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Phonological Structure and Phonetic Duration: The Role of the Mora*

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In this paper, I investigate the role of the mora in providing an adequate account of word-internal prosodic organization and its phonetic realization. I review several phonological arguments in favor of the mora, including the cross-linguistic pervasiveness of two-way weight contrasts, observed onset/rime asymmetries, the representation of weight bearing geminates vs. "doubled consonants", and evidence for superheavy syllables in some languages. I then present data showing phonetic manifestations of these patterns. The phonetic and phonological evidence support the conclusion that the mora serves as the connection or link between prosodic and segmental structure. Moreover, the nature of these manifestations of moraic structure in the phonetics supports the view that phonetics is the implementation of phonological structure in that both the more abstract phonological categories (in this case the mora) and the phonetic implementation (in this case duration) work together to achieve the observed physical realization.

1. Introduction

In this paper, I consider the role of prosodic structure in providing an adequate account of not only phonological phenomena, but also the phonetic realization of these patterns. I am most interested here in the role of prosodic structure internal to the word, focusing on the role of the mora and the nature of the interface between prosodic and segmental structure. I consider the following two questions: 1. Is the mora phonologically motivated? 2. And if so, is it purely abstract or is it also reflected in the phonetics? I review the arguments that lead us to answer yes to the first question and then provide evidence of manifestations of moraic structure in the phonetics. While the phonetic realization of the mora is not necessarily transparent, it is nevertheless systematic. First I briefly consider the nature of the relationship between the phonology and the phonetics, before turning to the role of prosodic structure.

1.1 The relationship between phonology and phonetics

As has been observed by a number of researchers (including Keating 1990, Pierrehumbert 1990, and Cohn 1990, among others), the patterning of phonology and phonetics are different as well as the symbols and vocabulary that characterize these patterns. The phonology is represented in terms of symbolic representations and

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qualitative categories, with rules or constraints manipulating these categories, while the phonetics is a physical realization, continuous in time and space. These different characteristics support the conclusion that phonetics and phonology are distinct (see Keating 1996 and Cohn 1998 for recent reviews). This is consistent with a view that understands the phonetic influence on phonological structure as arising through phonologization as proposed by Hyman (1976) and discussed more recently by Hyman (2001) and Hale and Reiss (2000).

There is extensive evidence suggesting that the phonetics, in effect, adds the quantitative, temporal dimension to the more abstract phonological representations. In other words, phonetic implementation *acts* on the phonological structure. To account for this, I assume a modular view of the phonology and the phonetics; this can be understood as partial serialization, although other interpretations of how these components or modules interact are also possible.

While an extensive body of literature supports the view that phonetics and phonology are distinct, an alternative view espoused by, for example, Browman and Goldstein (1992), Flemming (2001), Kirchner (1997, 1998), and Steriade (2000), assumes that both the quantitative and qualitative aspects of sound systems interact without restriction. While many of the cases discussed pose interesting problems, I do not agree with the conclusion that the quantitative aspects of phonetics impinge directly on the phonology. I would argue that these observations can also be understood in a framework where there is a mediated relationship between the quantitative and qualitative aspects of sound. While a non-mediated view seems to offer the simpler account in some cases (since no separate phonological and phonetic components are posited), this results in an unpredictive system, since no clustering of properties is predicted between the qualitative and quantitative, and the additive nature of phonetic implementation on top of phonological information is not captured. For fuller discussion of these issues within a constraint-based approach to phonology, see Cohn (1998).

1.2 Prosodic structure

It is widely assumed that prosodic structure, organized hierarchically, plays a role in phonology both above and below the word level, as shown in the work of Selkirk (1980), Nespor and Vogel (1986), Inkelas and Zec (1990), McCarthy and Prince (1993), among others. There is some variation, but a prosodic hierarchy along the following lines is widely assumed:

(1)		utterance
	above the word	phonological phrase
		(clitic group)
		phonological word
	within the word	metrical foot
		syllable
		mora

Above the word, the prosodic hierarchy is argued to provide an account of interactions between syntax and phonology. It is assumed that prosodic information is available in the phonetics and that the prosodic framework is referred to in phonetic implementation (e.g. Pierrehumbert and Beckman 1988). The pervasive role of phrasing in phonetic implementation has been recently documented by Fougeron (1998), Keating et al. (1999) and Cho and Keating (2001).

Let us consider the same questions about prosodic organization within the word. While there is some debate in the literature, it is fairly widely assumed that there is prosodic structure organized hierarchically within the word as well, including: the prosodic word which may or may not be isomorphic with the morphological word; metrical feet which account for metrical prominence and some other phonological phenomena; syllables which allow us to capture patterns of phonotactics and also condition the domain of rule or constraint application. Less agreement holds about the role of the mora. Recently Gordon (1997) and others have argued that the mora does not offer a unified account of weight phenomena and others have argued that the mora is insufficient to account for both weight and timing.

It is the status of the mora that I want to focus on here. Following a moraic approach to weight and timing (see for example Goodman 1995, also Broselow 1995), the mora is taken to be the lowest level of the prosodic hierarchy and it also serves as the link between prosodic and segmental information, represented by the root node and its dependents, leading to the structure shown in (2).

(2)
$$\begin{array}{c} \sigma \\ | \\ \mu \\ | \\ \text{[cons]} \end{array}$$

Root nodes, taken to coordinate subsegmental information, are represented here as having inherent content of the feature [consonantal] (following Goodman 1995, building on the proposal of McCarthy 1988 arguing that the root node consists of both [consonantal] and [sonorant]). Root nodes capture the segmental aspects of timing, while the moraic structure is predicted to capture the prosodic aspects. In fact, assuming root nodes as part of the hierarchical structure of segmental organization offers the equivalent of a timing tier without positing an extra level of representation, resolving to a large degree the debate about moras vs. timing units. (See Goodman 1995 and Broselow 1995 for fuller discussion of this issue.) Since root nodes are by definition segmental and moras are prosodic units, there is not necessarily a one-to-one mapping between them, and we should not be surprised to find certain asymmetrical mappings.

Turning now to the two questions posed above, in Section2, I consider phonological arguments in favor of the mora. In Section3, I present an interesting subclass of monosyllable in English, those consisting of a liquid rime, that provide further evidence for the role of the mora. In Section4, I turn to the question of phonetic manifestations of moraic structure, and in Section5, I report on the results of an acoustic study of the liquid rimes in English. I conclude in Section6.

2. Phonological arguments in favor of the mora

In this section, I review several sorts of arguments in favor of the mora as a prosodic organizing unit in the phonology. (See also Broselow 1995 for an excellent review of arguments in favor of the mora.)

2.1 Binary division of weight

First, a strikingly large number of languages divide a continuum of phonological weight properties into two categories, where both vowel length and the presence of coda consonants can contribute to weight, that is, the property that defines "heavy" vs. "light" in quantity-sensitive stress systems and other weight-sensitive phenomena. This continuum is schematized in (3).

(3) A continuum of phonological weight properties

Cə < CV < CVC < CVV < CVVC

What is noteworthy is that while most quantity sensitive stress systems (and other patterns such as word minimality effects, prosodic morphology, and tone assignment that are also often sensitive to weight) divide the cases into two categories, languages differ in how the continuum is sliced. Two common weight computations are shown in (4).

(4) Weight computations

	light $= \mu$	heavy $= \mu\mu$
a.	CV	CVC, CVV
b.	CV, CVC	CVV

In some languages, open syllables are light and both closed syllables and those with long vowels or diphthongs are heavy (the pattern in 4a). Another common pattern is that both open syllables and closed syllables with a short vowel pattern as light, while those with long vowels or diphthongs pattern as heavy (4b). Yet the prosodic behavior of the two categories is parallel in different languages. The assignment of one vs. two moras to the light vs. heavy categories in each case allows us to capture this limited variation (see Zec 1988 and Hayes 1989).

