# Title: Dynamic invariance in the phonetic expression of syllable structure: a case study of Moroccan Arabic consonant clusters

## Abstract

The relation between qualitative phonological organization and continuous phonetics is a fundamental problem in spoken language. We study a specific instance of this problem in the relation between syllable structure and phonetic indices for that structure. Specifically, we evaluate two hypotheses, simplex versus complex syllable onsets, in Moroccan Arabic with data acquired with Electromagnetic Articulography. Building on previous work, we first employ temporal stability-based heuristics for syllable structure. These are comprised of correspondences between a qualitative syllabic organization and a fixed instantiation of that organization in terms of phonetic parameter values. Such correspondences represent an assumption of static invariance in the relation between phonology and phonetics. We argue analytically, then demonstrate computationally and finally verify in the experimental data that static invariances offer only a partial understanding of the relation between qualitative organization and continuous indices of that organization. We then put forward a new perspective on how phonological organization is instantiated in continuous phonetics, the dynamic invariance view, and we show how that view enables one to reliably diagnose phonological organization from variable phonetic data. The main findings are as follows. Any given syllabic organization may be consistent with a range of possible stability indices (no static invariance). Different phonological organizations prescribe different ways in which stability indices change as phonetic parameters are scaled. Invariance is found in these patterns of change, rather than in static correspondences between phonological constructs and fixed values for their phonetic indices.

## 1.0 Introduction

Phonetic parameter values typically vary across instantiations of a given phonological form. Despite variation from numerous sources such as phonetic context, speech rate, talker identity (e.g., see respectively,\Allen, Miller, & DeSteno, 2003; Repp, 1982; Smith, 2002), it is often possible to identify ranges of phonetic values that may function under some conditions as heuristics for a particular phonological structure. In the case of syllables, phonetic heuristics are often temporal in nature. For instance, the acoustic duration of syllable rimes has been correlated with syllable weight (Broselow, Chen, & Huffman, 1997; Gordon, 2002; see also Nam, 2007). Syllable position, onset vs. coda, has been linked to the relative timing of articulators (Byrd, Tobin, Bresch, & Narayanan, 2009; Gick, Campbell, Oh, & Tamburri-Watt, 2006; Krakow, 1989, 1999; Sproat & Fujimura, 1993; Waals, 1999) and the acoustic duration of segments (Boucher, 1988; Waals, 1999). A related line of research has demonstrated correspondences between the syllabic parse of consonant clusters and characteristic patterns of temporal organization (e.g., Browman & Goldstein, 1988; Byrd, 1995; Goldstein, Chitoran, & Selkirk, 2007; Hermes, Grice, Mücke, & Niemann, in press). On the perceptual side, temporal patterns have been shown to influence judgments on syllabification when stress and phonotactics allow an ambiguous parse (de Jong, Lim, & Nagao, 2004; Redford & Randall, 2005; Tuller & Kelso, 1991). Taken together, these studies provide evidence for a systematic relation between syllabic organization and the timing of consonants and vowels in speech.

In addition to syllable structure, however, a number of other factors also influence the timing of consonants and vowels (Bombien, Mooshammer, Hoole, & Kühnert, 2010; Byrd, 1996; Byrd & Choi, 2010; Gafos, Hoole, Roon, & Zeroual, 2010; Nittrouer, Munhall, Kelso, Tuller, & Harris, 1988; Wright, 1996). For example, Nittrouer et al. (1988) showed that patterns of articulatory timing between singleton labial consonants and following vowels vary systematically and discretely as a function of rate, stress, consonant identity (/m/ or /p/) and syllable position. In consonant clusters, timing can be affected by the identity of the consonants in a cluster (Byrd, 1996; Chitoran, Goldstein, & Byrd, 2002; Redford, 2008), by word position (Gafos et al., 2010; Wright, 1996), by prosodic phrase position (Bombien et al., 2010), and, moreover, each of these factors can interact with syllable structure in shaping temporal patterns

(Byrd & Choi, 2010). These studies demonstrate cases in which patterns of temporal organization characteristic of syllabic structure are perturbed by linguistic and non-linguistic factors leading, in some cases, to ambiguous phonetic diagnostics. Such cases expose the main problem associated with a heuristic use of phonetic measurements. When the phonological structure of interest does not surface with the expected phonetics, the heuristics remain silent and offer the analyst no further recourse for action. Moving beyond the heuristic use of phonetic measurements requires a deeper understanding of the way abstract phonological organization shapes the continuous and variable phonetics.

Our study has two main aims. The first aim is to present new articulatory data bearing on the phonetic expression of syllable structure. By evaluating temporal patterns across highly distinct segmental instantiations of a common syllabic organization, we offer a conservative test of the relation between syllables and speech timing. Based on the analysis of this data, our second aim is to put forward a new perspective on how phonological organization is instantiated in the continuous phonetics. In pursuit of this aim, we use the prosodic variability naturally contributed by our speakers to study how phonetic indices for syllable structure change as various parameters are scaled.

The new data come from Electromagnetic Articulography (EMA) recordings of Moroccan Arabic. In the study of the relation between syllable structure and timing, Moroccan Arabic is of particular interest for two reasons. Much of the available articulatory data appropriate for evaluating how consonant clusters are organized syllabically comes from languages claimed to parse sequences of word-initial consonants into syllables with complex onsets (Browman & Goldstein, 1988; Goldstein et al., 2007; Honorof & Browman, 1995; Kühnert, Hoole, & Mooshammer, 2006b; Marin & Pouplier, 2010). One notable exception is Hermes *et al.* (in press), who investigate consonant clusters in Italian, including clusters parsed into both complex onsets, stop-liquid clusters, and simplex onsets, /s/-stop clusters (see Davis, 1990 for morpho-phonological evidence for these parses). Hermes *et al.* found temporal patterns consistent with these syllabic parses providing further support for a systematic relation between syllables and temporal organization. Languages claimed to parse *all* strings of two or three initial consonants, e.g. #CCVX or #CCCVX, into syllables with simplex onsets, e.g. #C.CVX[1] or #CC.CVX, are underrepresented in the literature. Two preliminary studies, Goldstein *et al.* (2007) on Berber and Shaw *et al.* (2009) on Moroccan Arabic, are limited in that they report data from just one speaker of each language. More recently, Hermes *et al.* (2011) reports new data from three speakers of Berber, and, in this study, we contribute articulatory data from four speakers of Moroccan Arabic.

The second reason for focusing on Moroccan Arabic is related to the variety of its consonant clusters. Like many languages, Moroccan Arabic allows word-initial consonant clusters, including #CCVX and #CCCVX sequences. Unlike many of the other languages for which such clusters are permissible, Moroccan Arabic allows instantiations of these clusters with both rising, e.g., *glih* ‘to grill’, *dfla* ‘oleander’, and falling, e.g., *msku* ‘to hold’, *rbaħ* ‘to win’, sonority contours. In conjunction with this property, Moroccan Arabic, like other Arabic dialects, is claimed to disallow syllables with complex onsets (Broselow, 1992; Kiparsky, 2003). Specifically, all word-initial consonant clusters regardless of the identity of the consonants or the sonority profile of the cluster are claimed to be parsed heterosyllabically, i.e., biconsonantal clusters are parsed as #C.CVX and tri-consonantal clusters are parsed as #CC.CVX (Dell & Elmedlaoui, 2002: chapter 8). We are interested in assessing whether this invariance on the phonological side – all clusters independent of their sonority profile conform to syllables with simplex onsets – finds a corresponding invariance in terms of temporal organization in our phonetic recordings.

Building on previous work, we begin with the assumption of a fixed correspondence between a qualitative syllabic organization and an instantiation of that organization in terms of phonetic parameters. This assumption implies a static invariance view of the relation between phonetics and phonology. According to this view, the phonetic reflexes of different

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[1] Here and throughout, we use “#” to represent the location of a word boundary and “.” to represent the location of a syllable boundary. “X” represents any string of consonants and vowels.

phonological organizations are fixed, as expressed in statements of the kind “simplex onsets surface with timing pattern A”, “complex onsets surface with timing pattern B, ” and so on. In exploring the natural variability of the data, we identify ranges of phonetic parameter values under which this assumption leads to misleading or at least ambiguous results. Across our data, we find that speakers vary considerably in the degree to which the durations of consonants and vowels are affected by increasing the length of a word. Instead of seeking invariance in individual phonetic parameters, we harness this variability by identifying *relations* between phonetic parameters that remain invariant and clearly predictive of syllable structure even as the phonetic parameters themselves vary. The presence of these relations leads us to a new perspective on how phonological organization is instantiated in continuous phonetics, which we refer to as the dynamic invariance view. In this view, any given phonological organization makes specific predictions about *the pattern of change* in the phonetic indices as parameters are scaled. Invariance is to be found in the distinct relations or patterns of change prescribed by the different phonological organizations, rather than in static statements such as “simplex onsets surface with timing pattern A” or “complex onsets surface with timing pattern B”.

## 2.0 Experimental methods

### *2.1 Speakers and materials*

Four speakers (three male, one female) of the Oujda dialect of Moroccan Arabic participated in the study. Stimuli consisted of nine target words organized into three triads, given in Table 1. The triads were constructed such that words differed only in the number of initial consonants, e.g. #CVX, #CCVX, #CCCVX. All two and three consonant clusters in the stimulus set are claimed to be parsed heterosyllabically, e.g., #C.CVX, #CC.CVX (Boudlal, 2001; Dell & Elmedlaoui, 2002; Kiparsky, 2003). The target stimuli were randomized within a larger set of words included for analysis in other experiments. Participants produced each target at least 10 times in the carrier phrase *zibi* ______*hnaja* ‘bring _____ here’. Participants comfortable with producing more than 10 repetitions were encouraged to continue cycling through the word list. In total, participants produced the target words between 10-18 times each, yielding a total of 552 tokens.

**Table 1 *Stimuli list***

| Target word | Gloss |
|---|---|
| lan | to become soft |
| flan | someone |
| kflan | nonce |
| | |
| bulha | her urine |
| sbulha | her ear (of grain) |
| ksbulha | to win for her |
| | |
| kulha | eat for her |
| skulha | nonce |
| mskulha | to hold for her |

### *2.2 Procedure*

Articulatory data were recorded using the Carstens AG500 3-D Electromagnetic Articulometry system (EMA) at the Institut für Phonetik und Sprachverarbeitung, Munich (Hoole & Zierdt, 2010; Hoole, Zierdt, & Geng, 2003; Zierdt, Hoole, & Tillmann, 1999). EMA is a flesh-point tracking system that uses receivers adhered to speech articulators to record movements in a magnetic field (Perkell et al., 1992). In the Carstens AG500 system, six transmitter coils affixed to a plastic cube apparatus produce alternating magnetic fields at different frequencies. The transmitters induce an electrical signal in the receivers placed inside the cube. The voltage of this signal is used to recover the distance and orientation of the receivers with respect to the transmitter coils. The system samples movement data at a rate of 200 Hz. Voltage-to-distance conversions used a filter cutoff of 40 Hz for the tongue tip receiver and 20 Hz for all other receivers. Head movement was removed from the signals computationally. The origin of the coordinate system was located at the lower front edge of the upper incisors. Audio data was collected concurrently with a directional microphone at a sampling rate of 24 kHz.

The EMA receivers (about 2 mm diameter) were placed on the tongue tip (at 1 cm behind apex), tongue mid (approximately halfway between the tip and tongue body sensor), tongue body (approximately at 5 cm behind the tip sensor), lower lip, upper lip, and jaw. Additional sensors used as reference points were placed on the upper incisors, bridge of the nose and the left and right side of the head behind the ears. Participants sat inside the plastic cube with receivers attached while target words were displayed in standard Arabic script on a computer screen placed outside of the cube. Speakers produced the words displayed on the screen within the carrier phrase at a comfortable speech rate.

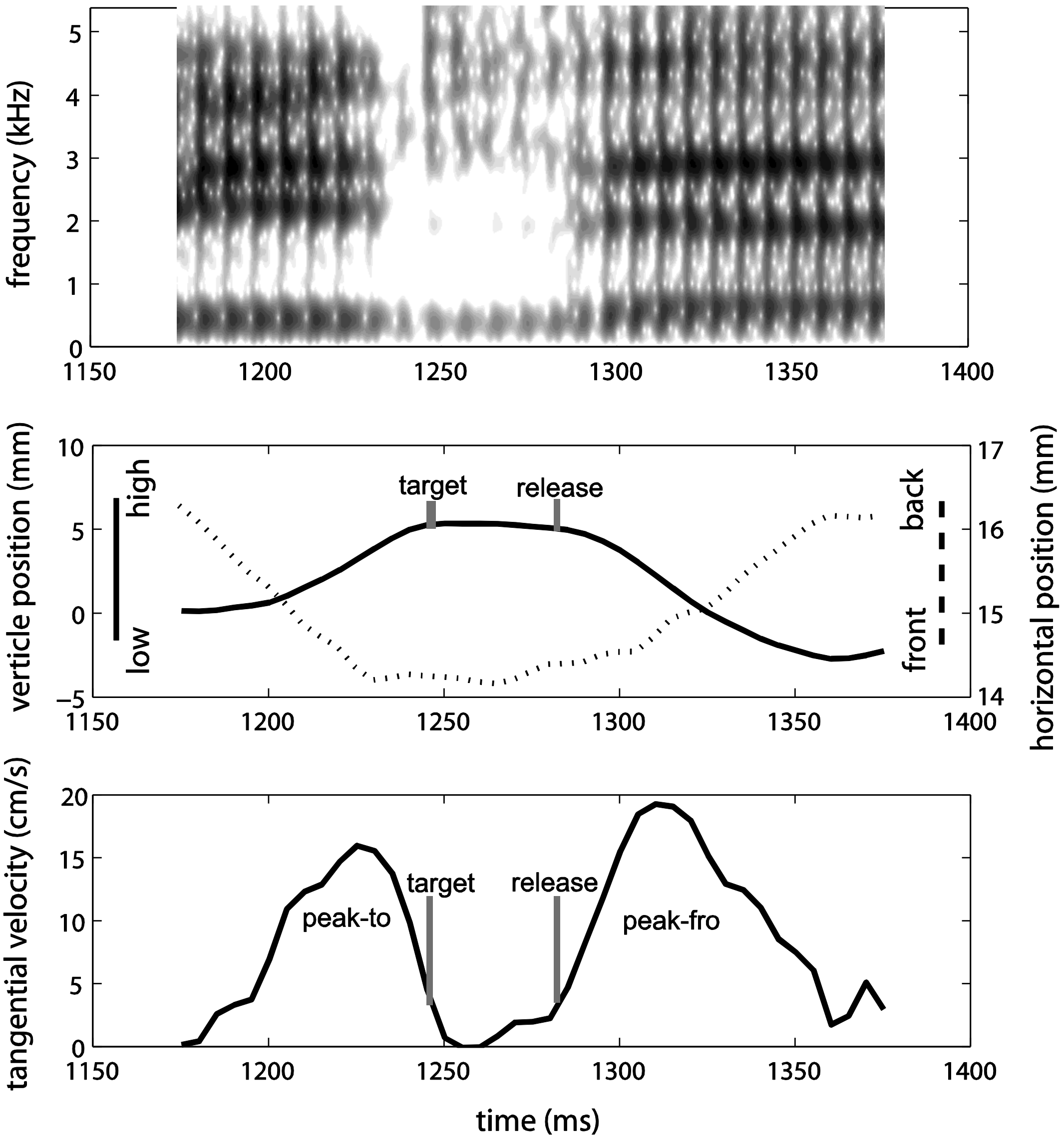
### *2.3 Measurements*

The articulatory data produced by the EMA recordings was analyzed using MVIEW, a MATLAB-based program developed at Haskins Laboratories by Mark Tiede and adapted to our data by us. The program displays the acoustic and positional signals together with the corresponding instantaneous velocity signals, which were calculated by differentiating the positional signals. 3-D EMA provides information about vertical, anterior-posterior and lateral movement. Our analysis focuses on the vertical and horizontal (i.e., anterior-posterior) movement within the midsagittal plane. The EMA receiver used to delineate movements associated with a consonant was the one corresponding to that consonant's primary oral articulator: tongue tip for [l n]; tongue body for [k]; lower lip for [b m f]. The receiver used for [s] was either the tongue tip or the tongue mid, depending on the speaker.

