Intonational tunes as compositional, but autonomous, dynamical objects

Variance and Invariance Workshop

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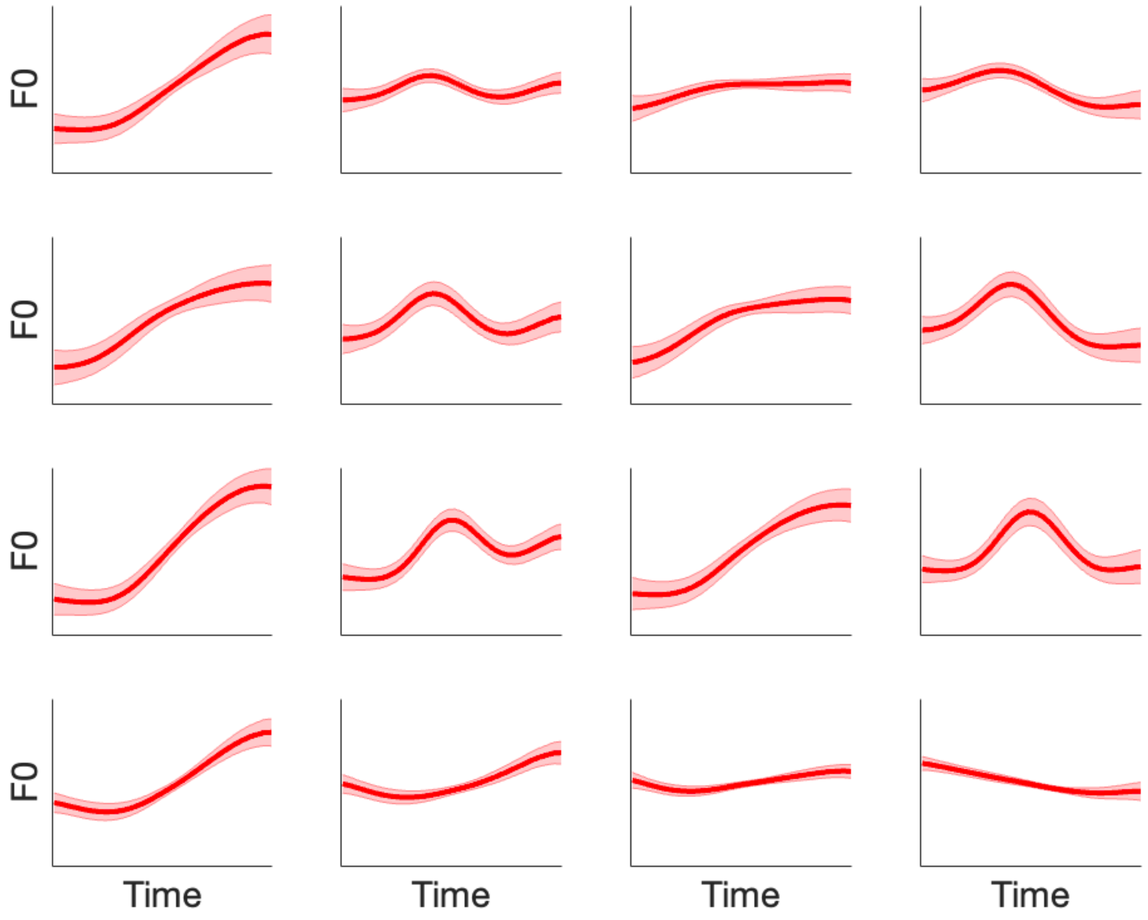
Variance-Invariance

Chao, Pike, Bolinger, others:

There is **a pattern** to the variable pitch events in the languages of the world, e.g., towards the ends of AE utterances, *nuclear tunes*.

Desire for a **grammar**: A simple **invariant** mechanism from which the time-varying tunes emerge from some specification.



AE tunes from Northwestern database

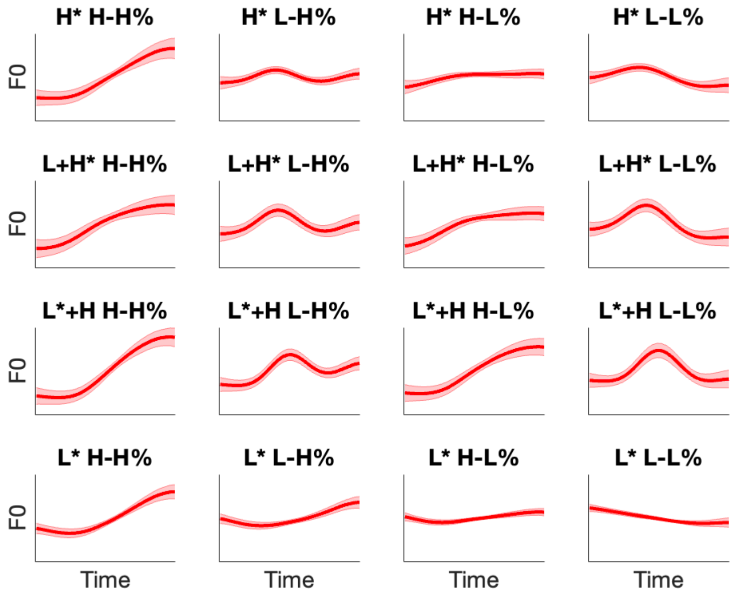
Structuralist Postulates and AM Phonology

Bloch (1948)

53.3. Corollary. A phoneme is a class of events.

Postulate 55. In any phrase, the phonemes occur in a particular order.

