduction

Although the vast majority of weight-sensitive stress systems ignore syllable onsets in their calculation of weight, there remain certain clear cases of onset-sensitive stress. For example, stress in Pirahã (Everett and Everett 1984, D. Everett 1988) is sensitive to a five-way weight hierarchy in which both the rime and the onset play a role. Stress falls on one of the final three syllables of a word. Within this window, stress falls on the heaviest syllable according to the following hierarchy: KVV > GVV > VV > KV > GV where K stands for a voiceless consonant and G for a voiced consonant. Pirahã lacks coda consonants and onsetless syllables consisting of a short vowel do not occur (D. Everett 1988). In case of a tie between two equally heavy syllables, the rightmost one takes stress.[2] In this system, both rime weight and onset weight are relevant. Vowel

---

[1] Thanks to Michael Kenstowicz and three anonymous reviewers for their many helpful comments on an earlier draft of this paper. A great debt of gratitude is owed to Dan Everett, Keren Everett, and Peter Ladefoged for graciously providing the Pirahã and Banawá data (originally collected as part of an NSF grant) and to the UCLA Phonetics Laboratory for making available a recording of Arrernte made by Andrew Butcher. Also, thanks to Adam Albright, Doug Pulleyblank, Bernard Tranel, Andy Wedel, Kie Zuraw and audiences at UCSB, UCI, NELS 32, and WCCFL 22 for their helpful feedback on this research. Any errors and misconceptions are solely the author's responsibility.

[2] D. Everett (1988: 212-5) discusses several diagnostics in support of these stress patterns, which are orthogonal to tonal contrasts. First, native speakers correct stress errors committed by non-native speakers. Furthermore, Everett reports working with a speaker who can make hand gestures during stressed syllables similar to an orchestra conductor. In addition, optional processes of posttonic devoicing and deletion target stressless vowels, e.g. pii.ˈhoa.bi.gi →

length is the dominant weight criterion, since a long voweled syllable, regardless of onset, is weightier than a syllable containing a short vowel. If, however, two rimes are equivalent in vowel length, onset type acts as a tiebreaker. Pirahã stress examples (from Everett and Everett 1984, D. Everett 1988) appear in (1). (Low tone is unmarked).

(1) Pirahã stress
KVV > GVV: ˈhoa.gái ‘come’, ˈkaa.gai ‘word’, ˈkai□.bai□ ‘monkey’
GVV > VV: poo.ˈgáí.hi.aí ‘banana’, ho.aa.ˈgai ‘type of fruit’, ˈgao.ii ‘proper name’
VV > KV: pia.hao.gi.so.ˈai.pi ‘cooking banana’, ho.ˈai□.pi ‘type of fish’, pi□.ˈai ‘also’
KV > GV: ˈʔa.ba.gi ‘toucan’, ti.ˈpo.gi ‘bird species’, ˈʔi□.bo.gi ‘milk’
Rightmost in case of tie: paó.hoa.ˈhai ‘anaconda’, bai.tói.ˈsái ‘wildcat’

Since the seminal work on onset-sensitive stress in Pirahã by Everett and Everett (1984) (see also D. Everett 1988, K. Everett 1998), there has been little attempt to explain either the basis for onset-sensitive stress or its rarity relative to onset-sensitive stress (see, however, Goedemans 1998, discussed in section 7, and Davis 1988). The most widely adopted phonological theory of weight, moraic theory (Hyman 1985, Hayes 1989), does not provide for representing onset weight since moras are assigned only to segments in the rime. The dearth of studies on onset weight contrasts with the extensive literature examining the phonological analysis of rimal weight (e.g. Jakobson 1931, Trubetzkoy 1939, Allen 1973, Hyman 1977, 1985, 1992, McCarthy 1979, Hayes 1989, Zec 1994) and correlations between the phonology of rimal weight and its phonetic manifestations (e.g. Maddieson 1993, Duanmu 1994, Hubbard 1994, 1995, Broselow et al. 1997, Ham 2001, Zhang 2001, Gordon 2002a, Arvaniti and Rose 2003). Languages like Pirahã raise several questions, however, about onset weight, both phonological and phonetic: What is the cross-linguistic range of variation in onset weight criteria? What is the proper phonological representation of the onset? Do interlanguage differences in onset weight criteria correspond to phonetic differences? Why is onset weight so rare relative to rimal weight?

This paper addresses these questions from a typological, phonological and phonetic perspective. Based on a typology of onset-driven weight, two recurrent patterns in onset weight behavior are identified. First, lower sonority onsets tend

---

pii.ˈhoa.b̥i̥.g̥i̥ or pii.ˈhoa ‘frog species’. Finally, a tonal shift process correlates with stress. Stress patterns are also corroborated by acoustic data analyzed by K. Everett (1998) showing that stressed vowels have greater intensity than unstressed vowels and that stressed syllables (but not vowels) are longer than unstressed ones.

to be heavier than higher sonority onsets, as in Pirahã. Second, onset weight characteristically occurs in languages that also observe rime-based distinctions, a pattern also found in Pirahã. In these languages, rimal weight takes precedence over onset weight, again as in Pirahã. Drawing on these typological observations, possible phonetic correlates for onset-sensitive weight are proposed; ultimately, it is shown that a measure of perceptual energy correlates well with onset-sensitive weight in three languages from which phonetic data were analyzed. It is also claimed that phonetic factors tend to discriminate against onset-based weight distinctions, in keeping with both their cross-linguistic rarity and their characteristic subordination to rime-based weight distinctions in languages with both rimal and onset driven weight. Finally, I show that onset-based weight can be formally modelled in an Optimality-Theoretic paradigm through a series of prominence constraints referencing a skeletal slot model of the syllable in which segments both in the onset and rime have timing positions.

2. A typology of onset-sensitive weight

A total of 13 languages with clearly onset-sensitive stress were located in the present study.[3] They are listed in table 1[4], along with their weight criteria, and the relevant data source(s).

Table 1. Languages with onset-sensitive stress (K = voiceless consonant, G = voiced consonant, W = glide, R = sonorant, O = obstruent)

Language	**Weight criteria**	**Source**
Alyawarra	CV > (W)V	Yallop 1977, Davis 1988, Goedemans 1998
Arrernte	CV > V	Strehlow 1942, Davis 1988, Goedemans 1998, Breen and Pensalfini 1999
Banawá	CV > V	Buller et al. 1993, Ladefoged et al. 1997
Bislama	CCVC > CVC > CCV > CV	Camden 1977
English	CVV, CVC > O(R)V > RV	Nanni 1977
Iowa-Oto	CV > V	Robinson 1975, Goedemans 1998

---

[3] Goedemans (1998) discusses other cases of onset-sensitive stress in Australian languages, for which data is sketchier and not discussed here.

[4] Other potential cases of onset stress are Italian (Davis and Napoli 1994) and Mathimathi (Hercus 1969), both of which may be alternatively analyzed (see Gahl 1996, Goedemans 1998 on Mathimathi and Gordon 1999 on Italian).

Júma	CV > V	Abrahamson and Abrahamson 1984
Lamalama	CV > V	Laycock 1969, Goedemans 1998
Manam	(C)VC > CV > V	Lichtenberk 1983, Buckley 1998
Mbabaram	(C)VC > CV > V	Dixon 1991, Goedemans 1998
Nankina	CCV > (C)V	Spaulding and Spaulding 1994
Pirahã	KVV > GVV > VV > KV > GV	Everett and Everett 1984, D. Everett 1988, K. Everett 1998, Davis 1988, Goedemans 1998
Tümpisa Shoshone	CVV > KV > GV	Dayley 1989

The most common type of onset-sensitive weight criterion, found in 5 languages, treats syllables with an onset as heavier than syllables lacking an onset. In Júma, the final syllable of a word is stressed unless it is onsetless, in which case stress retracts onto the penult. In Iowa-Oto, the first syllable carries stress unless it is onsetless, in which case the second is stressed. In Arrernte (see section 6.2 for further discussion), stress falls on the initial syllable of all disyllables and on the first syllable of a trisyllabic or longer word if it contains an onset, otherwise on the second syllable. The Lamalamic languages described by Laycock (1969), Lamalama, Umbuykamu, and Parimankutinma, employ the same onset-sensitive stress system but with no mention of an asymmetry between disyllabic and longer words. Banawá stress operates on the level of the rimal timing slot (equivalent to vocalic timing slots since Banawá lacks coda consonants), falling on the first rimal timing slot preceded by a consonant in words containing at least three rimal timing slots and on the first rimal timing slot of disyllabic words whether preceded by a consonant or not (see section 6.1 for further discussion). In vowel-initial words containing more than two timing slots in the rime, the second rimal timing slot attracts stress. In Mbabaram, vowel initial syllables do not carry stress, whereas consonant initial disyllables are roughly evenly split between those with initial and those with second syllable stress, unless the second syllable is closed in which case it virtually always (95%) attracts stress. Trisyllabic words carry stress on the second syllable.[5] In Manam, stress falls on final CVC, otherwise on the penult, unless the penult is onsetless in which case stress optionally retracts onto the antepenult. Finally, alongside distinctions based on onset voicing and vowel length (see section 1), Pirahã treats syllables containing an onset as heavier than those without an onset.

---

[5] Dixon (1991) states that long vowels are also stressed in Mbabaram. Long vowels are very rare, however; virtually all, if not all, are found in monosyllables and in the second syllable of vowel-initial words (p. 357), i.e. in contexts where they would independently be predicted to be stressed.

Two languages, Bislama and Nankina, treat syllables with complex onsets as heavier than syllables with single onsets. Camden (1977) describes a complex stress system in Bislama, according to which primary stress either falls on the penult or the final syllable depending on the shape of the final two syllables. In most words stress falls on the penult, but if the final syllable is heavier than the penult, stress falls on the ultima, where closed syllables are heavier than open syllables and syllables with complex onsets are heavier than those with simple onsets. Crucially, rime weight takes precedence over onset weight since closed syllables with a simple onset are heavier than open syllables with a complex onset. In Nankina, stress falls on either of the first two syllables of the word, where the location is sensitive to weight, number of syllables, and whether a word involves reduplication or not. The weight-sensitive aspect of the stress system involves both the rime and the onset. Stress generally falls on the first syllable of a word. However, if the first syllable contains the central vowel /ɨ/ it passes stress to the second syllable (cf. Kenstowicz 1997 on the lighter weight of centralized vowels in many languages). Stress also falls on the second syllable if the first syllable is onsetless and the second syllable begins with a consonant cluster.[6]

The remaining onset distinctions are based on voicing and/or manner of articulation. In Pirahã, voiceless onsets are heavier than voiced onsets. The same distinction is found in Tümpisa Shoshone, in which primary stress falls on the second syllable if it contains a long vowel following an initial CV syllable, and otherwise on the first syllable, except that stress optionally shifts to a second syllable with a short vowel if it has a voiceless onset. Alyawarra distinguishes between glides and other consonants in its weight-sensitive stress system. Stress falls on the first syllable unless it lacks an onset or begins with a glide. Finally, alongside the more salient weight distinction between heavy CVV, CVC and light CV in English (Chomsky and Halle 1968), Nanni (1977) observes that onsets are also relevant for stress in adjectives formed with the suffix *–ative*. The first vowel of this suffix carries secondary stress if its onset contains an obstruent: *invésti.gàtive*, *írri.tàtive*, *ínno.vàtive*, *quáli.tàtive*, *admíni.stràtive*, *légi.slàtive*. If, however, the suffix is preceded by a single sonorant onset, it lacks secondary stress: *nómi.native*, *géne.rative*, *manípu.lative*, *imági.native*, *íte.rative*.

---

[6] Spaulding and Spaulding (1994) also report cases in which the first and second syllable are equally stressed: if the first syllable is onsetless and the second syllable is CV(C), if the same vowel occurs in the first two syllables, and in trisyllabic words.

2.1. Typological generalizations

2.1.1. Primacy of rimal weight over onset weight

Two salient generalizations emerge from the cross-linguistic study of onset weight. First, more often than not languages with onset-sensitive stress also employ rime-based weight distinctions. This holds true of 7 languages: Bislama, Manam, Nankina, Mbabaram, English, Manam, and Pirahã. Another two languages are not diagnostic for rimal weight and thus do not contradict the generalization. One of these languages, Banawá (section 6.1), lacks coda consonants and determines stress on the level of the timing slot, so is not diagnostic for rimal weight. Iowa-Oto lacks phonemic vowel length and its only codas are the laryngeals /h/ and glottal stop, both of which occur only in compounding processes (Whitman 1947:236-7). This leaves Jumá and the three Australian languages/language families, Arrernte, Alyawarra and the Lamalamic languages in Laycock (1969), all of which have closed syllables but not phonemic vowel length, making them less than ideal candidates for a rimal weight distinction (see Hyman 1977, 1985 and Gordon 1999 on the bias against weight-sensitive stress in languages without phonemic vowel length). The presence of rime-based weight distinctions in the majority of languages with onset-driven stress accords with the overall cross-linguistic frequency of rime-based weight relative to onset-based weight. In a genetically balanced survey of 127 languages with weight-sensitive stress, Gordon (1999) finds only 5 languages with onset-sensitive stress, all of which are included in the more exhaustive survey in table 1.

Most significantly for assessing the relative contributions of onsets and rimes to weight, in languages with both rime-based and onset-based weight distinctions, onset weight is subordinate to rime weight when the two conflict, as we saw earlier for Pirahã. Thus, in Bislama, closed syllables are heavier than open syllables regardless of their onset structure. In Manam, final closed syllables attract stress whether they have an onset or not, whereas the absence of an onset in the penult is only relevant for conditioning a shift in stress to the antepenult, and this shift is optional. In Tümpisa Shoshone peninitial syllables with a voiceless onset only optionally attract stress away from an initial CV syllable, whereas a long vowel in the second syllable consistently attracts stress from initial CV. In Nankina, initial syllables containing a central vowel, regardless of their onset structure, pass their stress to the second syllable. Finally, in English, onset weight only rears its head in specialized morphological contexts where rimes are equivalent.

2.1.2 The greater weight of low sonority onsets

The second generalization involves the nature of onset-based weight distinctions. In languages in which type of onset (as opposed to the presence vs. absence of onset) is relevant, less sonorous onsets are heavier than more sonorous onsets. Thus, voiceless onsets are heavier than voiced ones in Pirahã and Tümpisa Shoshone, obstruent onsets are heavier than sonorant onsets in English, and consonantal onsets are heavier than glides in Alyawarra. The greater weight of less sonorant onsets is particularly striking in light of the fact that more sonorant consonants are heavier than less sonorant ones in languages with rime-based weight distinctions based on consonantal sonority. Thus, in Inga Quechua (Levinsohn 1976) and the Wakashan languages, Kwakw'ala (Boas 1947, Bach 1975, Wilson 1986) and Nuuchanulth (Wilson 1986), syllables closed by a sonorant coda attract stress over syllables with obstruent codas.[7] Section 4 will propose a perceptual analysis of weight accounting for both the onset vs. coda asymmetry in the relationship between sonority and weight as well as the primacy of rimal weight.