Articulatory landmarks associated with the hold phase, or plateau, of consonantal constrictions were parsed from the kinematic data by referencing the tangential velocity signal. The achievement of target, henceforth ‘target’, and release from constriction, henceforth ‘release’, landmarks define, respectively, the start and end of the consonantal plateau. These landmarks were obtained by identifying the timestamp at which the magnitude of instantaneous velocity falls below, in the case of the target landmark, or rise above, in the case of the release landmark, a 20% threshold of local tangential velocity peaks. Figure 1 shows the parse of target and release landmarks for the [l] in a production of *lan* by speaker A. The top panel shows the positional signal of the tongue tip receiver in both x- and y- dimensions. The bottom panel shows the tangential velocity signal. The velocity peak associated with movement to and away from the target constriction are labeled ‘peak-to’ and ‘peak-fro’, respectively. The target and release, as defined above, are labeled on both the tangential velocity signal and the corresponding positional signal.

All gestures were parsed using the tangential velocity signal with the exception of [k] in the *kulha~skulha~mskulha* triad. For [k] in this context, a single peak in the tangential velocity signal corresponded to both movement associated with the backing of the tongue body for [u], in the horizontal dimension, and movement associated with achievement of the [k] target, primarily in the vertical dimension. Therefore, only the component velocity from movement in the vertical dimension was referenced to identify landmarks for [k].

Figure 1
The middle panel shows the location of the tongue tip receiver in vertical (solid line) and horizontal (dotted line) coordinates during the [l] portion of *lan*. The scale for the vertical coordinate is shown on the left side of the panel. Increases on this scale correspond to increases in tongue tip height. The scale for the horizontal coordinate is shown on the right side of the panel. Increases on this scale correspond to tongue tip retraction (note different scaling of vertical and horizontal movement). The lower panel shows the corresponding tangential velocity signal. The location of the articulatory landmarks, ‘target’ and ‘release’, as parsed from the signal are shown on both the position and velocity signals. The top panel shows a spectrogram of the corresponding acoustic signal.



## 3.0 Stability-based heuristics of syllable structure

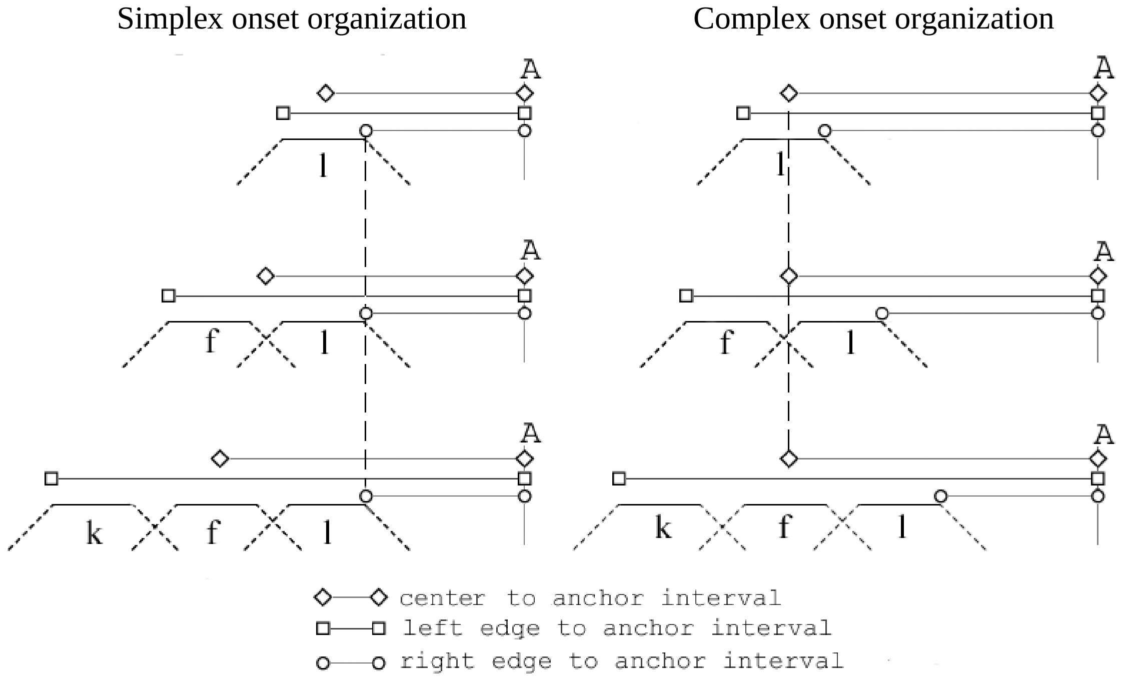
We begin our analysis from the perspective of static invariance. We adopt statements of a fixed correspondence between syllable structure and temporal stability (section 3.1), and apply those statements as phonetic heuristics to our data (section 3.2). We, next, highlight one corner of the data that deviates from the expected phonetic pattern (section 3.3) and call into question the validity of the static invariance approach (section 3.4).

### *3.1 Static invariance in the phonetic expression of syllable structure*

The landmarks described in the previous section were used to define intervals whose durations inform us about the temporal organization in our data. Three interval durations were measured for each token. These intervals correspond to those used to summarize timing patterns in related work (Browman & Goldstein, 1988; Byrd, 1995; Honorof & Browman, 1995; Shaw et al., 2009). The three intervals extend, respectively, from the left edge, center and right edge of the initial consonant (in #CVX words) or consonant cluster (in #CCVX and #CCCVX words) to a common anchor point. The left edge of the consonant cluster was identified by the target landmark of the initial consonant in the word, e.g. the target of [b] in *bulha*, the target of [s] in *sbulha* and so on. The right edge of the cluster was identified by the release landmark of the immediately prevocalic consonant, e.g. the release of [b] in *bulha*, *sbulha* and so on. The c-center landmark was determined by the midpoint of the initial consonant plateau in #CVX words and by the mean of the midpoints of each consonant’s plateau in the #CCVX and #CCCVX words, e.g. the center of [ksb] in *ksbulha* is the mean of the midpoints of the [k] plateau, the [s] plateau and the [b] plateau. The anchor point was defined by the timestamp of minimum velocity of the tongue tip sensor in the postvocalic consonant, which was either /l/ or /n/ for all words in the corpus.

In this section, the above intervals are used to evaluate the two competing hypotheses about temporal organization schematized in Figure 2. The schemas in Figure 2 illustrate distinct temporal organizations which have been considered in past work to be representative or typical manifestations of simplex (left) and complex (right) onsets. Moroccan Arabic, a language claimed to disallow sequences of consonants at the start of a syllable, is hypothesized to exhibit simplex onset organization, shown on the left. For comparison, the temporal schema thought to be representative of complex onset organization (as in English) is shown on the right. In Figure 2, the temporal life of each individual gesture, ***l***, ***f***, ***k***, is represented by three lines: a dotted line corresponding to movement toward constriction, a solid line corresponding to constriction duration and another dotted line corresponding to movement away from constriction. For each syllabic organization, three words differing in the number of initial consonants, ***l***, ***fl***, ***kfl*** are shown. In addition, the figure shows three intervals for each word. The intervals are left-delimited by the left edge, right edge and center of the single consonant or consonant cluster, as defined above, and right-delimited by a common anchor (A) such as the [n] following the [a] in *lan*, *flan* and *kflan*.

Figure 2
Schematic of the static invariance perspective on the phonetic expression of syllable structure: the schema on the left illustrates the temporal organization associated with simplex syllable onsets; the schema on the right illustrates the temporal organization associated with complex onset syllables.


Simplex onset organization

Complex onset organization

The schema in Figure 2, left, corresponds to a pattern whereby the right edge to anchor interval is more stable than the center to anchor and left edge to anchor intervals. The relative stability of the right edge to anchor interval in Figure 2, left, is indicated by the constant length of the horizontal line drawn between the right edge and the anchor. In reality, across word types and multiple repetitions of each word, the right edge to anchor interval is not constant.

However, the magnitude of durational changes in the right edge to anchor interval is expected, according to the schemas of Figure 2, to be smaller than the magnitude of changes in the other intervals. These differences in magnitude translate into greater stability for the right edge to anchor interval relative to the other two intervals.

In Figure 2, right, a different pattern is found whereby the center to anchor interval is more stable across words than the left edge to anchor and right edge to anchor intervals. This pattern has been found repeatedly in languages claimed have complex syllable onsets (Browman & Goldstein, 1988; Goldstein, Nam, Saltzman, & Chitoran, 2009; Honorof & Browman, 1995; Marin & Pouplier, 2010) but also, under some circumstances, in languages claimed to have simplex syllables onsets(Shaw et al., 2009). As shown in Figure 2, right, it is the horizontal line between the center and the anchor that remains constant across the two words. Again, Figure 2 is a schematic. In experimental data, the expectation about the center to anchor interval would not be that it remains constant but rather that it is the most stable interval relative to the other two, when stability is assessed across word types and multiple repetitions of each word.

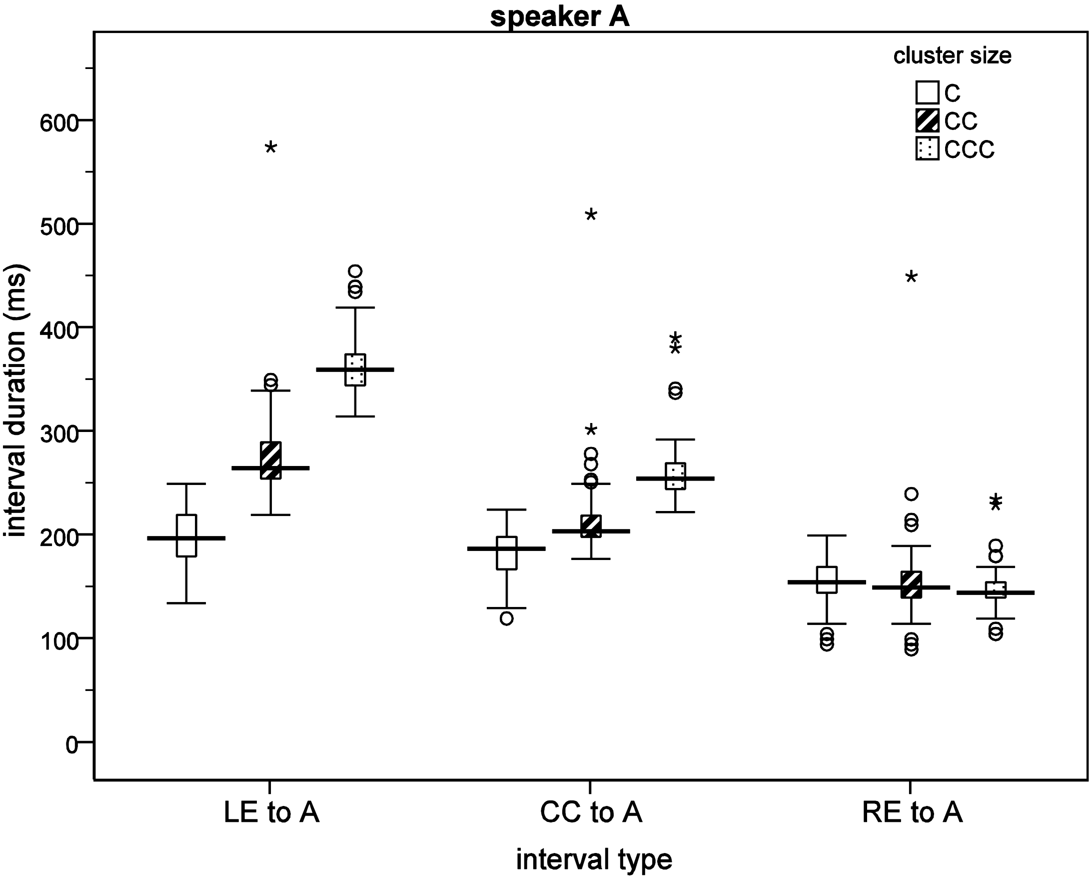
In the small number of languages for which relevant articulatory data are available, the patterning depicted in Figure 2 concurs with independent arguments from phonological theory. For example, American English is argued to allow complex onsets (Kahn, 1976) and has been shown to pattern as in Figure 2 (right). Moroccan Arabic is argued to disallow complex consonant clusters as syllable onsets (Boudlal, 2001; Dell & Elmedlaoui, 2002: chapter 8; Kiparsky, 2003). The same claim has been made for other Arabic dialects (Broselow, 1992; Kiparsky, 2003). Accordingly, the Moroccan Arabic string *kra* 'rent' would not be just a single syllable. Rather, [k] would be in a different syllable from [ra]. Intuitively, we can describe the correspondence between these theoretical ideas and the data patterns of Figure 2 as follows. Since in Arabic, theoretically, it is only the immediately prevocalic consonant that is in the same syllable as the vowel, their timing relation should remain unperturbed when another consonant is added to the beginning of the word. Thus, no change in the interval between the prevocalic consonant and the vowel is expected (Figure 2, left). In English, in contrast, since the added consonant is incorporated into the same syllable as the rest of the segments, the timing relation between these segments must change to accommodate the extra member of the syllable. Thus, we expect the interval between the prevocalic consonant and the vowel to change when another consonant is added (Figure 2, right).

