# Vowel and Consonant Sonority and Coda Weight: A Cross-Linguistic Study

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## 1. Introduction

In many stress systems, there are certain "heavy" syllable types that preferentially attract stress from other syllable types. For example, in Yana (Sapir and Swadesh 1960), stress falls on the rightmost heavy syllable in a word (1a), where heavy syllables include those containing a long vowel (CVV) or a coda consonant (CVC). In words lacking any heavy syllables, stress falls on the initial syllable (1b).

(1) a. sibúmk'ai 'sandstone', suk'ó:niya: 'name of Indian tribe', tsiniyá: 'no'
b. p'údiwi 'women'

Languages vary in terms of which syllables are considered heavy. For example, unlike Yana, which treats both CVV and CVC as heavy, Khalkha Mongolian only treats CVV as heavy (Bosson 1964, Poppe 1970, Walker 1995). Primary stress in Mongolian falls on the rightmost non-final heavy syllable (2a), or on the final syllable if the only long vowel is word-final (2b). In words with only light syllables, primary stress is on the first syllable (2c). Heavy syllables not receiving primary stress carry secondary stress (2d).

(2) a. á:rù:l 'dry cheese curds', ù:rtáegà:r 'angrily', úitgartàe 'sad'
b. galú: 'goose'
c. xáda 'mountain', únʃisan 'having read'
d. doló:dugà:r 'seventh', ulà:nbá:tarà:s 'Ulaanbaatar (ablat.)'

The dichotomy between languages that treat CVC as heavy, like Yana, and those that treat CVC as light, like Mongolian, accounts for the greatest source of cross-linguistic variation in weight criteria. In his survey of syllable weight in 408 languages, Gordon (2006) identifies 136 with weight-sensitive stress systems. Of these 136 languages, he finds 42 that treat CVC as heavy and 35 that treat CVC as light. The next most frequent type of weight distinction, which is based on the distinction between schwa and other vowels, is only found in 12 languages.

Recent years have witnessed a significant increase in the exploration of the phonetic correlates of syllable weight (e.g. Maddieson 1993, Hubbard 1994, 1995, Broselow et al. 1997, Goedemans 1998, Ham 2001, Gordon 2002a, 2005) with much of this research focused on identifying the phonetic basis for the language specific parameterization of CVC weight. Studies have demonstrated a link between phonological weight and a number of phonetic properties, both acoustic and perceptual. For example, Broselow et al. (1997) show that differences in the weight of CVC syllables between languages correspond to differences in duration: languages with light CVC display closed syllable vowel shortening whereas those with heavy CVC do not. They claim that this duration difference reflects a difference in moraic structure, such that the vowel and the coda consonant share a mora in languages

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with light CVC but not in languages with heavy CVC. Gordon (2002a) demonstrates a match between phonological weight and a measure of perceptual energy, the integration of loudness over time. In languages with heavy CVC, CVC has more energy relative to other syllable types than in languages with light CVC. Gordon (2002a,b) further proposes that the energy profile of CVC is predictable from the inventory of coda consonants, such that languages with a greater proportion of high energy codas, e.g. sonorants and voiced consonants, are more likely to treat CVC as heavy than languages with relatively fewer high energy codas. In his account, an overall energy profile of CVC is determined by averaging together the energy of all attested CVC syllables in a language. If CVC thus consists of proportionally more codas with substantial energy, it will have greater energy and will accordingly be treated as heavy by the stress system. Based on a typological survey of languages with heavy CVC and those with light CVC, Gordon proposes a threshold proportion value of one along two dimensions that serve as the best predictors of phonetic energy. If the proportion of voiced codas relative to voiceless codas and the proportion of sonorant codas relative to obstruent codas are both at least one, then CVC will be treated as heavy. If, on the other hand, the voiced-to-voiceless and the sonorant-to-obstruent ratios are less than one, then CVC will be light. Languages with split ratios, i.e. those in which one of the ratios is at least one but the other is less than one, may treat CVC as either heavy or light, depending on two factors: whether voicing or sonorancy exerts a bigger phonetic influence on energy values in a particular language and depending on the distribution of obstruent codas, with a larger proportion of fricatives relative to stops increasing the likelihood of CVC being heavy. Crucially, in Gordon's account, coda proportions are assessed on type frequency: whether a particular coda consonant is quite common or exceedingly rare, it contributes equally to the calculation of CVC's energy profile.