Consider the distribution of vowels in English. As has been widely observed, there are two sets of vowels in English that differ in their phonological behavior: these are sometimes referred to as *tense* vs. *lax* or *long* vs. *short*. Of interest here is that phonological weight properties of the two classes are different. If there is a lax vowel in the penult, stress falls on the antepenultimate syllable, while the tense vowels pattern together with diphthongs and closed syllables in attracting stress in the penultimate syllable, as illustrated in (5).

(5) Quantity-sensitive stress in English

light	heavy	
lax vowel	tense vowel/diphthong	closed syllable
América	Arizóna	agénda
Cánada	Bermúda	amálgam

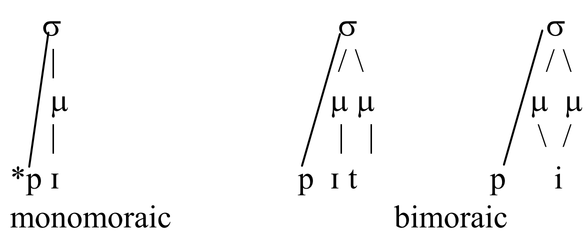
Furthermore, as shown in (6), the tense vowels (6a) and diphthongs (6b), but not the lax ones (6c), can also appear in open monosyllabic content words.

(6) English monosyllabic content words

a. tense vowels: pea, pay, Pooh, Po, paw
b. diphthongs: pie, pow, poy
but:
c. lax vowels: *[pɪ], *[pɛ], *[pæ], *[pʌ], *[pʊ]

The intuition is that the lax vowels are monomoraic, while the tense vowels and diphthongs are bimoraic (see also Hammond 1999 and Morén 1997, 1999), yielding the structures illustrated in (7).

(7)



This pattern results from a minimal word effect, whereby a well-formed word must be at least two moras.[1] (Clearly there needs to be a set of rules or constraints to account for the surface qualities of these pairs, an issue that we will not pursue here. See Clement 2000 for a recent analysis.)

[1] The reader is referred to Morén (1997) for arguments that /ɔ/ in General American English is bimoraic.

2.2 Onset/rime asymmetries

As mentioned above, since intrinsically root nodes are segmental and moras prosodic, there is not necessarily expected to be a one-to-one correspondence between root nodes and moras. There is no a priori reason that all root nodes should necessarily be dominated by moras. In other words, there is no reason to assume that either strict layering or exhaustive parsing (Selkirk 1984) obtains, since root nodes are not units of the prosodic hierarchy. Thus we should not be surprised to find asymmetrical mappings. Just such an asymmetry is observed in the contribution to weight. With few exceptions, in those languages that show weight sensitivity, segments in the rime contribute to weight, but onsets do not. (See Goedemans 1998 for discussion.)

A widely cited example of this sort of asymmetry is found in compensatory lengthening, where the loss of a consonant from the rime results in compensatory lengthening, but the loss of a consonant from the onset does not. This is precisely the argument made by Hayes (1989) in favor of moraic representations. Consider the case of Latin compensatory lengthening presented by Hayes, illustrated in (8):

(8) Latin compensatory lengthening (Hayes 1989, following Ingria 1980)

a.	*kasnus →	ka:nus	'gray'
	*kosmis →	ko:mis	'courteous'
b.	but		
	*smereo: →	mereo:	'deserve-1 sg.-res.'
	*snurus →	nurus	'daughter-in-law'

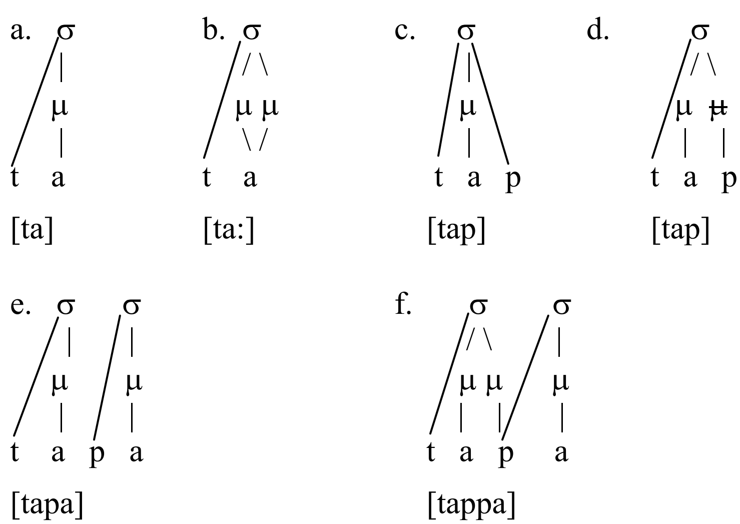
In a change that was conditioned by the segmental context, /s/ before an anterior sonorant was lost. Of interest here is the fact that when the /s/ was in coda position, compensatory lengthening occurred (8a), while if the /s/ was in onset position, there was no compensatory lengthening (8b). There is independent evidence from stress assignment and metrics in Latin that coda consonants contributed to weight. As discussed by Hayes, a moraic analysis whereby elements in the rime are dominated by moras, but onset elements are not, directly captures this asymmetry, while a timing tier approach cannot.

This onset-rime asymmetry is also found in stress assignment and related word minimality effects. For example, in English the number of consonants in the onset does not affect the observations above about well-formedness of monosyllabic content words. Adding consonants to the onset does not improve the illformedness of an open monosyllable consisting of a lax vowel. Forms such as *[plɪ], *[slɪ], *[splɪ] are just as bad as *[pɪ].

2.3 Representation of geminates

The moraic representation of geminates is structurally distinct from that of long vowels. This is in contrast to a timing unit approach to consonant geminates, where the representations for long vowels and geminates are completely parallel with both equalling two units. Following the moraic view, the inherent property of geminate consonants is their moraicity. The surface result of this, at least in medial position, is the well-known flopped representation, following Hayes (1989). In Optimality Theoretic terms, this is due to a high ranking ban on moraic consonants in onsets. These representations are sketched out in (9), starting with a review of basic syllables types.

(9)

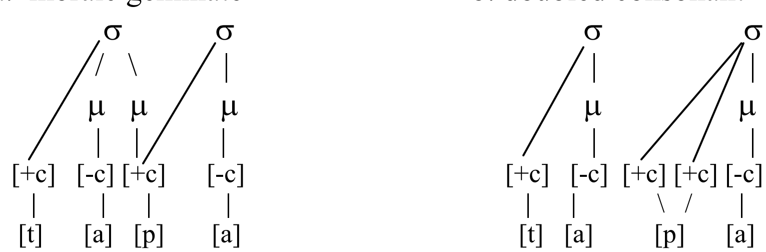


In (9a) vs. (9b), we see the contrast between a short vowel, dominated by a single mora, vs. a long vowel dominated by two moras. This is parallel to the contrast proposed above in (7) for the representation of lax vs. tense vowels in English. In (9c) is a case of a coda consonant that does not contribute weight to the syllable, while in (9d), the coda consonant does contribute weight. Following Hayes (1989), the consonant in this case is assigned weight-by-position (with a mora indicated with a strikethrough), but see also

Zec (1988) for another approach to assignment of weight to coda consonants. In (9e) is the case of a simple intervocalic consonant that forms the onset of the second syllable. In (9f) is the case of an underlying moraic consonant, which is realized as a geminate on the surface.[2]

There has been much debate in the recent literature as to whether geminates are weight bearing or not. (See Selkirk 1990, Tranel 1991, Davis 1994, 1999a & b, Broselow 1995, Goodman 1995, Hume et al. 1997, Ham 1998, among others.) In fact, the contradictory evidence in the literature strongly suggests that both weight-bearing geminates and non-weight-bearing ones exist. Following Ham (1998), I refer to the former as "geminates" and the latter, as "doubled consonants". Within a moraic framework, following Goodman (1995), both representations are available without reference to an additional timing tier, and in fact a moraic approach to geminates predicts that both sorts of cases should exist. A timing tier approach, on the other hand, does not predict two distinct sorts of long consonants. Following Goodman, where [consonantal] inherently defines the root node, we have the two representations sketched out in (10a) and (b).