3. The relationship between phonetics and syllable weight

Recent research on the phonetics/phonology interface suggests correlations between syllable weight and phonetic properties, e.g. Maddieson (1993), Hubbard (1994, 1995), and Broselow et al. (1997). For example, Broselow et al. (1997) find that languages like Malayalam, which treat codas as light, have shorter vowels in closed than in open syllables, while languages like Hindi, in which codas contribute weight, do not. They suggest that this duration difference is associated with differences in moraic structure. In Malayalam, a coda consonant shares a mora with the preceding vowel. In Hindi, on the other hand, the coda consonant is associated with its own mora. Gordon (2002a) finds that a measure of perceptual energy matches closely, better than duration, with a variety of weight distinctions. Syllables with greater perceptual energy are heavier than those with lesser energy, where perceptual energy is calculated as the integration of loudness over time. In his account, languages adopt weight distinctions that offer the greatest separation of heavy and light syllables in the perceptual energy domain. Goedemans (1998) finds that listeners in Dutch are better attuned to fluctuations in rime duration than onset duration, arguing that this relative

---

[7] Thanks to a reviewer, however, for pointing out a possible exception to this generalization: the English process of intersonorant destressing (Kiparsky 1979) by which syllables closed by a sonorant lose their stress before the suffixes *–ary*, *-ory*, e.g. *ínventòry*, *vóluntàry* but *trajéctory*, *perfúnctory*.

insensitivity to the duration of onsets is responsible for their weightless status cross-linguistically (see section 7 for further discussion).

The present work shares with the above research its exploration of phonetic correlates of syllable weight. It differs, however, from these works in certain respects. Unlike all of the aforementioned works except for Goedemans (1998) it examines onset-sensitive stress. Unlike Hubbard (1994, 1995), Maddieson (1993) and Broselow et al. (1997), but like Goedemans and Gordon (2002a), it focuses on perceptual, as opposed to acoustic, correlates of onset stress. Finally, unlike Goedemans, the present paper explores the perceptual factors behind cases of onset weight rather than reanalyzing apparent cases of onset-sensitive weight without appealing to onsets. Once onset-sensitive stress is recognized as a legitimate though rare phenomenon, certain interesting properties of onset-sensitive stress are open to quantitative investigation, most notably the greater weight of less sonorous onsets relative to more sonorous onsets and the subordination of onset-sensitive stress to rime-driven weight. Extending Gordon's (2002a) account of rime-based weight, it is hypothesized that a measure of perceptual energy offers an explanation for these and other characteristics of onset-sensitive stress.

4. Perceptual energy and onset weight

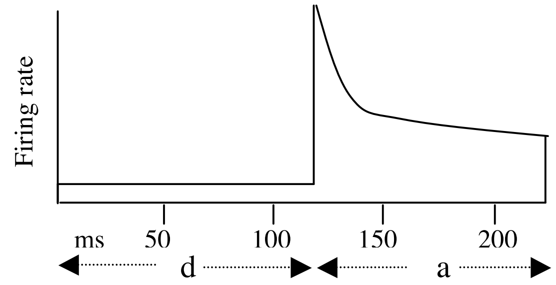
As a starting point in the investigation of onset weight, it is useful to consider the time varying response of the auditory system to a stimulus. Two salient temporal effects are observed. First, the auditory system is most sensitive to a stimulus at its onset before auditory sensitivity gradually declines. This decline in sensitivity, termed "adaptation", is reflected both in physiological experiments documenting firing rates of auditory nerve fibers (Delgutte 1982) and also in psychoacoustic experiments in which listeners are required to judge the loudness of a stimulus (Plomp 1964, Wilson 1970, Viemeister 1980). Another important temporal process affecting the auditory response to a stimulus is "recovery" (Delgutte 1982, Viemeister 1980). After a period of continued exposure to a stimulus during which auditory sensitivity declines, a period of silence or reduced acoustic intensity offers the auditory system a chance to recover before exposure to another more intense sound. After this recovery phase, auditory nerve firing rates and perceived loudness once again increase at the onset of the next relatively intense stimulus (Smith 1979, Delgutte 1980, Delgutte 1982, Delgutte and Kiang 1984).

Auditory adaptation and recovery play a role in the organization of phonological systems. Bladon (1986) argues that adaptation explains several phonological processes, including the cross-linguistic rarity of preaspiration and final /h/, the vocalization of post-vocalic laterals, the avoidance of fricative clusters, and vowel nasalization. Silverman (1997) shows that laryngeal timing patterns observed in Otomanguean vowels also follow from adaptation. Smith (2000, 2002) appeals to adaptation and recovery as independent support for her Optimality-theoretic analysis of onset fortition and epenthesis (see section 9.1 for further discussion of Smith's work).

Adaptation and recovery also offer an explanation for onset weight, given that the speech string consists of alternate sequences of relatively high intensity stimuli, the vowels, and relatively low intensity stimuli, the consonants. Consonants provide a relatively quiet phase during which the auditory system may recover between exposures to the relatively intense adjacent vowels. A vowel thus receives an auditory boost if it is preceded by an onset consonant. Conversely, a vowel immediately following another vowel, as in a hiatus context, does not benefit from recovery and auditory sensitivity continues to gradually decline throughout its duration. Given the auditory boost provided by an onset consonant, it is not surprising that syllables containing an onset consonant might be phonologically heavier than onsetless syllables in certain languages. Of the various types of onset consonants, ones with lesser acoustic intensity provide more of an auditory boost to a following vowel and are thus more likely to make their syllable prominent. This prediction is confirmed by the onset weight survey in section 2. Lower sonority, i.e. less intense, onsets such as voiceless consonants, obstruents, and true consonants (as opposed to glides) are heavier than higher sonority ones in some languages. A crucial feature of this account is that onsets themselves do not contribute to the auditory prominence of a syllable; it is only through their effect on the following rime that they potentially influence the weight of a syllable. This paper will show that adaptation and recovery provide an explanation for onset-sensitive weight distinctions found both word-medially as in Pirahã (section 5) and word-initially, as in Banawá (section 6.1) and Arrernte (section 6.2).

Although important for onset weight, the effects of adaptation and recovery on auditory prominence are relatively small compared to the contribution of the rime to prominence. Temporally, adaptation and recovery exert their greatest influence at the beginning of a vowel. Delgutte (1982:135) contains figures showing a sharp spike in auditory nerve firing rates during the first approximately 30-40 milliseconds of a vowel immediately following a voiced obstruent. After approximately 40 milliseconds, the auditory boost provided by the preceding onset has diminished sharply and adaptation triggers a gradual decrease in firing rates throughout the remainder of the vowel. Figure 1 contains a schematic illustration of the auditory nerve response to the sequence /da/ (based on figures in Delgutte 1982:135, 1997:531).

Figure 1. Auditory nerve response to /da/ stimulus



Studies by Plomp (1964) and Viemeister (1980) suggest that adaptation and recovery affect the perceived loudness of a sound by less than 10 decibels. Given that decibel levels for a normal conversation are typically between 60-70dB and that most speech sounds (other than voiceless stops) have decibel levels within 10-20dB of this range, the effects of adaptation and recovery on prominence are relatively minor compared to the influence of additional material in the rime. Thus, having a long vowel or a coda consonant is likely to increase the auditory prominence of a syllable much more than having a low sonority onset. The greater auditory contribution of the rime to perceived prominence accords with the prioritization of rimal weight over onset weight in languages with both types of weight distinctions, as well as the cross-linguistic rarity of onset-sensitive stress (see section 2 for further discussion).

4.1. Quantifying the auditory-basis for onset-sensitive stress

Although auditory adaptation and recovery offer an intuitive explanation for onset-sensitive stress patterns, it is important to quantify the auditory contributions of adaptation and recovery in relation to weight. Following work by Broselow et al. (1997) and Gordon (2002a) on rimal weight, it should be established that, in languages with onset-driven stress, phonological onset-based weight distinctions are phonetically more sensible than unexploited but logically possible weight distinctions sensitive to the rime or onset. Furthermore, the prioritization of rimal weight over onset weight in languages with both onset- and rime-driven stress should be empirically justified; it is predicted that rime-based phonological weight distinctions will be phonetically superior to onset-based distinctions in such languages. These predictions will be tested for three languages in this paper: Pirahã (section 5), Banawá (section 6.1) and Arrernte (section 6.2).

Before testing these predictions, however, two preliminary steps are necessary. First, a means of quantifying phonetic effectiveness must be in place.

Gordon (2002a) hypothesizes that a weight distinction is phonetically superior to another weight distinction if it offers better separation of heavy and light syllables along a given quantifiable phonetic dimension. Separation is compared on the basis of mean values: a weight distinction is superior to another weight distinction if the difference between its mean values for heavy and light syllables is larger. This definition appears in (3) (Gordon 2002:57).

(3) Definition of phonetic effectiveness

A weight distinction *x* is more effective than a weight distinction *y*, if the difference between the mean energy of heavy syllables and the mean energy of light syllables for distinction *x* is greater than the difference between the mean energy of heavy syllables and the mean energy of light syllables for distinction *y*.

The second step in quantifying the link between phonetics and onset weight is to quantitatively model the contribution of onsets to the perceived prominence of a syllable. Perceptual energy is quantified as the summation of loudness over time: a rime's energy is thus a function of both its duration and its intensity. It is well documented in the psychoacoustic literature that the auditory system integrates intensity over time (Lieberman 1960, Beckman 1986; see Moore 1995 for a review of the literature). Due to this temporal summation effect, given two sounds of equivalent intensity, the longer sound will be perceptually louder. Lieberman (1960) and Beckman (1986) show that a measure of intensity integrated over time correlates well with stress in English.

Adaptation and recovery can be incorporated into the integrated intensity measure for a syllable rime by comparing the intensity during any single window of time with a baseline loudness value computed over the portion of the syllable (including the onset, since it influences the rime's perceived loudness) up until that target window. If the baseline value is less than the intensity of the target window, the target value receives an additional boost in loudness, since it is following a relatively less intense phase (recovery). Conversely, if the baseline value is greater than the intensity of the target window, the loudness of the target is diminished, since it follows a phase characterized by greater intensity (adaptation). The greater the difference in baseline and target values, the greater the effect of either recovery or adaptation. The loudness values calculated over all the windows are then summed to give the total perceptual energy for a given rime; a longer rime will of course have more windows to sum reflecting its greater perceptual energy relative to shorter rimes. All that is left is to specify recovery and adaptation constants. Drawing on estimates from graphs in Viemeister (1980), a recovery constant of 2dB per 11millisecond window (the length of the windows over which intensity was calculated) and an adaptation constant of 4dB per 11millisecond window were adopted. These constants are multiplied by the difference in intensity between the baseline and the target values. The output of this operation is added to the input intensity values to yield loudness values for each frame. A schematic example of the calculation of perceptual energy for a hypothetical rime is provided in table 2 for a 44 millisecond rime consisting of four intensity windows.

Table 2. Schematic example of perceptual energy calculation

Step 1

Step 6

Step 3

	Window 1 (0-11ms)	Window 2 (11-22ms)	Window 3 (22ms-33ms)	Window 4 (33ms-44ms)	Total
Intensity Average	45.14dB	40.86	42.57	37.14	
Diff(Ave-Baseline)	0	-4.28	8.12	-5.43	
Recov/Adapt Value		4 (Adapt)	2 (Recov)	4 (Adapt)	
Recov/Adapt * Diff	0	-17.12	16.24	-21.72	
(Recov/Adapt *Diff) + Ave	45.14	23.76	58.81	15.42	**143.13**
Baseline	45.14	34.45	42.57	35.78	

Step 4

Step 6

Step 5

First, the intensity values for each spectrum are calculated, yielding values of 45.14, 40.86, 42.57 and 37.14dB. The intensity difference between the first window and the second window is then computed: -4.28dB. Since the intensity of the second window is lower than that of the first window, the intensity difference of –4.28 is multiplied by the adaptation constant yielding a value of –17.12, which is then subtracted from the intensity value of the second window (40.86). The resulting value of 23.76 is then averaged together with the loudness values of all the preceding windows, in this case 45.14, giving an updated baseline value of 34.45 which then is compared to the intensity of the third window, a process which proceeds from left to right through the entire rime. Finally, all the loudness values are summed together to give the total perceptual energy for the entire rime, 143.13 decibel milliseconds.

Gordon (1999, 2002a) shows that a measure of perceptual energy offers a better fit with rime-sensitive weight distinctions than phonetic duration, another potential phonetic correlate of weight. Perceptual energy also turns out to more closely correlate with onset-based weight distinctions than duration (see section 5.2.4).

5. A case study of Pirahã

5.1. Methodology

The procedure for calculating perceptual energy was applied to data from Pirahã, a language with the weight hierarchy KVV > GVV > VV > KV > GV[8], where K stands for a voiceless consonant and G for a voiced consonant (see section 1). The Pirahã data were provided by Peter Ladefoged and was collected as part of an investigation of Pirahã phonetics conducted by Dan Everett, Keren Everett, and Ladefoged. Data were recorded using high quality noise cancelling microphones onto DAT tape. For the current project, data were transferred onto computer using Praat (www.praat.org) and downsampled to 22.05 kHz. The intensity values serving as the basis for the perceptual energy measurements were calculated sequentially over the frequency range 0-11kHz going from left to right throughout the entire syllable.[9]

Although practical considerations precluded collection of a perfectly balanced data set, the available material contained a representative cross sample of syllable types including all those comprising the weight hierarchy. Different onset consonants were targeted for measurement in the present study and vowels were systematically varied between the monophthongs /i/ and /a/ and the diphthong /ai/. All of the target syllables were stressed in order to avoid a confound between weight and stress; it thus cannot be the case that heavier syllables have greater energy because they are stressed, since light syllables are

---

[8] Note that the weight distinction between long vowels lacking an onset and those preceded by an onset is not amenable to a reanalysis parallel to Buckley’s (1998) account of Manam, which also makes a distinction between onsetless vowels and those with an onset. In Buckley’s account, the retraction of stress from an onsetless penult to an antepenult is due to coalescense of the two vowels into a diphthong with stress localized to the first half of the diphthong, e.g. ˈau.ta not ˈa.u.ta ‘inland’ (Buckley 1998:13). This account does not readily extend to Pirahã for a few reasons. First, it would require positing tetraphthongs, an otherwise extremely marked (if not unattested) entity cross-linguistically, to account for stress in words with CVV preceding VV, e.g. ˈgaoii ‘proper name’ not ˈgao.ii. Furthermore, it would have to be stipulated that tetraphthongization is suppressed in syllables before the penult in order to capture the three syllable window effect, e.g. kao.ˈái□.bó.gi□ ‘jungle spirits’ (Everett and Everett 1984:707) rather than *ˈkaoái.□bó.gi□. It is also unclear how the reanalysis would be reconciled with phonetic facts about the realization of stress or with native speaker intuititons about syllabification (see Everett 1988 218-9). Finally, assuming tetraphthongs would not eliminate the need for reference to onsets in the stress system, as syllables with a voiceless onset are heavier than those with a voiced onset.

[9] In cases in which the beginning of the onset could not be determined, i.e. for voiceless onsets not preceded by a vowel, a closure duration of 200 milliseconds was assumed for purposes of calculating baseline intensity; this figure was based on a combination of measurements drawn from forms in which durations could be measured and duration results in Everett (1998).

also stressed in the corpus. The target syllables all appeared in words repeated twice in isolation (see the appendix for the corpus).

Data from three male speakers were examined and the resulting perceptual energy measurements were bifurcated in several different ways, each representing a different weight distinction, in order to test the hypothesis that Pirahã's phonological weight distinctions are the most effective phonetically of the logically possible weight distinctions. Relative phonetic effectiveness of the evaluated weight distinctions was determined using a two step procedure. First, energy values according to each weight distinction were submitted to a discriminant analysis in order to determine which weight distinctions classified rimes into reliably distinct heavy and light syllables. Significance levels and Wilkes' lambda values for each weight distinction were examined to determine how reliably various weight distinctions differentiated heavy and light syllables. Lower Wilkes' lambda values generally indicate greater statistical robustness in the difference between heavy and light syllables.[10]

Weight distinctions which were statistically robust (at the $p<.05$ level) according to the discriminant analysis were then rank ordered in terms of the difference in mean energy values between heavy and light syllables, where distinctions showing greater separation between heavy and light syllable values were deemed phonetically more effective than those with lesser separation of heavy and light syllables. Weight distinctions that were not statistically robust according to the discriminant analysis were mutually ranked following the same procedure used to rank order the statistically reliable distinctions. Mean values rather than results from the discriminant analysis were used to rank order weight distinctions due to imbalances in the data set that could potentially influence results of the discriminant analysis.[11]

A total of 9 binary weight distinctions were tested for their separation of heavy and light syllables. Three of these distinctions were ones that conflate to yield the 5-way Pirahã weight hierarchy: long voweled syllables heavier than short voweled syllables, syllables with an onset heavier than onsetless syllables, and syllables with voiceless onsets heavier than those with voiced onsets. Together these binary distinctions capture all of the dimensions relevant in the net

---

[10] The lower the Wilkes' lambda value, the greater the amount of variance attributed to differences between the heavy and light syllables and the less the variance attributed to intertoken differences within the heavy or light groups. Because the Wilkes' lambda values are affected by factors such as sample size which are not claimed to be relevant to the hypothesis examined here, they were not used as the definitive criterion for ranking weight distinctions in order of phonetic effectiveness; rather, as pointed out in the text, mean values were used to rank the relative phonetic effectiveness of distinctions.