High pitches are variable in and across tunes, but they belong to one invariant *class*, H; so also for L. The birth of H, L.



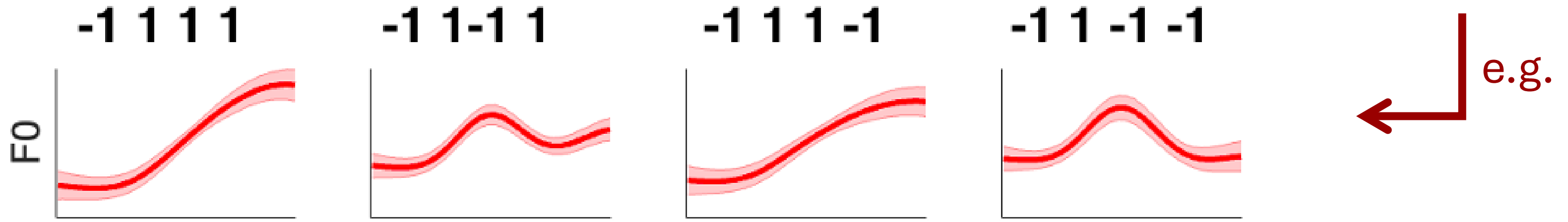
Goldsmith (1975)
Liberman (1976)
Bruce (1978)
Pierrehumbert (1980)

Pitch accents, phrase accent, boundary tone as local events in Bloch-order that compose to form a tune. An F0 Algorithm generates trajectory from the phonemes in order.

Dynamical Approach to Invariance

Fowler et al (1980)
Browman and Goldstein (1989)
Saltzman and Munhall (1989)

- Linguistic Variance and Invariance are an instantiation of motor variability (Variable tunes) + “equifinal” target achievement (Contrast).
- H, L → Constant targets of a *stable Equi* DS
- Equi DS’s executed in Bloch-Order via a **Task Dynamics** that *solves* this string of potentially overlapped systems for a predicted F0 trajectory



Claim: **Invariant** linguistic F0 patterning emerges from a general approach to motor control, dynamical systems

Problem 1: Targets H, L as input vs. *output*

Pierrehumbert & Pierrehumbert (1990)

Come on guys… Task Dynamics is just an interpolation algorithm, given H (1),L (-1) sequence, generate F0!

For *emergence* of a trajectory from a truly invariant dynamical account, H and L should be in the *output*… For TD, they're in the *input*.

A dynamical system that *predicts* linguistic structuring should not *postulate* that structure, targets and Bloch-order (anti-phase)

Problem 2: *Lessen* loan on intelligence

Perrier et al. (1988) | True trajectories of task change are more complex in their time-variability than predicted by stable equilibrium linear 2nd order dynamical systems.

Byrd & Saltzman (1998) | *Nonautonomous* approach: The linear equations should have in them time-varying components, designed by the intelligent researcher, that make the solution conform to reality.

Sorenson & Gafos (2016) Tilsen (2022) | *Autonomous* approach: An explanatory dynamic is *autonomous:* it predicts complex time-variation through feedback *from system state to system dynamics,* not a time-varying force from the researcher. So one or more coefficients now depends on the state, hence *nonlinearity*.