(10) a. moraic geminate b. doubled consonant[3]



[tappa] [tappa]

The phonological behavior of the two types of long consonants can often be diagnosed, in terms of contribution to weight, syllable affiliation, and so forth. As we will see below, there is also phonetic evidence for the contrast as well.

The strongest evidence for the need for both representations is the fact that the two representations can co-exist in the same language. In Ponepean, Goodman (1995)

[2] For discussion of the representation of initial geminates, see Ham (1998) and Davis (1999b) and for the discussion of final geminates, see Ham (1998).

shows that there are canonical geminates both initially and medially, but that the so-called long distance geminates (with CVC roots where $C_1=C_2$) are not weight bearing and have the structure of doubled consonants. In Swiss German, which is described as having geminates in initial, medial, and final position, Ham (1998) shows that the long consonants in medial and final position are canonical weight-bearing geminates, while the long consonants in initial position are non-weight bearing, having the structure of doubled consonants.

Most languages that exhibit a weight contrast show just a two-way contrast, light vs. heavy. However, some languages also have superheavy syllables. These are typically languages with both long vowels and geminates. It is important to note that while many languages allow complex coda clusters, it is not necessarily the case that these pattern as superheavy; for example, in English it is not the case that *sixths* [sɪksθs] is heavier than *sick* [sɪk]. However, there are well documented cases of superheavy syllables. Some languages that have both long vowels and geminates restrict their cooccurrence (through, for example, closed syllable shortening), but other languages allow the cooccurrence of long vowels and geminates; that is, there are syllables with long vowels followed by a geminate. Such is the case in Sinhalese (Letterman 1997) and also Hungarian (Ham 1998). In such cases, these syllables are analyzed as being trimoraic. In Optimality Theoretic terms, these cases violate the common ban on trimoraic syllables. Consider, for example, the distribution of syllable types in Hungarian, following Ham (1998, p. 160) as shown in (11).

(11) Hungarian syllable types

a. μ

i.	CV	ma	'today'
		fa	'tree'
ii.	CVC	bot	'stick' (N)
		ɲom	'trail'

[3] I leave aside the question of whether doubled consonants in medial position are heterosyllabic, as sketched out here, or tautosyllabic.

b. μμ			
i.	CV:	lo:	'horse'
		fy:	'grass'
ii.	CV:C	po:k	'spider'
		ka:d	'tub'
iii.	CVC:/CVCC	kɛd:	'Tuesday'
		ʃylt	'baked' (adj.)
c. μμμ			
	CV:C:/CV:CC	ro:t:	'notched' (adj.)
		hy:lt	'cooled' (adj.)
d.	*CVCCC, *CV:CCC		

In Hungarian, there are one, two, and three mora syllables, where vowel length, final geminates, and consonant clusters are all part of the computation. Final consonants in Hungarian are extrametrical. (As discussed by Ham, this maintains the contrast between final singleton vs. geminate consonants.) As shown in (11a), both CV and CVC are thus monomoraic. As shown in (11b), syllables with a long vowel with or without a final consonant, as well as syllables with a final geminate or a final cluster, all constitute bimoraic syllables. As shown in (11c), syllables consisting of a long vowel followed by either a geminate or a cluster are allowed. These are superheavy, constituting trimoraic syllables. Eventhough superheavy syllables are tolerated, there are still limits, as syllables with three final consonants are not tolerated. The allowable sequence of vowels and consonants can be defined straightforwardly in moraic terms. There appears to be an upper limit of three moras. Crucially there is still not a one-to-one relationship of moras to segments. (There appears to be an additional restriction, independent of mora count, as a syllable with three coda consonants after a short vowel would be expected to constitute a well-formed trimoraic syllable, since the final one of the cluster would be expected to be extrametrical.)

To summarize, in this section, we have seen several phonological arguments in favor of a moraic representation of weight, where weight is understood to be a property of moraic structure. This included evidence from a characteristic binary division of weight in languages that show sensitivity to weight, onset-rime asymmetries in weight computations, and the representation of geminates as moraic. Another important area of evidence comes from prosodic morphology as discussed at length by McCarthy and

Prince (1986). We turn now to a case from English where interesting differences in syllable weight are found, providing further evidence for a moraic representation.

3. English liquid rimes

In the case of superheavy syllables discussed above, although there is not a one-to-one correspondence between segments and moras, the weight properties are nevertheless defined transparently by sequences of vowels and consonants. However there are some cases where sonority plays a role in defining just a subclass of syllable types as superheavy; we consider now such a case in English. As discussed by Lavoie and Cohn (1999) and Cohn and Lavoie (2003), there is a subclass of English monosyllables that have a special property. These are forms with an /l/ or /r/ in the rime following certain vowels or diphthongs, as illustrated in (12).

(12)	/l/-rimes:	file, foul, foil; feel, fool, fail
	/r/-rimes:	fire, flour (coir)

What is interesting about these forms is that they fall somewhere between the clear monosyllables and disyllables, as many speakers have the impression that they are somewhat more than a monosyllable. In (13), I summarize the phonological distribution of the liquid rimes, indicating those that are felt to be more than a simple syllable.

(13) Phonological distribution of r/l rimes

Key:

merged vowels	superheavy	— non-occurring

	r	l	n	Ø
i	fear	feel	seen	fee
ɪ		fill	fin	—
e[4]	fair	fail	rain	Fay
ɛ		fell	Ben	—
æ		pal	fan	—
a	far	doll	Don	fa
ʌ	(fur)	dull	fun	—
ər	—	curl	fern	fur
u	poor	fool	soon	Pooh
ʊ		full	—	—
o[4]	four	sole	phone	foe
ɔ		fall	fawn	paw
aj	fire	file	fine	fie
aw	flour	foul	down	paw
oj	(coir)	foil	coin	poi

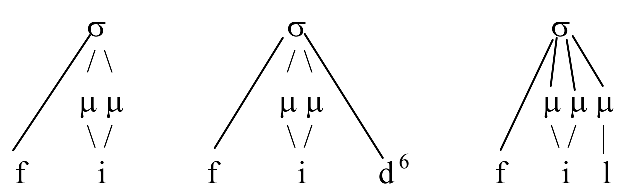
We refer to these as superheavy syllables, and these cases are enclosed in a double-lined box. This distribution is based on the judgments of the authors, as well as evidence from speaker intuition, metrical evidence, and morphophonology (see Lavoie and Cohn 1999 and Cohn and Lavoie 2003 for details). There are several observations to be made. 1) We observe that this property only holds for some /r/ and /l/ rimes, but not for other rime consonants. Thus *feel* /fil/ shows this property, but *seen* /sin/ does not. 2) The true diphthongs /aj, aw, oj/ exhibit this property in both /r/ and /l/ rimes, but differences are found with the other vowels. 3) For the /l/ rimes, there is a difference between tense vs. lax vowels, in that the tense vowels exhibit this property, while lax ones do not. Compare for example *feel* /fil/ vs. *fill* /fɪl/. 4) Vowel height is also relevant for the /l/ rimes, as this property obtains with non-low vowels, but not low vowels.[5] Compare *fail*

[4] The tense mid vowels are transcribed without an offglide, as we understand this to be part of the realization, but not a contrastive property of these vowels.
[5] The vowel /o/ is interesting in this regard as this is the one case where the authors are not in agreement. LL finds this case to be superheavy, while AC does not.

/fel/ vs. *fall* /fɔl/. 5) Finally, we observe that the neutralization of the tense-lax vowels before rime /r/ is also relevant. While the quality of these vowels is judged to be tenser by some speakers and laxer by others, these pattern phonologically as though they were lax, not exhibiting the property of being superheavy.