[11] Statistical significance values correspond closely to differences between means, such that weight distinctions entailing greater separation of heavy and light syllables according to mean values are also statistically more robust in virtually all cases.

weight hierarchy, with the rime-based distinction (long vowels vs. short vowels) taking precedence over the two onset-based distinctions. In addition to the actual distinctions employed by the Pirahã stress system, six other logically possible binary weight distinctions were tested. The first of these treated low voweled syllables as heavier than high voweled syllables ((C)a(a) > (C)i(i)); weight distinctions based on vowel quality are found in numerous languages, including Yimas (Foley 1991) and Kobon (see Kenstowicz 1997 on weight distinctions sensitive to vowel quality), and find an explanation in terms of the greater energy of low vowels relative to high vowels (Lehiste 1970). Also tested was a distinction between high-toned (i.e. level high tone, falling tone, and rising tone) and low-toned syllables, as high toned syllables are heavier than low toned syllables in many languages (see De Lacy 2002). A distinction between long monophthongs and diphthongs was also examined, since these two syllable types differ in weight in certain languages, e.g. Maori (Bauer 1993) and Dutch (Lahiri and Koreman 1988, Kager 1989). Also tested were several unattested but phonetically plausible distinctions, including the following: voiceless onsets followed by long /a/ heavier than other syllables (Kaa > others), syllables with voiceless onsets followed by a low vowel heavier than others (Ka(a) > others), and syllables with a long vowel or with a short vowel preceded by a voiceless onset heavier than others ((C)VV, KV > others).

The proposed account of onset weight predicts that the three binary distinctions comprising the Pirahã weight hierarchy should be phonetically superior to the other distinctions not exploited by Pirahã. Furthermore, because rime-based weight wins out over onset-driven factors in Pirahã (and in other languages in which they compete), the weight distinction based on vowel length should be phonetically superior to the two onset-based distinctions observed by Pirahã.

5.2. Results

5.2.1. Perceptual energy of the rime

The first phonetic dimension tested, the one offering the best match between phonetics and phonological weight, was total perceptual energy of the rime, a measure that entailed summing all the loudness values over the rime excluding the onset. Table 3 ranks the 9 tested weight distinctions in order of phonetic effectiveness according to the difference in the mean rimal perceptual energy of heavy and light syllables averaged over all speakers. Shaded weight distinctions fail to divide the heavy and light syllables into statistically distinct groups at $p<.05$. Phonological weight distinctions are in bold.

Table 3. Perceptual energy differences in the rime between heavy and light syllable mean values according to different weight distinctions in Pirahã

	Distinction	**Significance**	**Wilkes' λ**	**Diff (Heavy – Light) (arbitrary units)**
Best	Kaa > others	p=.000	.861	822.4
	(C)VV > CV	p=.000	.770	611.9
	(C)VV, Ka > others	p=.000	.820	585.4
	KV(V) > GV(V)	p=.000	.882	437.2
	CV(V) > V(V)	p=.009	.949	401.3
	(C)V_iV_j > (C)Vː	p=.364	.990	-139.2 (CVː >)
	High T > Low T	p=.204	.988	136.1
	Low V > High V	p=.307	.991	-121.7 (HiV >)
Worst	Ka(a) > others	p=.682	.999	53.2

As expected the four weight distinctions that are least robust in terms of their differentiation of heavy and light syllables are ones not observed by the stress system of Pirahã: long monophthongs vs. diphthongs, high toned syllables heavier than low toned syllables, low vowels heavier than high vowels and voiceless onsets plus low vowels heavier than other syllable types. It may be noted that low vowels have slightly less energy than high vowels and long monophthongs have slightly less energy than diphthongs (hence the negative value in the difference column for these two distinctions).

This leaves five reliable weight distinctions, including the three binary distinctions active in Pirahã, the best of which is the rime-based weight distinction, (C)VV > CV, as predicted. Unexpectedly, however, the rimal weight distinction, (C)VV > CV is phonetically inferior to another non-phonological weight distinction, the one that treats syllables with voiceless onsets followed by a long low vowel as heavy. Furthermore, the weight distinction which treats long voweled syllables and syllables containing a voiceless onset followed by a low vowel as heavy fares better than both of the onset-based distinctions exploited by Pirahã. Thus, contra the predictions of a purely phonetically informed model of weight, Pirahã does not incorporate the three phonetically best distinctions into its phonological weight system.

Gordon (2002a) offers an explanation for this apparent discrepancy between the predictions and the results, hypothesizing that the relationship between the phonetics and phonology of weight is mediated by structural complexity, which rules out certain phonetically effective weight distinctions that are sensitive to an overly complex combination of phonological dimensions. Based on a typology of weight in 388 languages, Gordon (2002a) finds a relatively small set of attested weight distinctions; these distinctions have in common that they are sensitive to a single phonological dimension. For example, many languages treat syllables with long vowels as heavier than those with short vowels. Others treat syllables with branching rimes, i.e. CVV and CVC, as heavy. Still others treat lower vowels as heavier than higher vowels. A few, including Pirahã, treat syllables with voiceless onsets as heavier than those with voiced onsets. Conspicuously absent are weight distinctions that simultaneously manipulate multiple phonological dimensions, e.g. distinctions which are sensitive to both onset voicing and vowel height (voiceless onsets plus low vowels heavy), or vowel height and length (long /aa/ heavy). Such distinctions are excluded on the basis of their phonological complexity, where Gordon (2002a:57) offers the following definition of this complexity threshold (4).

(4) Definition of complexity

A weight distinction is complex iff it refers to more than one place predicate.

OR

It makes reference to disjunct representations of the syllable.

Predicate in this definition refers to any association between a place feature and a theory neutral unit of weight, i.e. mora or timing position. A place feature linked to two weight units thus exceeds the complexity threshold.

The two unattested weight distinctions interspersed among the five phonetically best weight distinctions in Pirahã exceed this complexity threshold. The best weight distinction, the one treating Kaa as heavy, is complex since it refers to a place feature, [+low], linked to more than one weight unit. The phonetically third best weight distinction, the one which treats (C)VV and Ka heavy, is also complex, since it refers to both long vowels and low vowels preceded by a voiceless onset, thus requiring disjunct representations of heavy syllables, one for long vowels and the other for voiceless onsets followed by a low vowel.

In contrast, none of the weight distinctions actually employed by Pirahã exceeds the complexity threshold, since they can all be captured by a single representation of heavy syllables, as shown in figure 2. Heavy syllables are those consisting of minimally the structure contained in the representation of each distinction (see section 10 for further discussion and analysis).[12]

---

[12] In fact, we will see in section 10, that certain weight distinctions are better captured in terms of light rather than heavy syllables, such that light syllables maximally possess the predicates specified by the representation of a weight distinction. This does not affect the conclusions about structural complexity made here.

Figure 2. Representations of Pirahã weight distinctions

(C)VV > CV	KV(V) > GV(V)	CV(V) > V(V)
$[[X\ X]_R]_\sigma$	$[\underset{\substack{\vert \\ \text{-voice}}}{X}\ [X]_R]_\sigma$	$[X[X]_R]_\sigma$

Four other weight distinctions tested in Pirahã are also simple. The distinction between low and high vowels is simple, since it only makes reference to a single place feature. Similarly, the distinction between high and low toned syllables is simple since it refers to no place features. The distinction between long monophthongs and diphthongs is captured as a difference in number of root nodes: long monophthongs have two skeletal slots linked to a single root node, whereas diphthongs have two root nodes each of which is associated with its own skeletal slot. Finally, the distinction between syllables containing a voiceless onset followed by a low vowel is also simple since it requires reference to only a single place feature, the [+low] feature linked to the vowel. These simple weight distinctions fare poorly from a phonetic standpoint, since they fail to divide the heavy and light syllables into two reliably distinct groups.

Thus, if one assumes following Gordon (2002a) that choice of weight criterion is constrained by both phonetic effectiveness and phonological complexity, there is a perfect match between the predictions for Pirahã and the phonetic results: the three phonetically best of the simple weight distinctions are the actual phonological weight distinctions observed by Pirahã with the rime-based distinction being phonetically best among the simple distinctions.

Results for individual speakers follow a similar pattern with some minor differences, as shown in Table 4. Phonologically complex weight distinctions are omitted as they are eliminated as potential weight distinctions a priori due to their complexity.

Table 4. Perceptual energy differences in the rime between heavy and light syllable mean values according to different weight distinctions for individual speakers of Pirahã

Distinction	**Diff (Heavy – Light)**		
	Speaker 1	**Speaker 2**	**Speaker 3**
(C)VV > CV	643.5	477.3	737.4
KV(V) > GV(V)	396.8	531.8	376.0
CV(V) > V(V)	330.8	606.8	262.4
High T > Low T	158.7	178.3	71.6
(C)V_iV_j > (C)Vː	196.9	49.0	-172.2
Low V > High V	-64.8	-170.4	-144.2
Ka(a) > others	91.0	18.5	29.8

For all three speakers, the four phonetically least effective of the simple weight distinctions are the distinctions based on tone and vowel quality, the distinction between long monophthongs and diphthongs, and the distinction which treats voiceless onsets followed by low vowels as heavy. None of these distinctions are observed in Pirahã. The dominant pattern observed by two of the three speakers in keeping with the overall result in Table 3 is for the rime-based weight distinction to be phonetically superior to the two onset-sensitive distinctions. Only speaker 2 shows a reversal of this pattern, as the two onset-based distinctions fare slightly better phonetically than the rime-driven distinction. The other two speakers display the same rank ordering of the three phonological weight distinctions in terms of phonetic effectiveness.

5.2.2. Perceptual energy of the syllable

Perceptual energy of the entire syllable, i.e. onset plus rime, was also calculated. This measure differs from the measure of rimal energy in counting the onset not just in the calculation of baseline intensity but also in the total energy of the syllable. Table 5 ranks the 7 simple weight distinctions in order of phonetic effectiveness according to perceptual energy of the syllable.

Table 5. Perceptual energy differences in the syllable between heavy and light syllable mean values according to different weight distinctions

	Distinction	**Significance**	**Wilkes' λ**	**Diff (Heavy – Light) (dBms)**
Best	**CV(V) > V(V)**	p=.000	.791	1093.9
↑	**KV(V) > GV(V)**	p=.000	.735	808.0
	(C)VV > CV	p=.004	.939	423.5
	High T > Low T	p=.035	.967	302.0
	(C)V_iV_j > (C)Vː	p=.311	.988	-234.4
↓	Low V > High V	p=.216	.987	-189.6
Worst	Ka(a) > others	p=.484	.996	122.5

Parallel to the rimal energy results, the three phonetically most effective weight distinctions match the three phonological distinctions. However, the primary phonological distinction based on vowel length is only the third best of the three phonological distinctions in terms of phonetic separation of heavy and light syllables, indicating that perceptual energy of the entire syllable provides a worse fit to phonological weight in Pirahã than a measure of just rimal energy.

5.2.3. Acoustic energy

Total acoustic energy of the rime (factoring out adaptation and recovery) was also calculated. Differences in energy (expressed as the integration of intensity over time in decibel milliseconds) between heavy and light syllables for the simple weight distinctions appear in table 6.

Table 6. Acoustic energy differences between heavy and light syllable mean values according to different weight distinctions

	Distinction	**Significance**	**Wilkes' λ**	**Diff (Heavy – Light) (dBms)**
Best	**(C)VV > CV**	p=.000	.683	637.4
↑	**KV(V) > GV(V)**	p=.084	.974	183.7
	CV(V) > V(V)	p=.178	.986	184.5
	High T > Low T	p=.389	.994	82.0
	(C)V_iV_j > (C)Vː	p=.631	.997	-59.4
↓	Low V > High V	p=.139	.981	-157.6
Worst	Ka(a) > others	p=.365	.994	104.3

Although the primary phonological weight distinction based on rime length is phonetically superior to the other weight distinctions as predicted, the two onset-based phonological weight distinctions fare more poorly, failing to divide the heavy and light syllables into statistically distinct groups. Acoustic energy thus does not match up as well with phonological weight in Pirahã as a measure of perceptual energy incorporating adaptation and recovery.

To see why acoustic energy does not fare as well as rimal perceptual energy in predicting weight criteria, it is instructive to examine the correlation between the two phonetic dimensions. A regression analysis was performed to determine the extent to which acoustic energy and perceptual energy in the rime are correlated. As expected, the two dimensions are closely correlated if all data are pooled together, r^2=.903. More informative is the comparison of the relationship between perceptual and acoustic energy for syllables with different onsets. Because of adaptation and recovery we would expect perceptual energy to be greatest relative to acoustic energy for a rime following a voiceless onset, smallest for a rime following a vowel (i.e. in a hiatus context), and intermediate for a rime following a voiced onset. Figure 3 plots acoustic energy vs. perceptual energy values for rimes preceded by a voiceless onset (circles), rimes preceded by a voiced onset (squares), and rimes preceded by a vowel, i.e. lacking an onset (triangles). As expected, perceptual energy is greatest relative to acoustic energy for vowels preceded by a voiceless onset. Furthermore, perceptual energy is slightly greater relative to acoustic energy for vowels before a voiced onset than for immediately postvocalic vowels, as predicted. The differences between rimes as a function of preceding context is reflected in slope values for lines fitted to data points: the slope is shallowest in the case of rimes preceded by a voiceless onset, .853, steepest for rimes preceded by a vowel (i.e. lacking an onset), 1.069, and intermediate in steepness for rimes following a voiced onset, 1.058. In summary, the perceptual model of energy provides a better fit to the typology of onset weight than the acoustic model of energy.

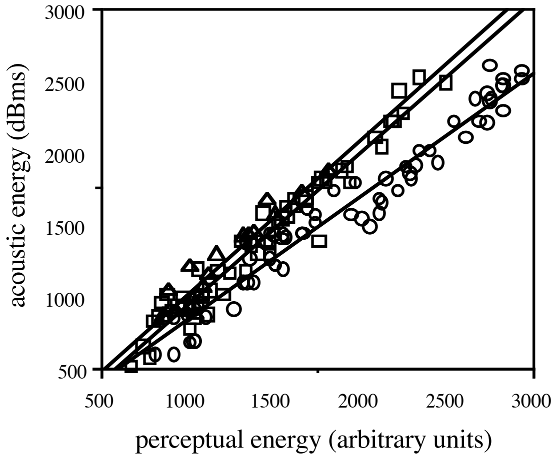


Figure 3. Perceptual energy (x-axis) plotted against acoustic energy (y-axis) for different rimes (circles = rimes after voiceless onset, squares = rimes after voiced onset, triangles = rimes after vowel)

5.2.4. Acoustic Duration

Syllable duration was also tested as a potential correlate of weight, since K. Everett (1998) found that syllable duration is a reliable correlate of stress in Pirahã. Results for the simple weight distinctions appear in table 7.