To sum up, Figure 2 represents a statement to the effect that different phonological organizations correspond to different phonetic indices. In more specific terms, there is a correspondence between timing patterns in articulatory data and syllable structure. Syllables with simplex onsets correspond to a pattern of temporal stability where the right edge to anchor interval is the most stable, i.e. more stable than the left edge to anchor and center to anchor intervals. Syllables with complex onsets correspond to a pattern of temporal stability where the center to anchor interval is the most stable, i.e. more stable than the right edge to anchor and left edge to anchor interval. We refer to these statements as the *stability-based heuristics of syllable structure*. Statements of this form promote the view that the relation between phonological organization and phonetic indices is spelled out in the form of fixed correspondences between particular syllable organizations and specific phonetic indices for these organizations. The validity of such stability-based heuristics, as methods of inferring phonological organization from phonetic data, is a major theme we take up after presenting the results of our data analysis.

### *3.2 Stability patterns in the data*

Figure 3 provides box plots for each speaker showing the duration of intervals, *y*-axis, as a function of consonant cluster size, *x*-axis. It can be seen from comparison of the speakers that there is substantial variation in average interval duration. As an example of this variation, consider the median left edge to anchor interval in words beginning with a singleton consonant. Figure 3 shows that this interval ranges from 150 ms for speaker B to 290 ms for speaker D. Despite such disparities in absolute durations across speakers, the main pattern of interval change, as consonant cluster size increases, is the same within each speaker. The left edge to anchor interval and the center to anchor interval both increase with the addition of each consonant (#CCCVX > #CCVX > #CVX). In contrast, the right edge to anchor interval remains relatively stable.[2] This is the pattern expected for simplex onset organization, according to the stability-based heuristics of Figure 2 (left). After quantifying the statistical reliability of this pattern, we then look more closely at individual words and identify items that deviate from the main trend shown in Figure 3.

Figure 3
Duration of three measured intervals (left edge to anchor, center to anchor, and right edge to anchor) by cluster size (C, CC, CCC) for four speakers pooled across triads. Boxes are defined by the upper and lower quartiles of the data. The solid line is the median duration, whiskers indicate sample minima and maxima, and circles and asterisks indicate outliers.



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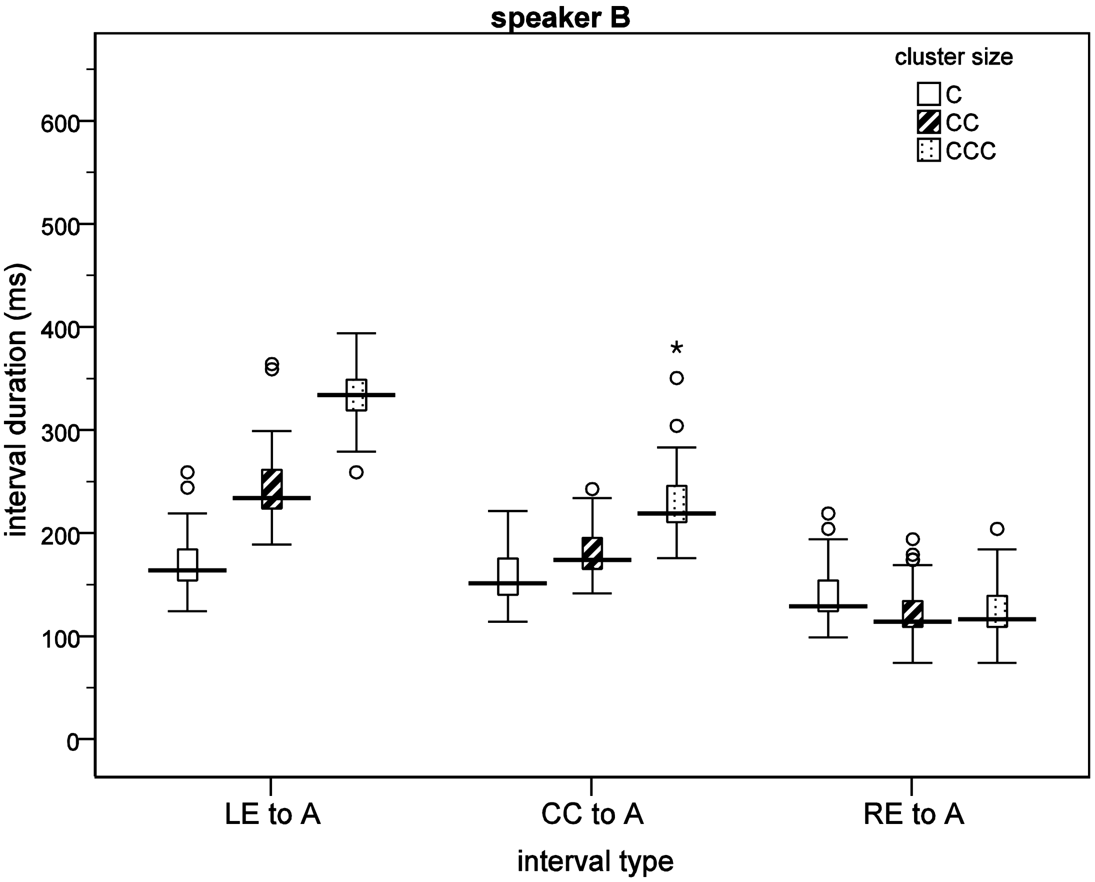
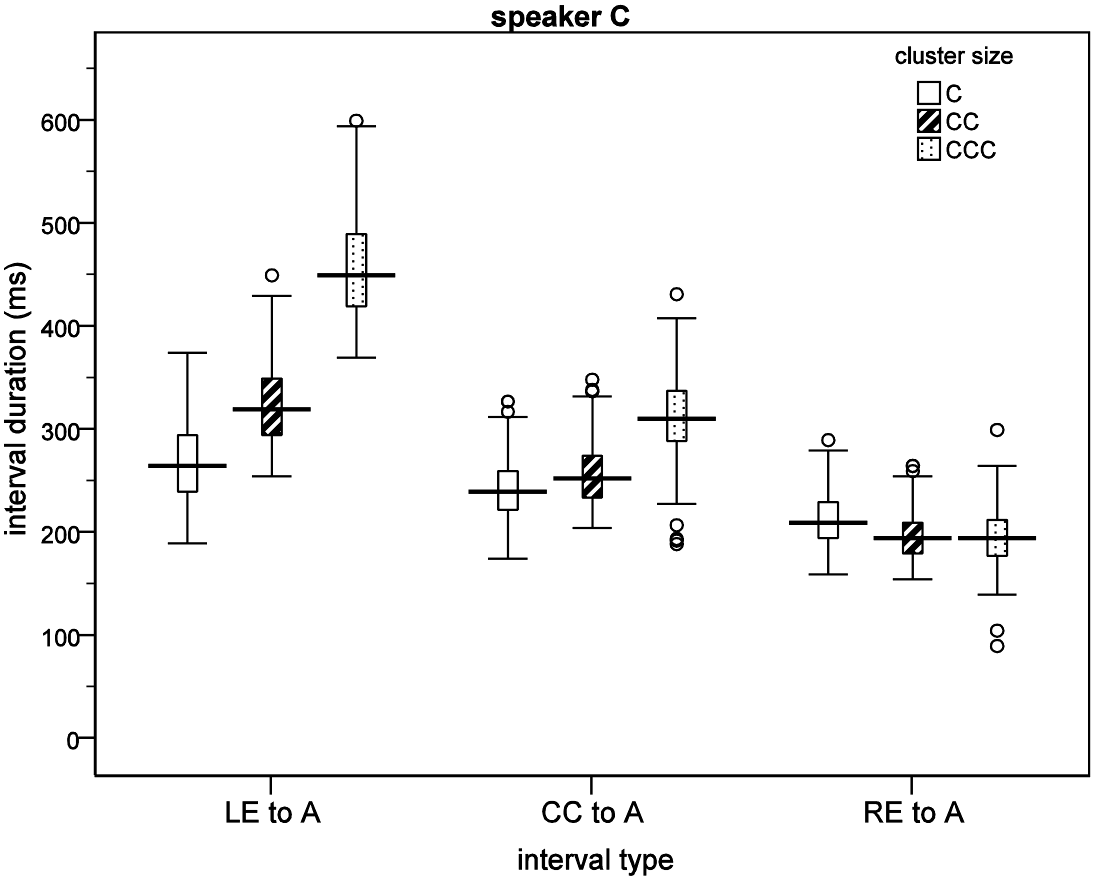
[2] For some speakers, the right edge to anchor interval decreases slightly in #CCVX words relative to #CVX words. Even for these speakers, as we report below, the right edge to anchor interval is indeed the most stable interval among the three intervals in our data, i.e., more stable than the left edge to anchor interval and the center to anchor interval. However, we will return to this change in the duration of the right edge to anchor in section 4.


speaker B
cluster size
C
CC
CCC
interval duration (ms)
0
100
200
300
400
500
600
LE to A
CC to A
RE to A
interval type


speaker C
cluster size
C
CC
CCC
interval duration (ms)
0
100
200
300
400
500
600
LE to A
CC to A
RE to A
interval type

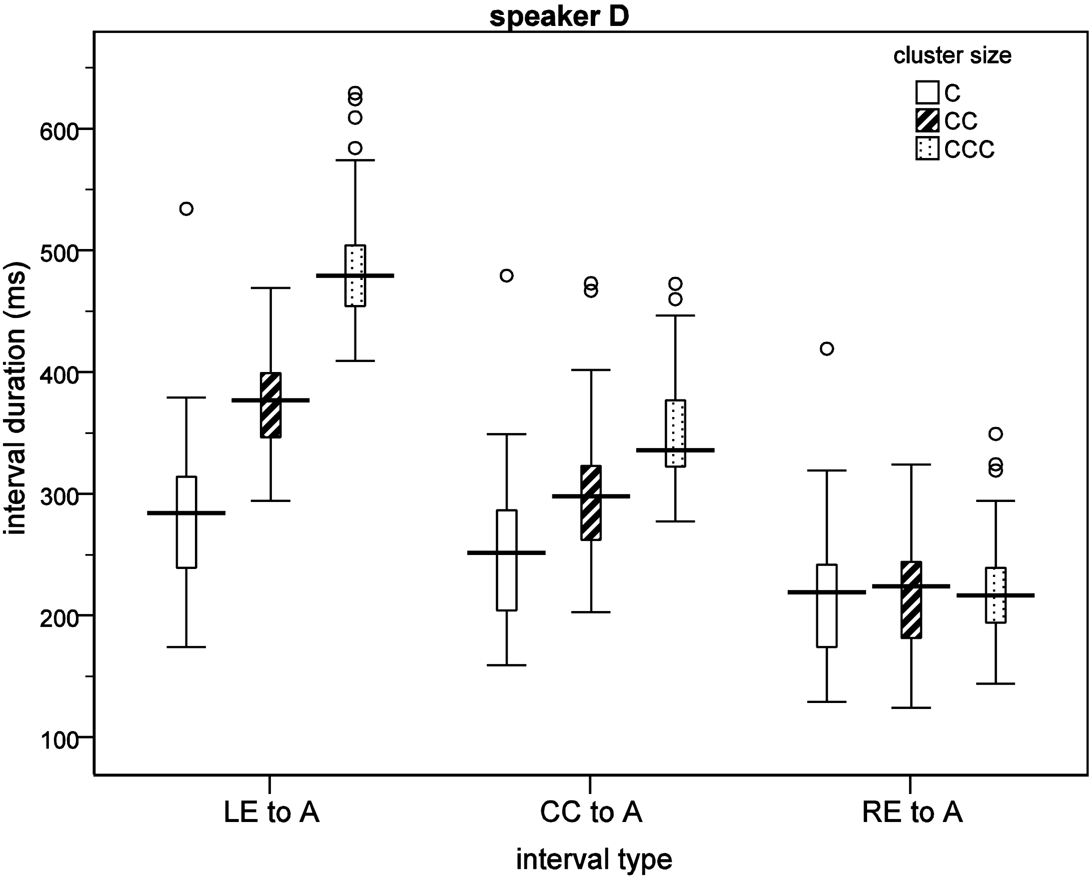


Table 2 provides measurements of interval duration for each combination of speaker and triad across C-, CC-, and CCC-initial words. The table shows the mean and standard deviation of the left edge to anchor, center to anchor and right edge to anchor intervals as well as the relative standard deviation of these intervals calculated across words of a triad (right column). The relative standard deviation, also known as the coefficient of variance, is the standard deviation divided by the mean. In consideration of the general property of motor behavior that the variance of a timed interval is correlated with its mean (Schöner, 2002; Wing & Kristofferson, 1973), we adopt the relative standard deviation (RSD) as our index of interval stability. In contrast to other widely used indices of stability such as the variance or standard deviation, relative standard deviation does not bias the interpretation of the results in favour of right edge to anchor stability (as the shortest of the three intervals shown in Figure 2, the right edge to anchor interval *is biased* toward having a lower *variance* or standard deviation than the other intervals), making it a conservative measure for assessing phonological organization using temporal stability measures (Shaw et al., 2009). For all combinations of speaker and triad, the RSD of the right edge to anchor interval (Table 2c, right column, in bold) was lower than the RSD of the other two intervals (Table 2a, 2b). This is the pattern of stability corresponding to simplex onsets according to the stability-based heuristics in the left panel of Figure 2.

A repeated measures ANOVA was conducted to evaluate the statistical reliability of the stability pattern. The dependent variable was RSD. Triad {*lan~flan~kflan, bulha~sbulha~ksbulha, kulha~skulha~mskulha*} and interval type {left edge to anchor, center to anchor, right edge to anchor} were included as repeated measures factors. Mauchly's test indicated that the assumption of sphericity was upheld for both factors (triad, $p = .094$; interval type, $p = .348$). The main effect of interval type [$F(2,6) = 56.4$, $p < .001$] and the interaction between interval type and triad were both significant [$F(4, 12) = 5.25$, $p = .011$]. The main effect of triad was not significant [$F(2, 6) = 3.51$, $p = .098$].

Post hoc ANOVAs showed significant differences in relative standard deviation between each level of interval type: center to anchor versus right edge to anchor [$F(1, 3) = 21.5$, $p < .019$]; center to anchor versus left edge to anchor [$F(1, 3) = 99.3$, $p = .002$]; right edge to anchor versus left edge to anchor [$F(1, 3) = 62.9$, $p < .01$]. This indicates that the stability advantage (lower RSD, as seen by comparing numbers in the right column of Table 2c, shown in bold, with corresponding numbers in Table 2a and Table 2b) of the right edge to anchor interval over the center/left edge to anchor interval is reliable.