Cohn and Lavoie (2003) argue that the property of being superheavy can best be understood in moraic terms. The superheavy syllables are trimoraic syllables. This results, we argue, from the requirement that a liquid in the rime bear a mora. In the case of a syllable with a bimoraic vowel (tense vowel or diphthong), this requirement on liquid rimes is in direct competition with a ban on trimoraic syllables. In English, this ban is not violated across the board, as it is in Hungarian, but only in this limited subset of cases. Thus there is a distinction between bimoraic and trimoraic syllables. The bimoraic syllables consist of a tense vowel or diphthong (sketched in14a), or a vowel followed by a non-liquid rime consonant (14b), and trimoraic syllables are those cases of rime liquids that have the property of being superheavy (14c).

(14) a. b. c.



bimoraic trimoraic

Consider the implication of these data for mora assignment. Crucially, the number of moras is not predictable from the number of segments in the rime. This can be seen above in (13), since only /r/ and /l/ have the possibility of inducing this additional mora. Also, the presence of additional coda consonants does not change the basic mora count as shown in (15):

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[6] There is phonetic evidence, discussed below in Section5, that /d/ does not share a mora with /i/ in English, as there is no interaction between the duration of /i/ and /d/.

(15)

heavy rime		superheavy rime
will	pine	while
wilt	pint	whiled
wilts	pints	whilst

The presence of additional coda consonants, whether in a heavy rime or a superheavy one does not change its mora count.

This subtle difference between heavy vs. superheavy syllables cannot be accounted for in a timing slot approach, since each rime consonant would be assigned a timing slot. This introduces another kind of asymmetry between mora and segment count. Above we saw cases of onset-rime asymmetries in their contributions to weight. We also saw that there can be a lack of one-to-one correspondence between the number of moras and the number of elements in the rime with the upper limit of trimoraic syllables in Hungarian. Here we see a similar case, but the property of being superheavy is defined by the interaction of sonority and specific properties of the preceding vowel.

This leads to the question as to whether asymmetrical segment-to-mora mappings should surprise us. I would argue that such asymmetrical mappings in fact are what we would predict, since segments and moras are inherently different sorts of entities. Since their mapping is the interface between segmental and prosodic material, usual principles of exhaustive parsing and strict layering need not hold. We therefore do not predict a one-to-one mapping. Any view that predicts a one-to-one mapping, such as a timing tier approach, has to stipulate the asymmetrical patterns, thereby missing important generalizations about the mapping of segments to syllables.

A question that has been raised is whether mora assignment is always consistent within a language. Based on data in three Bantu languages, Hyman (1992) provides evidence that there may be different weight computations within a single language. In a broad cross-linguistic study, Gordon (1997) provides further documentation that indeed the computation of moras may differ within a language. While the computation might not always match up as predicted under the simplest interpretation, e.g. the mora count for stress and tone might differ within a language, this alone does not show that a moraic approach to weight cannot account systematically for such variation. As discussed by Zec (1999), there are properties, most notably sonority, which are predicted to interact with mora count that offer a systematic explanation for such variation.

In conclusion to this section then, the distribution of superheavy liquid rimes in English can be accounted for through the limited distribution of trimoraic syllables, resulting from the requirement that liquids in the rime are moraic. This lends further support to the range of phonological evidence in favor of the interpretation of phonological weight in moraic terms reviewed in the previous section. Thus we reaffirm the conclusion that the mora has a fundamental role to play in our understanding of phonological structure and patterning.

4. Phonetic realization of the mora

We now turn to the question of the phonetic interpretation of the mora, where it will be shown that here too we see systematic manifestations of the mora. This provides further support for the role of the mora as a prosodic unit in the phonology and also supports the conclusion that phonetics and phonology are distinct.

4.1 Organization of phonetic duration

For a long time, the mora was assumed to be a purely abstract unit of structure, but a line of recent work has shown that there are systematic phonetic manifestations of the mora. Port et al. (1987), Hubbard (1995), Broselow et al. (1997) and others have argued that phonetic duration is organized around the mora. Consider, for example, phonetic durations of monosyllabic words in Hungarian, investigated by Ham (1998).

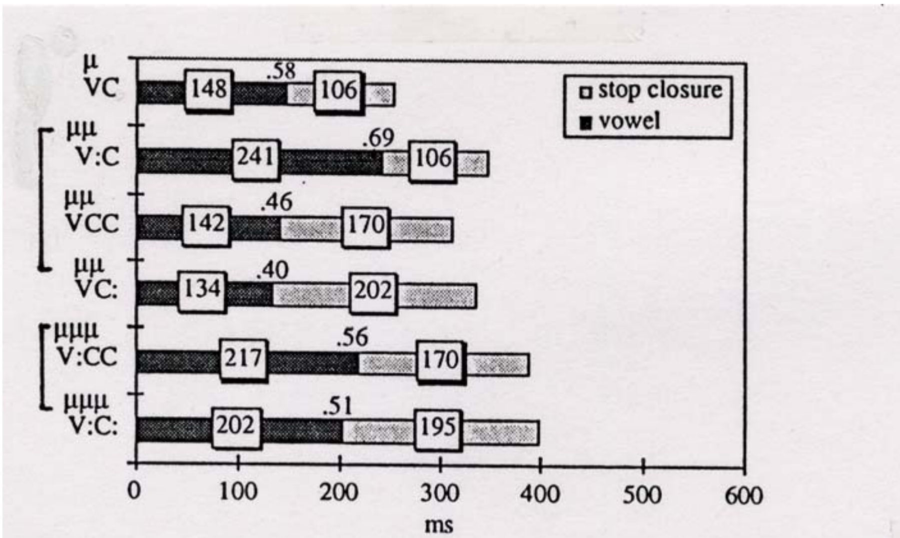


Figure 6.12. Timing of vowel-stop sequences plus V:V+C quotients in Hungarian monosyllabic words.

Figure 1: Duration patterns in Hungarian (Ham 1998)

Looking at the data in Figure 1, we can see that there is a strong correlation in duration of one, two, and three mora cases. This cuts across different vowel and consonant combinations. The monomoraic short vowel-consonant forms are the shortest. The bimoraic cases, whether consisting of a long vowel followed by a single consonant or a short vowel followed by a cluster or geminate, are longer. They are quite similar in overall rime duration to each other, although the ratio of vowel to total rime duration is different. Finally, the trimoraic cases are very close in duration to each other and are systematically longer than the bimoraic cases. This suggests a rather direct manifestation of moraic structure in terms of duration in the phonetic realization of these patterns.

Evidence from Ham as well as the researchers cited above provides convincing evidence that phonetic duration is organized around the mora. But, as discussed by Ham (1998), this is only half of the picture, since segmental duration is also clearly important; that is, non-moraic consonants also take up duration. Ham proposes an integrated model of phonetic duration where both the segmental and prosodic structure contribute to the physical duration. This suggests that in cases where the mora is present, but not playing a contrastive role, subtler differences in duration may be observed.

We are now ready to consider the phonetic manifestations of the mora for cases discussed above in Section2. We consider three cases: 1) phonetic realization of onset/rime asymmetries (Section4.2), 2) phonetic differences between weight-bearing geminates and doubled consonants (Section4.3), and 3) phonetic evidence for the interpretation of the tense/lax contrast in English in moraic terms (Section4.4).

4.2 Phonetic realization of onset/rime asymmetries

As discussed in Section2.2, onset-rime asymmetries in weight are the norm cross-linguistically, where rimes, but not onsets, contribute to weight. There is both articulatory and perceptual evidence for such onset-rime asymmetries. Much of the articulatory evidence comes from work in the Articulatory Phonology literature that has focused on the nature of coordination of articulatory gestures. See Krakow (1999) for a recent review and discussion of this evidence. What this literature shows is that the organization of gestures is often different in onset and coda position, with tighter organization in onset than rime position. For example, Browman and Goldstein (1988) reach the following conclusion:

> To summarize, it seems that within words or syllables, postvocalic (syllable-final) consonants may behave differently than prevocalic (syllable-initial) ones. While initial consonants are related to their words in terms of a single global metric for the entire cluster, the C-center, final consonants appear to be related to their words in terms of the local metric of achievement of targets ... rather than in terms of C-centers. (p. 149)

Goedemans (1998) carried out a series of perceptual experiments to see whether there was perceptual evidence for the role of the mora. He concludes “In any case, we may safely assume that perceived duration is the primary phonetic correlate of phonological weight. The weightlessness of the onset is reflected in its relative durational invariance and its high JND [just noticeable difference]” (p. 78).

