Relations between speech rhythm and segmental deletion

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1 Introduction

This study investigates how the rhythm of speech influences the likelihood of segmental deletion. An important issue here is how speech rhythm can be measured, quantified, and distinguished from rate of speaking. For current purposes, "rhythm" is best conceptualized as *periodicity*, and should be understood in a pretheoretical, phonetic sense, as opposed to a grouping based upon metrical categories. The quantification of rhythm in this study uses a relatively new methodology that employs low-frequency Fourier analysis of the amplitude envelope of vocalic energy in speech (Tilsen & Johnson 2008). A phonetically-transcribed conversational English corpus was used to identify deletions of consonants and vowels.

While most prior work on speech rhythm has focused on general cross-linguistic differences, our objective here is to understand how local rhythms in a given utterance influence the likelihood of deletion. Yet the findings and methodologies of the cross-linguistic work provide us an instructive point of departure. Rhythmic typology has long been concerned with a distinction between stress-timed and syllable-timed languages (Pike 1945). Stress-timed languages (such as English and Dutch) purportedly exhibit more regularity in intervals between stressed syllables, while syllable-timed languages exhibit more regularity between successive syllables, regardless of stress. Abercrombie (1965) reformulated this distinction as the *rhythm class hypothesis*, proposing that interstress durations should be relatively less variable (more isochronous) in stress-timed languages, and vice versa for intersyllable durations in syllable-timed languages. However, there has been a general failure to find positive evidence for this distinction, or for any systematic cross-linguistic differences in isochrony of intersyllable and interfoot durations (Bolinger 1965; Lehiste 1977; Dauer 1983).

A different sort of analysis has been used by Ramus et. al. (1999) with some success. Their approach compares the ratios and variabilities of consonantal and vocalic interval durations in sentences read by speakers of various languages, and has been able to differentiate between syllable- and stress-timed languages. A plausible reason for the success of this approach may be found in the observation that syllable-timed languages tend to exhibit relatively less deletion, less vowel-reduction, and simpler syllable structure (Dauer 1983).

Both of the approaches described above rely on the same type of measurements, namely, interval durations. These interval-based approaches measure rhythmic properties using durations between syllables, stressed syllables, moras, and sequences of consonants and vowels. In all these cases the interval endpoints are defined by pre-conceived units, such as C, V, μ, σ, and Ft.

Importantly, these units are conceptualized as CONTAINERS, and the sizes (durations) of the containers represent their contribution to perceived rhythms. So doing, these methodologies ignore the contents of the containers, or endow them with abstract labels such as “consonantal” or “vocalic”. There are many phonological patterns that motivate linguistic units such as C, V, μ, σ, and Ft, but there is no *a priori* reason to believe these categories are the most relevant markers of rhythmic organization in speech. It is worth noting that in the acoustic speech signal alone, or in articulatory trajectories for that matter, these units and the intervals between them are not so well-defined. With that in mind, let us consider a very different approach to measuring rhythm.

2 Method

2.1 Low-frequency Fourier analysis of speech rhythm

Spectral analysis of speech rhythm relies much less upon interval durations than previous methods of analyzing rhythm. There are two main steps in this approach. First, the speech signal is transformed into a slowly-varying representation of vocalic energy in the signal, called the *vocalic energy amplitude envelope*. Fig. 1 illustrates this step with a 2.6 s stretch of speech in which a male speaker says “at least based on money raised it seems like…”. Fig. 1 (a) shows the vocalic-energy amplitude envelope superimposed over the bandpass-filtered signal, and Fig. 1 (b) shows the amplitude envelope over the original signal.

The amplitude envelope is obtained by lowpass-filtering (4^{th} order Butterworth, 10 Hz cutoff) the magnitude (absolute value) of the bandpass-filtered (1^{st} order Butterworth, 700-1300 Hz) original waveform. The 700-1300 Hz passband Butterworth filter (which has gradual roll-offs in the frequency domain) provides a fairly good representation of vocalic and sonorant energy in the signal, primarily by eliminating high frequency noise due to frication and low frequency energy due to F0. Cummins & Port (1998), following Scott (1993), used this passband to approximate p-centers, which are the locations of syllable beats (Allen 1972, 1975; Morton, Marcus, & Frankish 1976). The fact that such energy is relatively loud and perceptually salient makes it a good source of a continuous signal corresponding more closely to rhythmic percepts.