Table 7. Duration differences between heavy and light syllable mean values according to different weight distinctions

	Distinction	Significance	Wilkes' λ	Diff (Heavy – Light) (ms)
Best	**CV(V) > V(V)**	p=.000	.858	119.7
↑	**KV(V) > GV(V)**	p=.000	.724	111.9
	(C)VV > CV	p=.002	.929	60.8
	High T > Low T	p=.072	.976	34.3
	(C)V_iV_j > (C)Vː	p=.734	.999	-10.2
↓	Low V > High V	p=.086	.974	-35.0
Worst	Ka(a) > others	p=.698	.999	9.2

Duration matches up fairly well with phonological weight, as the three phonetically best weight distinctions that are not complex are those observed by the Pirahã stress system. However, the duration measure ranks the rime-based weight distinction behind the two onset-driven ones in terms of phonetic effectiveness, even though rimal weight takes precedence over onset weight in the phonological system. Thus, duration does not provide as good a fit to phonological weight as a measure of rimal perceptual energy.

In summary, rimal perceptual energy provides the closest fit to phonological weight in Pirahã. This close match between perceptual energy of the rime and phonological onset weight raises questions about the directionality of the phonetics-phonology relationship. This issue will be discussed further in section 9, where it is claimed that a bidirectional relationship holds between phonetic energy and phonological weight. First, however, section 6 explores the phonetic basis for onset weight in word-initial syllables.

6. Word initial onset weight distinctions

Unlike Pirahã, there are also languages in which onset weight is relevant only word-initially.[13] For example, in certain languages (Alyawarra, Arrernte, Mbabaram, Iowa-Oto, Banawá), a vowel-initial word has stress on the second syllable (but only in words longer than two syllables in Arrernte and containing more than two rimal timing positions in Banawá), while a consonant-initial word stresses its first syllable. It is not immediately clear how an account based on auditory adaptation applies to such systems, since a vowel-initial word uttered in utterance-initial position or isolation, a subtype of utterance-initial position, has no preceding vowel that would trigger adaptation. In these contexts, a vowel in initial position is preceded by silence, which should provide a perceptual boost to the following vowel. We would thus not expect an onsetless word-initial syllable to be any lighter than a word-initial syllable containing an onset.

There is, however, an important consideration that might account for the lesser weight of onsetless syllables in word-initial positions. Given that words are not always uttered in isolation (or utterance-initial position), there are contexts in which a word-initial vowel would be preceded by a word ending in a vowel, in which case adaptation would adversely affect the word-initial vowel. These phrase-medial instantiations of a vowel-initial word would thus contribute to a reduction in the overall perceptual energy profile of word-initial vowels. This account is particularly compelling for languages in which word-final syllables characteristically end in a vowel. In such languages, the majority of word-initial vowels would suffer a reduction in prominence due to auditory adaptation in the hiatus context spanning the word boundary. Of the five languages surveyed with a word-initial onset-based weight distinction, two (Banawá and Iowa-Oto) end all words with a vowel. Phonetic evidence for the role of adaptation in explaining

---

[13] Pirahã lacks words beginning with a vowel; the weight distinction between onsetless syllables and those with an onset thus does not come into play word-initially.

the light status of onsetless syllables word-initially will be shown for Banawá in the next section. The other three surveyed languages with an onset weight distinction in initial syllables (Arrernte, Mbabaram, Lamalama) , however, do not have vowel sequences across word boundaries. For these languages, the account based on adaptation across a word-boundary is unsatisfactory and an alternative analysis will be considered in section 6.2 drawing on phonetic data from Arrernte.

6.1. The phonetic basis for hiatus-induced word-initial onset weight: a case study of Banawá

In Banawá (Buller et al. 1993, Ladefoged et al. 1997), an Arawan language of Brazil, stress is based on counting rimal timing slots (i.e. vocalic timing positions), with primary stress falling on the initial rimal timing slot of words containing fewer than three rimal timing slots. Onset-sensitivity reveals itself in words containing at least three rimal timing slots; such words carry primary stress on the first rimal timing slot preceded by an onset consonant. Secondary stress falls on every second rimal timing slot counting from the primary stress. There are no coda consonants and vowel length is not phonemic; vowels are phonetically long in monosyllables. Examples of Banawá stress appear in (5).

(5) Banawá stress (examples from Ladefoged et al. 1997:108 and Everett, Everett and Ladefoged fieldwork word list) (periods separate vocalic timing slots)

Initial stress		*Peninitial stress*	
ˈuwi	‘cry’	uˈwi.a	‘go out (as of a fire)’
ˈbita	‘mosquito’	uˈwari.ˌa	‘one’
ˈwaraˌbu	‘ear’	uˈfabuˌne	‘I drink’
ˈwanaˌkuri	‘spider’	iˈde.i	‘he spears’
ˈka.iˌɟara	‘to take pride in oneself’	iˈbufa	‘to dump into water’

6.1.1. Methodology

Data from three male speakers of Banawá collected by Dan Everett and Peter Ladefoged as part of a phonetic study of the language (Ladefoged et al. 1997) were examined, with the corpus for the present study consisting of vowels both preceded by an onset and those lacking an onset. The target vowels occurred in two contexts in order to reflect differences in the positions in which vowel-initial words may occur in Banawá. The first context was a non-hiatus context, in utterance-initial position. All target vowels under this condition came from words containing two rimal timing slots and were stressed in order to eliminate stress as a confounding factor. The second context was a hiatus context, immediately following another vowel. Due to constraints of the data set, the target vowels were all in unstressed final syllables immediately following another vocalic timing slot. Though non-initial vowels in hiatus contexts are not strictly equivalent to initial vowels in a hiatus context spanning a word boundary, they offer a means for estimating the effect of a vowel on the perceptual energy of an immediately following vowel. In order to allow for examination of onset as a factor, the data set also contained vowels preceded by an onset in both non-hiatus and potential hiatus (i.e. utterance-non-initial) contexts. Table 8 exemplifies some of the words (target vowels and consonants in bold) in the corpus; see the appendix for the complete corpus.

Table 8. Sample words in the Banawá corpus

	Postvocalic (potential hiatus)	*Initial (no hiatus)*
Onset consonant	ˈba**da** ‘proper name’	ˈ**a**ba ‘fish’
No onset consonant	oˈwi.**a** ‘go out (fire)’	ˈ**da**ma ‘to hold securely’

The target vowels were /i/ and /a/ and the target onset consonants represented a cross-section of onsets found in Banawá, including voiced stops, voiceless stops, nasals, and fricatives. Varying both vowel height and type of onset allowed for testing the phonetic effectiveness of various weight distinctions. Each word was repeated twice by each speaker and recorded onto DAT tape. For the current project, data were transferred onto computer using Praat and downsampled to 22.05 kHz for analysis.

Data analysis procedures followed those employed in the Pirahã experiment discussed in section 5.1 with certain additional provisions. The duration values for word-initial voiceless stop closures used in the perceptual energy calculations were based on measurements from equivalent intervocalic consonants. These values were also applied to absolute-word initial vowels in order to model the recovery afforded by the silence preceding an utterance-initial vowel. In the case of initial vowels with a glottalized onset (common in the case of /a/), the duration of the silent phase was reduced by the duration of glottalization.

6.1.2. Results

Table 9 contains a list of phonologically simple weight distinctions and their phonetic effectiveness in Banawá along the dimension of rimal perceptual energy.

Table 9. Perceptual energy differences in the rime between heavy and light syllable mean values according to different weight distinctions in Banawá

	Distinction	**Significance**	**Wilkes' λ**	**Diff (Heavy – Light) (dBms)**
Best	**CV > V**	p=.001	.925	136.8
↕	Ka > others	p=.060	.975	101.5
	KV > GV	p=.142	.977	62.8
Worst	Low V > High V	p=.767	.999	11.9

The phonetically most effective of the simple weight distinctions is the actual phonological distinction between onsetless vowels and vowels preceded by an onset. Other weight distinctions do not fare as well phonetically, failing to reliably differentiate heavy and light syllables. Similar results obtain for individual speakers as shown in table 10.

Table 10. Perceptual energy differences between heavy and light syllable mean values for individual speakers of Banawá

Distinction	**Diff (Heavy – Light)**		
	Speaker 1	**Speaker 2**	**Speaker 3**
CV > V	203.7	111.9	93.9
Ka > others	107.5	100.2	91.7
KV > GV	74.6	65.1	48.7
Low V > High V	-28.3	6.3	55.6

Crucially, the onset weight distinction is only phonetically effective if vowels in hiatus contexts are included in the results. In utterance-initial position, there was no significant difference in perceptual energy between onsetless vowels and those preceded by an onset: t(1,68)=.207, p=.071 according to an unpaired t-test pooled over all speakers. In fact, vowels lacking an onset have marginally greater perceptual energy than those with an onset: 744.6 vs. 736.0.[14] If, however, postvocalic vowels are factored into the equation, a robust difference in perceptual energy between onsetless vowels and vowels preceded by a consonant emerges, as predicted: 651.4 for vowels preceded by an onset vs. 514.6 for postvocalic vowels: t(1, 140)=3.366, p=.004. In summary, data from Banawá

---

[14] The reason for the lack of a reliable difference between the two is attributed to the slightly greater length of onsetless utterance-initial vowels: 121ms vs. 108ms, a difference which was barely significant according to a t-test: t(1,68)=1.729, p=.048. The greater energy of onsetless vowels offsets their slightly (but not statistically reliable) reduced acoustic intensity relative to vowels preceded by an onset: 60.2 dB vs. 62.2 dB.

offer support for the hypothesis that word-initial onset weight distinctions can be attributed to adaptation effects parallel to those responsible for word-internal onset distinctions. In the case of word-initial onset weight, however, adaptation is only relevant for utterance-non-initial instantiations of a word where hiatus is present across word boundaries. These instantiations contribute to the reduction in the overall perceptual energy profile of vowel-initial words thereby triggering their light phonological status.

6.2. The prioritization of rimal weight over onset-weight: a phonetic study of Arrernte

This section explores the phonetic basis for another type of word-initial onset weight distinction, one found in Arrernte (Strehlow 1942, Breen and Pensalfini 1999) that is less plausibly attributed to adaptation. In Arrernte disyllables (there are no monosyllables), stress falls on the first syllable in both consonant-initial and vowel-initial words.[15] In trisyllabic or longer words, however, stress only falls on the first syllable if the word begins with a consonant; vowel-initial words place stress on the second syllable. Secondary stress falls on alternating non-final syllables after the primary stress. Examples from Arrernte appear in (6).

(6) Arrernte stress (examples from Davis 1988:1)

Initial stress		*Peninitial stress*	
ˈkama	‘to cut’	erˈguma	‘to seize’
ˈilba	‘ear’	arˈt̪anama	‘to run’
ˈtukura	‘ulcer’	utˈnadaˌwara	place name
ˈwoyour			

---

[15] Breen and Pensalfini (1999) propose an analysis of Arrernte in which all words begin with a vowel, which is subject to deletion in many cases. Pursuing this analysis within a derivational paradigm, one could analyze stress as consistently peninitial provided stress applies prior to deletion. If one were to adopt a quantity-insensitive analysis of Arrerente stress in a parallelist constraint-based model, one would have to assume that a word-initial consonant forms its own syllable distinct from a following vowel, with stress falling on the second syllable. An onset-based analysis is pursued here, since there is disagreement in the literature about whether all syllables are onsetless on the surface (see Evans 1995 for discussion), the relevant level for assessing well-formedness in a constraint-based analysis of the kind assumed later in this paper (section 10). In any case, although an analysis with onsetless syllables could possibly be extended to other Australian languages (Mbabaram and Alyawarra) in which word-initial onsetless syllables are light and in which initial vowels are prone to deletion, such an analysis would not carry over to other languages with a similar weight criterion, such as Banawá or Iowa-Oto, neither of which are reported to delete initial vowels (see section 6.1 for phonetic data on Banawá).

The Arrernte data is interesting for two reasons. First, unlike Banawá, Arrernte has words that end in a consonant utterance-medially. This means that the rejection of stress by onsetless word-initial syllables is not likely to result from auditory adaptation across a word boundary, since a consonant-final word affords a period of auditory recovery to an immediately following word-initial vowel. In fact, Breen and Pensalfini (1999:2) argue that all words underlying begin with a vowel and end with a consonant, with an epenthetic vowel optionally occurring utterance-finally. Hiatus is thus absent across word boundaries in Arrernte, meaning that an alternative explanation must be sought for the rejection of stress by word-initial syllables lacking an onset.

The second point of interest concerns the prioritization of onset weight over rime weight. As examples like erˈguma 'to seize' show, a coda consonant is not enough to attract stress to a vowel-initial word. It is thus evident that the rime is ignored in the calculation of weight in favor of the onset, a pattern contrary to that found in most languages.[16] Thus, investigating the match between phonetic effectiveness and phonological weight is particularly important for Arrernte, since, based on the auditory effects claimed to underlie onset weight in this paper, onset-based distinctions would not a priori be expected to be phonetically superior to rime-based distinctions.

6.2.1. Methodology

In order to test the match between phonetic effectiveness and phonological weight in Arrernte, a phonetic study of perceptual energy was conducted. Data from one female speaker of Eastern Arrernte recorded by Andrew Butcher and on file in the UCLA Phonetics Laboratory were examined. The measured data (see appendix) consisted of stressed syllables that were also word initial in all but one word. The target syllables varied along three dimensions: vowel quality (/i/ or /a/), whether they had an onset or not, and whether they had a coda consonant or not. The target words were all repeated three times. Measurement procedures followed those adopted for the Banawá experiment. The available data allowed for testing three weight distinctions: the phonological distinction based on the presence vs. absence of an onset, a rime-based distinction based on the presence vs. absence of a coda consonant, and a distinction based on vowel height.

6.2.2. Results

Results for perceptual energy in the rime appear in table 11.

---

[16] It may be noted, though, that rimal weight distinctions are relatively rare in languages that lack phonemic vowel like Arrernte (Hyman 1977, Gordon 1999).

Table 11. Perceptual energy differences in the rime between heavy and light syllable mean values according to different weight distinctions in Eastern Arrernte

Distinction	Significance	Wilkes' λ	Diff (Heavy – Light) (dBms)
CV > V	p=.000	.566	481.1
CVC > CV	p=.023	.787	337.4
Low V > High V	p=.663	.991	68.4

The phonetically most effective distinction is the one based on the onset with the rime-based distinction ranking next. The distinction based on vowel height fared poorly in terms of phonetic effectiveness. Although this result is consistent with the correlation between phonetic effectiveness and phonological weight established for Pirahã and Banawá, the greater effect of onsets than rimes on perceptual energy is somewhat surprising from a phonetic perspective.

As it turns out, two language specific phonetic properties of Arrernte account for the result. First, vowels are very short in onsetless syllables relative to syllables with an onset: 72 milliseconds vs. 146 milliseconds averaged over the current data, a more pronounced version of the smaller absolute utterance-initial shortening effect found for nasals in Korean (Cho and Keating 1999) and English (Fougeron and Keating 1997). Second, vowels are longer in open syllables than in closed syllables, following a common cross-linguistic trend (Maddieson 1985): 119 milliseconds vs. 103 milliseconds.[17] This open syllable lengthening effect is confined to syllables with an onset (168ms vs. 123ms), and is not present in onsetless syllables, where closed syllables are in fact shorter than open syllables (60ms vs. 83ms).

The shortening of onsetless vowels and lengthening of vowels in open syllables with an onset has a dramatic effect on the relative size of the phonetic effect of the onset as compared to the rime on perceptual energy. First, the shortening of onsetless vowels increases the difference in energy between onsetless syllables and those with an onset. Second, the lengthening of vowels in open syllables diminishes the difference in energy between CV and CVC. Together these two phonetic effects thus enhance the phonetic effectiveness of the onset-based distinction relative to its rime-based counterpart, thereby offering an explanation for the results in table 9.