To evaluate the interaction between triad and interval type, post hoc ANOVAs were conducted on each level of interval type with triad as a within-subjects factor. These tests indicated that the significant interaction between triad and interval type was due to the RSD of the left edge to anchor interval. There was a significant effect of triad on the left edge to anchor interval [$F(2, 6) = 9.56$, $p < .05$] attributable to the *kulha~skulha~mskulha* triad, which had a lower left edge to anchor RSD than the other triads. The effect of triad on the other two intervals, center to anchor interval [$F(2, 6) < 1$] and right edge to anchor interval [$F(2, 6) = 3.32$, $p = .11$], was not significant. Since the RSD patterns of the center to anchor interval and the right edge to anchor interval were not significantly different across triads, the interaction between triad and interval type has no relevant consequence for the theoretical hypotheses under evaluation. This is because, as per the stability-based heuristics of Figure 2, the prediction of complex onset organization refers to center to anchor stability and the prediction of simplex onset organization refers to right edge to anchor stability.

In sum, the statistical analysis indicates a reliable pattern of right edge stability, the timing pattern proposed to be characteristic of simplex onset organization (as per Figure 2, left).

Table 2 Duration *mean and standard deviation (SD) of three measured intervals, left edge to anchor (a), center to anchor (b), and right edge to anchor (c), for each speaker and word in a triad. The relative standard deviation (RSD) calculated across words in a triad is provided for each interval and speaker (rightmost column). For each combination of speaker and triad, the lowest RSD values are found for the right edge to anchor interval (shown in bold).*

(a) left edge to anchor interval

| Triad | Speaker | C Mean(SD) | CC Mean(SD) | CCC Mean(SD) | Total RSD |
|---|---|---|---|---|---|
| lan~flan~kflan | A | 199(11) | 273(25) | 387(34) | 27.6% |
| | B | 158(10) | 229(8) | 334(12) | 29.9% |
| | C | 308(33) | 380(33) | 513(37) | 23.0% |
| | D | 243(40) | 366(36) | 484(35) | 29.4% |
| bulha~sbulha~ksbulha | A | 173(21) | 265(19) | 354(17) | 29.3% |
| | B | 141(8) | 219(16) | 329(11) | 34.4% |
| | C | 242(21) | 307(29) | 448(30) | 27.4% |
| | D | 284(26) | 352(36) | 470(30) | 22.5% |
| kulha~skulha~mskulha | A | 226(13) | 270(25) | 345(18) | 18.9% |
| | B | 168(21) | 227(15) | 302(18) | 25.1% |
| | C | 278(27) | 311(21) | 424(27) | 20.0% |
| | D | 327(23) | 387(27) | 464(34) | 15.9% |

(b) center to anchor interval

| Triad | Speaker | C Mean(SD) | CC Mean(SD) | CCC Mean(SD) | Total RSD |
|---|---|---|---|---|---|
| lan~flan~kflan | A | 181(10) | 212(22) | 273(31) | 16.7% |
| | B | 141(9) | 171(6) | 206(16) | 16.6% |
| | C | 275(28) | 302(24) | 360(22) | 13.8% |
| | D | 216(33) | 266(25) | 324(25) | 19.9% |
| bulha~sbulha~ksbulha | A | 153(18) | 203(14) | 248(13) | 20.7% |
| | B | 128(7) | 158(8) | 222(38) | 27.0% |
| | C | 224(21) | 250(21) | 295(31) | 14.8% |
| | D | 261(26) | 287(28) | 330(23) | 13.0% |
| kulha~skulha~mskulha | A | 199(14) | 204(16) | 260(42) | 17.5% |
| | B | 164(14) | 168(13) | 220(12) | 15.5% |
| | C | 245(19) | 242(18) | 290(38) | 13.2% |
| | D | 284(23) | 319(50) | 355(27) | 14.2% |

(c) right edge to anchor interval

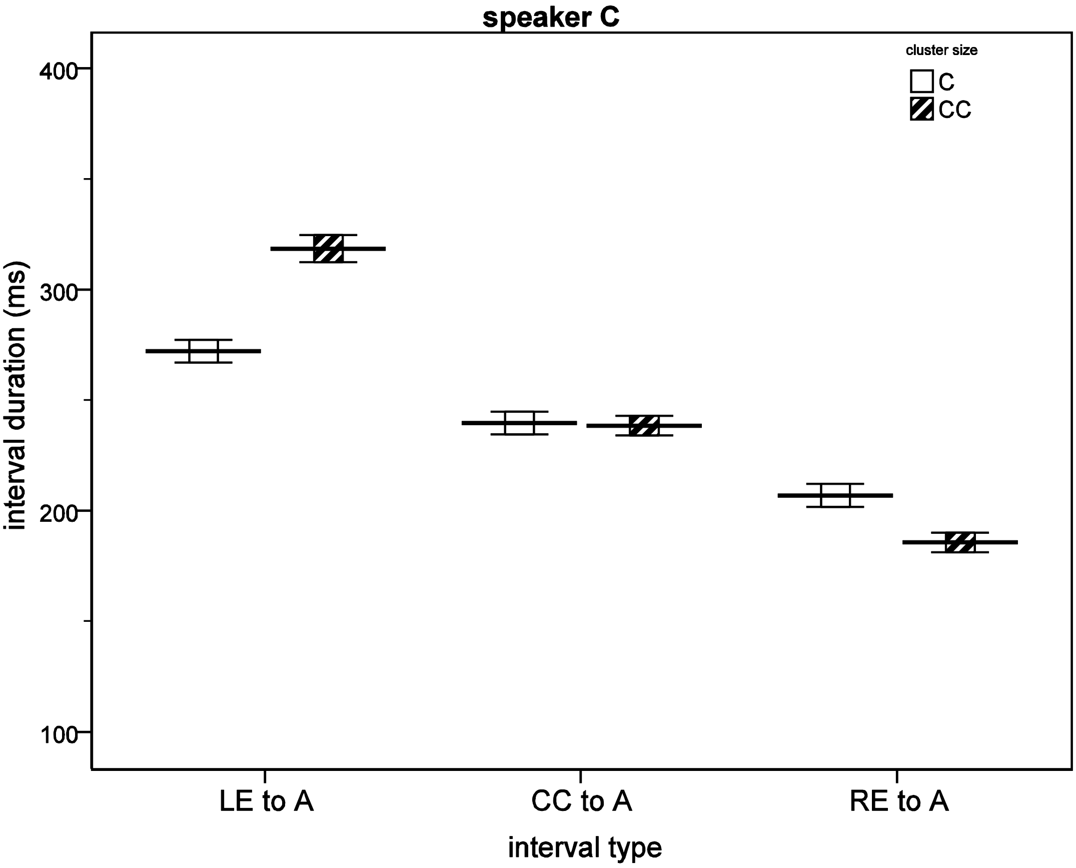
| | | C | CC | CCC | Total |
|---|---|---|---|---|---|
| Triad | Speaker | Mean(SD) | Mean(SD) | Mean(SD) | RSD |
| lan~flan~kflan | A | 163(11) | 155(18) | 161(31) | **9.7%** |
| | B | 123(9) | 114(6) | 110(5) | **7.4%** |
| | C | 242(23) | 229(20) | 230(16) | **8.9%** |
| | D | 189(28) | 177(17) | 182(22) | **12.9%** |
| bulha~sbulha~ksbulha | A | 134(20) | 141(22) | 138(18) | **14.4%** |
| | B | 114(9) | 100(14) | 105(14) | **12.5%** |
| | C | 207(21) | 196(17) | 189(28) | **11.8%** |
| | D | 239(28) | 226(29) | 211(25) | **12.9%** |
| kulha~skulha~mskulha | A | 171(17) | 153(17) | 143(11) | **12.1%** |
| | B | 134(17) | 115(13) | 120(14) | **13.2%** |
| | C | 213(14) | 191(15) | 185(12) | **9.3%** |
| | D | 241(26) | 227(21) | 217(24) | **11.0%** |

### *3.3 Exceptional patterns*

A closer look at the results of Table 2 reveals some potential exceptions. For three speakers, A, B and C, the center to anchor interval does not show a substantial increase in duration from *kulha* to *skulha*. That is, for this subset of the data, we find center to anchor interval stability. This patterning, no substantial change in the means from #CVX to #CCVX is non-canonical from the perspective of the heuristics for simplex onset organization in Figure 2. As depicted by these heuristics, stability of the center to anchor interval is seen as the canonical manifestation of complex onset syllables (Browman & Goldstein, 1988; Goldstein et al., 2007; Hermes et al., in press; Honorof & Browman, 1995; Marin & Pouplier, 2010).

To further illustrate the exceptional patterning of center to anchor interval duration in *kulha~skulha*, Figure 4 shows a box plot for just this data produced by speaker C. The box plot shows that the center to anchor interval is stable across C and CC words while the right edge to anchor interval decreases from C, *kulha*, to CC, *skulha*. This pattern reflects the predictions of complex onset organization, as shown in Figure 2 (right).

Figure 4
Duration of three measured intervals (left edge to anchor, center to anchor, and right edge to anchor) by cluster size (C, CC) for *kulha~skulha* as produced by speaker C.



To explore how the changes in duration highlighted in Figure 4 affect our measure of interval stability, we isolated the *kulha~skulha* data and calculated interval stability over just these words. Table 3 shows the results. For speaker D, the right edge to anchor is more stable than the center to anchor interval and the left edge to anchor interval. From the perspective of the heuristics in Figure 2, speaker D shows the canonical pattern of simplex onset organization. However, the other three speakers, A, B, and C, show a stability pattern consistent with the predictions of complex onset organization. For these speakers, the center to anchor interval has lower RSD than both the left edge to anchor interval and the right edge to anchor interval. We take up this exceptional pattern in section 4.0 where we discuss the reliability of stability-based heuristics for syllable structure.

Table 3 Duration *mean, standard deviation (SD), and relative standard deviation (RSD) of three intervals, left edge to anchor, center to anchor, and right edge to anchor, of the kulha~skulha dyad for each speaker. For each speaker, the interval with the lowest RSD, i.e., the most stable interval, is shown in bold.*

| kulha~skulha | | | | | | |
|---|---|---|---|---|---|---|
| Speaker | Left Edge | | Center | | Right Edge | |
| | Mean(SD) | RSD | Mean(SD) | RSD | Mean(SD) | RSD |
| A | 248(30) | 12.0% | 201(15) | **7.5%** | 162(19) | 11.8% |
| B | 197(35) | 17.7% | 166(13) | **7.8%** | 125(17) | 14.0% |
| C | 294(29) | 9.8% | 244(18) | **7.4%** | 202(18) | 9.1% |
| D | 358(39) | 10.9% | 303(43) | 14.2% | 234(24) | **10.4%** |

### *3.4 Taking stock: preliminary summary*

The overall patterns of interval stability are largely consistent with the predictions for simplex onset syllables as expected by the stability-based heuristics for syllable structure. Across words beginning with one, two, and three initial consonants, the right edge to anchor interval is more stable than the left edge to anchor interval or the center to anchor interval. This stability pattern derives from the direction and magnitude of changes in interval duration across increases in the number of consonants at the start of a word. As the number of consonants increases, the durations of the left edge to anchor interval and the center to anchor interval increase. The right edge to anchor interval decreases from #CVX to #CCVX and remains roughly equivalent across #CCVX and #CCCVX. Across #CVX, #CCVX, and #CCCVX word types, the magnitude by which the left edge to anchor and center to anchor intervals increase is substantially greater than the magnitude by which the right edge to anchor interval decreases. These differences lead to a stability advantage for the right edge to anchor interval over the other two intervals. This fact is summarized by the relative standard deviation statistic reported in Table 2. For all combinations of speaker and triad, the right edge to anchor interval showed a significantly lower RSD than the other two intervals.

We have also seen, however, that it is possible to isolate some pieces of the larger corpus that are consistent with the stability-based heuristics for complex onset syllables. Specifically, patterns of interval duration across *kulha* and *skulha* (excluding *mskulha*) deviated, for some speakers, from the main trend in the data. Three out of four speakers produced *kulha~skulha* (but not *bulha~sbulha* or *lan~flan*) with stable center to anchor intervals. Center to anchor stability has provided an informative heuristic for complex syllable onsets (Browman & Goldstein, 1988; Goldstein et al., 2007; Hermes et al., in press; Kühnert, Hoole, & Mooshammer, 2006a; Marin & Pouplier, 2010). In the current study, center to anchor stability is sometimes observed for the *kulha~skulha* dyad (a dyad refers to a #CCVX word and its segmentally matched #CVX counterpart). The exceptional stability of the center to anchor interval for just a single word pair is important in the context of theories of syllable structure. Such theories typically aim at capturing aspects of linguistic knowledge shared by members of a speech community, i.e. differences in syllabification across subjects are not expected. Further, while there are various proposals that treat the phonological organization of consonant clusters and/or the temporal organization of consonant clusters differently depending on the identity of the consonants in the cluster, our data do not conform to these proposals. For example, *s*-obstruent clusters, such as those in *s<u>k</u>ulha* and *<u>sb</u>ulha*, are sometimes claimed to be phonologically different from rising sonority clusters, such as the initial cluster in *flan* (e.g., Fudge, 1969; Selkirk, 1982; Zuraw, 2007). In our data, uniformity is found across *sbulha* and *flan* (not across *skulha* and *sbulha*). In other data, the temporal patterning of consonant clusters is influenced by the ordering of the place of articulation of the consonants, i.e., front-to-back clusters, those in which the place of articulation of the first consonant is anterior to the place of articulation of the second consonant, show differences in timing patterns from back-to-front clusters (Byrd, 1996; Chitoran et al., 2002; Gafos et al., 2010; Goldstein et al., 2009; Hardcastle & Roach, 1979; Surprenant & Goldstein, 1998; Wright, 1996; Zsiga, 1994). In our data, *fl* and *sk*, the back-to-front clusters, do not pattern to the exclusion of *sb*, the front-to-back cluster. Thus, the exceptional data in our corpus does not readily fit into existing proposals. Moreover, interpreting center to anchor stability as support for complex onset organization in our data would lead us to the rather puzzling conclusion that for speakers A, B, and C, the initial cluster of *skulha* has a different syllabification than the initial cluster of *sbulha* or the initial cluster of *flan*.

The alternative is that syllabic organization remains unchanged throughout our entire dataset, and that therefore our understanding of the relation between syllable structure and phonetic indices, as encoded in the stability-based heuristics of Figure 2, is incomplete. In sum, our data offer an opportunity, taken up in the following section, to assess the validity of stability-based heuristics of syllable structure and thus improve our understanding of the relation between phonological form and phonetic indices.

## 4.0 Limitations of stability-based heuristics for syllable structure

An important question for addressing the relation between syllabic organization and experimental data is how reliably stability measures of temporal organization, extracted from the inherently variable and continuous phonetic signal, reflect syllable structure. Here we use our data, including the ‘exceptional’ data pointed out in section 3.3, to study how stability-based patterns change under natural prosodic modulations contributed by the speakers in our experiments.