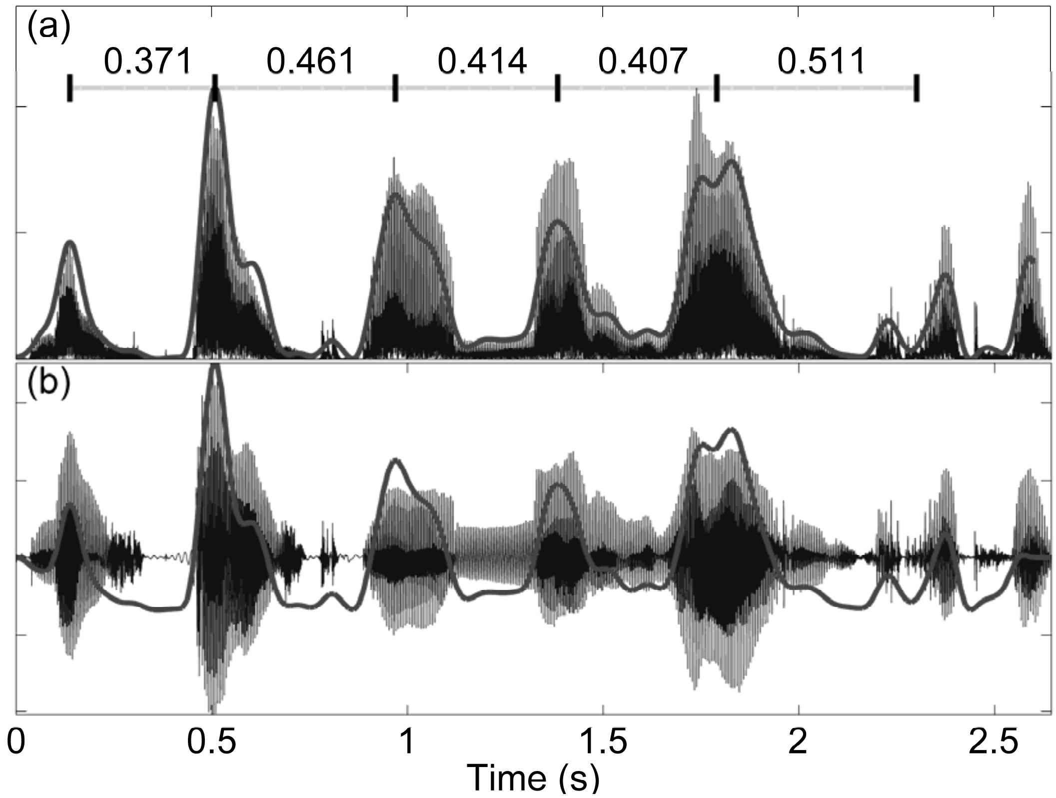

Figure 1: A 2.6 s stretch of speech in which a male speaker says "at least based on money raised it looks like…" (a) lowpass-filtered magnitude of bandpass-filtered speech signal (b) amplitude envelope superimposed over original waveform.

To prepare the amplitude envelope for Fourier analysis, the mean is subtracted and the signal windowed (Tukey, $r = 0.1$), as can be seen in Fig. 1 (b). Then after zero-padding to N samples and normalization to unit variance, a Fourier transform is applied. The result is a frequency-domain representation of the signal, where the variance of the time series has been partitioned into components of differing amplitude at N analysis frequencies. The normalization of the amplitude envelope carries through to the sum of the magnitudes of the Fourier coefficients, which follows from Parseval's Theorem (c.f. Chatfield 1975; Jenkins 1968). The power spectrum, which is the squared magnitude of the Fourier coefficients, reveals the contributions of various frequencies to the amplitude envelope.

Fig. 2 shows the power spectrum corresponding to the amplitude envelope of the utterance in Fig. 1. Notice that the intervals between peaks in the amplitude envelope cluster around 430 ms, and that this corresponds to a frequency of approximately 2.3 Hz in the power spectrum in Fig. 2. The higher the spectral peak, the more regular (periodic) the rhythm of the stretch of speech being analyzed. The location of the peak on the frequency axis (horizontal) indicates how quickly the rhythmic pattern recurs.