Gordon's (2002a) phonetic case studies of weight support the proposed link between coda inventory and CVC weight. The two languages in his experiment with heavy CVC, Finnish and Japanese, have voiced-to-voiceless and sonorant-to-obstruent coda ratios of at least one, whereas the language with light CVC, Khalkha Mongolian, has a voiced-to-voiceless and a sonorant-to-obstruent ratio of less than one. As he shows, these ratios produce substantial differences in the energy profile of CVC: in Finnish and Japanese, CVC is closer in energy to the universally heavy CVV while in Mongolian, CVC is closer in energy to universally light CV.

Gordon's study does not, however, consider the match between perceptual energy and phonological weight for any languages with binary weight distinctions and split ratios in which one of the relevant proportions is at least one while the other is less than one. It is thus unclear whether the close fit between weight and energy that he observes in Japanese, Finnish, and Mongolian extends to languages where the distribution of codas does not transparently predict the overall perceptual energy of CVC. It is also uncertain whether the type frequency-based metric for evaluating coda inventory proposed by Gordon yields more accurate predictions about CVC weight than an alternative measure of frequency based on token counts. In fact, Gordon suggests that token frequency may allow for superior predictions about the weight of CVC, though he does not pursue this possibility. For example, a relatively sparsely occurring type of coda may contribute less to the calculation of the overall energy profile of CVC than a very frequently attested coda. From a language acquisition standpoint, this possibility is tenable since learners may weigh more frequently encountered syllable types more heavily than other rarely observed syllable types.

## 2. Methodology of the present study

The present study tests the predictions of Gordon's (2002a,b) account of weight by examining perceptual energy data for a different set of languages from those analyzed in Gordon's study. Crucially, unlike the three languages Gordon used to test the correlation between perceptual energy and weight of CVC, a subset (three of four) of those targeted in the present work contain mismatched sonorant-to-obstruent and voiced-to-voiceless ratios. The evaluation of data from these languages thus provides a more rigorous test of the fit between phonological weight and a measure of perceptual energy. In addition, the present study includes data from a larger number of speakers (four to five) than Gordon's work, which considered data from only a single speaker of each language. A final difference between Gordon's work and the present research is the procedure for calculating perceptual energy. Whereas Gordon's (2002a) measure of perceptual energy uses overall loudness values, the present work employs a more sophisticated algorithm for computing energy in the perceptual domain incorporating a number of factors demonstrated in physiological and psychoacoustic data to influence the mapping between acoustic and auditory prominence. These factors include the dependence of loudness on frequency, the bandpass filtering characteristics of the auditory system, and temporal effects such as adaptation and recovery. The auditory model used in the present experiment is implemented in the custom-made software "Cricket", which is available at the following website: *http://www.linguistics.ucsb.edu/faculty/gordon/projects.html*.

