Limit Cycle Dynamics in Prosody

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Abstract: Two experiments demonstrate the emergence of rhythmic patterns in speech. Each places co-ordinative demands on the speaker. The speaker's response is to establish a stable limit cycle coextensive with the stress foot.

RHYTHM NARROWLY DEFINED

When rhythm and language are mentioned together, the former typically refers only to an alternating series of relatively strong and weak elements. For cardiologists and jugglers, however, rhythm is essentially concerned with temporal intervals as well as relative prominence. A rhythmic heartbeat is not only a succession of pumping or electromyographic events, these events must happen at precisely the right time, as dictated by the biomechanical and hydrodynamic properties of heart and blood. Felicitous juggling is constrained not only by a sequence of catches and throws, but by the dynamics of hands and balls under the influence of gravity.

Rhythm in this strict temporal sense is manifestly a vehicle for coordination, defined as actions or processes properly combined for the production of one result (OED). The "proper combination" implies a constraint on temporal organization, or in mathematical terms, a dynamic. Models which exhibit limit cycle dynamics provide an appropriate class with which to describe relative timing in rhythmic patterns. Minimally, a limit cycle dynamic provides a measure of phase, allowing the specification of the timing of events with respect to the repeating cycle. Establishment of a reference cycle allows the construction of patterns in which relative timing is specified independently of absolute time. This allows a pattern to remain essentially invariant across changes in absolute rate. Rhythm facilitates coordination.

By these standards, speech is usually thought of as marginally rhythmic, if at all. The laboratory investigation of articulator organization has sometimes turned to syllable repetition tasks to study relative timing, but measures of more natural speech do not show the tight temporal organization found in heart cells or jugglers' hands. Proportional timing is not found across all speech rates (1). Here we summarize two experimental tasks which place considerable coordinative demands on speakers. Under these conditions, the temporal organization of speech at a macroscopic level is revealed by the emergence of rhythm in the strictly temporal sense.

SPEECH CYCLING

In a speech cycling task, subjects listen to an auditory metronome and attempt to repeat a phrase in time with the signal, aligning syllable onsets with tones or clicks. In one experiment, 8 subjects repeated phrases such as beg for a dime in time with a stimulus (2). The stimulus provided one repeating tone to cue phrase onsets (beg) and one repeating tone for the final stressed syllable (dime). The relative timing of dime with respect to the succession of phrase onsets was experimentally varied over a wide range of possible values. All subjects reliably produced just three simple rhythmic patterns. The three patterns are illustrated using musical notation in Figure 1.

![Figure 1](image_url)

FIGURE 1. Three rhythmic patterns produced when subjects repeat beg for a dime along with a metronome.

Each pattern arises from the nesting of two or three prosodic units (stress feet) within the overall repetition cycle. In the first pattern, the interval from (the vowel onsets of) dime to beg is twice as long as the interval...
from beg to dime, suggesting a silent stress foot cycle at the end of the phrase. In the third pattern the stress feet are constituted differently, with a nonce stress falling on for. These three patterns are the only stable patterns produced by subjects in this task. They reveal strong constraints on the form of temporal organization available to speakers as they respond to macroscopic coordinative demands. The nesting of an integral number of feet within the phrase repetition cycle reveals the coupling between two limit cycles, one coextensive with the stress foot, the other delimited by successive phrase onsets.

**RAPID SPEECH**

In another experiment, subjects were asked to repeat a short text at a wide variety of rates (3). A sample text is *Didn't he say painful SHOT? The message was painful BLOW. Surely that's not what he said!* The capitalized syllables were given contrastive emphasis. The second sentence of each text contained the foot *message was*, and the reciprocal of the duration of this foot was used as an index of articulatory rate (“feet-per-second”). In order to assess any tendency towards isochrony, the duration of the final foot of the second sentence was compared to the duration of the preceding foot by taking their ratio. In the above example the feet are delimited by the vowel onsets of pain, blow and surely and the index of isochrony is the ratio of the second duration to the first. The numerator term includes any pause which may be inserted between the second and third sentences.

![Figure 2](image-url)  
**FIGURE 2.** Ratio of successive foot durations. Fast speech is to the right. A cubic spline illustrates the local trend.

Figure 2 shows this ratio for 180 utterances of a single speaker. This speaker is notable for producing a great range of articulatory rates, including some extremely rapid productions. It is obvious that the high variability of the ratio at slower rates disappears at the fastest rates, where it converges to unity, indicating isochrony. This effect is found only at very fast articulatory rates and evidences a coordinative strategy whereby a fixed rhythmic structure emerges to facilitate the precise timing of rapid gestures.

Each of these experiments places unusual coordinative demands on subjects. Whether trying to simultaneously align two distant points within a repeating cycle, or trying to speak as rapidly as possible, speech production becomes rhythmically constrained. The emergence of a limit cycle dynamic at the stress foot level provides a temporal grid which appears to facilitate coordination.

**REFERENCES**