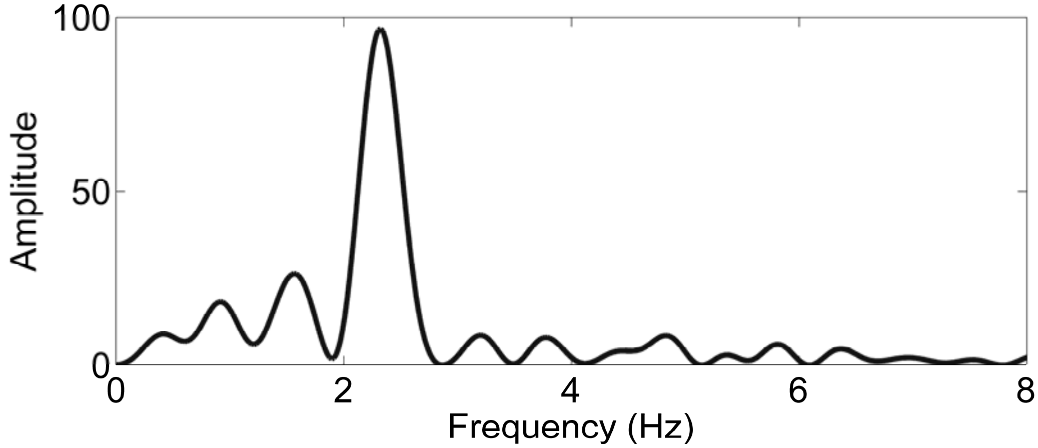

Figure 2: Power spectrum of the amplitude envelope in Figure 1.

The technique of Fourier analysis of speech amplitude envelopes is not a perfect method, one reason being that the signal is not of infinite duration. This causes sidelobes (smaller bumps) to be present in the spectrum. This is mitigated to some extent by cautious windowing. Note that Hamming windows and the like more drastically alter the shape of the utterance and may not be entirely appropriate. In general, only relatively high peaks in each spectrum should be taken to represent rhythmic characteristics of an utterance.

A fair argument can be made that the power spectrum is more appropriate for measuring rhythm than interval durations are. The spectral profile represents a wisdom of the crowd: each sample in the amplitude envelope contributes to the power spectrum. This constitutes a substantial departure from interval-based approaches, since no intervals need be defined (other than the interval of speech to analyze). Further details of this method can be found in Tilsen & Johnson (2008).

2.2 Buckeye Corpus

Speech analyzed for this study was taken from the Buckeye corpus (Pitt, Johnson, Hume, Kiesling, & Raymond 2005). The Buckeye corpus contains approximately 300,000 words of conversational speech between interviewers and 40 central native Ohio English speakers from a balanced set of ages and genders. Transcribers using acoustic and spectrographic information labeled the corpus with phonetic transcription. This allows for occurrences of deletions to be identified by comparison of the phonetic transcription to citation forms taken from a pronunciation dictionary.

Stretches of speech ranging uniformly in duration from 2-3 s were extracted from the corpus. Fig. 3 shows an example. The top panel shows the amplitude envelope and original signal, along with the citation, transcription, and deletions (in this case, the second vowel of "actually" and the first vowel of "Columbus" were deleted). The bottom panel shows the power spectrum (peaked line) against the average power spectrum for all 2-3 chunks (flatter line), and their 2.5 standard deviation region (filled).