Our Aim: An autonomous tune

Step 1: Kinetic approach to targets

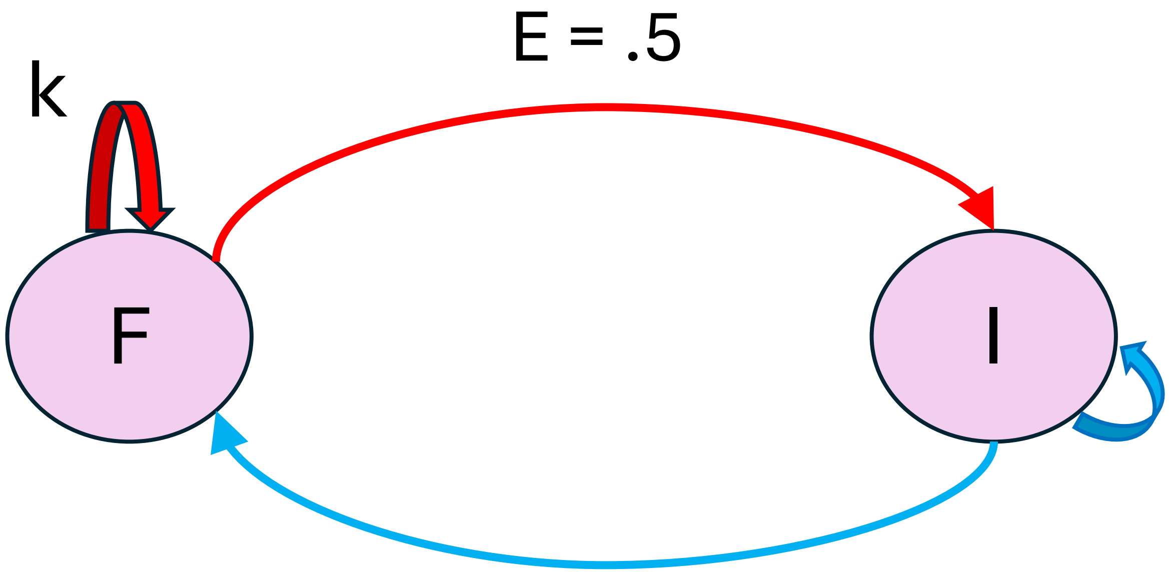
Iskarous, Cole, and Steffman (2024) advanced a dynamical model of the pitch accent part, which in AM include H*, L+H*, L*+H, L*, from which H and L are claimed to *emerge* from an embodied dynamics (Simko and Cummins, 2010).

- There are 2 dynamical variables:

  F: *pitch setting forces on laryngeal muscles*

  I: *pitch inhibiting forces on laryngeal muscles*
- The two variables dynamically interact, kinetically, in a circuit, conditioned by the phonology of a language
- Parametric kinetics of interaction lead to pitch accents (cf. Goldsmith, 1994).

The Kinetics



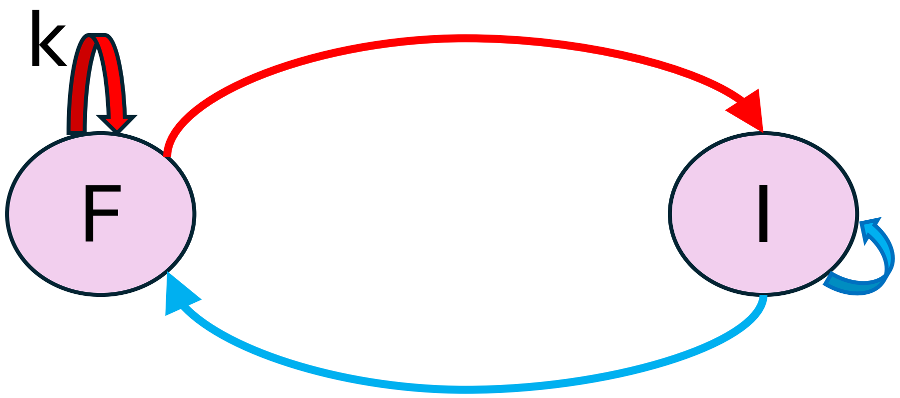
- **F** makes itself grow by a coefficient k
- **F** excites ***I by constant E***
- **I** inhibits **F** and itself

$$\frac{dF}{dt} = kF - F^3 - I + .5$$
$$\frac{dI}{dt} = EF - I$$

- **Read:**
  - **Slope of F is a function of F through a phonological constant k, I, and a constant energy source.**
  - **Slope of I is a function of F & I.**

<u>The true F0 trajectory is the One that conforms most to this dynamic *at every single point in time*</u>