## *2.1. Languages*

Four languages were targeted for study: Khalkha Mongolian, Malayalam, Egyptian Arabic, and Hindi. In two of these languages, Egyptian Arabic (Mitchell 1960) and Hindi (Kelkar 1968, Dixit 1963 cited in Ohala 1977), CVC is heavy in the stress system, whereas in the other two languages, Khalkha Mongolian (Bosson 1964, Poppe 1970, Walker 1995) and Malayalam (Mohanan 1986), CVC is light. Three of these languages, Malayalam, Arabic, and Hindi, were examined in Broselow et al.'s (1997) study of durational correlates of syllable weight, while Mongolian was one of the languages included in Gordon's (2002a) study of perceptual energy. Three of the four languages, all except Mongolian, have type frequency ratios of voiced-to-voiceless codas and sonorant-to-obstruent codas that fall on different sides of the threshold of one proposed by Gordon (2002a,b) to be a predictor of CVC weight. In these three languages, the ratio of voiced-to-voiceless codas is at least one, whereas the ratio of sonorant-to-obstruent codas is less than one. Mongolian, on the other hand, has both a voiced-to-voiceless and sonorant-to-obstruent ratio that is less than one. The number of sonorant, obstruent, voiced, and voiceless codas for the four targeted languages is summarized in table 1.

Table 1. The number of sonorant, obstruent, voiced, and voiceless codas in the target languages

| **CVC weight** | **Language** | **Sonorant** | **Obstruent** | **Voiced** | **Voiceless** |
|---|---|---|---|---|---|
| Heavy | Arabic | 6 | 20 | 14 | 12 |
| Heavy | Hindi | 8 | 25 | 19 | 14 |
| Light | Mongolian | 5 | 11 | 7 | 9 |
| Light | Malayalam | 7 | 18 | 16 | 9 |

While the coda inventory of Mongolian is in line with the light status of CVC according to Gordon's account, the predictions for the other three languages are less clear. Despite the similar coda inventories in the three languages, two languages, Arabic and Hindi, treat CVC as heavy, while the third language, Malayalam, treats CVC as light. Either there are phonetic differences between Malayalam, on the one hand, and Arabic and Hindi, on the other hand, that match up with differences in the phonological weight of CVC, or there is a mismatch between perceptual energy and phonological weight for one set of languages. We explore these two possibilities in this paper.

## *2.2. Data*

In order to test the fit between perceptual energy and phonological weight, phonetic data was recorded from the four target languages. The recorded data in each language consisted of a series of disyllabic words in which the first syllable was targeted for measurement. The structure of the rime of the first syllable was systematically manipulated such that all attested rimes in the language were represented in the data set. The vowel in the target syllable was a low vowel in all languages. The first syllable, the target syllable, was stressed throughout the corpus in each language while the second syllable was uniformly an unstressed light syllable, a symmetry that was made possible by the stress system of all the examined languages: in all four languages, final light syllables are unstressed. All of the target words were embedded in a semantically neutral carrier phrase such that the target word was focused throughout the corpus.

Speakers repeated each phrase containing a target word five times. Recordings were made in a sound attenuating booth using a DAT recorder connected to a high quality unidirectional condenser microphone. After each recording session, data were converted to a .wav file for analysis using Cricket. Data from four to five native speakers of each language are considered in this paper: five speakers each of Arabic (two male and three female) and Mongolian (three male and two female) and four each of Hindi (three male and one female) and Malayalam (three female and one male).

### *2.3. Measurements*

The perceptual energy of each token of each target vowel and each target rime was calculated using Cricket, custom-made software designed to map an acoustic signal to one that more accurately reflects the perception of that signal by the human auditory system. Cricket takes an acoustic signal and employs a number of quantitative transforms representing various stages in the auditory processing of that signal. We briefly summarize here the various stages of the mapping from acoustic to perceptual stimulus. The first two stages in the auditory transform model the bandpass filtering properties of the outer and middle ear. The first filter is an outer ear filter capturing effects of the pinna and the outer auditory canal (the meatus). The natural resonating frequency of the outer ear is about 2.5 kHz with an approximately 10 dB per octave attenuation on either side of 2.5 kHz (Shaw 1974). The lower skirt of this filter becomes flat at 1.25 kHz, one octave below 2.5 kHz. The next filter captures the filtering by the middle ear, where pressure fluctuations on the eardrum are converted to mechanical energy by the ossicles. The middle ear is a maximally effective transducer of energy at approximately 1.5 kHz with a 15 dB per octave attenuation at frequencies above and below 1.5 kHz (Nedzelnitsky 1980). The next step in the auditory transform models the bandpass filtering characteristics of the auditory system (Patterson et al. 1982, Moore and Glasberg 1983). Cricket employs a symmetric filter with a 60 dB attenuation linearly interpolated from the center frequency to the base of the skirts, which increase in breadth as frequency increases. The net response at any frequency is the sum of the responses to the filter as it progresses through the frequency domain. The overall loudness of each spectrum is then calculated by summing the outputs of all the filters. The final step involves the modeling of temporal effects in the auditory response as adaptation and recovery functions (e.g. Plomp 1964, Wilson 1970, Viemeister 1980). The adaptation function captures the gradual decline in sensation to a continued stimulus, while the recovery function reflects the boost in auditory response after a reduction in stimulus intensity.