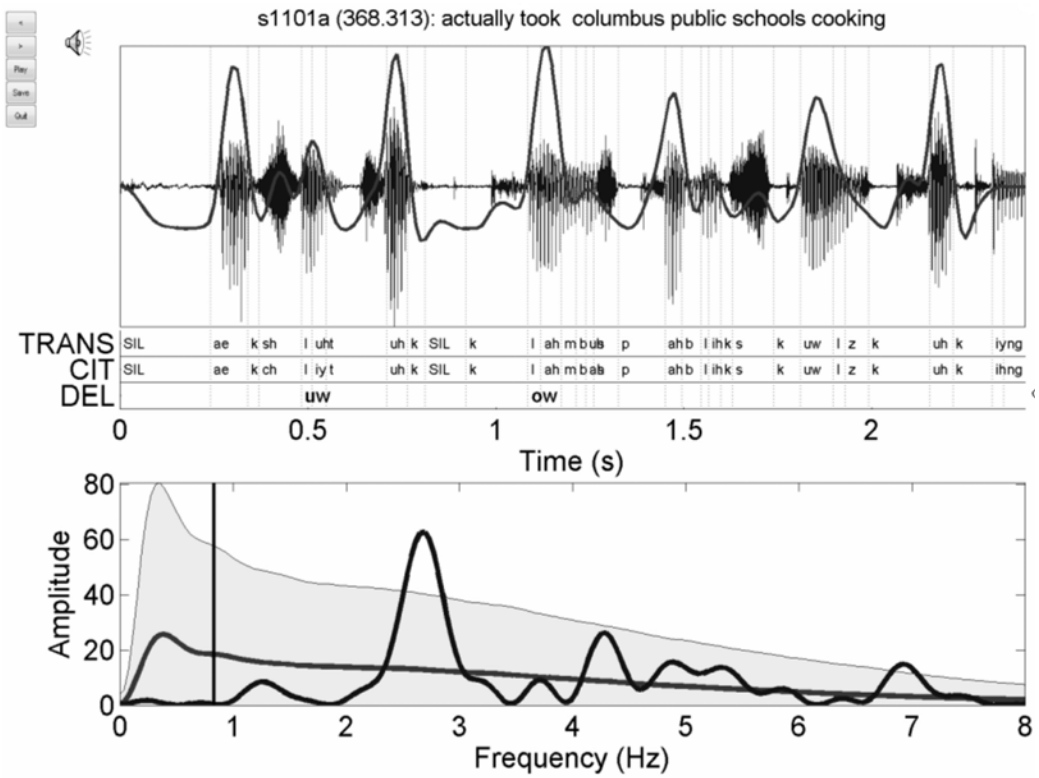

Figure 3: Example chunk of speech. (Top) waveform and amplitude envelope, along with citation, transcription, and deletions. (Bottom) Power spectrum (peaked line) against average (flatter line) and 2.5 standard deviation region (filled) for the entire corpus.

The vertical line in Fig. 3 is at twice the frequency corresponding to the duration of the chunk (for a 2.5 s chunk, this is 0.8 Hz). Spectral peaks below this line are not analyzed because they do not represent true periodicities in the signal, i.e. amplitude variations that occurred at least twice. These false peaks arise due to the zero-padding, which is necessary to achieve detailed frequency resolution. Note that the range of chunk durations analyzed should accord with the rhythms one intends to study: analysis of longer chunk durations reveals lower-frequency phrasal rhythms while blurring higher-frequency syllabic rhythms. The 2-3 s range of chunk durations used here were chosen because this range is suitable for analysis of syllabic rhythms that occur on the timescale of several metrical feet. Note that chunks in the deletion datasets are centered on the deletion, so that the amplitude envelope before and after the deletion location contribute approximately equally to the spectrum.

Not all deletions identified in the corpus occur with the same frequency. A fair amount of pseudo-deletions are attributable to overspecification of the citation form. Alternatively, some of these deletions may be categorical deletions subject to phonological rules. Here we are interested in phonetic deletions whose probability of occurrence is closer to chance. To avoid confounding categorical deletions with chance ones, only “active” deletions that occur between 25% and 75% of the time in their respective words are considered in the datasets below.

3 Analysis

The analysis of rhythmic patterns here uses a two-dimensional “rhythm space” in which the frequency and amplitude values of the highest peak from each spectrum are plotted. This provides a 2-dimensional histogram, which is transformed into a density distribution using a Gaussian kernel density estimator. Fig. 4 shows two such density distributions in rhythm spaces, for consonants (left) and for vowels (right).