Predictions of the Kinetic Theory



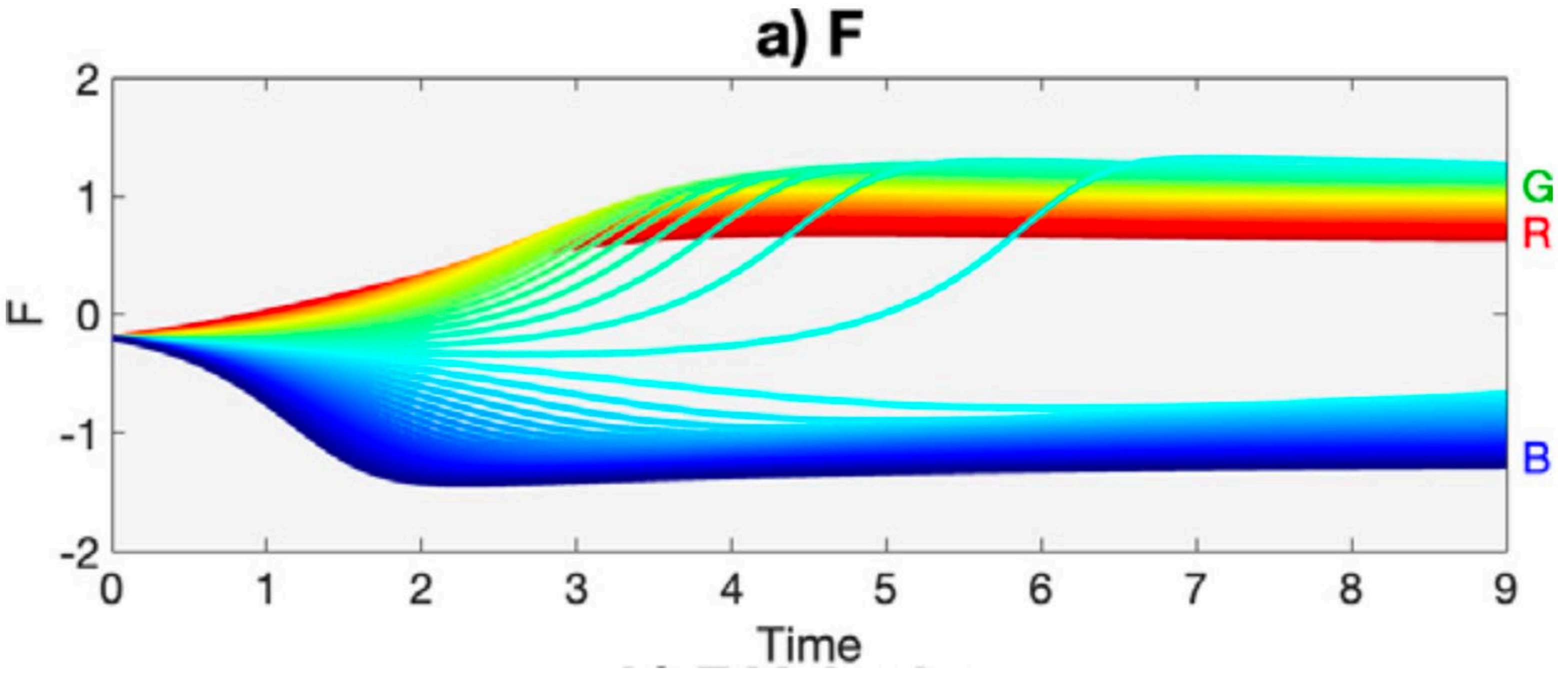
When k is phonology-fixed, we get one optimal *F-trajectory*, here color-coded by k from lowest (red) to (highest).