Perceptual energy values were considered along two dimensions. First, values were compared between syllables differing in the voicing (i.e. voiced vs. voiceless) and the sonorancy (i.e. sonorant vs. obstruent) of the coda consonants. The working hypothesis was that rimes closed by codas of greater sonority, i.e. voiced and sonorant codas, would have greater energy than rimes closed by codas of lesser sonority, i.e. voiceless and obstruent codas. The overall energy profile of CVC syllables as a class was then calculated and compared to that of CV and CVV syllables. The hypothesis was that CVC as a class would have an energy profile closer to CVV than to CV in languages with heavy CVC but closer to CV than to CVV in languages with light CVC.

## 3. Results

### *3.1. Rime energy as a function of coda consonant*

The comparison of rimes containing different types of codas indicated considerable inter-language and inter-speaker diversity. Figures 1-4 show average perceptual energy values for different rime types for each speaker in the four target languages. Male speakers are labeled by a number followed by 'm', while female speakers are indicated by a numeral followed by 'f'. Rimes closed by a sonorant are compared with those closed by an obstruent on the left side of each figure, while the right side compares rimes closed by a voiced coda with those closed by a voiceless coda. The dark bars in the figures represent the rimes hypothesized to have greater energy, i.e. rimes closed by a sonorant (CVR) on the left and rimes closed by a voiced consonant (CVG) on the right, whereas the light bars represent rimes expected to have less energy, i.e. rimes closed by an obstruent (CVO) on the left and rimes closed by a voiceless consonant (CVK) on the right.

In Arabic, only three of the five speakers make a reliable distinction along either the sonorancy or the voicing dimensions. Two speakers, 2m and 4f, have more energetic rimes closed by sonorants and voiced codas than by obstruent and voiceless codas, respectively. Another speaker, 3f, however, displays a reversal along the sonorancy dimension, whereby rimes closed by an obstruent have greater energy than those closed by a sonorant. In Hindi, all four speakers display the expected patterns; rimes closed by a sonorant and those closed by a voiced coda have greater energy than those closed by an obstruent or a voiceless coda, respectively. In Malayalam, only two of the four speakers (1f and 3f) make the expected distinctions and display greater energy in rimes closed by a sonorant and those closed by a voiced coda. Strikingly, in Mongolian, only one speaker (5m) shows any difference in rimal energy as a function of the examined classes. For this speaker, rimes closed by a sonorant and rimes closed by a voiced consonant have only slightly more energy than those closed by an obstruent or a voiceless coda. In summary, in all but one of the four languages (Hindi being the exception) neither sonorancy nor voicing of the coda makes a consistent difference in overall rimal energy for the majority of speakers. Hindi, the exception to this pattern, conforms to prior expectations: rimes closed by a sonorant or a voiced coda have greater energy than those closed by an obstruent or a voiceless coda, respectively.