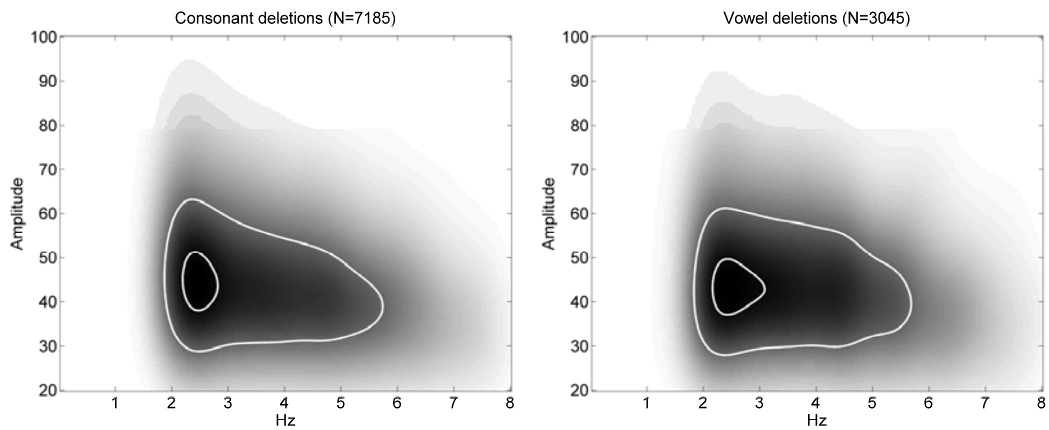

Figure 4: Density distributions of amplitude/frequency values of the highest spectral peaks in each chunk. (Left) consonant deletions, (right) vowel deletions.

The density distributions in Fig. 4 indicate that the amplitude values of the highest peaks taken from each spectrum in the deletion datasets cluster around 40-50 normalized amplitude units, and the frequency values range from 2-6 Hz. White lines show 50% and 90% density contours. The distributions are more useful analytic tools when compared to other density distributions. They are particularly revealing when compared to the density distribution for a set of spectra taken from chunks without a deletion, as in Fig. 5.

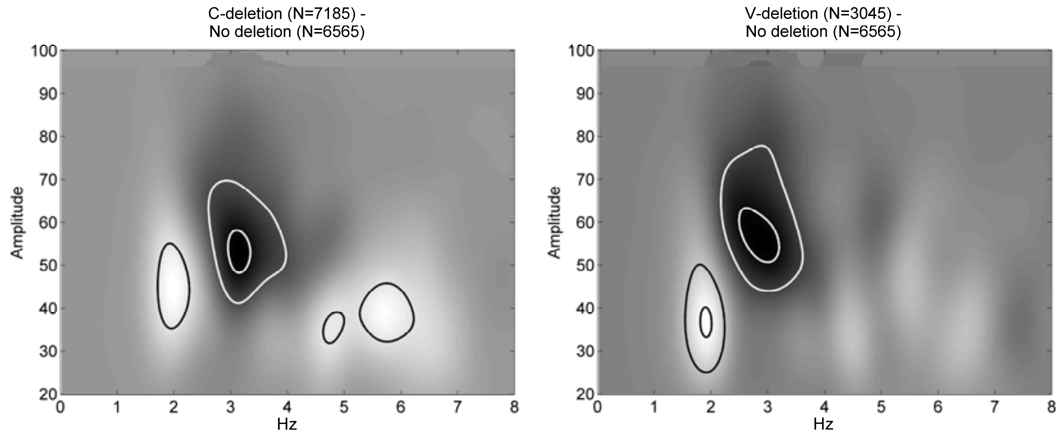

Figure 5: Frequency-amplitude peak density differences between the no-deletion subject and the consonant (left) and vowel (right) deletion subsets. Light areas indicate a relative predominance of peaks from chunks with deletion, dark areas a predominance of no deletion. Lines trace 50% and 95% density difference contours.

Fig. 5 shows that C-deletion is associated with low frequency (2 Hz) and high frequency (5-6 Hz) rhythms. V-deletion is strongly associated only with low-frequency rhythms. The light areas indicate a statistical predominance of spectral peaks taken from chunks with a deletion, and dark areas indicate a predominance of no deletion (the absence of deletion, i.e. *preservation*). The figure shows that segmental preservation is associated with high-amplitude rhythms in the 2.5-3.5 Hz range.