H*: **k ~ .5**

L+H*: **k ~ 1**

L*+H: **k ~ 1.5**

L*: **k ~ 2**

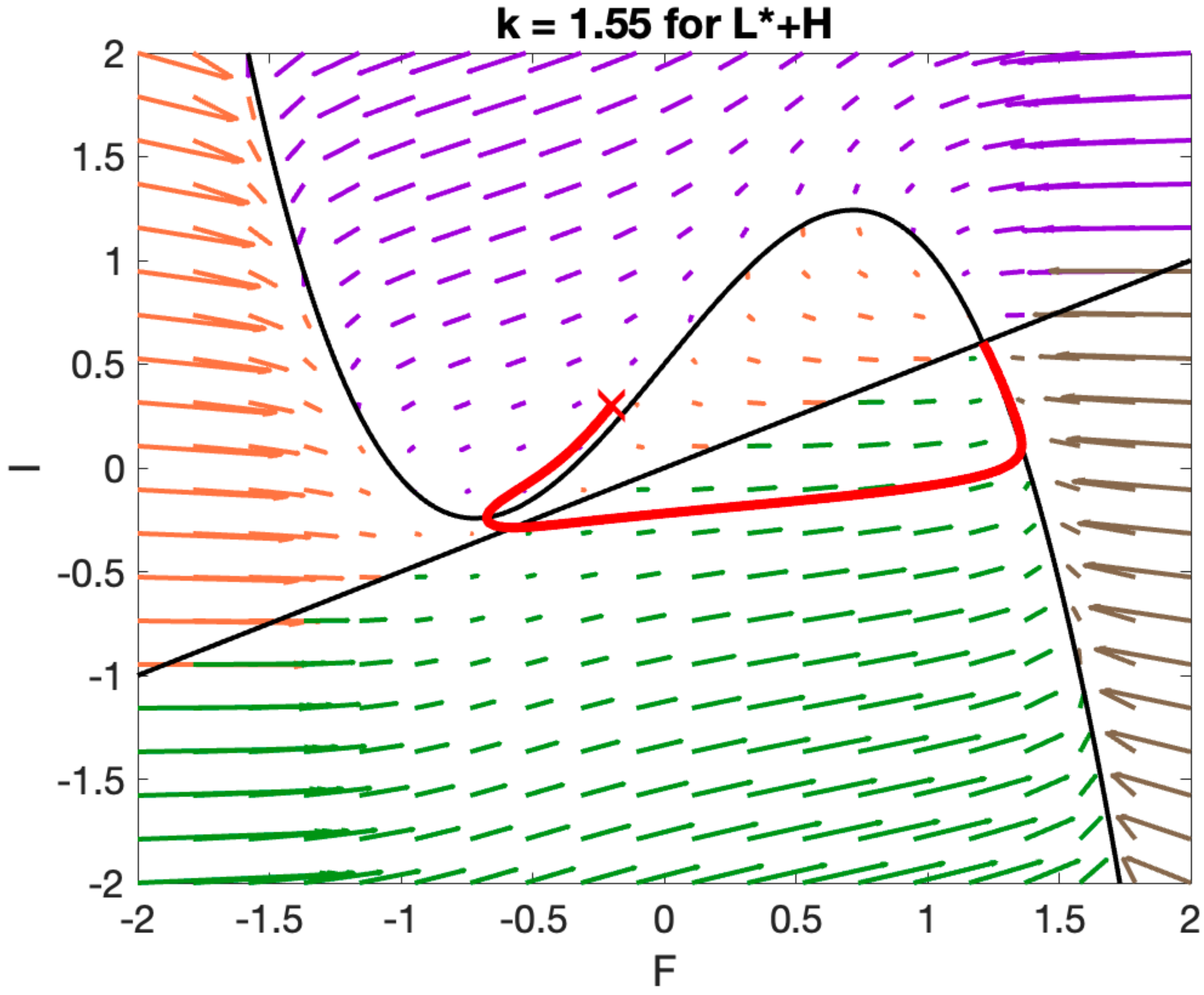


Iskarous et al. (2024)

Is this just another F0 algorithm? No, due to Equivalence Classes

$$\frac{dF}{dt} = kF - F^3 - I + .5$$
$$\frac{dI}{dt} = EF - I$$

<u>Dynamics *divides* infinitely continuous phonetic space into equivalence classes</u>