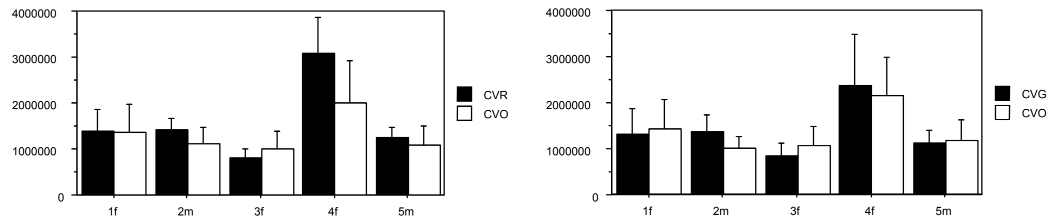

Figure 1. Comparison of rimes closed by a sonorant with those closed by an obstruent (on left) and comparison of rimes closed by a voiced coda with those closed by a voiceless coda (on right) for five speakers of Egyptian Arabic

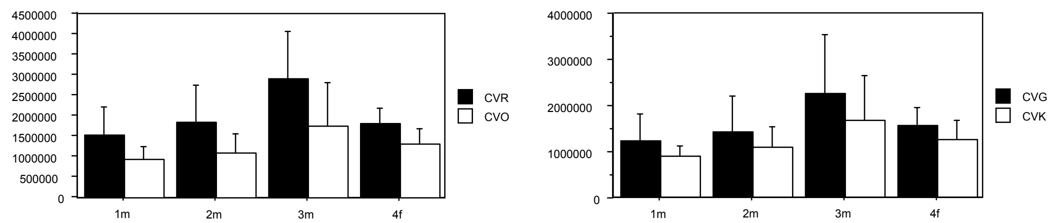

Figure 2. Comparison of rimes closed by a sonorant with those closed by an obstruent (on left) and comparison of rimes closed by a voiced coda with those closed by a voiceless coda (on right) for four speakers of Hindi

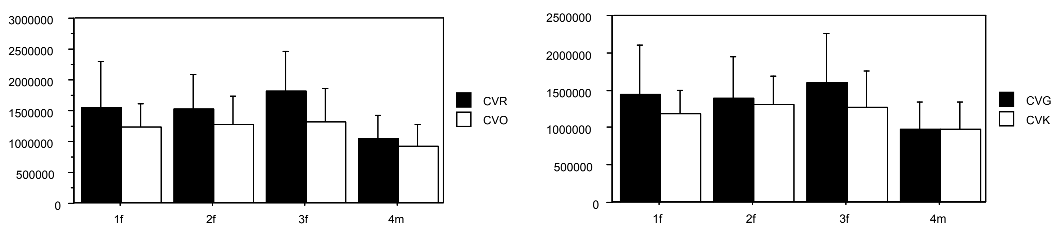

Figure 3. Comparison of rimes closed by a sonorant with those closed by an obstruent (on left) and comparison of rimes closed by a voiced coda with those closed by a voiceless coda (on right) for four speakers of Malayalam

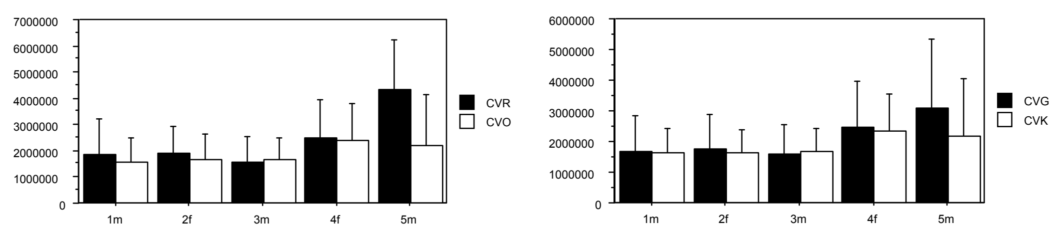

Figure 4. Comparison of rimes closed by a sonorant with those closed by an obstruent (on left) and comparison of rimes closed by a voiced coda with those closed by a voiceless coda (on right) for five speakers of Khalkha Mongolian

### *3.2. Overall energy of CVC*

Figures 5 and 6 depict average energy values for CVC syllables as a whole relative to both CV and CVV(C) syllables for the four examined languages. Figure 5 contains results for the two languages with heavy CVC, Arabic and Hindi, while figure 6 shows results for the two languages with light CVC, Mongolian and Malayalam.