It is convenient to use linguistically meaningful labels to refer to frequency ranges, even if there is a fair degree of arbitrariness in the definition of those ranges. For example, one can say that both C- and V-deletion tend to occur relatively more frequently in chunks with a dominant rhythm on the slow foot (1-2.2 Hz) timescale. C-deletion also tends to occur more frequently on the fast syllable (4-6 Hz) timescale. Preservation tends to occur more commonly on a fast Ft (2.2-3.5 Hz) and slow syllable (3-4 Hz) timescales.

The existence of a region of the rhythm space where spectral peaks from no-deletion chunks are relatively more prevalent suggests that there may exist a sort of "stability zone" in which segmental deletion becomes less likely, perhaps due to increased stability in timing of articulatory gestures. We will speculate on explanations for this and other patterns later on.

The analysis of Fig. 5 does not take into account one important consideration mentioned earlier: namely, that we must distinguish speech rate from speech rhythm. In order to accomplish this, deletion and no deletion data subsets were constructed in which only chunks where speech rate (syllables per second) is within one standard deviation of the mean speech rate (calculated over all datasets). This ensures that all speech considered will be within a very normal range, and makes the amplitude dimension of the rhythm space more meaningfully represent periodicity.

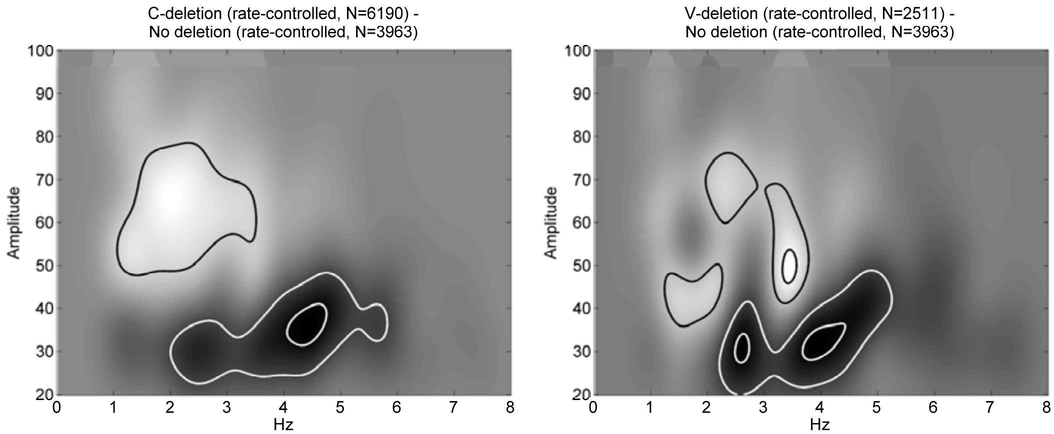

Figure 6: Frequency-amplitude peak density differences between rate-controlled (± 1 s.d.) no-deletion subset and the consonant (left) and vowel (right) deletion subsets. Light areas indicate a relative predominance of peaks from chunks with deletion, dark areas a predominance of preservation (no deletion). Lines trace 50% and 95% density difference contours.

The rate-controlled density differences in Fig. 6. show a markedly different pattern than that of Fig. 5. Here we see that consonant deletions are associated with high-amplitude peaks in the slow-foot and fast-foot ranges (1-3 Hz). Vowel deletions are associated with higher-amplitude peaks (i.e. more periodic rhythm) in the slow-syllable range (3-4 Hz) and to a lesser extent in the fast-foot timescale (2-3 Hz). Preservation of both types of segments is more likely to occur with lower amplitude peaks (i.e. less periodic rhythms). This means that the effect of periodicity on consonant and vowel deletion is frequency-dependent, and this dependence differs between consonants and vowels. To wit, C-deletion is more strongly associated with foot timescale rhythms, and V-deletion is more strongly associated with slow-syllable rhythms.

4 Discussion

In this section, several accounts of the above results will be considered. A sufficient justification of the background for these hypotheses is beyond our scope, so to fully understand the basis of the accounts the reader may find it helpful to consult some of the references. The main findings from above are reiterated below:

(1) In data not controlled for speech rate, there exists a frequency range in the rhythm spectrum—corresponding to fast Ft-timing—where deletion is less likely.