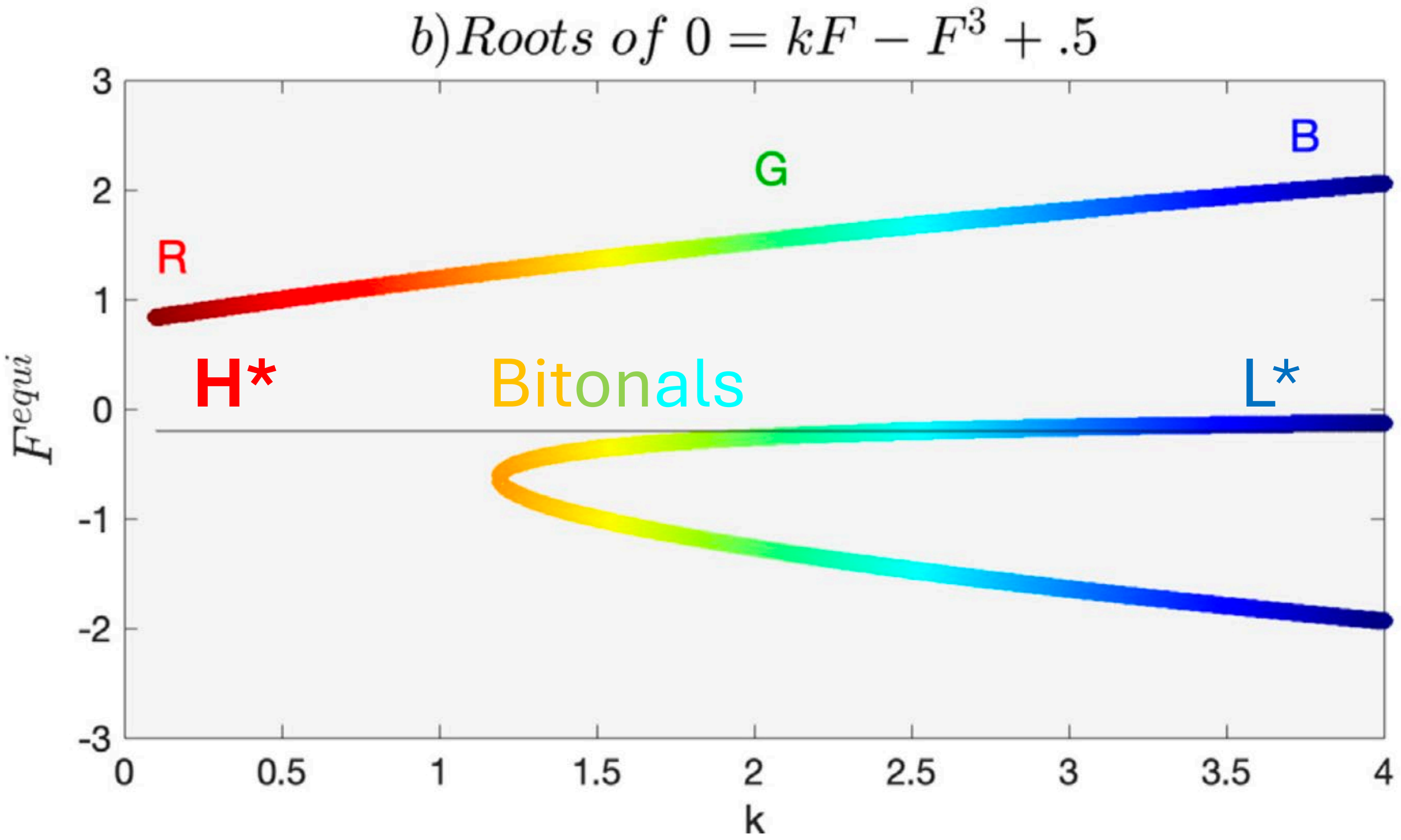


Note: E is slope of I-Nullcline

Is this just another F0 algorithm? No, due to quantal behavior

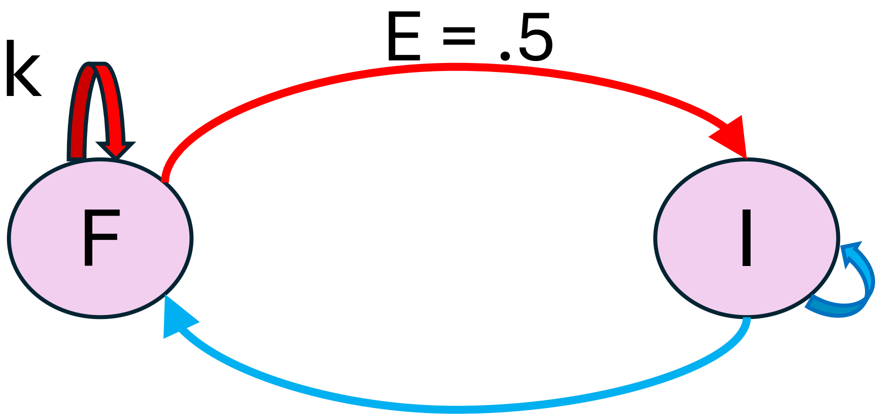
Iskarous et al. (2024) show that this model predicts phonological quantal-theory like discreteness as k varies

(Figure shows 1-variable model simplification)