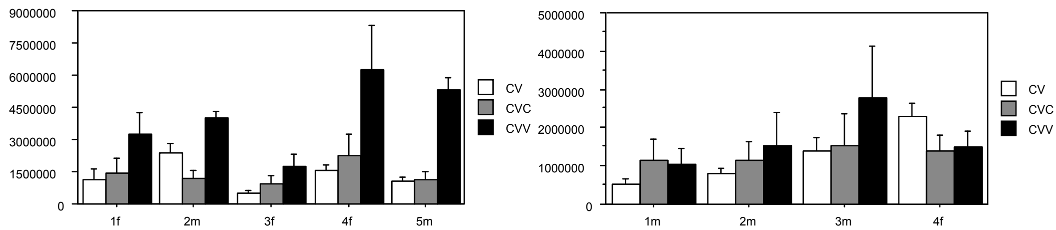


Figure 5. Average perceptual energy values for CVC syllables relative to CV and CVV(C) syllables in two languages in which CVC is heavy: Arabic (on left) and Hindi (on right)

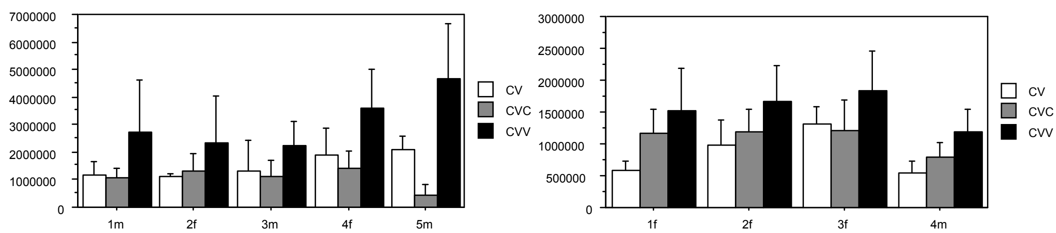


Figure 6. Average perceptual energy values for CVC syllables relative to CV and CVV(C) syllables in two languages in which CVC is light: Mongolian (on left) and Malayalam (on right)

Looking first at the two languages with heavy CVC in figure 5, CVC does not have greater energy than CV for all the speakers in either language. In Arabic, only two of the five speakers (3f and 5f) have greater energy for CVC than CV contra expectations for a language in which CVC is heavy. Moreover, even for the two speakers conforming to expectation, CVC is closer in energy to CV than to CVV contrary to what Gordon (2002a) found for Finnish and Japanese, the two languages in his study that treat CVC as heavy. Results for Hindi conform to predictions only slightly better. Three of the four speakers (all except 6f) have greater energy for CVC than CV. However, for two of these three speakers (3m and 5m) energy values for CVC are more like those of CV than those of CVV, again an unexpected finding in light of the heavy status of CVC.

Turning to the results for the two languages with light CVC, there is a closer match between energy values and phonological weight. In Mongolian, energy values for CVC are similar to those for CV and substantially less than values for CVV in keeping with the light status of CVC. A similar pattern emerges in Malayalam, with CVC having less energy than CVV for all four speakers. For two of the speakers (2f and 3f) CVC is clearly closer in energy to CV than to CVV, while for the other two, CVC is roughly equidistant from CV and CVV in energy.

The results thus far suggest that perceptual energy is only matched with phonological weight in languages with light CVC and not in languages with heavy CVC unlike the results from Gordon (2002a) in which perceptual energy fit with a variety of weight criteria including both heavy and light CVC.