(2) In rate-controlled data, more rhythmic speech contains more deletion.

(3) Consonants and vowels differ with regard to (2). C-deletion is more strongly associated with high-amplitude rhythms in the Ft-timescale, while V-deletion is more strongly associated with high-amplitude rhythms in the slow-syllable timescale.

The first finding is somewhat difficult to interpret due to the lack of control for speech rate. Highly rhythmic speech in the fast foot and slow syllable timescales was strongly associated with preservation of segmental articulations. Without controlling for rate, we cannot know if the relative absence of deletion at those frequencies is due merely to high propensities for deletion in very slow, perhaps disfluent speech, as well as in very fast, hypoarticulated speech. In other words, rhythmicity (periodicity) and speech-rate may be confounded and no strong conclusions can be drawn. Indeed, if one takes the view that the patterns are due specifically to speech rate, then preservation may occur in the midrange of frequencies precisely because very slow speech is disfluent and very fast speech is hypoarticulatory.

The second finding raises an important question: why is rhythmicity associated with deletion? One account involves a hypothesized interaction between rhythm and gestural phasing. This account can be best understood in the framework of task dynamics using concepts of dynamical systems theory. It posits that rhythmic and gestural timing are both regulated by systems of synchronized coupled oscillators, and further assumes that rhythmic systems interact with gestural systems through coupling. On occasion this has the effect of producing *rhythmically-driven gestural overlap*. This explanation is inspired, on the one hand, by work on rhythmic timing which has successfully incorporated the concept of dynamic coupling to explain observed patterns between syllables, feet, and phrases, and on the other hand, by work on gestural dynamics which has likewise captured observed temporal patterns.

In the rhythmic domain, Cummins & Port (1998), in a metronome-driven phrase repetition task, found evidence for biases in production toward low-order harmonic ratios of intervals between stressed syllables and phrases, as well as increased variance of rhythmic timing with more difficult (less harmonic) metronome rhythms. Cummins & Port showed how these patterns can be modeled with a coupled system of a phrase and foot oscillator. Likewise, O'Dell & Nieminen (2000) modeled temporal patterns of foot duration in stress- and syllable-timed languages using a system of coupled oscillators, one corresponding to feet (inter-stress intervals), the other corresponding to syllables—the parameter they manipulated to simulate empirical duration patterns was the degree of coupling between these two oscillators. Hence there is precedent for understanding rhythmic patterns as arising from dynamical systems.

In the gestural domain, intergestural timing patterns such as the c-center effect (Browman & Goldstein 1988, 1990), have been argued to arise from competing lexical specification of relative phasing (Browman & Goldstein 2000), and have been modeled with a system of coupled oscillators (Saltzman & Nam 2003). Such models use stabilized relative phases to determine the relative timing of gestural trajectories as described in the task-dynamic model of Saltzman & Munhall (1989). For current purposes, it is convenient to assume that segmental deletions (the active ones considered here) arise from a substantial overlap of gestures. Hence to understand correlations between deletion and rhythm we need a mechanism that increases the likelihood of gestural overlap that is substantial enough to result in the perception of deletion.

With dynamical models of rhythmic and gestural systems, it becomes possible to construct a model which integrates the two domains. A key aspect of such a model is multifrequency coupling (Saltzman & Byrd 2003). There are several logical possibilities in such a model. First, there may exist no interaction between rhythmic and gestural systems—in which case we would expect no correlations between rhythmicity and likelihood of deletion, assuming no other mechanism of rhythmic-gestural interaction is present. A second possibility is that rhythmic systems drive gestural systems, in which case rhythm should affect gesture, but not vice versa. The third possibility is the reverse: gestures drive rhythms. A fourth possibility is that rhythmic and gestural systems mutually interact. The interactional forces could be symmetric or nearly symmetric, or dominated by systems in one or the other domain.