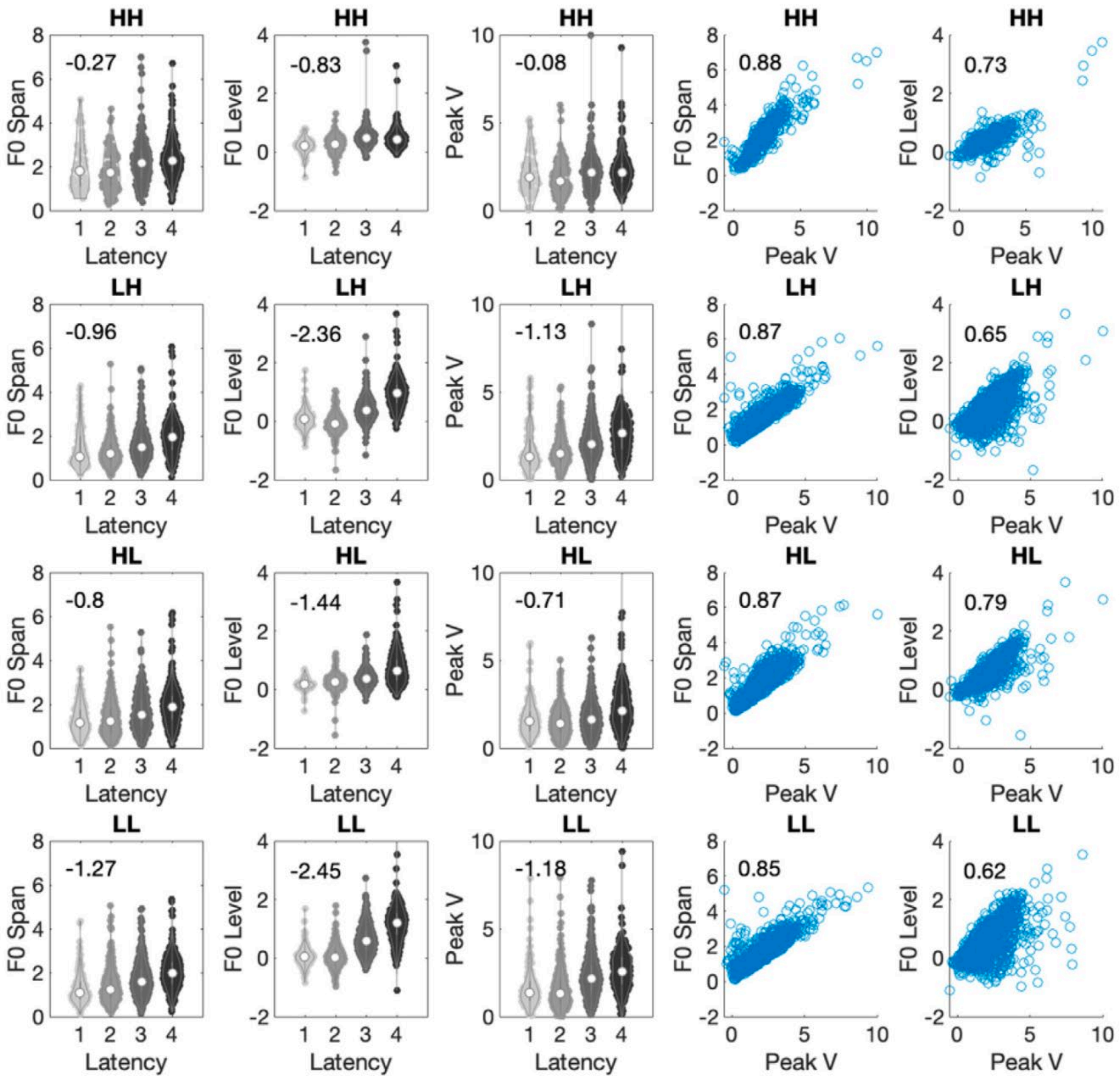


Claim: **Variance-Invariance in one model**

And several phonetic facts on details of time-variability from a corpus of 130 speakers are predicted by model

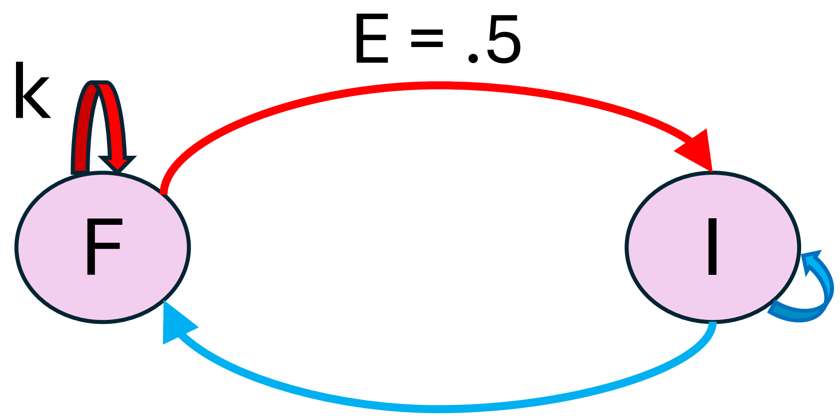


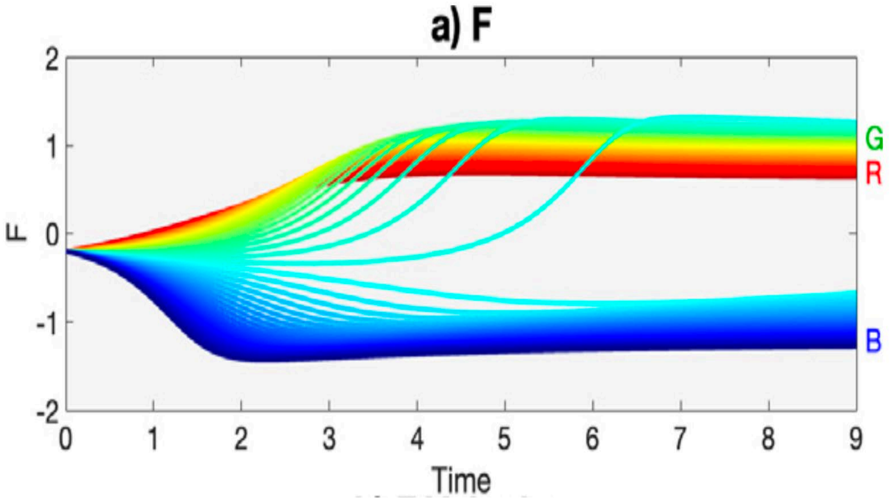
Iskarous et al. (2024)



Addressing P & P (1990) and S & G (2016)

- The **k**-mediated struggle between **F** and **I** determines whether pitch goes low or high.
- We derive the scooped L*+H (down then up), from a single specification of **k**, just as for H*, L*
- **Bitonals are *saddles, not stable equilibria*** 😇
- Tones arise autonomously without time-variation in **k**, through the kinetics of the phonologically-mediated motor circuit
- Btw: this circuit has been fundamental to biological development and neuroscience since its initial description by Turing (1952), *The Chemical Basis of Morphogenesis,* see also Iskarous (2019) on the morphogenesis of gestures.