Our experimental manipulation invites consideration of two well-known prosodic modulation effects contributed by adding segments to a word, i.e. #CVX, #CCVX, #CCCVX. The first concerns the duration of the prevocalic consonant in #CVX sequences compared to #CCVX, #CCCVX. There are reasons to expect that the duration of that consonant would be longer in #CVX. Consonants at the first position of a word tend to be longer or strengthened compared to instances of the same consonants at a non-initial position (Byrd, Lee, Riggs, & Adams, 2005; Byrd & Saltzman, 2003; Fougeron & Keating, 1997) and consonants in clusters tend to be shorter than in isolation (Haggard, 1973; Klatt, 1976; Umeda, 1977).[3]

The second effect is vowel or syllable compression as additional segments are appended to the word. There is considerable evidence that the underlined portion of the #CVC sequences shortens in #CCVC or #CCCVC sequences due to the addition of the extra segments (e.g., Kim & Cole, 2005; Klatt, 1973; Lehiste, 1972 on English; and Strangert, 1985 for a cross-linguistic review).

In this section, we pursue an analysis of the influences these prosodic modulations have on stability-based indices of syllable structure. We take up pre-vocalic consonant shortening in section 4.1 and turn to syllable compression in section 4.2. Using a computational model of temporal organization, we make explicit the behavior of temporal stability indices as phonetic parameters are scaled. We find that under simplex onset organization, the two effects lead to improved center to anchor stability. Crucially, for complex onset organization, the shortening effects observed in our data make different predictions. These predictions enable us to diagnose syllabic organization in our data even in cases where stability-based heuristics fail to be

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[3] We say ‘tend to’ because these effects are not omnipresent. There are studies which report lack of such effects for specific consonants or phonetic contexts (Hoole, Fuchs, & Dahlmeier, 2003). Our argument does not depend on whether the shortening effects are omnipresent. From our perspective, the essential question is how such effects, if present, modulate stability indices for different syllabic organizations.

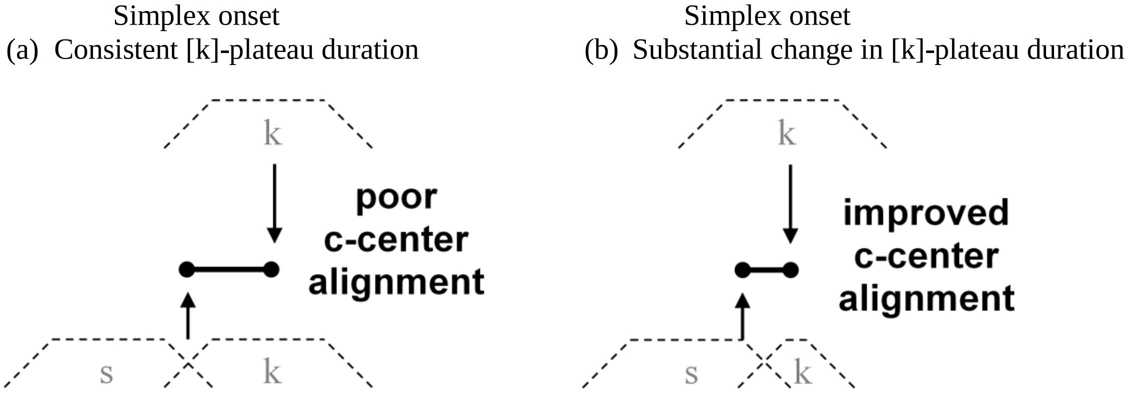
informative. In short, in the approach put forward, the natural prosodic variability in our experimental data becomes crucial in elucidating the relation between phonological organization and phonetic indices. It is only when we understand the effect of this variability on the stability patterns that we can reliably infer syllabic organization from our phonetic data.

### *4.1 Effects of consonant duration on interval stability*

Under certain structural conditions, center to anchor interval stability, as calculated across #CVX and #CCVX forms, can be influenced by the temporal properties of the immediately prevocalic consonant, i.e., the underscored consonant in #CVX and #CCVX. Three speakers exhibited center to anchor stability for *kulha~skulha*. When [s] joins the [kVX] in *kulha* to form [skVX] in *skulha*, it shifts the c-center (the landmark left-delimiting the center to anchor interval) to the left or, in other words, it stretches the center to anchor interval by adding duration to it. If the addition of [s] is accompanied by shortening of [k], the duration added to the center to anchor interval by [s] may be reduced or even obliterated. Thus, across [kVX] and [skVX] sequences, the center to anchor interval may not change much. Therefore, the relative standard deviation of that interval may be relatively low (center to anchor interval stability). Importantly, however, the effects of prevocalic consonant duration on center to anchor stability depend on syllable structure. Syllables with complex onsets yield different predictions than syllables with simplex onsets.

Figure 5 illustrates the predicted relationship between consonant shortening and center to anchor interval duration for simplex onset syllables. In Figure 5a the plateau duration of [k] remains relatively invariant across the [k]/[sk] contexts whereas in Figure 5b [k]’s plateau duration is shorter in [sk] than in [k]. The left side of the figure, Figure 5a, shows the canonical pattern of simplex onset organization. This parallels the simplex onset schema shown in Figure 2. In both Figure 2 and here in Figure 5a, consonant duration remains invariant across the [k]/[sk] sequences. Under these idealised conditions, addition of [s] to [k] lengthens the center to anchor interval in [sk] relative to [k]. Consequently, as Figure 5a shows, the c-center landmark, which left-delimits the center to anchor interval, is poorly aligned across [k] and [sk]. Such misalignment lowers the stability of the center to anchor interval. In Figure 5b, [k]’s plateau duration is shorter in [sk] than in [k]. In this case, shortening of [k] cancels out some of the duration added to the center to anchor interval by [s]. As a consequence, the c-center of [k] and [sk] are better aligned on the right, Figure 5b, than on the left, Figure 5a.

Figure 5
Comparison of c-center alignment under a simplex onset parse of #C and #CC in two conditions of consonant plateau duration. The left panel, (a), shows consistent consonant durations across #*s* and #*sk*. The right panel, (b), shows a decrease in *k* plateau duration in #*sk* relative to #*k*. The length of the solid bold line indicates the difference between the c-center of [k] and [sk] serving as an index of center to anchor interval stability.

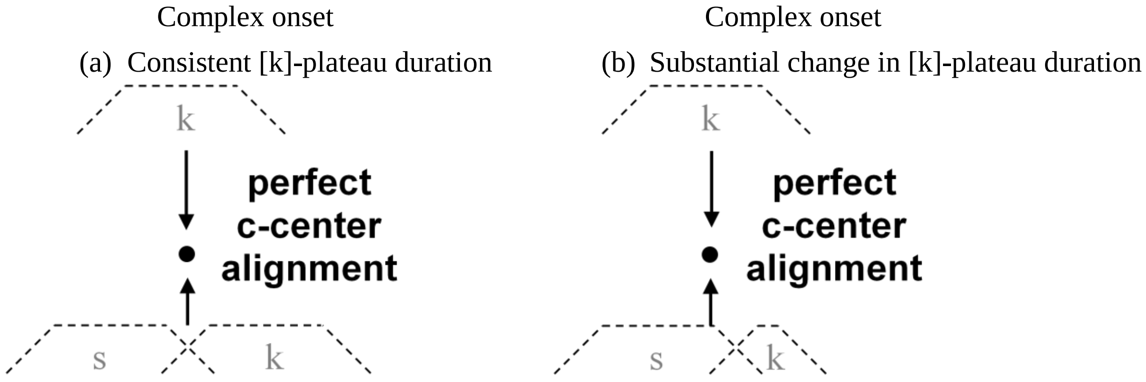

Simplex onset
(a) Consistent [k]-plateau duration

Simplex onset
(b) Substantial change in [k]-plateau duration

The main point of Figure 5 is that consonantal shortening improves center to anchor stability under simplex onset organization. There is a direct relationship between center to anchor stability and differences in consonant plateau duration. As the difference between plateau duration (across #CVX and #CCVX) increases, the difference in c-center location decreases. This is not a prediction of syllables with complex onsets.

In complex onset syllables, consonant plateau shortening is predicted to be unrelated to center to anchor stability. Figure 6 illustrates this by redisplaying the same sequences, [k] and [sk], under complex onset organization. The left panel, Figure 6a, replicates our first introduction of the complex onset schema (Figure 2, right). In this panel, the duration of [k] remains the same in both [k] and in the [sk] cluster. The right panel, Figure 6b, shows changes in [k] plateau duration across [k] and [sk]. It can be seen from the comparison of Figure 6a and Figure 6b that the location of the c-center is unaffected by changes in plateau duration. Complex onset organization predicts that there is no relationship between consonant shortening and center to anchor interval stability.

Figure 6
Comparison of c-center alignment under a complex onset organization of #C and #CC in two conditions of consonant plateau duration. The left panel, (a), shows consistent consonant durations across #*s* and #*sk*. The right panel, (b), shows a decrease in *k* plateau duration in #*sk* relative to #*k*. In both panels, the c-centers of #C and #CC remain aligned.

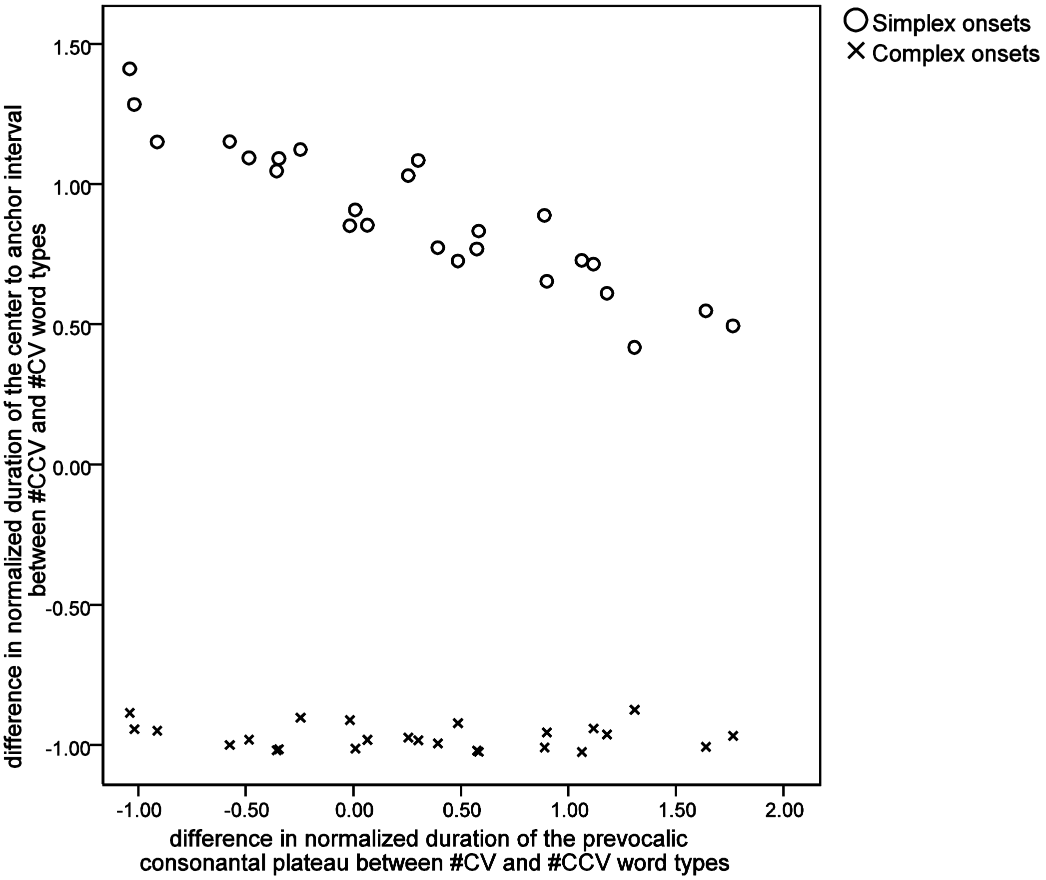


To check the predictions illustrated in Figures 5 and 6, we used a computational model of temporal organization to simulate word dyads under conditions of prevocalic consonant shortening. Given a set of word types, e.g., #CVX, #CCVX, the model simulates the temporal organization for each word by generating articulatory landmarks defining the plateau of each constituent segment. These landmarks are generated from stochastic versions of local timing relations between consonants and vowels. Landmark generation proceeds by first selecting the timestamp of the release landmark of the immediately prevocalic consonant, $C_n^{Rel}$ , from a Gaussian distribution. The immediately preceding landmark, the target of that consonant, $C_n^{Tar}$, is then generated by subtracting consonant plateau duration, $k_p$, from $C_n^{Rel}$ and adding a noise term. These two landmarks, $C_n^{Tar}$ and $C_n^{Rel}$, define the plateau of the immediately prevocalic consonant. For words with two initial consonants, the release landmark of the preceding consonant, $C_{n-1}$ ($C_1$ in $\#C_1C_2V$ words), is generated with reference to $C_n^{Tar}$. The inter-plateau interval, $k_{ipi}$, is subtracted from $C_n^{Tar}$ and a noise term is added. The target landmark of the initial consonant, $C_{n-1}^{Tar}$, is then calculated by subtracting plateau duration from $C_{n-1}^{Rel}$ and adding a noise term. Anchor points were generated according to syllabic organization by subtracting a constant, $k_v$, from either the midpoint of only the immediately prevocalic consonant, under simplex onset organization, or from the midpoint of the entire cluster of prevocalic consonants, under complex onset organization. In this way, word dyads, #CVX and #CCVX forms, were simulated under complex and simplex onset organization.[4] On each run of the simulation, fifteen instances of #CVX and fifteen instances of #CCVX words were simulated. Across thirty runs of the simulation, the duration of the immediately prevocalic consonant in #CCVX was systematically varied from one hundred milliseconds to ten milliseconds in four millisecond steps. Relevant measurements of the simulated data are summarized in Figure 7.

Figure 7 plots the absolute value of the difference in center to anchor interval duration between #CCVX and #CVX words against the difference in prevocalic consonant plateau duration across these word types. Both of these parameters were normalized by z-scoring.

The figure shows that the relation between the parameters depends on syllabic organization. For simplex onset organization, plotted as ‘o’s, there is a negative correlation. As the effect of consonant shortening increases, higher *x*-axis values, the difference in center to anchor interval duration between #CCVX and #CVX decreases, lower *y*-axis values. For complex onset organization, plotted as ‘x’s, there is no such relation. The difference in duration of the center to anchor interval does not change in any systematic way as duration of the immediately prevocalic consonant is scaled.