I would speculate that both of the substantial subphonemic durational effects (lengthening and shortening) in Arrernte are to be attributed to two language-specific features of the phonology: the absence of phonemic vowel length and the

---

[17] As a reviewer points out, the open syllable lengthening effect seen in Arrernte (and many other languages) provides evidence that perceptual energy must be calculated over the entire rime and not just the vocalic nucleus; otherwise we would expect languages in which CV is heavier than CVC, a pattern which appears to be unattested.

unusually small vowel inventory of Arrernte. Breen and Pensalfini (1999) report only three vowels: a low vowel /a/, a high vowel /i/, which is relatively rare, and a featureless vowel, which assumes its quality based on its surrounding environment. The small vowel inventory is ideal from the point of view of perceptual distinctiveness, since extreme shortening of vowels in Arrernte would be less likely to render them insufficiently distinct than in a language with a larger vowel inventory, under the assumption that perceptual distinctiveness of a property increases with length of realization (cf. Kaun 1995 on vowel harmony). Furthermore and more importantly, the absence of phonemic vowel length leaves more room for subphonemic length differences between vowels without jeopardizing the perceptibility of phonemic contrasts.

Although I do not have phonetic data to test the hypothesis, it is quite possible that other languages which have closed syllables and in which word-initial onsets contribute weight, including Mbabaram, Alyawarra, and Lamalama, display phonetic properties similar to Arrernte which could conspire to make their phonological onset-based distinctions phonetically more effective than rime-based distinctions. These languages also lack phonemic vowel length and/or possess unusually small vowel inventories as well. Phonemic vowel length has a marginal status in Mbabaram and the only vowel which occurs in absolute word-initial position is /a/ (Dixon 1991). Alyawarra possesses only three phonemic vowels, /a/, /i/, /u/, and long vowels are limited to /iː/ and /uː/ both of which are rare and have an alternative diphthongal pronunciation (Yallop 1977:27). Data on the vowel system of Lamalama is far sketchier. Laycock (1969) does not report vowel length, recording six phonemic vowels which, however, he asserts is "almost certainly at least one vowel too many."

6.3. Perceptual energy and onset weight: a summary

In summary, we have seen that a measure of perceptual energy integrated over the rime correlates well with onset weight in three languages displaying different syllable structures and/or different stress patterns. The complex weight hierarchy of Pirahã, in which rimal weight is superordinate to onset weight, corresponded closely to a hierarchy of phonetic effectiveness. Investigation of Banawá's binary onset distinction in word-initial position further supported the match between perceptual energy and weight. The Banawá data were also consistent with the hypothesis that hiatus spanning a word boundary can trigger the adaptation effect responsible for the light status of onsetless syllables in certain languages. Finally, the greater phonetic effectiveness of Arrernte's word-initial onset weight distinction relative to other hypothetical rimal distinctions was attributed to language specific duration patterns made possible by Arrernte's small vowel inventory. In the next section, the present approach grounded in perceptual energy is compared with another phonetically driven account of onset weight, that of Goedemans (1998).

7. Goedemans (1998) phonetic approach to onset weight

In his seminal work on the phonetic basis for onset weight, Goedemans (1998) argues that the characteristic weightless status of onsets is attributed to listeners' relative insensitivity to onset duration. In a series of perception experiments using synthetic stimuli, he shows that Dutch listeners perceive fluctuations in onset duration less accurately than changes in either vowel or coda duration. For example, in one experiment, listeners were asked to adjust the duration of a comparison stimulus (a sawtooth wave or a band of white noise depending on the reference syllable) to match the duration of two synthetic CVC syllables whose onset, vowel, and coda durations were systematically manipulated. One syllable was *mam*, the Dutch word for 'mother', while another was *sas*, the Dutch word for 'good humour'. When adjusting the comparison signal to the CVC reference syllables, listeners dramatically underestimated fluctuations in onset duration, slightly underestimated changes in coda duration, and marginally overestimated adjustments in vowel duration. Shifts in vowel duration in the comparison stimulus were roughly equivalent for both the *mam* and *sas* reference stimuli. For the *mam* stimulus, listeners overestimated duration changes in the nucleus by an average factor of 1.17, i.e. listeners adjusted the comparison stimulus by 35 milliseconds when the duration of the nucleus in the reference stimulus was changed by 30 milliseconds. The overestimation factor for the vowel in the *sas* stimulus was 1.33. A clear difference emerged between the *mam* and *sas* stimuli in the perception of shifts in consonant duration, such that listeners were better able to estimate duration shifts for sonorant consonants than for obstruents. Thus, changes in coda duration were underestimated by a factor of .3 for the *mam* stimulus, while the underestimation factor rose to .54 for *sas*. For the *mam* stimulus, changes in onset duration were underestimated by a factor of 2. The underestimation factor climbed to 3 for the *sas* reference stimulus.

As Goedemans' claims, the underestimation of changes in onset duration is consistent with the typological rarity of onset sensitive stress systems. Furthermore, his results line up well with the prioritization of rimal weight over onset weight in languages with both types of weight distinctions. Goedemans' results have the additional virtue of reflecting the implicational relationship between coda and vocalic weight, whereby vowels are universally weight-bearing but coda consonants may or may not contribute weight on a language specific basis. One area, however, in which results from Goedemans' psychoacoustic experiments do not appear to accord with the typology of onset weight, is the relationship between sonority and weight in onset position. Listeners were better able to discern duration shifts in sonorant consonants than in obstruents in Goedemans' data, suggesting that sonorants might be heavier than obstruents in certain languages. Although this asymmetry is found for codas in certain languages, e.g. Kwakw'ala (see section 2.2), exactly the opposite pattern holds for onset position, where lower sonority onsets are heavier than higher sonority ones in certain languages, e.g. Pirahã, Tümpisa Shoshone. The approach based on perceptual energy in contrast makes the correct predictions about the relationship between sonority and weight in onset position.[18]

Goedemans' work also differs from the present work in its view of the directionality of the relationship between phonetics and the phonology of weight. In interpreting the results from his initial round of experiments, Goedemans' poses the possibility that the relative insensitivity to duration changes in onsets could be due to their weightless status. In order to tease apart this approach from an alternative in which the weightlessness of onsets is attributed to human beings' inherent insensitivities to onset duration, Goedemans designed a follow-up experiment in which he tested just-noticeable differences (JNDs) in duration using *non-speech* stimuli, consisting of a sawtooth wave (rather than a synthesized vowel) flanked by noise on both sides. He found that JNDs were virtually identical for the noise on both sides of the sawtooth wave and for the sawtooth wave itself. Equating the flanking noise with onset and coda and the sawtooth wave, which is a periodic signal like a vowel, with the nucleus, Goedemans' concludes that the results found in his original experiments using speech stimuli were attributed to the phonological weightlessness of onsets rather than to inherent biases against perceiving onset duration.

The present study differs from Goedemans' phonology-drives-phonetics position in assuming a bidirectional relationship between the phonetics and phonology of weight, such that the phonology of weight not only influences phonetic properties but is also shaped by the auditory system's temporal response to speech stimuli. In particular, if adaptation and recovery are taken as primitive factors playing a role in the development of phonological systems, a number of typological features of onset weight can be explained, including the prioritization of rimal weight over onset weight and the inverse correlation between consonantal sonority and weight in onset position. The nature of this relationship between the phonetics and phonology of onset weight is discussed further in section 9.

---

[18] Goedemans (p. 143-8) suggests that the heavier status of voiceless onsets in Pirahã is due to the sonority difference between a voiceless consonant and a vowel which enhances the prominence of the vowel. The recovery and adaptation effects claimed to underlie onset weight in this paper offer an explicit and quantifiable mechanism for explaining the effect of the sonority difference between onset and rime on the perceptual prominence of the rime.

8. The role of the syllable in onset-weight

The existence of at least two languages in the survey, Bislama and Nankina, sensitive to branching onsets in their calculation of weight raises issues about the function of syllabic constituency in predicting onset weight. If branching onsets are heavier than single onsets, syllables preceded by a closed syllable might be expected to be heavier than ones preceded by an open syllable, since the combination of coda consonant followed by an onset offers in principle the same recovery phase to a following vowel afforded by a complex onset. In both cases, two consonants precede the vowel in question: VC.CV vs. V.CCV. I am unaware, however, of any languages in which a closed syllable contributes weight to the following syllable.

I believe that the apparent absence of such systems is an accidental gap related to the temporal nature of auditory recovery coupled with cross-linguistic syllabification conventions. Data in Delgutte (1982) suggests that the bulk of the auditory recovery process takes place fairly rapidly, well within the time span provided by a single consonant. Delgutte (1982) contains graphs showing the effect of lengthening the duration of a silent stop closure on the perception of a following fricative. Of the three silence durations shown, 0, 40, and 100 milliseconds, the greatest difference in auditory nerve firing rates occurs going from the 0 to the 40 millisecond condition, with a considerably more modest effect exerted by increasing the preceding silence from 40 to 100 milliseconds. Given that consonants are virtually always longer than 40 milliseconds (see Lehiste 1970 for a cross-linguistic overview of consonant duration), Delgutte's results suggest that the greatest auditory boost to a following vowel is provided by the consonant immediately preceding the vowel with only a slight additional boost provided by a second consonant. This physiological fact fits in with the phonological observation that the branching status of the onset rarely plays a role in stress compared to the distinction between syllables with an onset and those without (see section 2). The lesser auditory contribution of the first consonant in a cluster is particularly evident when the second consonant is less sonorous than the first consonant; in such cases, the second consonant is likely to be almost entirely responsible for the recovery effect on the following vowel. In contrast, the first consonant in a cluster is likely to trigger a greater recovery effect if it is less sonorous than C2. However, clusters in which C1 is less sonorous than C2 are far more likely to syllabify as a complex onset word-medially than clusters in which C1 is more sonorous than C2. As a result, the clusters that are most likely to be relevant for weight are least likely to span a syllable boundary. Thus the prospect of finding a language in which a second prevocalic consonant is both decisive for weight (an unlikely occurrence due to the temporal nature of recovery) and also belongs to the coda of a preceding syllable is slim, though not logically precluded.

9. The directionality of the relationship between phonology and phonetics

Thus far, this paper has focused on establishing a correlation between phonological weight and a phonetic measure of energy without taking an explicit stand on the directionality of the relationship between phonetics and phonology. A priori there are at least three possible characterizations of this relationship, all of which are compatible in principle with the Pirahã, Banawá, and Arrernte data. One possibility is that languages arbitrarily choose weight distinctions without regard to phonetic properties and then tailor their phonetics to be in sync with the phonology, thereby enhancing the expression of their phonological weight distinctions. Another view takes phonetic factors as basic and assumes that languages choose weight criteria that are well coordinated with phonetic properties. Yet another possibility is that the relationship between phonetics and phonology is bidirectional. Under this view, languages prefer to adopt weight criteria that are well suited to their phonetic map, but can also adjust their phonetic properties to better match their phonological weight criteria.

There is evidence, I believe, that this last position is closest to reality. Section 9.1 discusses segmental effects that appear to argue that phonology influences phonetics. Section 9.2 discusses results of an energy simulation suggesting that languages are sensitive to phonetic considerations in choosing from among potential weight criteria.

9.1. Stress-driven segmental effects on the onset

In her discussion of positional augmentation, Smith (2002) discusses languages in which stressed syllables undergo processes designed to enhance their prominence. Certain of these processes are predicted by the present account of onset-sensitive stress. For example, Dutch (Booij 1995) has a process of glottal stop epenthesis between two vowels, the second of which is stressed; epenthesis does not interrupt vowel sequences in which the second vowel is unstressed. We thus have pairs such as xá.ɔs 'chaos' and a.ʔɔ́r.ta 'aorta' in which the presence of glottal stop is predictable based on stress. The insertion of glottal stop may be viewed as another instantiation of the association between auditory prominence and onset-sensitive weight: in the Dutch case, insertion of a glottal stop provides an auditory boost to the following stressed vowel.

Lengthening of an onset consonant is another strategy for providing a following stressed vowel with an auditory boost through enhancement of the recovery phase prior to the onset of the vowel. Estonian regularly lengthens consonants in the onset of stressed syllables, by approximately 15-23 milliseconds (Gordon 1997). Similarly, in stressed syllables, Karo (Gabas 1999) lengthens voiceless onsets, the type of onsets that contribute most to the perceptual prominence of a following vowel.

Both the lengthening of onset consonants and the insertion of glottal stop before stressed vowels may be viewed as attempts to enhance the perceptual realization of phonological stress. Increasing the distance between a stressed vowel and a preceding vowel increases the auditory prominence of the stressed vowels, thereby ensuring a better match between the phonetics and phonology of stress. A parallel beefing up of stressed syllables is observed for the rime in many languages. For example, many languages lengthen stressed vowels or add a coda consonant to stressed syllables by geminating the following onset (see Hayes 1995:82-85 for discussion).

It is also possible that a similar phonetic enhancement of phonological weight contributes to the correlation between energy and weight observed in the data examined in this paper. For example, it is conceivable that Pirahã enhances the phonetic effectiveness of existing weight distinctions through a number of low level phonetic processes, e.g. lengthening the onset and rime, increasing the intensity of voiced onsets, lowering the intensity of voiceless onsets, etc. Similarly, Arrernte and Banawá may shorten or make less intense their onsetless vowels in order to enhance the energy difference between onsetless syllables and those with an onset. All of these hypothesized phonetic adjustments would contribute to the strong match between phonetic effectiveness and phonological weight observed in this paper.

9.2. Phonetic influences of weight

There is also evidence that languages are responsive to phonetic considerations in selecting weight distinctions. One piece of evidence concerns the asymmetry between onsets and codas in the relationship between sonority and weight. Recall from section 2 that lower sonority consonants are heavier in onset position, but lighter in coda position in certain languages. As we have seen, there is a phonetic explanation for this asymmetry: the perceptual energy of the rime is enhanced by a lower sonority onset due to the recovery period it provides, whereas a higher sonority onset affords less of a perceptual boost. In contrast, greater sonority in the rime helps to offset the reduction in perceptual energy due to adaptation. If the phonology of weight were not sensitive to the different phonetic effects of sonority in onset and coda position, the asymmetrical relationship between sonority and weight in the two contexts would be coincidental.

Phonetic considerations also offer an explanation for the primacy of rimal weight over onset weight, reflected both in the cross-linguistic rarity of onset weight and the subordination of onset weight to rimal weight in languages with both rime-based and onset-based weight criteria. As discussed in section 4, the auditory boost provided by an onset is most salient at the beginning of the vowel before gradually diminishing throughout the duration of the vowel. Furthermore, the perceptual boost in loudness at any point in time attributed to the onset is relatively small compared to the absolute intensity values characteristic of speech. For these two reasons, the effect of the onset on perceptual energy of the rime is predisposed to be relatively small compared to that of the rime itself.

Another way to address the directionality of the relationship between perceptual energy and phonological weight is through energy simulations representative of languages without weight-sensitive stress. Languages without weight-sensitive stress would have no reason to make rime-based weight distinctions phonetically more effective than onset-based ones. If rime-based weight distinctions were to turn out phonetically superior to onset-based distinctions in weight-insensitive stress systems, this would count as strong evidence that the rarity of onset weight is due to the lesser phonetic effectiveness of onset distinctions relative to rimal ones.