4.3 Phonetic differences between geminates and doubled consonants

As discussed in Section2.3, a moraic representation of weight coupled with a feature geometric organization of subsegmental structure straightforwardly offers representations of both weight-bearing geminates and non-weight-bearing doubled consonants. Appeal to both representations resolves the debate in the literature, and evidence of the coexistence of these two types of long consonants within the same languages offers strong support for the necessity of these two distinct representations. Ham (1998) looks for phonetic evidence of this difference. He first looks for evidence for the phonetic effects of geminates as inherently weight bearing and then contrasts this with the lack of such effects in the case of doubled consonants. He extends a proposal of Hubbard (1995) of moraic primacy in phonetic timing and draws the following prediction: "Hubbard's proposal for moraic primacy in phonetic timing. . . taken together with the moraic view of geminates. . . makes the strong prediction that segment-level timing effects should be smaller in geminates than in singletons, since only the former are moraic" (pp. 334-5). He tests this hypothesis by investigating the effects of place of articulation and voicing on duration in singletons and geminates in four languages (Bernese (a dialect of Swiss German), Hungarian, Levantine Arabic, and Madurese) and finds quite striking evidence in support of the hypothesis. We consider first the effects of place of articulation (shown in Figure 2) and then the effects of voicing (shown in Figure 3).

Ham notes the "widely observed cross-linguistic tendency for closure duration to decrease as the point of oral constriction along the vocal tract becomes less anterior" (p. 336, as discussed by Ohala 1983 among others). The prediction is that if moraic primacy holds, then the differences in duration due to place of articulation should be smaller in geminates than singletons, exactly the opposite of what would be predicted a priori. To test this, Ham measured the percentage differences in mean closure duration between stops at adjacent places of articulation [p]-[t], [t]-[k], etc. and averaged the absolute difference.

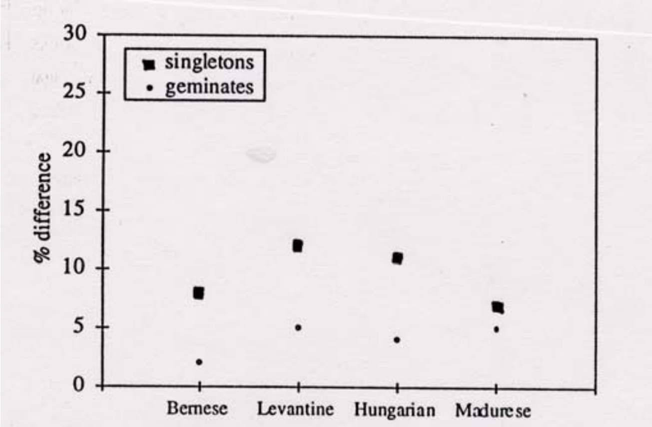


Figure 7.4. Mean absolute percentage differences in singleton and geminate stop closure duration conditioned by place of articulation.

Figure 2: Effects of place of articulation (Ham 1998, p. 337, Figure 7.4)

As seen in Figure 2, for each of the four languages studied, there was a large percentage difference with the geminates (small circles) systematically showing less effect than the singletons (small squares), strongly supporting the hypothesis of moraic primacy. (The case with the smallest difference, Madurese, is the case where the evidence for the moraic representation of geminates is least robust.)

Similarly Ham considers the widely observed cross-linguistic tendency for voiced stops to be shorter than voiceless ones “due to the aerodynamic difficulties associated with maintaining vocal fold vibration in the presence of a complete oral seal" (p. 338, also discussed by Ohala 1983). Here again following moraic primacy, geminates are predicted to show smaller effects than singletons. To test this, Ham measured the percentage difference in voiceless-voiced pairs between geminates and singletons, as shown in Figure 3. (Bernese is not included in this comparison as there are not phonetically voiced stops.).

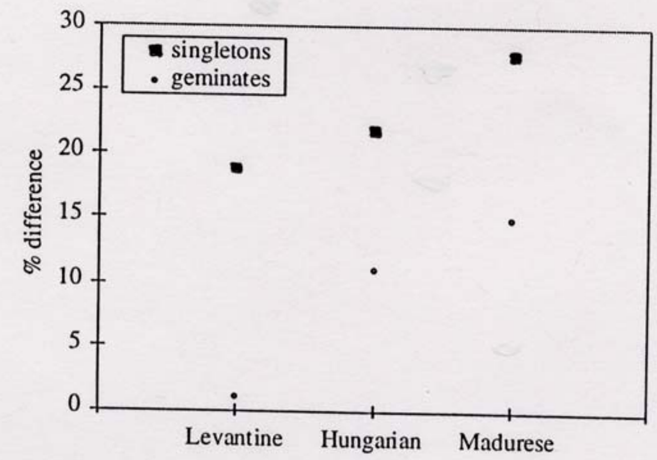


Figure 7.5. Mean absolute percentage differences in singleton and geminate stop closure duration conditioned by voicing.

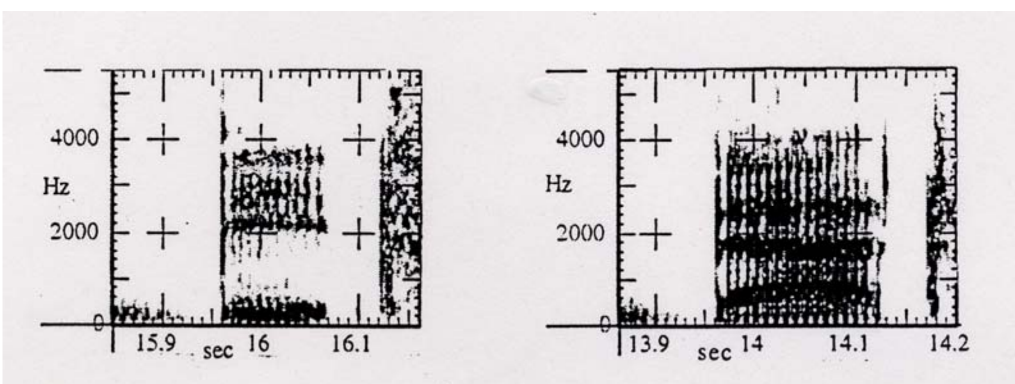
Figure 3: Effects of voicing (Ham 1998, p. 339, figure 7.5)

For each of the three languages, there is a very large difference in the percentage differences between the geminates (small circles) and singletons (small squares), with the geminates systematically showing much less difference than singletons. This again supports the hypothesis.

The logic of the argument is that if the appropriate representation of geminates is as moraic consonants, then they will show effects of moraic primacy. But how do we know this is not true of all long consonants? In fact, Ham is able to make just this comparison in Bernese, where he argues that the medial and final long consonants are geminates, but that the initial ones are doubled consonants. The prediction is that the sorts of segmental effects on duration seen above should not be more constrained in doubled consonants than singletons. Ham (1998) measured the effect of place conditioned duration differences and found the following: "Intriguingly what we found is that place-conditioned durational differences are on average 15% larger in the doubled consonant cases. . . This represents a complete reversal of the situation reported for (moraic) word-medial and word-final stops in Bernese. . ." (p. 354). Ham goes on to observe: "What this difference suggests is that segment-level durational effects tend to be *enhanced* in doubled consonants (which encompass two-root-nodes). . . but tend to be *muted* in geminates" (p. 354). These results strongly suggest that there are phonetic differences between geminates and doubled consonants; reinforcing the phonological conclusions above that a geminate representation using timing units alone is insufficient, since in fact there are systematic phonetic differences between geminates and doubled consonants. Additional phonetic studies of this sort in other languages exhibiting geminates or doubled consonants would be very valuable.