Figure 7
Scatter plot of data simulated under simplex onset organization, ‘o’, and complex onset organization, ‘x’. The *y*-axis shows the absolute value of the difference in center to anchor interval duration calculated across dyads. The *x*-axis shows the difference in prevocalic consonant duration between #CCVX and #CVX. Higher values on the *x*-axis correspond to greater degrees of shortening.



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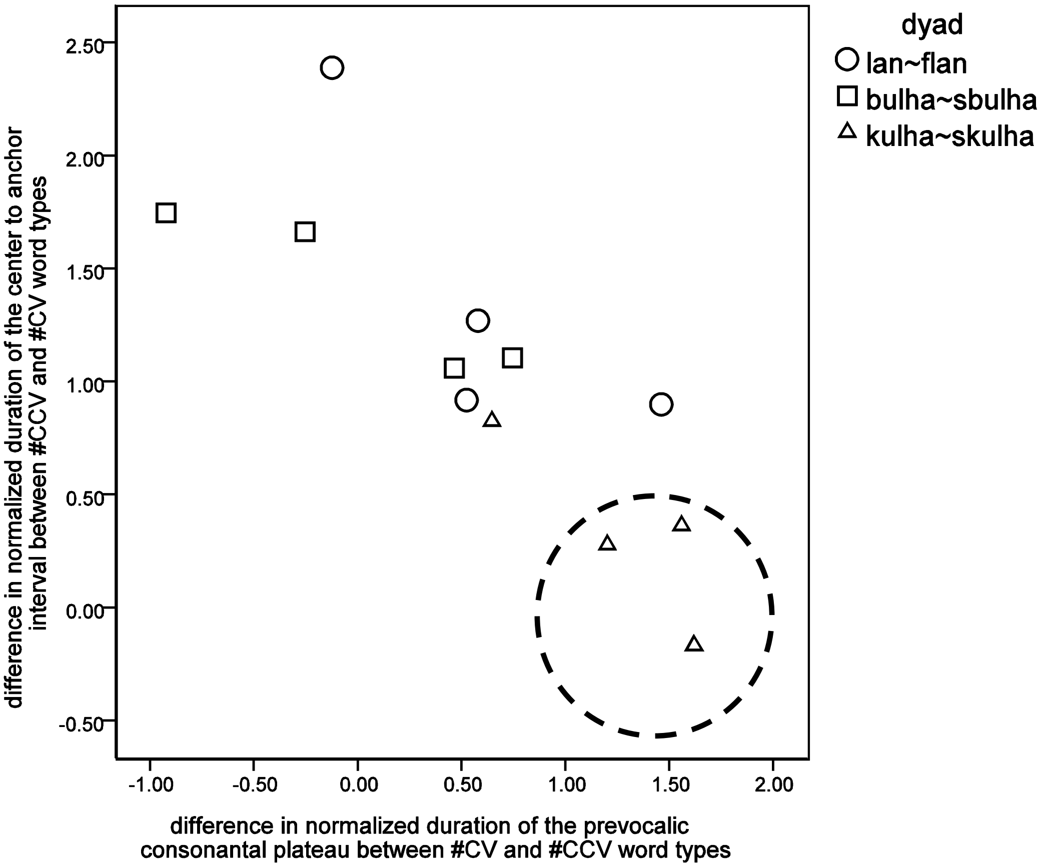
[4] The constants in the model reflected averages in the data, with the following means and corresponding standard deviations: $k_{ipi}$ (inter-plateau interval) = 49(12); $k_p$ (consonant plateau) = 47(11); $k_v$ (vowel duration) = 250(5). The duration of the immediately prevocalic consonant was varied between 100 ms and 10 ms.

We now turn to our data to evaluate these predictions. Across one and two consonant clusters, simplex onset organization predicts a negative correlation between differences in center to anchor interval duration and differences in prevocalic consonant duration. This means that the greater the shortening of the prevocalic C̲ across #C̲VX and #CC̲VX, the smaller the difference in c-center location across #CVX and #CCVX. Figure 8 plots these two differences for each combination of speaker and word dyad in the data. Since absolute duration varies greatly across speakers, both differences were normalized within speaker by calculating *z*-scores for each value. The normalized difference in center to anchor duration, *y*-axis, is plotted against the normalized difference in the duration of the prevocalic consonant plateau, *x*-axis. For speaker*dyad combinations with stable prevocalic consonant duration across words, i.e. values around zero on the *x*-axis, Figure 8 shows large differences in center to anchor interval duration. In contrast, speaker*dyad combinations with large differences in prevocalic consonant duration show small differences in center to anchor interval durations, i.e. values around zero on the *y*-axis. Pearson's correlation coefficient indicates a significant negative correlation between the two variables ($r = -.844$, $p < .001$). Thus, as predicted by simplex onset organization, consonant shortening is related to c-center alignment—the greater the shortening of prevocalic C, the smaller the difference in c-center location.

Figure 8
Scatter plot of the normalized difference in center to anchor interval duration calculated across dyads, *y*-axis, against the normalized difference in prevocalic consonant duration, *x*-axis. The dotted circle designates the "exceptional" data points, *kulha~skulha*, as produced by speakers A, B, and C.



In the context of the main trend in the data, we can now make sense of the pattern of center to anchor stability observed for the exceptional *kulha~skulha* dyad. The three speakers that produced *kulha~skulha* with stable center to anchor intervals are circled in the bottom right of Figure 8. For these cases, stability-based heuristics pointed at first to complex onset syllables. But we can now see that stability of the center to anchor interval in this data is a lawful consequence of simplex onset organization and prevocalic consonant shortening.

The central point illustrated here, then, is that the same qualitative syllabic organization can have a range of concrete phonetic manifestations as various parameters are changed. Simplex onset organization can give rise to kinematic patterns that, from the perspective of the stability-based heuristics in Figure 2, would be canonical manifestations of complex onset syllables. We thus see that stability-based heuristics break down under particular conditions. Nevertheless, there are relations between phonetic parameters that remain intact across the range of variation in the data.

### *4.2 Effects of syllable compression on interval stability*

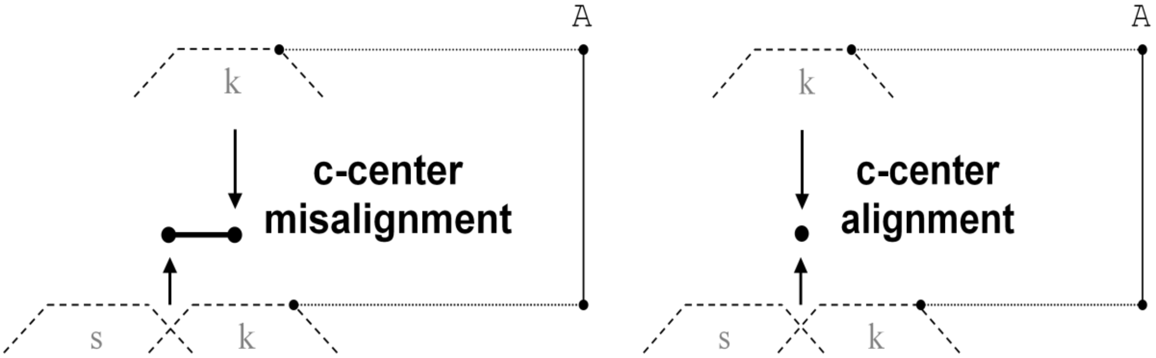
In this section, we illustrate how the second prosodic modulation effect, vowel or syllable compression, interacts with stability-based indices for syllable structure. As with the previous section, we make explicit that the influence compression has on center to anchor stability depends crucially on the syllabic organization of consonant clusters.

Figure 9 illustrates what happens to c-center alignment when syllable duration is perturbed such that the VC portions of #CCVC sequences are shorter than in corresponding #CVC sequences. We first discuss predictions of simplex onset organization. To establish a baseline, the left panel, Figure 9a, shows #CVX and #CCVX sequences without shortening. Since the duration of all segments is held constant and consonant clusters are organized into simplex onset syllables, the right edges of the consonants are better aligned than the c-centers. As we have seen before, adding a consonant lengthens the center to anchor interval in #CCVX relative to #CVX yielding low center to anchor interval stability. The right panel, Figure 8b, shows the same sequences under syllabic compression. While the effect we focus on here is a consequence of syllable shortening regardless of what part of the syllable shortens, for the purposes of illustration we indicate syllable compression in the figure by manipulating the right edge to anchor interval. In Figure 9b, the right edge to anchor interval is substantially shorter in #CCVX than in #CVX. As a consequence of this shortening, the c-center of #CCVX is brought into alignment with the c-center of #CVX. This results in improved center to anchor interval stability across #CVX and #CCVX sequences in Figure 9b compared to Figure 9a. Thus, syllable compression in #CCVX relative to #CVX sequences improves center to anchor interval stability. Crucially, however, this is a prediction of simplex onset syllables only.

Figure 9
Comparison of c-center alignment under a simplex onset parse of #CVX and #CCVX in two conditions of syllabic compression. The left panel, (a), shows consistent right edge to anchor durations across #*sVX* and #*skVX*. The right panel, (b), shows a decrease in right edge to anchor interval duration in #*skVX* relative to #*kVX*. The length of the solid bold line indicates the difference between the c-center of [k] and [sk] serving as an index of center to anchor interval stability.

Simplex onset
(a) No syllabic compression from C to CC

Simplex onset
(b) Syllabic compression from C to CC

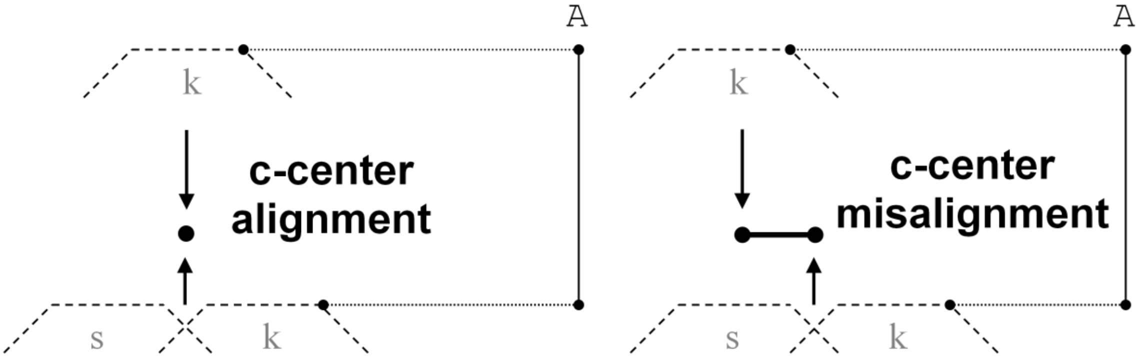


Under complex onset organization, syllabic shortening has the opposite effect on center to anchor interval stability. This is illustrated in Figure 10. The left panel, Figure 10a, shows the idealised version of the complex onset schema first introduced in Figure 2. In this schema, the c-center landmarks of #CVX and #CCVX are perfectly aligned. This alignment pattern underlies center to anchor interval stability. The right panel, Figure 10b, illustrates the effects of syllable shortening. This is indicated by the right edge to anchor interval, which is reduced in size in Figure 10b relative to Figure 10a. Syllabic compression reduces the duration of the center to anchor interval causing the c-centers of #CVX and #CCVX to be misaligned. Since the c-center landmark left-delimits the center to anchor interval, perturbations of the c-center across #CVX and #CCVX sequences reduce the stability of the center to anchor interval. We thus see that for complex onset syllables, the syllable compression reflected in the shortening of the right edge to anchor interval serves to degrade center to anchor stability.

Figure 10
Comparison of c-center alignment under a complex onset parse of #CVX and #CCVX in two conditions of syllabic compression. The left panel, (a), shows right edge to anchor durations expected of #*sVX* and #*skVX* without syllabic compression. The right panel, (b), shows a large decrease in right edge to anchor interval duration in #*sk*<u>*VX*</u> relative to #*k*<u>*VX*</u> due to syllabic compression. The length of the solid bold line indicates the difference between the c-center of [k] and [sk] serving as an index of center to anchor interval stability.

Complex onset
(a) No syllabic compression from #CVX to #CCVX

Complex onset
(b) Syllabic compression from #CVX to #CCVX

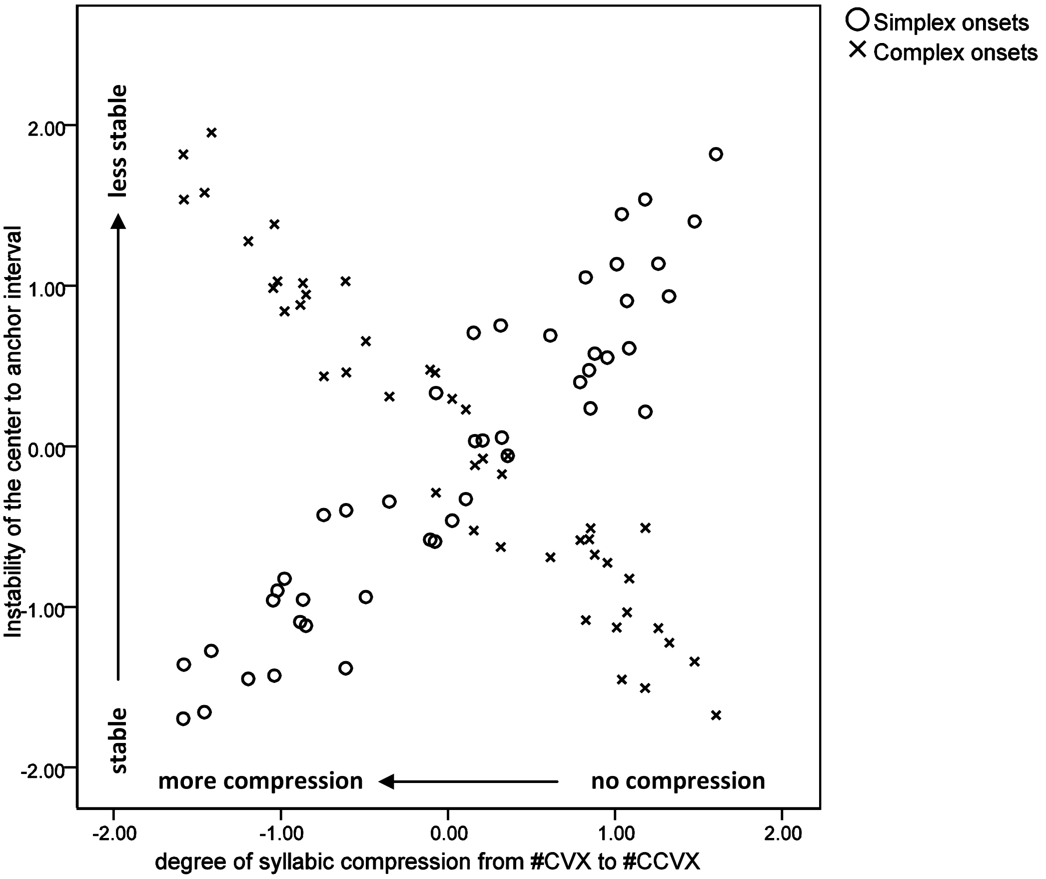


To check predictions of syllabic compression on simplex (Figure 9) and complex (Figure 10) onset organizations, we again conducted simulations. Word dyads, #CVX and #CCVX forms, were simulated using the same parameter values as before. On each run of the simulation, fifteen instances of #CVX and fifteen instances of #CCVX words were simulated. We ran the simulation fifty times. On each run, the duration of the vowel in #CC<u>V</u>X was systematically decreased. On the first run, it was drawn from the same distribution for both #CVX and #CCVX words. On each subsequent run, the duration of the vowel in #CCVX forms was decreased by 1 ms. Measurements of the simulated data are reported in Figure 11.