In order to address this issue, a series of energy simulations were carried out using intensity and duration values typical of the world's languages. The values used for the simulations reflected the synthesis of cross-linguistic phonetic tendencies, such as the greater duration of low vowels (Peterson and Lehiste 1960) and of vowels in open syllables (Maddieson 1985), and data on several languages whose phonetic properties were examined in other experiments (Gordon 1999, Gordon 2002a): Bole, French, Finnish, Chickasaw, Italian, Czech, Russian, Farsi, Japanese, Hausa, Lithuanian, Telugu, Javanese. Several of the languages forming the basis for the simulation do not have weight-sensitive stress systems, e.g. Bole, French, Farsi, Hausa, Lithuanian, Russian and would thus not be predisposed to display phonetic properties more compatible with particular weight distinctions. The initial simulation included a cross-section of onset and rime types, all of which were cross-classified to yield a variety of syllable types. Onset and coda consonants included a sonorant, a voiceless fricative, a voiced fricative, a voiced stop, and a voiceless stop, while the vowel was varied between short and long /a/ and /i/. Subsequent simulations eliminated more marked consonants, e.g. voiced fricatives in any position, voiced coda obstruents. Conversion from acoustic to perceptual energy followed the same procedure used in the experiments on Pirahã (section 5.1). The duration and intensity values adopted in the original simulation appear in the appendix.

Results from four representative simulations differing along dimensions representative of common sources of cross-linguistic variation appear in table 12. In the first simulation, the full set of onset and coda consonants and both short and long vowels were included. In the second simulation, long vowels were excluded.

The third simulation omitted voiced obstruent codas. The fourth simulation excluded voiced obstruent codas and voiced fricatives in onset position.

Table 12. Perceptual energy differences in the rime between heavy and light syllables according to different weight distinctions in simulations

Distinction	**Difference (Heavy – Light)**			
	Simulation 1	Simulation 2	Simulation 3	Simulation 4
VV, VC > V	354.6	303.2	369.3	365.8
VV > VC, V	359.0	-----	395.4	400.3
CV > V	118.4	123.8	128.8	139.7
KV > GV	135.8	136.0	135.5	140.7
Low V > High V	79.5	59.9	80.7	80.0

In all four simulations, the two phonetically most effective distinctions are rimal ones: one treating branching rimes as heavy (VV, VC > V) and the other treating long vowels as heavy (VV > VC, V). Crucially, both of the onset distinctions are poorer than ones sensitive to vowel length and coda consonants. Other simulations cross-classifying these dimensions of variations and employing slightly different duration and intensity values were also run with only minor differences in outcomes with one exception. Increasing the duration and intensity difference between low and high vowels markedly improves the weight distinction based on vowel quality.

The phonetic superiority of distinctions based on vowel length and coda consonant in the simulation accords with the cross-linguistic predominance of rime-based weight distinctions, strongly suggesting that the rarity of onset-sensitive stress has a phonetic basis. Assuming that rime-based weight distinctions are phonetically superior to onset-driven distinctions, it follows that a language with weight-sensitive stress is unlikely to employ an onset-based weight criterion unless it also has a rime-based weight criterion. Thus, onset-based weight is relatively unlikely to be found except in languages with greater than a binary distinction between heavy and light syllables. Languages sensitive to greater than two degrees of weight are rare cross-linguistically, as Gordon's (1999) survey suggests: only 18 of the 127 (14%) weight-sensitive stress systems in the survey are sensitive to more than two degrees of weight. In summary, given the bias against complex weight hierarchies coupled with the greater phonetic effectiveness of rime-sensitive weight, it is not surprising that the onset rarely plays a role in weight systems.

The predominance of rimal weight does not, however, automatically preclude languages, such as Arrernte, in which onset weight takes priority over rimal weight. It merely means that phonetic considerations bias a language against adopting an onset-based weight distinction over a rime-based one. Language specific considerations may override this bias. Thus, the extreme shortening of initial vowels in Arrernte, itself made possible by the small vowel inventory, makes an onset-based distinction phonetically more effective as discussed in section 6.2.

The energy simulation also provides an opportunity for examining the perceptual energy of different rimes. The two most common weight criteria for stress cross-linguistically (Hyman 1985, Hayes 1989, Gordon 1999) are the one that treats both CVV and CVC heavy and the one that treats only CVV heavy. Conflating these two weight distinctions yields the implicational weight hierarchy CVV > CVC > CV. Assuming a correlation between phonological weight and phonetic energy, we would predict that this hierarchy corresponds to a hierarchy of perceptual energy, whereby CVV has the greatest energy followed by CVC followed by CV, with different languages drawing different cuts between heavy and light syllables along this scale. Figure 4 shows perceptual energy values for CVV, CVC, and CV under the four simulations.

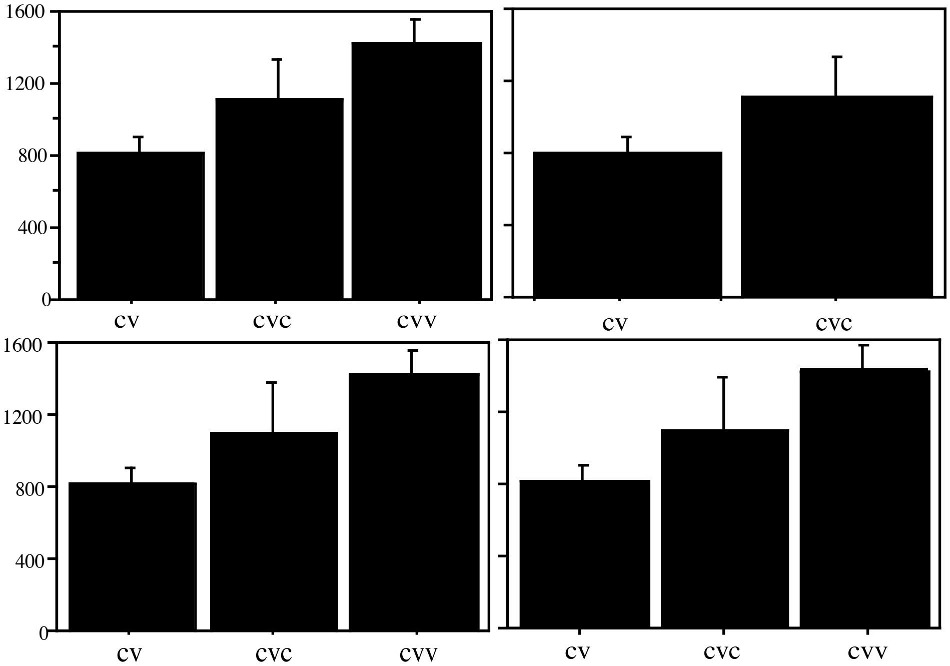


Figure 4. Perceptual energy (in arbitrary units) for CV, CVC, and CVV under four simulations: simulation one (upper left), simulation two (upper right), simulation three (lower left), simulation four (lower right)

As predicted, in all four simulations, CVC has greater energy than CV. In the three simulations containing long vowels, CVV has greater energy than CVC. Thus, the simulations not only provide corroboration for the cross-linguistic patterns in onset weight, but also support the phonetic effectiveness of rime-based weight criteria (see also Gordon 2002a on the link between energy and rimal weight).

10. The representation of onset weight

Representing onset weight is problematic in most theories of weight, which are primarily designed to handle rime-sensitive weight. Because moraic theory has no provisions for assigning moras to onset consonants, researchers have appealed to other orthogonal representations of prominence to account for onset-driven stress. For example, D. Everett (1988) and Hayes (1995) assume a prominence grid on which weight is assessed in Pirahã: differences in weight are reflected in differences in the number of prominence grid marks associated with syllables in the weight hierarchy. Thus, KVV has five levels of prominence grid marks, GVV has four, VV has three, KV has two, and GV has a single grid mark. Primary stress selects the most prominent of the syllables on which to dock. Prominence scales of a slightly different nature are also assumed by other researchers including Davis (1988), Goedemans (1998), Levin (1985).

Recent work, e.g. Steriade (1991), Crowhurst (1991), Hyman (1992), Hayes (1995), Gordon (1999), has indicated the existence of many languages, like Pirahã, in which weight observes more than a binary distinction, either for a single phenomenon as in Pirahã or conflated across multiple phenomena, e.g. as in Khalkha Mongolian which treats only CVV as heavy for stress but both CVV and CVC as heavy for its minimal word requirement. These cases of complex weight hierarchies and conflicted weight criteria across different phenomena indicate that a theory designed to handle only binary weight distinctions such as moraic theory is too restrictive to account for the range of variation found in languages. Furthermore, cases of onset-sensitive stress argue that a theory designed only to capture rime-based weight is descriptively inadequate.

Gordon (1999) argues that a skeletal slot model such as that proposed by Levin (1985), in which all short segments are linked to one weight unit and all long segments receive two, regardless of their syllabic affiliation, is better suited than moraic theory to analyzing complex hierarchies of weight. In his account, weight distinctions are not reflected in differences in number of weight units, as in moraic theory, but rather through a combination of differences in number of weight units and differences in featural information, following Steriade (1991). Thus, a difference in weight between CVV and CVC reflects a difference in the number of weight units associated with a [+vocalic] feature: CVV has two

[+vocalic] weight units, whereas CVC has only one [+vocalic] weight unit. A distinction between CVC and CV, on the other hand, is simply represented as a difference in number of weight units. In this way, the three-way weight hierarchy CVV > CVC > CV is captured as a combined difference in number of weight units and the featural specifications of those units. Different processes within the same language may make reference to different syllable types in their calculation of weight. For example, the minimal word requirement in Khalkha treats all syllables with two rimal weight units as heavy while the stress system only treats syllables with two [+vocalic] weight units as heavy.[19] The actual weight units assumed are irrelevant, whether they be moras or skeletal slots. What is crucial, however, in light of the onset-weight facts, is that segments in both the rime and onset carry a weight unit; in this respect, the proposed theory is virtually identical to Levin's (1985) theory differing only in the trivial manner of capturing the distinction between CVV and CVC featurally using [vocalic] rather than in terms of rime and nucleus constituents.

Given these representations, we are in a position to represent onset weight distinctions. I consider the Pirahã case here since it is the most complex of the onset-driven distinctions found cross-linguistically. The heaviest syllable in the Pirahã hierarchy, KVV, minimally has two vocalic timing positions preceded by a [-voice] onset. The second heaviest syllable, GVV, minimally has two vocalic timing positions preceded by a [+voice] onset. The third syllable in the hierarchy, VV, minimally has two vocalic timing positions. The second lightest syllable, KV, minimally has a single vocalic timing position preceded by a [-voice] onset. Finally, the lightest syllable, GV, minimally has a single vocalic timing position following a [+voice] onset. Representations for the syllable types comprising the Pirahã hierarchy appear in Figure 5.

Figure 5. Representations of different levels of weight in the Pirahã hierarchy

$$\begin{array}{lllllllll}
\text{KVV} & \gg & \text{GVV} & \gg & \text{VV} & \gg & \text{KV} & \gg & \text{GV} \\
[\text{X}\ [\text{X X}]_{\text{R}}]_{\sigma} & & [\text{X}\ [\text{X X}]_{\text{R}}]_{\sigma} & & [[\text{X X}]_{\text{R}}]_{\sigma} & & [\text{X}\ [\text{X}]_{\text{R}}]_{\sigma} & & [\text{X}\ [\text{X}]_{\text{R}}]_{\sigma} \\
| & & | & & & & | & & | \\
\text{-voice} & & \text{+voice} & & & & \text{-voice} & & \text{+voice}
\end{array}$$

Onset distinctions found in other languages, including ones based on presence vs. absence of an onset, complexity of the onset, and sonority of the onset, can likewise be captured by a combination of weight units and featural specifications

---

[19] A parallel is found in Hayes' (1995) two-tiered version of moraic theory in which different phenomena may make reference to different tiers.

(see section 10.1 for formal analysis). It may also be noted that rime based weight distinctions involving more than two degrees of weight can also be decomposed into simple binary distinctions. For example, the CVV > CVC > CV hierarchy found in Klamath (Barker 1964) consists of two binary distinctions, both of which are simple since they do not refer to any place predicates: CVV heavy and CVX heavy.

The model of the syllable adopted here eliminates the need for a separate tier of moras, since weight distinctions are not reflected solely in differences in number of timing units but also may refer to features. The present approach thus differs from theories that assume both skeletal slots and moras (e.g. Hock 1986, Tranel 1991, Hume et al. 1997). In their analysis of Leti, Hume et al. (1997), for example, argue for a model in which rime-based weight is captured with moras while onset-based processes make reference to skeletal slots. Although hybrid skeletal slot/mora models can handle weight distinctions based on number of timing positions in the onset, as Hume et al. show for Leti, they are not equipped to handle sonority based distinctions involving the onset. For example, the Pirahã distinction between voiceless and voiced onsets, which is handled in the theory proposed here by referencing features, does not correspond to a difference in number of timing slots and thus is not easily captured in the hybrid skeletal slot/mora theory.

A consequence of the proposed model's reference to both timing units and features to capture weight distinctions is that phonetic dimensions of prominence cannot be read directly off of the weight representations. A timing unit thus does not correspond to a fixed amount of a phonetic property. For this reason, although the present research belongs to the research program investigating the role of phonetics in phonology, it differs from studies that demonstrate a quantifiable relationship between phonological representations and phonetic properties, specifically duration in the relevant studies, e.g. Maddieson (1993), Hubbard (1994, 1995), Broselow et al. (1997). Rather the present study is consistent with research suggesting a non-transparent relationship between phonetic properties and phonological representations, e.g. Lahiri and Koreman (1988), Tranel (1991), Arvaniti and Rose (2003).

One possible objection to the proposed representations of weight is the loss of restrictiveness they entail relative to moraic theory. However, given the documentation of onset-sensitive stress as well as the existence of rime-based weight inconsistencies between different processes within the same language, it is clear that a theory that merely counts weight units is insufficiently rich to handle the diversity of weight phenomena found cross-linguistically. I would argue that, relative to a modified version of moraic theory which assumes prominence representations orthogonal to metrical strength (as in accounts which assume a prominence tier in addition to a metrical tier), the representations assumed here are at least as well-motivated, arguably more so, since the principles governing them are consistent across languages and predictable given basic assumptions about phonemic contrasts in duration and features. In contrast, prominence grids must be arbitrarily defined on a language specific basis according to which syllable types comprise a weight hierarchy in a given language.

Furthermore, the loss of restrictiveness in the proposed theory is mitigated somewhat by other ingredients that act to constrain the actual employment of the proposed representations in phonological systems. First, all potential representations are evaluated by the complexity metric (see section 5.2.1), which ensures that the set of representations that can be manipulated by the phonological system of a language is a subset of the total set of logically possible representations of weight distinctions. Second, the set of weight distinctions that pass the complexity filter is subject to further trimming on a language specific basis by evaluating phonetic effectiveness, since the set of phonetically plausible weight distinctions is a subset of the phonologically simple ones in any language. In summary, both the complexity and the phonetic effectiveness criteria conspire to constrain the actual set of weight distinctions manipulated by languages, thereby compensating for some of the restrictiveness lost by abandoning moraic theory.