4.4 Phonetic realization of the tense/lax contrast in English

We turn now to the phonetic realization of tense/lax vowels in English. I suggested above in Section2.1 that the distributional facts follow from assigning two moras to tense vowels and diphthongs, but only one to the lax vowels. Within a close pair such as [i, ɪ], or [e, ɛ], there are systematic phonetic duration differences with the tense member of each pair being longer (and usually more diphthongal). However, considering tense-lax pairs that do not agree in height, the situation is not so straightforward. Here the mora count is not necessarily realized transparently in durational terms. Consider, for example, tense /i/, taken to be bimoraic, compared with lax /æ/, taken to be monomoraic, as shown in the spectrograms in Figure 4 comparing *beet* vs. *bat*. In fact, /i/ is much shorter than /æ/, the opposite of what is predicted by the mora count alone.



b i t b æ t

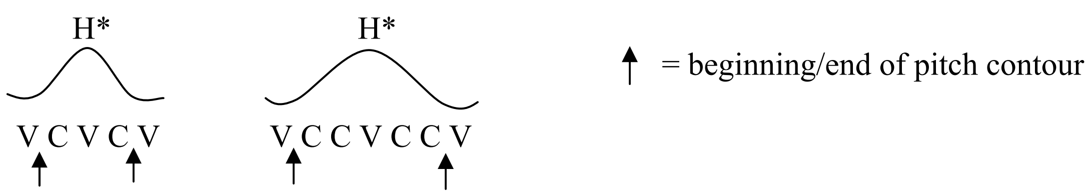
Figure 4: *beet* vs. *bat* said in the frame sentence *Please say X for me*

What we observe here is that the effect of intrinsic duration on vowel height, whereby low vowels are longer than high ones (Peterson and Lehiste 1960), has a more robust effect on duration than the mora count. How do we know then, that we were not just wrong about the moraic structure of the tense-lax contrast in English proposed above?

Perhaps the distributional facts of tense vs. lax vowels in English are just frozen distributional properties of the lexicon.

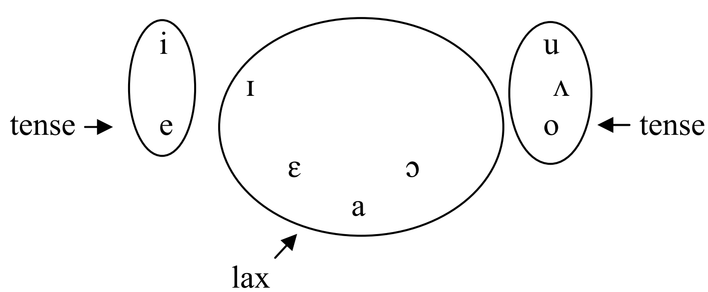
Recent work by Ladd and others on the alignment of suprasegmental information to segmental information (including Arvantiti, Ladd, and Mennen 1998 and Ladd, Mennen, and Schepman 2000) provides striking evidence of the mora count difference of the tense-lax contrast in English and reinforces the conclusion that the relationship between mora count and phonetic duration is systematic, albeit complex. To lay out this argument, consider first the general finding of the anchoring of tone to segments, exemplified for Greek. Arvaniti et al. (1998) find that alignment and duration of the pitch contour are influenced by segment count as well as syllable structure. As schematized in (15), the contour begins at the end of the pretonic vowel and ends at the beginning of the post-tonic vowel, irrespective of the structure of the tonic syllable itself.

(15) Alignment pattern in Greek (Arvaniti et al. 1998)



In some unpublished work, Ladd (p.c.) has been investigating Scottish English. He argues that tense and lax vowels of Scottish English are grouped as shown in (16).

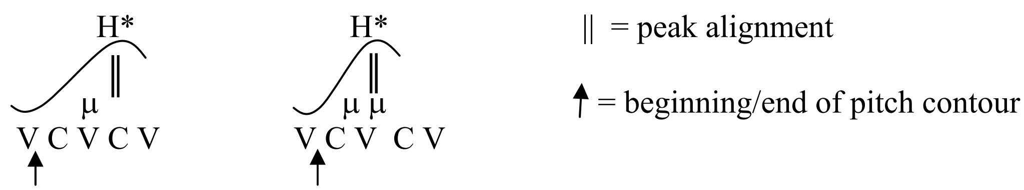
(16) Scottish English vowels (Ladd p.c.)



Of particular interest to us is the alignment pattern found in Scottish English. The lax vowels show a different pattern from the tense ones. As schematized in (17), in the case of the lax vowels (17a), the peak of the contour occurs during the following consonant, while in the case of the tense vowels (17b), the alignment occurs during the second part of the vowel.

(17) Scottish English alignment (Ladd p.c.)

a. lax vowels b. tense vowels



What is of most interest to us here is that these different patterns of peak alignment are completely independent of intrinsic duration of the particular vowels. In Figure 5, the peak alignment relative to the tonic vowel and following consonant is shown for the tense vowels [i, e] compared with lax vowels [ɪ, ɛ, a, ɔ].

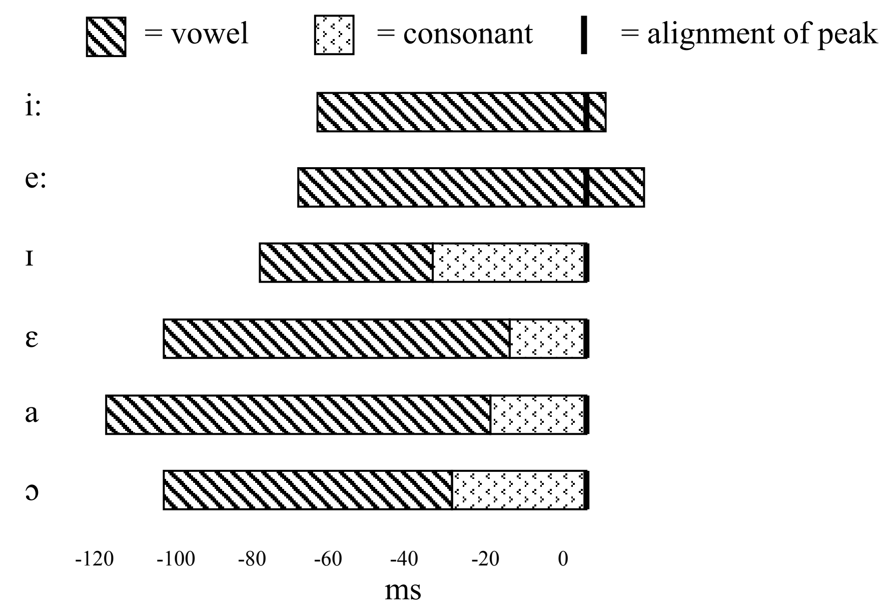


Figure 5: Peak alignment relative to tonic vowel and following consonant for tense and lax vowels in Scottish English (Ladd p.c.)

In Figure 5, the vowels are lined up on the right edge at the point of peak alignment with the H tone. For [i, e], argued by Ladd to be tense, the peak alignment occurs toward the end of the tonic vowel. For [ɪ], which is argued to be lax, the alignment occurs well into the following consonant. Based just on these cases, we might conclude that the pitch contour is aligned relative to the beginning of the vowel, but looking at the pattern for [ɛ, a, ɔ], all argued to be lax, we see this generalization does not hold. Rather for the lax vowels, no matter whether they are high and therefore intrinsically short ([ɪ]) or low or mid and therefore long ([ɛ, a, ɔ]), peak alignment occurs well into the following consonants. To account for this pattern, reference needs to be made to the distinction between tense/lax, argued here to be accounted for by one vs. two moras. Similar to the pattern for Greek, prosodic structure (in this case the mora) as well as detailed phonetic duration both play a crucial role in segmental alignment of tone.

In this section we have seen evidence of the phonetic manifestation of moraic structure for a range of cases. Now we return to the question of phonetic evidence of three-way weight contrasts. Above in Section4.1, we saw evidence for a three-way weight contrast in Hungarian. We now turn to the phonetic realization of the liquid rimes in English, which in Section3 were argued to be trimoraic.