Despite the apparent mismatch between energy and weight in languages with light CVC, there remains another possibility to explore. It could be the case that computing the average energy profile for CVC based on a simple measure of type frequency is less accurate than a more sophisticated measure of frequency based on token number. Thus, there could be imbalances in the frequency of various syllable types that would change the average energy value of CVC in some or all of the examined languages. For example, if the ratio of voiced-to-voiceless and/or the ratio of sonorant-to-obstruent codas in Hindi and Arabic speech were substantially greater than the ratios found in simple inventory counts, this could elevate average energy values for CVC in the two languages in keeping with the heavy status of CVC in both languages. This possibility is particularly intriguing in the case of Hindi, where it was shown earlier that syllables closed by a sonorant or a voiced coda have much greater energy than those closed by an obstruent or a voiceless coda. For Arabic, the relationship between coda type and energy was less consistent across speakers; nevertheless, some speakers did display the expected relationship between coda type and rimal energy values.

Token frequency values were collected from corpora in three of the four languages targeted for the phonetic phase of the study, all except Arabic. In the case of Mongolian, the corpora consisted of approximately 17,000 syllables occurring in an online newspaper available at Mongolia online (www.mol.mn). The Hindi corpus contained roughly 50,000 syllables tabulated by Ghatage (1964) in his corpus study of written Hindi gleaned from a variety of genres. The Malayalam corpus consisted of approximately 57,000 syllables in Ghatage's (1994) syllable count calculations taken from several different sources. Results of the token frequency counts for syllables closed by a sonorant, an obstruent, a voiced consonant, and a voiceless consonant are presented in table 2.

Table 2. Token frequency counts for syllables closed by different consonants in three languages

| **CVC weight** | **Language** | **Sonorant** | **Obstruent** | **Voiced** | **Voiceless** | **Source** |
|---|---|---|---|---|---|---|
| Heavy | Hindi | 23297 (45.9%) | 27525 (54.1%) | 305832 (60.2%) | 30582 (39.8%) | Ghatage (1964) |
| Light | Mongolian | 10954 (62.8%) | 6478 (37.2%) | 14257 (81.8%) | 3175 (18.2%) | Mongolia online www.mol.mn |
| Light | Malayalam | 52658 (92.3%) | 4374 (7.7%) | 53966 (94.6%) | 3066 (5.4%) | Ghatage (1994) |

Interestingly, there is a much greater bias toward more energetic codas, i.e. sonorants and voiced consonants, in the two languages with light CVC than in the language with heavy CVC. Strikingly, virtually all of the codas in Malayalam are sonorants and voiced even though CVC is light. If token frequency offered an account of CVC weight, we would expect exactly the opposite distribution: for a higher proportion of high energy codas to occur in the language with heavy CVC than in the languages with light CVC. It is thus doubtful that a token frequency count of codas offers an explanation for the weight of CVC, at least in the examined languages.

### *3.3. Energy of the nucleus in CVC*

As a final step in this study, we examine the perceptual energy of just the vowel nucleus in CVC relative to the energy in the vowel of CV and CVV(C). Following Broselow et al.'s (1997) study, in which they found vowel duration to be the crucial predictor of CVC weight, it is conceivable that the fit between phonetics and phonological weight is evaluated over only the nucleus and not the entire rime. If this were true for the phonetic dimension of energy, we would expect the energy of the nucleus in CVC to be more like that of the nucleus in CVV and less like that of the nucleus in CV in languages with heavy CVC and for the opposite to be true in languages with heavy CVC. Figures 7 and 8 show perceptual energy of the nucleus in the two target languages with heavy CVC and the two languages with light CVC, respectively.