10.1. Onset weight in Optimality Theory

With the representations in figure 5, we are in a position to provide formal analyses of onset-sensitive stress. Following Prince and Smolensky (1993) and Kenstowicz (1997), I posit a series of prominence constraints requiring that different syllable types be stressed or not. The family of PROM constraints consists of all constraints referring to phonologically simple weight distinctions where simplicity is determined according to the discussion in section 5.2.1. The constraints fall into two groups according to whether they refer to rimal or onset predicates. For example, one rimal constraint requires that syllables with a branching rime carry stress, PROM $[[XX]_R]_\sigma$. One onset-based constraint demands that syllables lacking an onset not be stressed, *PROM $[\text{Ø}[X]_R]_\sigma$. Another requires that syllables with a voiceless onset carry stress PROM $[X_{[-\text{voice}]}[X]_R]_\sigma$. Within each subsyllabic constituent, i.e. rime and onset, the ranking of certain constraints is universally fixed, capturing what Prince and Smolensky (1993:38) term “prominential enhancement that calls directly on contrasts in the intrinsic prominence of syllables.” Thus, the constraint requiring that syllables with a voiceless onset be stressed is universally ranked above the constraint requiring that syllables with a voiced onset be stressed, PROM $[X_{[+\text{voice}]}[X]_R]_\sigma$. Similarly, the constraint requiring that syllables without an onset be unstressed is universally ranked above a constraint requiring that syllables with an onset be unstressed, *PROM $[X[X]_R]_\sigma$. The ranking of these constraints finds a phonetic basis: syllables that are less prominent are never preferentially stressed over more prominent syllables, unless some other independent higher ranked non-prominence constraint e.g. anti-lapse or anti-clash constraints, mandates this. Conversely, syllables that are more prominent never pass stress to a less prominent syllable barring the effects of another stress constraint. In this view, constraints themselves are not phonetically sensitive, only their ranking is (see also Steriade 1999, 2001).

Onset-sensitive prominence constraints are interleaved with both rime-sensitive prominence constraints and other non-prominence stress constraints, e.g. ALIGN constraints (McCarthy and Prince 1993), NONFINALITY (Prince and Smolensky 1993), etc. Typically at least one of the rime-sensitive prominence constraints is ranked above all onset-sensitive prominence constraints, in keeping with the greater phonetic effectiveness of rimal distinctions. There are, however, isolated languages such as Arrernte in which an onset-driven prominence constraint may be ranked above all rimal prominence constraints, a ranking that corresponds to the typologically atypical phonetic patterns found in such languages.

In most languages, i.e. those with binary weight distinctions, only one prominence constraint is ranked highly enough to exert an influence on stress. In languages with more than a binary distinction in weight, however, more than one prominence constraint plays an observable role. Furthermore, although the onset and rime characteristically function as orthogonal dimensions in the determination of weight, there is also a possibility for a single weight distinction to refer to both the onset and rime. For example, in Pirahã, the heaviest syllable type has a voiceless onset followed by a branching rime, reflecting the conjunction of onset and rime predicates in a single constraint. As an illustration of multiple prominence constraints at work in a single language, the Pirahã stress system is analyzed in the next section. Section 10.1.2 analyzes a simpler but more common onset-based distinction in which onsetless word-initial syllables reject stress.

10.1.1. An OT analysis of Pirahã stress

As discussed in section 1, Pirahã observes a five way weight hierarchy: KVV > GVV > VV > KV > GV, with stress falling on the rightmost syllable that is heaviest along this hierarchy within a three syllable window at the right edge of a word. This hierarchy can be decomposed into a series of binary weight distinctions following discussion in section 5. One distinction treats branching rimes as heavy, another treats syllables with an onset as heavy, and a third treats syllables with a voiceless onset as heavy. Each of these distinctions corresponds to a constraint. First, the greater weight of syllables with a voiceless onset indicates that the constraint PROM $[X_{[-voice]}[X]_R]_\sigma$ is ranked above an alignment constraint forcing stress rightward, ALIGN (σ́, R, PrWd), as in (7).

(7)

ʔabagi ‘toucan’	PROM $[X_{[-voice]}[X]_R]_\sigma$	ALIGN (σ́, R, PrWd)
☞ ˈʔa.ba.gi		**
ʔa.ba.ˈgi	*!	

The greater weight of syllables with branching rimes relative to KV results from PROM $[[XX]_R]_\sigma$ being ranked above PROM $[X_{[-voice]}[X]_R]_\sigma$, *PROM $[Ø[X]_R]_\sigma$ and ALIGN (σ́, R, PrWd), in keeping with the prioritization of rimal weight over onset weight (8).

(8)

hoai□pi ‘type of fish’	PROM $[[XX]_R]_\sigma$	PROM $[X_{[-voice]}[X]_R]_\sigma$	*PROM $[Ø[X]_R]_\sigma$	ALIGN (σ́, R, PrWd)
☞ ho.ˈai□.pi		*	*	*
ho.ai□.ˈpi	*!			

The division between GVV and VV reflects the ranking of *PROM $[Ø[X]_R]_\sigma$ above ALIGN (σ́, R, PrWd) (9).

(9)

gaoii ‘proper name’	*PROM $[Ø[X]_R]_\sigma$	ALIGN (σ́, R, PrWd)
☞ ˈgao.ii		*
gao.ˈii	*!	

The attraction of stress by KVV over GVV follows from the ranking of a prominence constraint conflating voiceless onsets and branching rimes, PROM $[X_{[-voice]}[XX]_R]_\sigma$, above ALIGN (σ́, R, PrWd) (10).

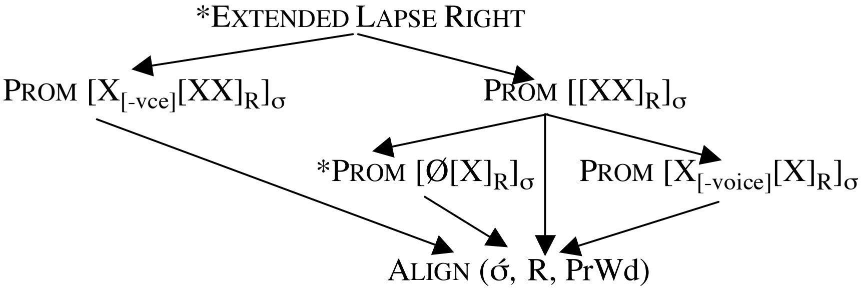
(10)

kaagai ‘word’	PROM $[X_{[-vce]}[XX]_R]_\sigma$	ALIGN (σ́, R, PrWd)
☞ ˈkaa.gai		*
kaa.ˈgai	*!	

Finally, following the spirit of Green and Kenstowicz' (1995) analysis of Pirahã, the three syllable stress window is captured by an anti-lapse constraint. I assume that the apodal constraint *Extended Lapse Right (Gordon 2002b; see also Elenbaas and Kager 1999) bans a sequence of greater than two consecutive stressless syllables at the right edge of a word. This constraint crucially outranks all of the prominence constraints.

The final ranking hierarchy for Pirahã appears in (11).

(11) Constraint rakings for Pirahã



10.1.2. Word-initial onset weight distinctions

A common type of onset-sensitive stress pattern is the one found in Arrernte, Mbabaram, Lamalama, Iowa-Oto, and Banawá, in which stress falls on the first vowel preceded by an onset (see Banawá in section 6.1 and Arrernte in section 6.2). Otherwise, stress falls on the second syllable (rimal timing slot in Banawá). Arrernte and Banawá also display a binary secondary stress pattern after the initial stress with a non-finality clause in Arrernte.

I focus first on primary stress assignment, which adheres to the same principles in all surveyed languages with word-initial onset weight distinctions. The passing over of an onsetless initial syllable follows from the ranking of *Prom $[Ø[X]_{R}]_{\sigma}$ over a leftward stress Align constraint. This ranking is shown for Iowa-Oto (forms from Robinson 1975) in (12).

(12)

ahata 'outside'	*Prom $[Ø[X]_{R}]_{\sigma}$	Align (σ́, L, PrWd)
☞ a'hata		*
'ahata	*!	

In words beginning with a consonant, the ranking ALIGN (σ́, L, PrWd) >> ALIGN (σ́, R, PrWd) ensures that stress falls on the initial syllable, as shown for Iowa-Oto in (13).

(13)

paxuti 'Iowa'	ALIGN (σ́, L, PrWd)	ALIGN (σ́, R, PrWd)
☞ 'paxotʃe		*
paxo'tʃe	*!	

The presence of binary secondary stress in certain languages with a word-initial onset weight distinction, e.g. Arrernte and Banawá, requires additional constraint rankings. An anti-lapse constraint, *LAPSE (see Gordon 2002b drawing on Prince 1983, Selkirk 1984),[20] is ranked above ALIGN-L. Strict binarity of the type found in Banawá reflects the ranking of *LAPSE over NONFINALITY. In Arrernte, the opposite ranking obtains, leading to consecutive stressless syllables word-finally in even parity words with peninitial stress and odd parity words with initial stress, e.g. ar't̪anama 'to run', 'tukura 'ulcer'. In Arrernte, NONFINALITY outranks *PROM $[Ø[X]_{R}]_{\sigma}$, as an onsetless initial syllable in disyllabic words carries stress, e.g. 'ilba 'ear'.

Strict binarity without nonfinality requires an additional constraint to ensure that odd-numbered syllables rather than even-numbered syllables are stressed in odd parity words with initial stress, i.e. Banawá 'waraˌbu 'ear' not *wa'rabu. Given the ranking of ALIGN-L over ALIGN-R, we would incorrectly predict stress on even-numbered syllables. The new constraint is ALIGN EDGES (Gordon 2002b) and requires that the first and last stresseable elements, rimal timing slots in Banawá, be stressed. One violation is assigned if either the first or last stressable element is unstressed and two violations are incurred if both are unstressed. ALIGN EDGES is ranked above ALIGN-L (14).

(14)

warabu 'ear'	ALIGN EDGES $[x□]_{R}$	ALIGN ($[x□]_{R}$, L, PrWd)
☞ 'waraˌbu		**
wa'rabu	*!*	*

ALIGN EDGES is ranked below *PROM $[Ø[X]_{R}]_{\sigma}$, since absolute word-initial vocalic timing slots, i.e. those lacking an onset, do not attract stress (15).

---

[20] In Banawá, *LAPSE and ALIGN refer to timing slots not syllables (see Kager 1993 on *LAPSE at the moraic level).

(15)

uwi.a ‘to go out (of fire)’	*PROM $[\text{Ø}[X]_R]_{\sigma}$	ALIGN EDGES $[\text{x}\square]_R$
☞ u'wi.a		**
'uwi.ˌa	*!*	

To complete the analysis for Banawá, words containing only two vocalic timing slots have initial stress even in words beginning with a vowel, e.g. 'uwi ‘cry’. This indicates that NONFINALITY is ranked above *PROM $[\text{Ø}[X]_R]_{\sigma}$.

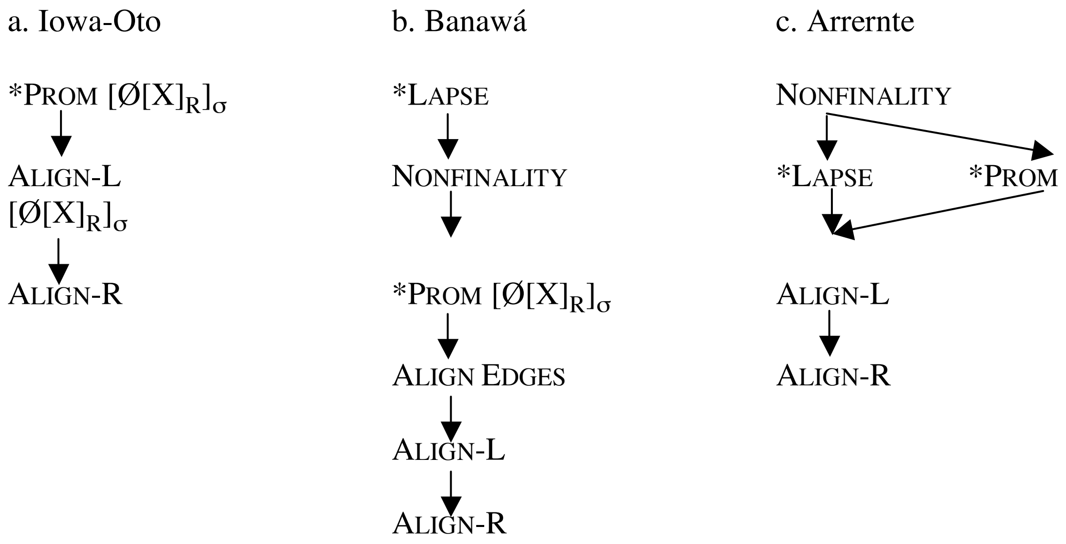
As it turns out, the strictly binary nature of secondary stress in Banawá provides evidence for capturing the rejection of stress by onsetless syllables as a negatively formulated constraint *PROM $[\text{Ø}[X]_R]_{\sigma}$ rather than a positively stated constraint requiring that syllables with an onset be stressed, i.e. PROM $[X[X]_R]_{\sigma}$. The argument comes from odd parity words with an onsetless initial syllable, e.g. i'bufa ‘to dump into water’. The winning onsetless candidate, i'bufa, would violate the hypothetical positively formulated constraint PROM $[X[X]_R]_{\sigma}$ once, as would a rival with stress on both the final and initial (onsetless) mora, 'ibuˌfa. PROM $[X[X]_R]_{\sigma}$ is thus unable to select a unique winner, leaving ALIGN EDGES to choose the (incorrect) candidate with initial and final stress. In contrast, *PROM $[\text{Ø}[X]_R]_{\sigma}$ correctly rules out the candidate with stress on a vowel not preceded by an onset. This is one of the few instances where evidence can be adduced in favor of either a negatively or positively formulated prominence constraint over its oppositely specified counterpart (see Kenstowicz 1997 for evidence for negatively stated prominence constraints for vowel-quality based weight distinctions).[21]

Rankings for the three subtypes of stress systems (single stress [Iowa-Oto], strict binary [Banawá], and binarity with non-finality [Arrernte]) with initial onset distinctions appear in (16).

---

[21] The failure of the positively specified counterpart to *PROM $[\text{Ø}[X]_R]_{\sigma}$ cannot, however, be taken as evidence against all positively specified prominence constraints. There are stress systems in which only positively specified prominence constraints capture the facts, including those which lack binary stress but which stress all heavy syllables, e.g. Malayalam (Mohanan 1986). If positively stated constraints were not adopted, there would be no way to account for the secondary stresses on heavy syllables. Taken together, the evidence for positively and negatively specified prominence constraints accords with the function of weight distinctions on an intuitive level. Certain syllables, the lightest ones in a multi-level weight hierarchy, are not prominent and thus resist stress, e.g. onsetless syllables, while others, the heaviest ones in a weight hierarchy, are prominent and thus attract stress, e.g. syllables with long vowels. Syllables that are intermediate in weight along a continuum may be viewed as either stress attracting or stress rejecting; accordingly, their formulation is not crucial for predicting the correct results.

(16) Rankings for systems with word-initial onset weight distinctions



11. Conclusion

In summary, a survey of onset-sensitive stress systems indicates certain recurring patterns that find an explanation in perceptual factors. In contrast to lower sonority codas, which are phonologically light in certain languages, lower sonority onsets are heavier cross-linguistically because of the perceptual boost they provide to a following vowel. In keeping with the prioritization of rimal weight over onset weight, however, the perceptual boost provided by a low sonority onset is relatively small in comparison to the perceptual contribution of the rime. Cross-linguistic variation in onset-based weight criteria is associated with differences in the relative phonetic effectiveness of different weight distinctions: phonological weight criteria are phonetically more effective than other logically possible weight criteria falling within an upper threshold of phonological complexity. Parallel to rime-sensitive stress, the phonology of onset-sensitive stress can also be analyzed using a series of prominence constraints interleaved with other metrical stress constraints. The proposed prominence constraints refer to skeletal slot representations of the syllable, which are better suited than moraic models to capturing both onset-based weight distinctions and multi-tiered weight hierarchies.

References

Abrahamson, A. and J. Abrahamson. 1984. Os fonemas da língua Júma. In Dooley, R. (ed.), *Estudos sobre línguas tupí do brasil* [*Série Lingüística* 11], pp. 157-174. Brasília: Summer Institute of Linguistics.

Allen, W. Sidney. 1973. *Accent and rhythm*. Cambridge: Cambridge University Press.

Arvaniti, A. and S. Rose. 2003. Two sources of evidence against the moraic timing of geminates. Paper presented at the Linguistic Society of America Annual Meeting, Atlanta, GA (*available at http://ling.ucsd.edu/~arvaniti/publications.html*).