5. Phonetic evidence for superheavy syllables: English /l/-rimes

In order to find additional support for the analysis of liquid rimes in English as trimoraic and also to further the investigation of the phonetic manifestion of moraic structure, Lavoie and Cohn (1999) carried out a small acoustic study of the /l/-rimes comparing the phonetic realization of heavy and superheavy syllables. (Cohn and Lavoie have since replicated the results reported on here in a larger study, reported by Cohn and Lavoie 2003). The prediction being tested is that trimoraic rimes will show longer overall duration than similar bimoraic ones.

Real English words of the shape CV(C)(C) were used. As summarized in Table 1, the initial consonant was /s/ or /f/ in most cases. Tense and lax vowels differing in height as well as diphthongs were used. These were followed either by nothing, /l/, /d/, or /ld/. Two female American English speakers produced four repetitions of each word produced in the frame sentence *Please say ____ for me*, of which three repetitions were analyzed.

C	V	(C)(C)
s/f	μ: ɪ, ʊ μμ: a, ɔ i,u μμ: aj, aw	Ø d μ: l, ld

Table 1: Structure of word list for acoustic study of /l/ rimes in American English

I report here on the durations of the low vowels plus /l/, cases such as *Sol*, *doll* (which are not judged to be superheavy), with the durations of the diphthongs plus /l/, such as *file*, *foul* (which *are* judged to be superheavy), because the vowel durations are comparable.

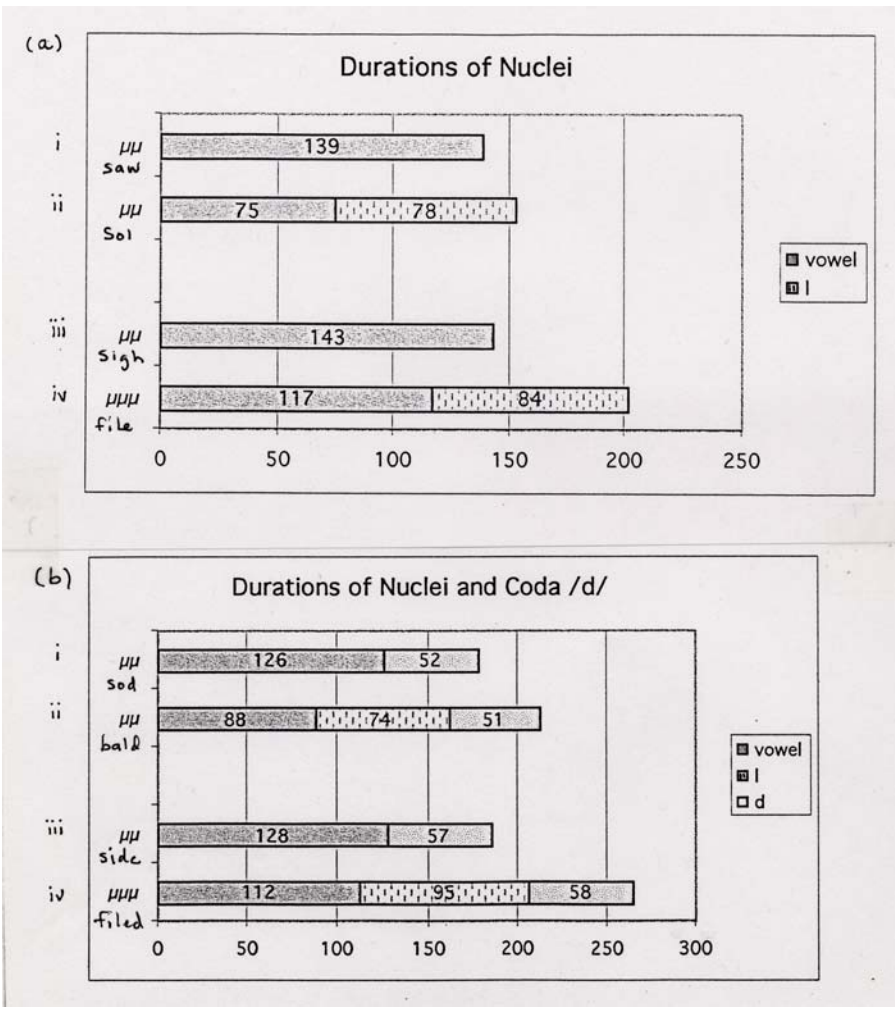


Figure 6: Result for rime duration of /l/ rimes (a) vowel + /l/ and (b) vowel + /l/ + /d/

We compared the duration of rime + /l/ cases, taken to be trimoraic, with the cases taken to be bimoraic. The former cases are indeed systematically longer than the latter.

Looking first at the vowel + /l/ case in Figure 6a, rimes consisting of a diphthong + /l/ (the bottom bar, iv, e.g. *file*) are systematically longer than the rime consisting of a low vowel (e.g. *saw)*, a low vowel + /l/ (e.g. *Sol*), or just a diphthong (e.g. *sigh*) in (i) through (iii). For the vowel + /l/ cases, argued to be bimoraic, the average low vowel rime duration is 154 ms, while for the diphthong + /l/ cases, argued to be trimoraic, the average duration is 201 ms. As we see in Figure 6b, the presence of a /d/ in the rime has a different kind of effect on the duration of the word; it contributes a constant duration regardless of the mora count of the form. In all of these cases, /d/ contributes a duration of about 55 ms, showing the duration of /d/ to be independent of moraic structure, in contrast to vowel + /l/ rimes which have additional duration from the presence of /l/. (These results support the representation presented above in 14b, where coda /d/ does not share the mora of the preceeding vowel.) The duration of the vowel + /l/ portion is very similar to that in the previous figure. As argued above, we cannot capture the differing effect of post vocalic /l/ vs. /d/ nor of /l/ following a diphthong or non-low tense vowel, but not a low vowel or lax vowel by reference to the number of segments. These systematic differences in duration correlating with the proposed differences in mora count provide a strong confirmation of our hypothesis regarding weight structure. This case lends further support to the conclusion that moraic structure is systematically manifested in the phonetics.

The results about coda /d/ lead to a broader issue of the weight-bearing vs. non-weight-bearing status of codas. As shown by Duanmu (1994), syllables in Mandarin, taken to have moraic codas, are systematically longer than in Shanghai (Wu), where codas are argued not to be moraic. We are currently investigating this question in English where we find that the /d/ in cases like [bɪd], where it is argued to be moraic due to word minimality, is slightly but systematically longer than in cases like [bid], where it is not. In a language where moraic structure is not contrastive, that is, where there is not a singleton-geminate contrast, more subtle phonetic differences may be associated with the presence or absence of a mora.

6. Conclusions

In conclusion, we return to the two questions posed at the outset and answer yes to both. First we have seen that moraic structure indeed plays a systematic role in characterizing phonological patterns, reaffirming extensive phonological evidence in the literature. The mora serves as the connection or link between prosodic and segmental structure. Not surprisingly, the mapping of moras to segments is not one-to-one, since segmental structure and prosodic structure are inherently different kinds of representations. Second, we observe systematic manifestations of moraic structure in the phonetics, even in cases where the relationship may not be transparent. We have seen these systematic manifestations in the realization of singleton-geminate contrasts, onset-rime asymmetries, the realization of tense vs. lax vowels in English, and finally in the case of superheavy liquid rimes in American English. The nature of these manifestations supports the view that phonetics is the implementation of phonological structure in that both the more abstract phonological categories (in this case the mora) and the physical dimension (phonetic duration) work together in accounting for the observed patterns.

References

Arvantiti, A., D. R. Ladd, and I. Mennen (1998) Stability of tonal alignment: The case of Greek prenuclear accents. *Journal of Phonetics* 26, 3-25.

Broselow, E. (1995) Skeletal positions and moras. In Goldsmith, J. (ed.) *The Handbook of Phonological Theory*. Oxford: Blackwells, pp. 175-205.

Broselow, E. S.-I. Chen and M. Huffman (1997) Syllable weight: convergence of phonology and phonetics. *Phonology* 14, 47-83.