Figure 11 plots a normalized index of center to anchor interval (in)stability, *y*-axis, against a normalized index of syllabic compression, *x*-axis. As an index of compression, we subtracted the duration of the right edge to anchor interval in #CVX words from the duration of the right edge to anchor interval in corresponding #CCVX words. The right edge to anchor interval is a suitable index of compression since it delimits the period of open vocal tract, indicative of a vowel, and extends to the post-vocalic consonant. On this index, zero indicates the average amount of shortening in the simulation, negative numbers indicate larger degrees of shortening, and positive numbers indicate smaller degrees of shortening. As an index of center to anchor stability, we subtracted the duration of the center to anchor interval in #CVX words from the center to anchor interval in #CCVX words and report the absolute value of this difference. On this index, which was normalized by z-scoring, zero indicates the average level of instability across runs of the simulation, positive numbers indicate larger (greater than average) decreases in center to anchor stability and negative numbers indicate smaller (smaller than average) decreases in center to anchor stability.

Figure 11 shows that syllable compression has opposite effects on the two syllabic organizations considered. Under simplex onset organization center to anchor stability *improves* with syllable compression. Under complex onset organization, center to anchor stability *degrades* with syllable compression. If we focus on those dyads that have the most stable center to anchor intervals, values near -2.0 on the *y*-axis, we see that they come from both simplex and complex onset organization under different degrees of syllable compression. This confirms the predictions sketched in Figure 9 and Figure 10.

Figure 11
Scatter plot of phonetic parameters in data simulated under simplex onset organization, ‘o’s, and complex onset organization, ‘x’s. The *y*-axis shows an index of center to anchor stability and the *x*-axis shows an index of syllable compression. The index of center to anchor stability is the absolute value of the difference in center to anchor interval duration across dyads; the index of syllable compression is the degree of right edge to anchor interval difference across dyads.



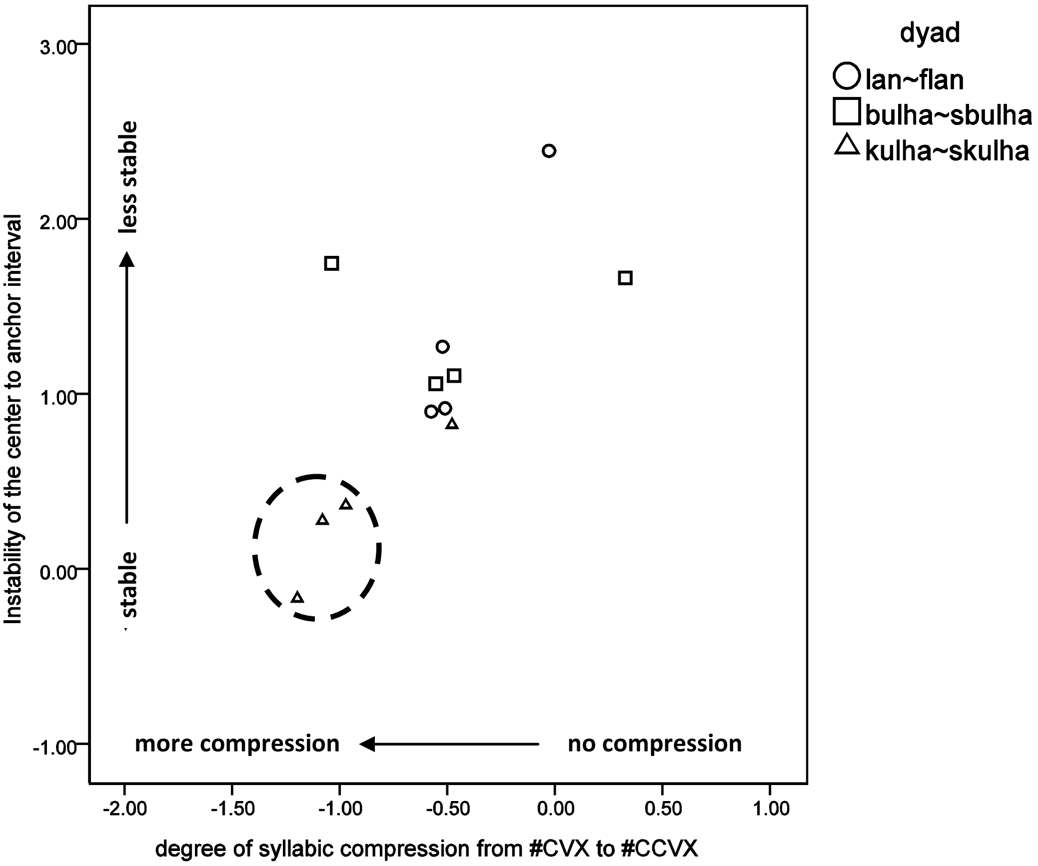
The main point illustrated in Figure 7 and Figure 11 is that syllabic compression accompanying the addition of a segment to a string may cause stability-based heuristics to break down. When compression applies to syllables with simplex onsets, the result is improved center to anchor interval stability. When compression applies to syllables with complex onsets, the result is either degraded center to anchor interval stability (when compression is localized in the rime) or no effect (when compression is localized in the syllable onset).

These results are important for two reasons. First, they show that syllable compression can invalidate certain stability-based heuristics for syllable structure. Specifically, center to anchor stability across #CVX and #CCVX, which has served as a heuristic for complex syllable onsets, can be a consequence of simplex syllable onsets when vowels, or other parts of the syllable, shorten.

The second, more constructive point is that the precise way in which syllable compression affects center to anchor stability depends on syllabic structure. We have seen that simplex and complex organizations make different predictions about the stability of the center to anchor interval. For simplex onset syllables, there is a specific relation between center to anchor stability and syllabic compression. As syllabic compression increases, center to anchor stability improves. For complex onset syllables, there is a different relation between syllabic compression and center to anchor stability. For complex onset organization, this relation depends on the locus of compression. Center to anchor stability is either degraded (Figure 11) or unaffected (Figure 7) by compression. Overall, then, the computational simulations tell us that variability in the stability-based indices is not random but structured in that each qualitative organization (simplex, complex) is characterized by a continuum of correlated values among different parameters. Different qualitative organizations (simplex, complex) can be distinguished because they structure variability in different ways.

We now return to our experimental data to verify the predictions from the computational model. For each combination of speaker and #CVX ~ #CCVX dyad in the corpus, Figure 12 plots for the experimental data the same indices of syllable compression and center to anchor (in)stability plotted for the simulations. The pattern is indicative of simplex syllable onsets. Compression improves center to anchor stability such that greater degrees of right edge to anchor compression, the ‘more compression’ range on the *x*-axis, go hand in hand with greater degrees of center to anchor interval stability. These two variables, right edge to anchor compression and center to anchor stability, are positively correlated ($r = .698$) and the correlation is statistically significant ($p = .012$).

Figure 12
Scatter plot of an index of center to anchor stability, *y*-axis, against an index of syllabic compression, *x*-axis: the index of center to anchor stability is the normalized difference in center to anchor interval duration across dyads; the index of syllable compression is the normalized degree of right edge to anchor interval difference across dyads. The dotted circle designates the "exceptional" data points, *kulha~skulha*, as produced by speakers A, B, and C.



Again, the data which exhibited the "exceptional" behaviour are not exceptions but rather direct predictions of simplex onset organization. The "exceptional" cases of center to anchor stability, contributed by productions of *kulha~skulha* by speaker A, B and C, are circled in the bottom left-hand side of Figure 12. The figure shows that this corner of the data is part of a well-behaved pattern. This pattern is a prediction of simplex syllable onsets and is, crucially, inconsistent with complex syllable onsets. Since the relation between syllable compression and center to anchor stability exhibited in our corpus is compatible only with simplex onset syllables, the presence of this relation supports this analysis of the data.

We conclude with a note on the relation between our model and our data. Although we have focused in this section on how scaling various parameters influences center to anchor stability, we could, in principle, study the effect of prosodic variation on any interval. For example, scaling the duration of the pre-vocalic consonant also makes predictions about changes in right edge to anchor interval stability. As a comparison of Figures 5 and 6 suggests, shortening the underlined consonant in #C<u>C</u>VX relative to #<u>C</u>VX has differential effects on right edge to anchor stability depending on syllabic parse. Under a complex onset parse, as shown in Figure 6, right edge to anchor stability improves with consonant shortening, i.e., the right edges of C and CC are more closely aligned in Figure 6b than in Figure 6a. Under a simplex onset parse, as shown in Figure 5, we see a different pattern. Right edge to anchor stability degrades with consonant shortening, i.e., the right edges of C and CC are more closely aligned in Figure 5a than in Figure 5b.We have verified through computational simulation that, in the absence of other modulations, the pattern of change in right edge to anchor stability as pre-vocalic consonant duration is scaled can distinguish syllabic parses, in the way described above for Figures 5 and 6. In our data, however, the effect of consonant shortening on right edge to anchor interval stability is cancelled out by syllabic compression, the second prosodic modulation we have observed. This cancelling takes place because, under a simplex onset parse, consonant shortening increases and syllabic compression decreases the right edge to anchor interval. Note that for the center to anchor interval, both consonant shortening and syllabic compression decrease the center to anchor interval. By focusing on center to anchor stability, as we have done in this section, we have chosen an interval that allows us to verify model predictions for consonant shortening and syllabic compression independently. This highlights an important point. There is a distinction between what can be studied with modelling and what can be evaluated in the data. Not all parameter modulations are equally revealing for a given data set. Informative use of the model – data relation requires dual consideration of the particular data set and model predictions. In our case, the structure of the data, segmentally matched CVX~CCVX~CCCVX triads, invites prosodic modulations that, under the hypothesis of simplex onset organization, bring out revealing patterns of change in the center to anchor interval.

### *4.3 From static to dynamic invariance*

In this section, we consider implications of our results for the relation between phonological organization and phonetic indices, a fundamental problem in spoken language research. The central point illustrated in the preceding two sections can be described as follows. Any given syllabic organization prescribes a range of possible stability patterns, which may overlap with the range of stability patterns from a different syllabic organization. For instance, we have seen that simplex onset organization is instantiated in our data in terms of right edge to anchor interval stability, as seen in the overwhelming majority of our data in Table 2, but also in terms of center to anchor interval stability, as seen in the data isolated in Table 3. From the perspective of the stability-based heuristics for syllable structure, the former stability pattern is considered as the canonical manifestation of simplex onset organization (Figure 2, left) whereas the latter stability pattern is considered as the canonical manifestation of complex onset organization (Figure 2, right).

What is the significance of such results for the classical question of how qualitative, phonological organization is instantiated in the continuous phonetics? We argue that our results require a change of perspective on this question from the view represented in Figure 2. Figure 2 states that the relation between phonological organization and phonetic indices is characterized by static invariance. According to the statically invariant view, the phonetic reflexes of different phonological organizations are fixed, as expressed in statements of the kind “simplex onsets surface with right edge to anchor stability”, “complex onsets surface with center to anchor interval stability” and so on. This is an attractive view because it makes strong predictions about the relation between phonology and phonetics.

We contrast the static invariance view with the alternative we put forward here, the dynamic invariance view. According to the latter, the reflexes of phonological organization need not be invariant. This seems like a retreat from the search for invariance or from a principled theory of the relation between phonology and phonetics. Simplex onset organization is manifest as right edge to anchor interval stability, in one set of circumstances, but also as center to anchor interval stability, in a different set of circumstances. This, however, does not mean that everything goes in the relation between phonological organization and phonetic indices. In fact, the dynamic invariance view is stronger than the static invariance view, because it offers predictions also in circumstances where the latter view ceases to be valid. In our data, we have seen that the static view ceases to make predictions when prosodic modulations affect the units (consonants and vowels) depicted in the schemas of Figure 2 or if it does make any predictions, these are demonstrably wrong because as we have seen the stability patterns can change. In contrast, the dynamic invariance view continues to make predictions also in these cases.

In the dynamic invariance view, any given phonological organization makes specific predictions about *the pattern of change* in the phonetic indices as parameters are scaled. Figure

7 and Figure 11 provide concrete examples. Figure 7 instantiates stability predictions of simplex onsets, *y*-axis, as prevocalic consonant plateau duration, *x*-axis, is scaled. The pattern of change shown in this figure is an invariant, because it speaks about a specific relation between two parameters. The individual parameters themselves are allowed to change, but their relation remains invariant, owing to the phonological organization they instantiate. Figure 11 also states a relation between stability predictions of simplex onsets, *y*-axis, as the parameter of syllable compression, *x*-axis, is scaled. As we have seen (Figure 11), simplex and complex onset organizations make different predictions about the form of the relation between these two parameters. When compression applies to syllables with simplex onsets, the result is improved center to anchor interval stability. When compression applies to syllables with complex onsets, the result is degraded center to anchor interval stability.

In short, qualitative phonological organizations impose constraints on the kinematics in the form of reciprocal relations between phonetic parameters. Invariance is to be found in the distinct relations or patterns of change prescribed by the different phonological organizations, rather than in static statements such as "simplex onsets surface with right edge to anchor stability" or "complex onsets surface with center to anchor interval stability".

## 5.0 Conclusion

Analysis of articulatory data on Moroccan Arabic consonant clusters revealed clear evidence for the claim that this language disallows complex syllable onsets. Beyond this result we explored how the natural prosodic variation found in the data interacts with phonetic heuristics for syllable structure.

We adopted at first the static invariance view, whereby fixed phonetic criteria are used to assess phonological structure. In past work, right edge to anchor stability has been used as a phonetic characteristic of syllables with simplex onsets and center to anchor stability has been used as a characteristic of syllables with complex onsets. These stability patterns reflect the predictions of canonical or simplified temporal organizations under the assumption that Cs and Vs maintain constant duration across #CVX, #CCVX, and #CCCVX sequences. In our data, these predictions were largely upheld. The same overall stability pattern (right edge to anchor interval more stable than center to anchor interval) emerged across speakers and across triads with different segmental content constituting both rising, e.g. *((k)f)lan*, and falling, e.g. *((m)s)kulha*, sonority profiles.