Bach, E. 1975. Long vowels and stress in Kwakiutl. *Texas Linguistic Forum* 2, 9-19.

Barker, M.A.R. 1964. *Klamath grammar*. University of California Publications in Linguistics 32. Berkeley: University of California Press.

Bauer, W. 1993. *Maori*. New York: Routledge.

Beckman, M. 1986. *Stress and non-stress accent*. Dordrecht: Foris.

Bladon, A. 1986. Phonetics for hearers. In McGregor, G. (ed.), *Language for hearers*, pp. 1-24. Oxford: Pergamon Press.

Boas, Franz. 1947. *Kwakiutl grammar with a glossary of the suffixes*, ed. by H. Boas Yampolsky and Z. Harris. *Transactions of the American Philosophical Society* 37:3, 201-377.

Booij, G. 1985. *The phonology of Dutch*. Oxford: Oxford University Press.

Breen, G. and R. Pensalfini. 1999. Arrerente: a language with no syllable onsets. *Linguistic Inquiry* 30, 1-25.

Broselow, Ellen, Chen, Susan, and Marie Huffman. 1997. Syllable weight: convergence of phonology and phonetics. *Phonology* 14, 1.47-82.

Buckley, Eugene. 1998. Alignment in Manam stress. *Linguistic Inquiry* 29. 475-496.

Buller, B., Buller, E. & D. Everett. 1993. Stress placement, syllable structure, and minimality in Banawá. *International Journal of American Linguistics* 59, 280-293.

Camden, W. G. 1977. *A descriptive dictionary: Bislama to English*. Rosebery, Australia: Bridge Printery.

Cho, T. & P. Keating. 1999. Articulatory and acoustic studies of domain-initial strengthening in Korean. *UCLA Working Papers in Phonetics* 97, 139-151.

Crowhurst, M. 1991. Demorification in Tübatulabal: Evidence from initial reduplication and stress. *Proceedings of the Northeastern Linguistics Society* 21, 49-63.

Davis, S. 1988. Syllable onsets as a factor in stress rules. *Phonology* 5, 1-19.

Davis, S. and D. Napoli. 1994. *A prosodic template in historical change: the passage of the Latin second conjugation into Romance*. Torino: Rosenberg and Sellier.

Dayley, J. 1989. *Tümpisa (Panamint) Shoshone grammar* [*University of California Publications in Linguistics* 115]. Berkeley: University of California Press.

De Lacy, P. 2002. The interaction of tone and stress in Optimality Theory. *Phonology* 19, 1-32.

Delgutte, B. 1982. Some correlates of phonetic distinctions at the level of the auditory nerve. In Carlson, R. and B. Granström (eds.), *The representation of speech in the peripheral auditory system*, pp. 131-50. Amsterdam: Elsevier.

Delgutte, B. 1997. Auditory neural processing of speech. In Hardcastle, W. and J. Laver (eds.), *The handbook of phonetic sciences*, pp. 507-38. Oxford: Blackwells.

Delgutte, B. and Kiang, N.Y.S. 1984. Speech coding in the auditory nerve I: vowel-like sounds. Journal of the Acoustical Society of America 75, 879-86.

Dixon, R. M. W. 1991. Mbabaram. In Dixon, R.M.W. & B. Blake (eds.), *The handbook of Australian languages*, volume 4. New York: Oxford.

Duanmu, S. 1994. Syllabic weight and syllabic duration: A correlation between phonology and phonetics. *Phonology* 11, 1-24.

Elenbaas, N and Kager, R. 1999. Ternary rhythm and the lapse constraint. *Phonology* 16, 273-329.

Evans, N. 1995. Current issues in the phonology of Australian languages. In Goldsmith, J. (ed.), *The handbook of phonological theory*, pp. 723-761. Cambridge, Mass: Blackwells.

Everett, D. 1988. On metrical constituent structure in Pirahã phonology. *Natural Language and Linguistic Theory* 6, 207-246.

Everett, D. and K. Everett. 1984. Syllable onsets and stress placement in Pirahã. *Proceedings of the West Coast Conference on Formal Linguistics* 3, 105-16.

Everett, K. 1998. The acoustic correlates of stress in Pirahã. *The Journal of Amazonian Languages* 1:2, 104-162.

Foley, W. A. 1991. *The Yimas language of New Guinea*. Stanford: Stanford University Press.

Fougeron, C. & P. Keating. 1997. Articulatory strengthening at edges of prosodic domains. *Journal of the Acoustical Society of America* 101(6), 3728-3740

Gabas, N. 1999. *A grammar of Karo, Tupi (Brazil)*. UCSB PhD dissertation.

Gahl, S. 1996. Syllables as a factor in stress rules: the case of Mathimathi revisited. *Phonology* 13, 329-44.

Goedemans, R. 1998. *Weightless segments*. The Hague: Holland Academic Graphics.

Gordon, M. 1997. Phonetic correlates of stress and the prosodic hierarchy in Estonian. In Ross, J. and I. Lehiste *Estonian prosody: papers from a symposium,* pp. 100-24. Tallinn: Institute of Estonian Language.

Gordon, M. 1999. *Syllable weight: phonetics, phonology, and typology*. UCLA PhD dissertation

Gordon, M. 2000. The tonal basis of final weight criteria, *Chicago Linguistics Society* 36, 141-156.

Gordon, M. 2002a. A phonetically-driven account of syllable weight. *Language* 78, 51-80.

Gordon, M. 2002b. A factorial typology of quantity insensitive stress. *Natural Language and Linguistic Theory* 20, 491-552.

Green, T. and M. Kenstowicz. 1996. The Lapse constraint. *Proceedings of the 6th Annual Meeting of the Formal Linguistics Society of the Midwest*,1-15.

Ham, W. 2001. *Phonetic and phonological aspects of geminate timing*. New York: Routledge.

Hayes, B. 1989. Compensatory lengthening in moraic phonology. *Linguistic Inquiry* 20, 253-306.

Hayes, B. 1995. *Metrical stress theory: principles and case studies*. Chicago: University of Chicago Press.

Hercus, L. 1969. *The languages of Victoria: a late survey*. Canberra: Australian Institute of Aboriginal Studies.

Hubbard, K. 1994. *Duration in moraic theory*. Berkeley: University of California, Berkeley dissertation.

Hubbard, K. 1995. 'Prenasalised consonants' and syllable timing: evidence from Runyambo and Luganda. *Phonology* 12, 235-56.

Hyman, L. 1977. On the nature of linguistic stress. In Hyman, L. (ed.), *Studies in stress and accent*. *(Southern California Occasional Papers in Linguistics 4*), pp. 37-82.

Hyman, L. 1985. *A theory of phonological weight*. Dordrecht: Foris.

Hyman, L. 1992. Moraic mismatches in Bantu. *Phonology* 9, 255-266.

Jakobson, R. 1931. Die Betonung und ihre Rolle in der Wort- und Syntagma-Phonologie. In *Roman Jakobson, Selected Writings* I, 117-136. The Hague: Mouton.

Kager, R. 1989. *A metrical theory of stress and destressing in English and Dutch*. Dordrecht: Foris.

Kager, R. 1993. Alternatives to the iambic-trochaic law. *Natural Language and Linguistic Theory* 11, 381-432.

Kaun, A. 1995. *The typology of rounding harmony: an optimality theoretic approach*. UCLA PhD dissertation (*UCLA Dissertations in Linguistics 8*).

Kenstowicz, M. 1997. Quality-sensitive stress. *Rivista di Linguistica* 9, 157-188.

Kiparsky, P. 1979. Metrical stucture assignment is cyclic. *Linguistic Inquiry* 10, 421-441.

Ladefoged, P., Ladefoged. J. and D. Everett. 1997. Phonetic structures of Banawá, an endangered language. *Phonetica* 54, 94-111.

Lahiri, A. and Koreman, J. 1988. Syllable weight and quantity in Dutch. *Proceedings of the West Coast Conference on Formal Linguistics* 7, 217-228.

Laycock, D. 1969. Three Lamalamic languages of North Queensland. *Papers in Australian Linguistics* 4 (*Series A*), 71-97. Canberra: The Australian National University.

Lehiste, I. 1970. *Suprasegmentals*. Cambridge, Mass.: MIT Press.

Levin, J. 1985. *A metrical theory of syllabicity*. Cambridge, MA: MIT dissertation.

Lieberman, P. 1960. Some acoustic correlates of word stress in American English. *Journal of the Acoustical Society of America* 32, 451-454.

Lichtenberk, F. 1983. *A grammar of Manam* [*Oceanic Linguistics Special Publications* 18]. Honolulu: University of Hawaii Press.

Maddieson, I. 1993. Splitting the mora. *UCLA Working Papers in Phonetics* 83, 9-18.

Maddieson, I. 1985. Phonetic cues to syllabification, in Fromkin, V. (ed.), *Phonetic linguistics: essays in honor of Peter Ladefoged*, pp. 203-21. Orlando: Academic Press.

McCarthy, J. 1979. On Stress and syllabification. *Linguistic Inquiry* 10, 443-65.

McCarthy, J. and A. Prince. 1993, Generalized alignment, Ms., University of Massachusetts and Rutgers University. Available on Rutgers Optimality Archive, ROA-7, http://roa.rutgers.edu.

Mohanan, K. P. 1986. *The theory of lexical phonology*. Dordrecht: Reidel.

Moore, B. 1995. An introduction to the psychology of hearing. San Diego: Academic Press.

Nanni, D. 1977. Stressing words in -Ative. *Linguistic Inquiry* 8, 752-62.

Peterson, G. and I. Lehiste. 1960. Duration of syllable nuclei in English. *Journal of the Acoustical Society of America* 32, 693-703.

Plomp, R. 1964. Rate of decay of auditory sensation. *Journal of the Acoustical Society of America* 36, 277-282.

Prince, A. and P. Smolensky. 1993. *Optimality Theory: constraint interaction in generative grammar*. Ms. Rutgers University and University of Colorado at Boulder.

Robinson, L. 1975. Some phonological rules of Iowa-Oto (Siouan). *Proceedings of the 1975 Mid-America Linguistics Conference*, 439-48.

Selkirk, E. 1984. *Phonology and Syntax: The Relation between Sound and Structure*. Cambridge, Mass., MIT Press.

Silverman, D. 1997. Laryngeal complexity in Otomanguean vowels, *Phonology* 14, 235-62.

Smith, J. 2000. Prominence, augmentation, and neutralization in phonology. *Proceedings of Berkeley Linguistics Society* 26, 247-257.

Smith, J. 2002. *Phonological augmentation in prominent positions*. University of Massachusetts, Amherst PhD dissertation.

Smith, R.L. 1979. Adaptation, saturation and physiological masking in single auditory nerve fibers. *Journal of the Acoustical Society of America* 65, 166-78.

Spaulding, C. and P. Spaulding. 1994. *Phonology and grammar of Nankina*. [*Data papers on Papua New Guinea languages* 41]. Ukarumpa, New Guinea: Summer Institute of Linguistics.

Steriade, D. 1991. Moras and other slots. In *Proceedings of the Formal Linguistics Society of Midamerica* 1, 254-80.

Steriade, D. 1999. Licensing laryngeal features. *UCLA Working Papers in Linguistics 3, Papers in Phonology* 2, 25-146.

Steriade, D. 2001. Directional asymmetries in place assimilatin. In Hume, E. and Johnson, K. (eds.), *The role of speech perception in phonology*, pp. 219-250. San Diego: Academic Press.

Strehlow, T. 1942. Aranda phonetics. *Oceania* 12, 255-302.

Tranel, B. 1991. CVC light syllables, geminates and Moraic Theory. *Phonology* 8, 291-302.

Trubetzkoy, N.S. 1939/1958. *Grundzüge der Phonologie*. Göttingen: Vandenhoeck and Ruprecht.

Viemeister, N. 1980. Adaptation of masking. In van den Brink, G. and Bilsen, F.A. (eds.), *Psychophysical, Physiological and Behavioural Studies in Hearing, Proceedings of the 5th International Symposium on Hearing*, pp. 190-198. Delft: Delft University Press.

Wilson, J. P. 1966. An auditory afterimage. In Plomp, R. and Smoorenberg, G. F. (eds.), *Frequency Analysis and Psychophysics of Hearing*, pp. 303-315. Leiden: Sijthoff.

Wilson, S. 1986. Metrical structure in Wakashan phonology. *Berkeley Linguistics Society* 12, 283-291.

Yallop, C. 1977. *Alyawarra: an aboriginal language of central Australia*. Canberra: Australian Institute of Aboriginal Studies.

Zec, D. 1994. *Sonority constraints on prosodic structure*. New York: Garland Press.

Zhang, J. 2001. *The effects of duration and sonority on contour tone distribution--typological survey and formal analysis*. UCLA PhD dissertation.

Appendices

Corpora (target segments in bold)

Pirahã[22]

bo.ˈ**gí**	my breast	ˈ**mii**	blood
pi.ˈ**ba**ó.í [piˈ**ba**ẃí]	otter	ʔa.ˈ**gi□ɪ**	cold
ˈ**ti**	I	ˈ**máa**.gi.so	many
hi.ˈ**ʔi**□	rat	ˈ**náa**.ta	can
ko.ˈ**si**	eye	ˈ**hii**.si□	sun
ˈ**ʔa**.ba.gi	toucan	ˈ**tii**	residue
ˈ**ka**.ba	no/not	ˈ**pii**	water
ta.ga.ˈ**sá**.ga	machete	ˈ**kaá**.bi	full
ʔo.ˈ**ii**	catfish	ˈ**paá**.si	fruit (sp.)
ʔi.ˈ**aa**.pi.si□	her arm	i.ˈ**kai**□	daughter
po.ˈ**ai**	mango	ti.ˈ**gai**.ti	bushmaster snake

Banawá (periods separate vocalic timing slots)

ˈ**i**bi	each other	ˈ**sa**ma	down river
ˈ**i**ba	to put/place	ˈ**si**ma	sister
ˈ**a**ba	fish	ˈ**ta**ma	vine
ˈ**a**wa	wood	ˈ**ti**ma	upstream
ɔˈwi.**a**	go out (fire)	ˈba**da**	proper name
ˈti.**a** ˈtike.i ˈjariˌne	happy	ˈbi**di**	small
ˈkaniˌka.**i**	to buy	ˈba**na**	she hits
ˈɾabiˌka.**i**	sick	ˈki**ni**	green
ˈ**da**ma	to hold securely	ˈba**sa**	to put a stick up high
ˈ**bi**ɾa	battery	ˈki**si**	to descend
ˈ**ma**no	arm	ˈba**ta**	rotten
ˈ**mi**na	morning	ˈki**ti**	strong

Arrernte

ˈ**i.**tə	throat	ˈ**il.**t̪ə	hand
ˈ**a**.l̪ə	nose	ˈ**al**.kŋə	eye
ˈ**t̪i**.pə	bird	ˈ**mpʷal**.t̪ə	frog
ˈ**ka**.kə	elder brother	il.ˈ**t̪ʷil**.t̪ə	grasshopper

---

[22] A controlled comparison of tone and syllable location using other available data indicated that energy did not differ substantially as a function of tone or syllable location.

Duration and intensity values adopted in the perceptual energy simulations

Segment	**Duration (in ms)**	**Intensity (in dB)**
/a/	121 (open syllables), 110 (closed syllables)	72 (dB of preceding V = 71)
/i/	110 (open syllables), 99 (closed syllables)	70 (dB of preceding V = 71)
Long vowels	Short vowels x 2	Same as short V
Sonorants	110	68
Voiceless fricatives	110	60
Voiceless stops	110	45 (includes release and any voicing present)
Voiced fricatives	77	66.5
Voiced stops	77	65