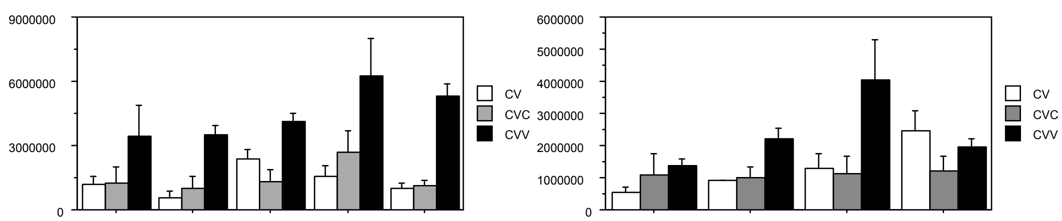


Figure 7. Average perceptual energy values for the nucleus of CVC relative to the nucleus of CV and CVV(C) syllables in two languages in which CVC is heavy: Arabic (on left) and Hindi (on right)

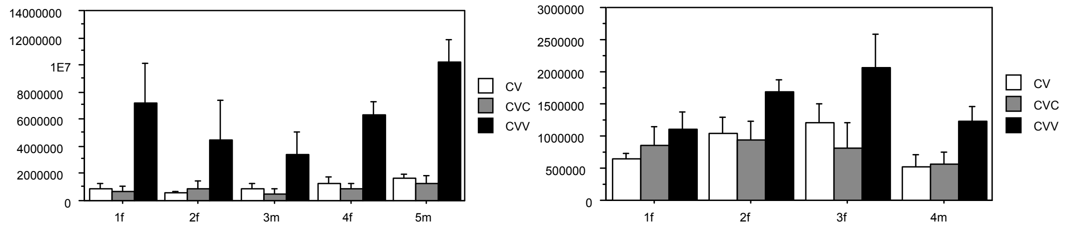

Figure 8. Average perceptual energy values for the nucleus of CVC relative to the nucleus of CV and CVV(C) syllables in two languages in which CVC is light: Mongolian (on left) and Malayalam (on right)

Results do not suggest any better fit between phonological weight and a measure of energy that just encompasses the nucleus. In the two languages with heavy CVC, there is no consistent tendency for the energy of the vowel in CVC to be more like that of the vowel in CVV than CV. In fact, for three of the four Hindi speakers and three of the five Arabic speakers, average energy values for the vowel in CVC are not even greater than those of the vowel in CV. In the two languages with light CVC, the match between CVC weight and vowel energy is better: in Hindi and especially Mongolian, the energy of the vowel in CVC is similar to that of the vowel in CV and much less than that characteristic of CVV. In summary, a measure of energy only including the nucleus does not improve the fit between weight of CVC and perceptual energy in languages with heavy CVC.

## 4. Conclusions

A more extensive study of syllable weight and perceptual energy building on Gordon (2002a) found a close fit between energy and CVC weight but only in languages in which CVC is light. In these languages, the average energy of the rime in CVC is closer to that of CV than CVV in keeping with the light status of CVC. The present study did not, however, find a match between energy and weight in languages with heavy CVC unlike Gordon's study. In the present study, which was based on more speakers and employed a more sophisticated measure of perceptual energy than Gordon, the energy of the rime in CVC was not reliably closer to that of CVV than CV in languages with heavy CVC contrary to expectations. Similar results obtained for a measure of energy calculated over the entire rime and one calculated over only the nucleus. Furthermore, a comparison of rimes differing in the sonority of their coda consonants along two dimensions (sonorant vs. obstruent and voiced vs. voiceless) showed only an inconsistent tendency for rimes ending in higher sonority codas (sonorants and voiced consonants) to have greater energy than those ending in lower sonority codas (obstruents and voiceless consonants). Finally, a corpus-based tabulation of codas based on token rather than type frequency failed to account for the parameter of CVC weight: languages with heavy CVC did not show a greater skewing toward higher sonority codas than languages with light CVC. The present results underscore the complexity of the relationship between phonetic properties and phonological weight and suggest that there might not be a single phonetic dimension that successfully predicts the full range of attested weight criteria.

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