Through computational simulations, however, we demonstrated that the static invariance view can break down when the assumption of constant C and V durations is not met. Adding consonants to the word, i.e., adding *s* to *#kulha* to form *#skulha*, had the effect of compressing segment durations to varying degrees. This compression was reflected in a decrease in the right edge to anchor interval from #CVX to #CCVX, which was found for 11 out of 12 combinations of speaker and dyad, and a decrease in the duration of the prevocalic consonant in #CCVX relative to #CVX, which was found for 9 out of 12 combinations. Where these compression effects were strongest, in the *kulha~skulha* dyad produced by speakers A, B, and C, the center to anchor interval was more stable than the right edge to anchor interval. Thus, whereas in the majority of the data we found clear support for simplex onset organization, in this data subset, we saw a stability pattern that, from the static invariance perspective, is associated with complex onset organization. This case illustrated, in line with model predictions, how natural prosodic variation can lead to a breakdown of phonetic heuristics. The identification of such conditions is key to improving our understanding of the relation between phonological organization and the inherently variable and continuous phonetic signal.

We have put forward a new perspective on how phonological organization is instantiated in continuous phonetics, the dynamic invariance view, and we have shown how this view enables one to reliably diagnose phonological organization from variable phonetic data. Dynamic invariance, the persistence of reciprocal relations between phonetic parameters across variation in those parameters, made it possible to provide a unified phonological account of the data. Where static heuristics break down, relations persist between phonetic parameters that distinguish simplex onset organization from complex onset organization. We argued this point analytically, demonstrated it computationally and verified it in the experimental data.

In the new perspective, the natural prosodic variability in our experimental data becomes crucial in elucidating the relation between phonological organization and phonetic indices. It is only when we understand the effects of this variability that we can reliably infer phonological organization from phonetic data.

# References

Allen, J.S., J.L. Miller, & D. DeSteno. (2003). Individual talker differences in voice-onset-time. *The Journal of the Acoustical Society of America, 113*, 544.

Bombien, Lasse, Christine Mooshammer, Philip Hoole, & Barbara Kühnert. (2010). Prosodic and segmental effects on EPG contact patterns of word-initial German clusters. *Journal of Phonetics, 38*(3), 388-403.

Boucher, Victor. (1988). A parameter of syllabification for VstopV and relative-timing invariance. *Journal of Phonetics, 16*, 299-326.

Boudlal, Abdelaziz. (2001). *Constraint Interaction in the Phonology and Morphology of Casablanca Moroccan Arabic.* PhD dissertation, Mohammed V University, Rabat, Morocco.

Broselow, Ellen. (1992). Parametric variation in Arabic dialect phonology. In E. Broselow, M. Eid & J. J. McCarthy (Eds.), *Perspectives on Arabic Linguistics IV: Papers from the Fourth Symposium on Arabic Linguistics* (Vol. 4, pp. 7-45). Amsterdam and Philadelphia: John Benjamins.

Broselow, Ellen, Su-I Chen, & Marie Huffman. (1997). Syllable weight: Convergence of phonology and phonetics. *Phonology, 14*, 47-82.

Browman, Catherine P., & Louis Goldstein. (1988). Some Notes on Syllable Structure in Articulatory Phonology. *Phonetica, 45*, 140-155.

Byrd, Dani. (1995). C-centers revisited. *Phonetica, 52*, 285-306.

Byrd, Dani. (1996). Influences on Articulatory Timing in Consonant Sequences. *Journal of Phonetics, 24*(2), 209-244.

Byrd, Dani, & Susie Choi. (2010). At the juncture of prosody, phonology, and phonetics: the interaction of phrasal and syllable structure in shaping the timing of consonant gestures. In C. Fougeron, B. Kühnert, M. D'Imperio & N. Vallée (Eds.), *Laboratory Phonology* (Vol. 10, pp. 31-59). Berlin, New York: Mouton de Gruyter.

Byrd, Dani, Sungbok Lee, Daylen Riggs, & Jason Adams. (2005). Interacting effects of syllable and phrase position on consonant articulation. *Journal of Acoustical Society of America, 118*(6), 3860-3873.

Byrd, Dani, & Elliot Saltzman. (2003). The elastic phrase: modeling the dynamics of boundary-adjacent lengthening. *Journal of Phonetics, 31*, 149-180.

Byrd, Dani, Stephen Tobin, Erik Bresch, & Shrikanth Narayanan. (2009). Timing effects of syllable structure and stress on nasals: A real-time MRI examination. *Journal of Phonetics, 37*, 97-110.

Chitoran, Ioana, Louis Goldstein, & Dani Byrd. (2002). Gestural overlap and recoverability: articulatory evidence from Georgian. In C. Gussenhoven & N. Warner (Eds.), *Laboratory Phonology 7* (pp. 419-447). Berlin, New York: Mouton de Gruyter.

Davis, Stuart. (1990). Italian onset structure and the distribution of *il* and *lo*. *Linguistics, 28*, 43-55.

de Jong, Kenneth J., Byung-jin Lim, & Kyoko Nagao. (2004). The Perception of Syllable Affiliation of Singleton Stops in Repetitive Speech. *Language and Speech, 47*(3), 241-266.

Dell, François, & Mohamed Elmedlaoui. (2002). *Syllables in Tashlhiyt Berber and in Moroccan Arabic*. Dordrecht, Netherlands, and Boston, MA: Kluwer Academic Publishers.

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

Fudge, Erik. (1969). Syllables. *Journal of Linguistics, 5*, 253-287.

Gafos, Adamantios, Phil Hoole, Kevin Roon, & Chakir Zeroual. (2010). Variation in timing and phonological grammar in Moroccan Arabic clusters. In C. Fougeron, B. Kühnert, M. d'Imperio & N. Vallée (Eds.), *Laboratory Phonology* (Vol. 10, pp. 657-698). Berlin, New York: Mouton de Gruyter.

Gick, Bryan, Fiona Campbell, Sunyoung Oh, & Linda Tamburri-Watt. (2006). Towards universals in the gestural organization of syllables: A cross-linguistic study of liquids. *Journal of Phonetics, 34*(1), 49-72.

Goldstein, L. H., Hosung Nam, E. Saltzman, & I Chitoran. (2009). Coupled oscillator planning model of speech timing and syllable structure. In G. Fant, H. Fujisaki & J. Shen (Eds.), *Frontiers in Phonetics and Speech Science: Festschrift for Wu Zongji* (pp. 239-249). Beijing: Commercial Press.

Goldstein, L. M., I. Chitoran, & Elisabeth Selkirk. (2007). Syllable structure as coupled oscillator modes: evidence from Georgian vs. Tashlhiyt Berber., *XVIth International Congress of Phonetic Sciences* (pp. 241-244). Saabrucken, Germany.

Gordon, Matthew. (2002). A phonetically-driven account of syllable weight. *Language, 78*, 51-80.

Haggard, Mark. (1973). Abbreviations of consonants in English pre- and post-vocalic clusters. *Journal of Phonetics, 1*, 9-24.

Hardcastle, William, & Peter Roach. (1979). An instrumental investigation of coarticulation in stop consonant sequences. In H. Hollien & P. A. Hollien (Eds.), *Current Issues in the Phonetic Sciences* (pp. 531-540). Amsterdam: John Benjamins.

Hermes, Anne, Martine Grice, Doris Mücke, & Henrik Niemann. (in press). Articulatory coordination and the syllabification of word initial consonant clusters in Italian. In P. Hoole, L. Bombien, M. Pouplier, C. Mooshammer & B. Kühnert (Eds.), *Consonant clusters and structural complexity*: de Gruyter.

Hermes, Anne, Rachid Ridouane, Doris Mücke, & Martine Grice. (2011). Kinematics of Syllable Structure in Tashlhiyt Berber: The Case of Vocalic and Consonantal Nuclei, *International Seminar on Speech Production* (pp. 401-408). Montreal.

Honorof, Douglas N., & Catherine P. Browman. (1995). The center or the edge: how are consonant clusters organised with respect to the vowel? In K. Elenius & P. Branderud (Eds.), *XIIIth International Congress of Phonetic Sciences* (Vol. 3, pp. 552-555). Stockholm, Sweden.

Hoole, Phil, Susanne Fuchs, & Klaus Dahlmeier. (2003). Interarticulator timing in initital consonant clusters. In S. Palethorpe & M. Tabain (Eds.), *Sixth International Seminar on Speech Production* (pp. 101-106). Macquarie University: Sydney, Australia.

Hoole, Phil, & Andreas Zierdt. (2010). Five-dimensional articulography. In B. Maassen & P. H. H. M. van Lieshout (Eds.), *Speech Motor Control: New developments in basic and applied research* (pp. 331-349): OUP.

Hoole, Phil, Andreas Zierdt, & Christian Geng. (2003). Beyond 2D in articulatory data acquisition and analysis, *15th International Congress of Phonetics Sciences* (pp. 265-268). Barcelona, Spain.

Kahn, Daniel. (1976). *Syllable-based generalizations in English phonology*. PhD dissertation, MIT, Cambridge, MA.

Kim, Heejin, & Jennifer Cole. (2005). The stress foot as a unit of planned timing: Evidence from shortening in the prosodic phrase, *Interspeech* (pp. 2365-2368). Lisbon, Portugal.

Kiparsky, Paul. (2003). Syllables and moras in Arabic. In C. Féry & R. Vijver (Eds.), *The optimal syllable* (pp. 143-161). Cambridge: Cambridge University Press.

Klatt, Dennis H. (1973). Interaction between two factors that influence vowel duration. *Journal of Acoustical Society of America, 54*(4), 1102-1104.

Klatt, Dennis H. (1976). Linguistic uses of segmental duration in English: Acoustic and perceptual evidence. *Journal of Acoustical Society of America, 59*(5), 1208-1221.

Krakow, Rena A. (1989). *The articulatory organization of syllables: a kinematic analysis of labial and velic gestures.* PhD dissertation, Yale University, New Haven, CT.

Krakow, Rena A. (1999). Physiological Organization of Syllables: A Review. *Journal of Phonetics, 27*(1), 23-54.

Kühnert, B., P. Hoole, & C. Mooshammer. (2006a). *Gestural overlap and C-center in selected French consonant clusters.* Paper presented at the 7th International Seminar on Speech Production.

Kühnert, Barbara, Phil Hoole, & Christine Mooshammer. (2006b). Gestural overlap and C-center in selected French consonant clusters, *7th International Seminar on Speech Production* (pp. 327-334). Belo Horizonte, Brazil.

Lehiste, Ilse. (1972). The Timing of Utterances and Linguistic Boundaries. *Journal of Acoustical Society of America, 51*(6B), 2018-2024.

Marin, Stefania, & Marianne Pouplier. (2010). Temporal organization of complex onsets and codas in American English: Testing the predictions of a gesture coupling model. *Motor Control, 14,* 380-407.

Nam, Hosung. (2007). Syllable-level intergestural timing model: Split-gesture dynamics focusing on positional asymmetry and moraic structure. In J. Cole & J. I. Hualde (Eds.), *Laboratory Phonology 9* (pp. 483-506): Mouton De Gruyter.

Nittrouer, Susan, Kevin G. Munhall, J.A. Scott Kelso, Betty Tuller, & Katherine S. Harris. (1988). Patterns of interarticulator phasing and their relation to linguistic structure. *Journal of Acoustical Society of America, 84,* 1653-1661.

Perkell, Joseph S., Marc H. Cohen, Mario A. Svirsky, Melanie L. Matthies, Iñaki Garabieta, & Michael T. T. Jackson. (1992). Electromagnetic midsagittal articulometer systems for transducing speech articulatory movements. *Journal of Acoustical Society of America, 92,* 3078-3096.

Redford, M.A. (2008). Production constraints on learning novel onset phonotactics. *Cognition, 107,* 785-816.

Redford, Melissa A., & Patrick Randall. (2005). The role of juncture cues and phonological knowledge in English syllabification judgements. *Journal of Phonetics, 33,* 27-46.

Repp, B.H. (1982). Phonetic trading relations and context effects: New experimental evidence for a speech mode of perception. *Psychological Bulletin, 92*(1), 81.

Schöner, Gregor. (2002). Timing, clocks, and dynamical systems. *Brain and Cognition, 48,* 31-51.

Selkirk, Elisabeth. (1982). The syllable. In H. v. d. Hulst & N. Smith (Eds.), *The Structure of Phonological Representations* (Vol. Part II). Dordrecht: Foris Publications.

Shaw, Jason A., Adamantios I. Gafos, Phil Hoole, & Chakir Zeroual. (2009). Syllabification in Moroccan Arabic: evidence from patterns of temporal stability in articulation. *Phonology, 26*, 187-215.

Smith, B. L. (2002). Effects of Speaking Rate on Temporal Patterns of English. *Phonetica*, *59*(4), 232-244.

Sproat, Robert, & Osamu Fujimura. (1993). Allophonic variation in English /l/ and its implications for phonetic implementation. *Journal of Phonetics, 21*.

Strangert, Eva. (1985). *Swedish speech rhythm in a cross-language perspective*. Stockholm, Sweden: Almqvist & Wiksell International.

Surprenant, Aimée M, & Louis Goldstein. (1998). The perception of speech gestures. *Journal of Acoustical Society of America*, *104*(1), 518-529.

Tuller, Betty, & J.A.S. Kelso. (1991). The production and perception of syllable structure. *Journal of Speech and Hearing Research, 34*, 501-508.

Umeda, Noriko. (1977). Consonant duration in American English. *Journal of Acoustical Society of America, 60*, 846-858.

Waals, Juliette. (1999). *An experimental view on the Dutch syllable* (Vol. 18). Utrecht, Netherlands: LOT.

Wing, Alan M., & Alfred B. Kristofferson. (1973). Response delays and the timing of discrete motor response. *Perception and Psychophysics, 14*, 4-12.

Wright, Richard. (1996). *Consonant Clusters and Cue Preservation in Tsou.* PhD dissertation, UCLA, Los Angeles.

Zierdt, Andreas, Phil Hoole, & Hans G. Tillmann. (1999). Development of a system for three-dimensional fleshpoint measurement of speech movements, *14th International Congress of Phonetic Sciences* (pp. 735-738). San Francisco.

Zsiga, Elizabeth. (1994). Acoustic evidence for gestural overlap in consonant sequences. *Journal of Phonetics, 22*, 121-140.

Zuraw, Kie. (2007). The role of phonetic knowledge in phonological patterning: corpus and survey evidence from Tagalog infixation. *Language, 83*(2), 277-316.