The observed correlation between rhythmicity and deletion in the corpus data can be understood in the following way. Assume that rhythmic systems drive gestural ones—which means that there are forces which compel gestural systems to synchronize in-phase with syllables and feet. Lexical specifications between gestures work against these forces, by compelling adjacent gestures to synchronize in an anti-phase relation. Stochastic noise, transient perturbations, and contextual influences can subvert the intergestural phase specifications, especially if driving forces exerted by rhythmic systems on gestural systems become stronger. So, if one assumes that rhythmo-gestural interactional forces increase when speech is more rhythmic (i.e. when inter-rhythmic coupling forces are stronger), then gestures would be more likely to overlap. In other words, more rhythmic speech exhibits more gestural overlap, resulting in more deletion.

A different account of the deletion-rhythm correlation employs the hypothesis that transcribers were perceptually biased to perceive deletion in more rhythmic speech. It is not inconceivable that given some indirect and non-causal rhythm-deletion association, listeners expect more deletion in more rhythmic speech. In that case, given acoustically similar sequences of segments, the sequence in a more rhythmic context is more likely to be transcribed without a segment.

While this *perceptual bias* hypothesis cannot be rejected outright, there are several reasons to be suspicious of its validity. For one, the transcribers were trained to use visual spectrographic information, which may mitigate against their expectations based purely upon auditory information. Moreover, the effect of any such bias is unlikely to be large enough in magnitude to account for the full extent of the patterns.

A third account views speech rhythmicity as an emergent quality that arises from segmental deletion. There are two versions of this *emergent rhythmicity* hypothesis. In the teleological version, speakers employ deletion in order to make their speech more rhythmic, perhaps for stylistic reasons. In the non-teleological version, segmental deletion occurs randomly, and the effect of it happens to be more rhythmic speech. In both cases, some mechanism is needed to understand *why* the effect of deletion would be more rhythmic speech.

This mechanism may be comprehensible again in a dynamical framework. However, in this account, gestures drive rhythmic systems (or exert a stronger, asymmetric influence on them). Because the gestures are often anti-phase synchronized, their interactional forces upon rhythmic systems will have competing effects. These competing forces will induce greater variability in the timing of syllables and feet. The reasoning behind emergent rhythmicity is as follows. Segmental deletions arise from complete or extensive overlap of gestures, which occurs because the gestures have become in-phase synchronized (for whatever reason). In-phase synchronized gestures exert more coherent coupling forces on rhythmic systems, which means that the relative timing of those systems will be less variable—hence more rhythmic.

Both the rhythmically-driven gestural overlap account and the emergent rhythmicity account utilize concepts from dynamical systems theory, but differ with regard to whether gesture or rhythm is considered responsible for the observed correlations between deletion and rhythmic speech. It is possible, but perhaps more difficult to articulate, that both effects exist simultaneously.

The third finding of this study was that consonant and vowel deletion were differently affiliated with rhythmic frequency. Caution should be exercised in interpreting this pattern, because of inhomogeneity in the dataset. For example, some vowel deletions correspond to the loss of a syllable, while others are offset by the syllabification of a following liquid or nasal. Likewise, some consonant deletions result in vowel hiatus, others occur phrase-finally, and various effects on syllable structure can result from such deletion. The diversity of these deletion patterns calls into question any account which distinguishes only between consonants and vowels.

5 Conclusion and future directions

Using spectral analysis to characterize speech rhythm, we have seen that there are strong tendencies for deletion to occur more often in more rhythmic speech. This is an important finding because it implies that rhythm and articulation interact. It is incumbent upon speech researchers to understand the nature and causes of this interaction.

There are some limitations on understanding deletion patterns in the current study, which derive from the inhomogeneity of deletion. There are a couple ways in which future corpus analyses might remedy this problem. One is to study rhythmic differences between deletion/non-deletion on a word-by-word basis, which introduces a much higher degree of control over type of deletion.

Preliminary single-word analyses have unexpectedly revealed remarkably different rhythm-space distributions of deletion in different words; however, sample sizes were small—for this approach to be fruitful a large corpus is required. A different technique is to simulate deletion by removing a vowel from the signal, or to epenthesize a vowel where a deletion occurred.

There is also room for refinement of spectral analysis techniques for measuring rhythm, which may improve our ability to conduct studies of the sort reported here. That said, this work has demonstrated the utility of rhythm spectrum analysis and illuminated a set of issues and directions of research that will hopefully lead to a better understanding of speech rhythm and gesture.

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