Browman, C. and L. Goldstein (1988) Some notes on syllable structure in Articulatory Phonology. *Phonetica* 45, 140-155.

Browman, C. and L. Goldstein (1992) Articulatory Phonology: an overview. *Phonetica* 49, 155-180.

Cho, T. and P. Keating (2001) Articulatory and acoustic studies on domain-initial strengthening in Korean. *Journal of Phonetics* 29, 155-190.

Clements, N. (2000) Phonological monophthongs, phonetic diphthongs: evidence from English. *Bulletin de la Communication Parlée* 5, 57-75.

Cohn, A. (1990) *Phonetic and Phonological Rules of Nasalization*. Ph.D. dissertation, UCLA. Distributed as *UCLA Working Papers in Phonetics 76*.

Cohn, A. (1998) The phonetics-phonology interface revisited: Where's phonetics? *Texas Linguistic Forum* 41, 25-40.

Cohn, A. and L. Lavoie (2003) Superheavy monosyllables in American English. Cornell University and MIT ms.

Davis, S. (1994) Geminate consonants in moraic phonology. *WCCFL* 13, 32-45.

Davis, S. (1999a) On the moraic representation of underlying geminates: Evidence from prosodic morphology. In H. van der Hust, R. Kager, and W. Zonneveld (eds.) *The Prosody-Morphology Interface*. Cambridge: CUP, pp. 39-61.

Davis, S. (1999b) On the representation of initial geminates. *Phonology* 16, 93-104.

Duanmu, S. (1994) Syllabic weight and syllabic duration: A correlation between phonology and phonetics. *Phonology* 14, 1-24.

Flemming, E. (2001) Scalar and categorical phenomena in a unified model of phonetics and phonology. *Phonology* 18, 7-44.

Fougeron, C. (1998) *Variations Articulatoires en Début de Constituants Prosodiques de Différants Niveaux en Français*. Ph.D. dissertation, Université Paris III.

Goedemans, R. (1998) *Weightless Segments*. Ph.D. dissertation, Rijksuniversiteit te Leiden.

Goodman, B. (1995) *Features in Ponapean Phonology*. Ph.D. dissertation, Cornell University.

Gordon, M. (1997) Syllable weight and the phonetics/phonology interface. *Proceedings of the 23rd meeting of BLS*, 111-122

Hale, M. and C. Reiss (2000) Phonology as cognition. In Burton-Roberts, Carr & Docherty (eds.) *Phonological Knowledge: Conceptual and Empirical Issues*. New York: Oxford University Press, pp. 161-184.

Ham, W. (1998) *Phonetic and Phonological Aspects of Geminate Timing*. Ph.D. dissertation, Cornell University.

Hammond, M. (1999) *The Phonology of English: A Prosodic Optimality-Theoretic Approach*. Oxford: Oxford University Press.

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

Hubbard, K. (1995) Toward a theory of phonological and phonetic timing: Evidence from Bantu. In B. Connell and A. Arvaniti (eds.) *Phonological and Phonetic Evidence: Papers in Laboratory Phonology IV*. Cambridge: CUP, pp. 168-187.

Hume, E., J. Muller, and A. van Engelenhoven (1997) Non-moraic geminates in Leti. *Phonology* 14, 371-402.

Hyman, L. (1976) Phonologization. In A. Juilland (ed.) *Linguistic Studies Offered to Joseph Greenberg*. Vol. 2 Saratoga: Anma Libri, pp. 407-418.

Hyman, L. (1992) Moraic mismatches in Bantu. *Phonology* 9, 255-265.

Hyman, L. (2001) The limits of phonetic determinism in phonology: *NC revisited. In E. Hume and K. Johnson (eds.) *The Role of Speech Perception in Phonology*. San Diego: Academic Press, pp. 141-185.

Ingria, R. (1980) Compensatory lengthening as a metrical phenomena. *Linguistic Inquiry* 11, 465-495.

Inkelas, S. and D. Zec (1990) *The Phonology-Syntax Connection*. Chicago: University of Chicago Press.

Keating, P. (1990) The window model of coarticulation: articulatory evidence. In Kingston and Beckman (eds.) *Papers in Laboratory Phonology I: Between the Grammar and the Physics of Speech*. Cambridge: CUP, pp. 406-434.

Keating, P. (1996) The Phonology-Phonetics interface. *UCLA Working Papers in Phonetics* 92: 45-60.

Keating, P. Fougeron, C, Cho, T, Hsu, C, Hayashi, W., Wright, R., Zhang, J. and M. Ueyama (1999) *UCLA Working Papers in Phonetics* 97.

Kirchner, R. (1997) Contrastiveness and faithfulness. *Phonology* 14: 83-111.

Kirchner R. (1998) *An Effort-Based Approach to Consonant Lenition*. Ph.D dissertation, UCLA.

Krakow, R. (1999) Physiological organization of syllables: a review. *Journal of Phonetics* 27, 23-54.

Ladd, D. R., I. Mennen, A. Schepman (2000) Phonological conditioning of peak alignment of rising pitch accents in Dutch. *JASA* 107, 2685-2696.

Lavoie, L. and A. Cohn (1999) The sesquisyllables of English: The structure of vowel-liquid syllables. *Proceedings of the International Congress of Phonetic Sciences 14*, 109-112.

Letterman, R. (1997) *The Effect of Word-internal Prosody in Sinhala: A Constraint-based Analysis*. Ph.D. dissertation, Cornell University.

McCarthy, J. (1988) Feature geometry and dependency: a review. *Phonetica* 45, 84-108.

McCarthy, J. and A. Prince (1986) *Prosodic Morphology*. UMass Amherst and Brandeis University ms.

McCarthy, J. and A. Prince (1993) Generalized alignment. In G. Booij and J. van Marle (eds) *Morphology Yearbook 1993*. Dordrecht: Kluwer, pp. 79-153.

Morén, B. (1997) *Markedness and Faithfulness Constraints on the Association of Moras: The Dependency between Vowel Length and Consonant Weight*. MA Thesis, University of Maryland.

Morén, B. (1999) *Distinctiveness, Coercion and Sonority: A Unified Theory of Weight*. Ph.D. dissertation, University of Maryland, published by Garland Publications 2001.

Nespor, M. and I. Vogel (1986) *Prosodic Phonology*. Dordrecht: Foris.

Ohala, J. (1983) The origin of sound patterns in vocal tract constraints. In P. MacNeilage (ed.) *The Production of Speech*. New York: Springer Verlag, pp. 189-216.

Peterson, G. and I. Lehiste (1960) Duration of syllable nuclei in English. *JASA* 32.6, 693-703.

Pierrehumbert, J. (1990) Phonological and phonetic representation. *Journal of Phonetics* 18, 375-394.

Pierrehumbert, J. and M. Beckman (1988) *Japanese Tone Structure*. Cambridge: MIT Press.

Port, R., J. Dalby and M. O'Dell (1987) Evidence for mora timing in Japanese. *JASA* 81, 1574-85.

Selkirk, E. (1980) Prosodic domains in phonology: Sanskrit revisited. In M. Aronoff and M.-L. Kean (eds.) *Juncture*. Saratoga, CA: Anma Libri, pp. 107-129.

Selkirk, E. (1984) *Phonology and Syntax*. Cambridge: MIT Press.

Selkirk, E. (1990) A two root node theory of length. Umass Amherst ms.

Steriade, D. (2000) The phonology of perceptual effects: the P-map and its consequences for constraint organization. UCLA ms.

Tranel, B. (1991) CVC light syllables, geminates and moraic theory. *Phonology* 8, 291-

302.

Zec, D. (1988) *Sonority Constraints on Prosodic Structure*. Ph.D. dissertation, Stanford University, published by Garland Publications 1994.

Zec, D. (1999) Multiple sonority thresholds. In T. King and I. Sekerina (eds.) *[Formal] Approaches to [Slavic] Linguistics*, 8. Ann Arbor: Michigan Slavic Publications, pp. 382-413.