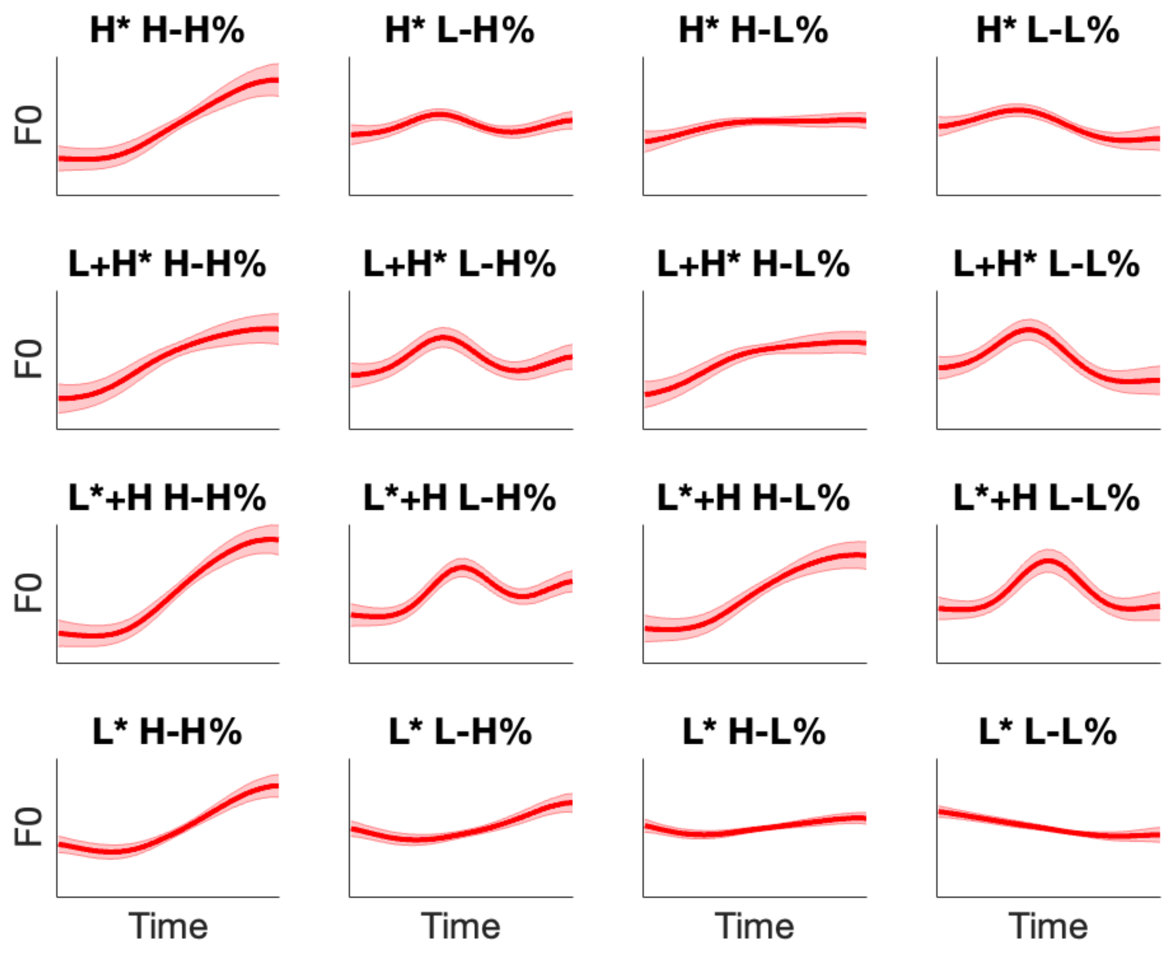




Challenge: What about full nuclear tunes?

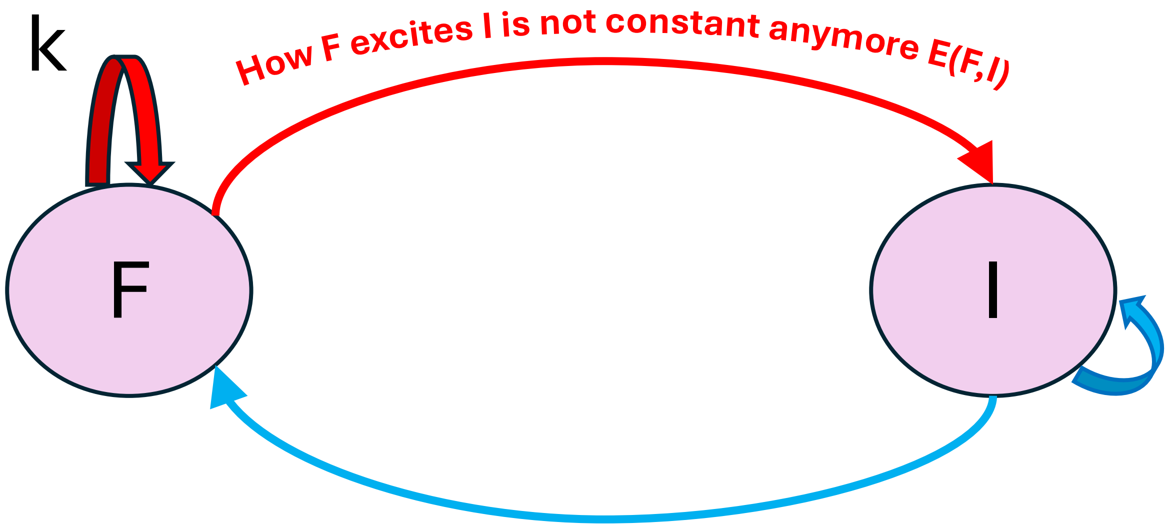
Is it possible to extend the dynamical interaction to account for full tunes?

Specifically, can one heed the advice of P& P and account for all targets in a tune in the ***output***, not ***input*** of dynamics, *and* S & G on autonomy of entire tune?



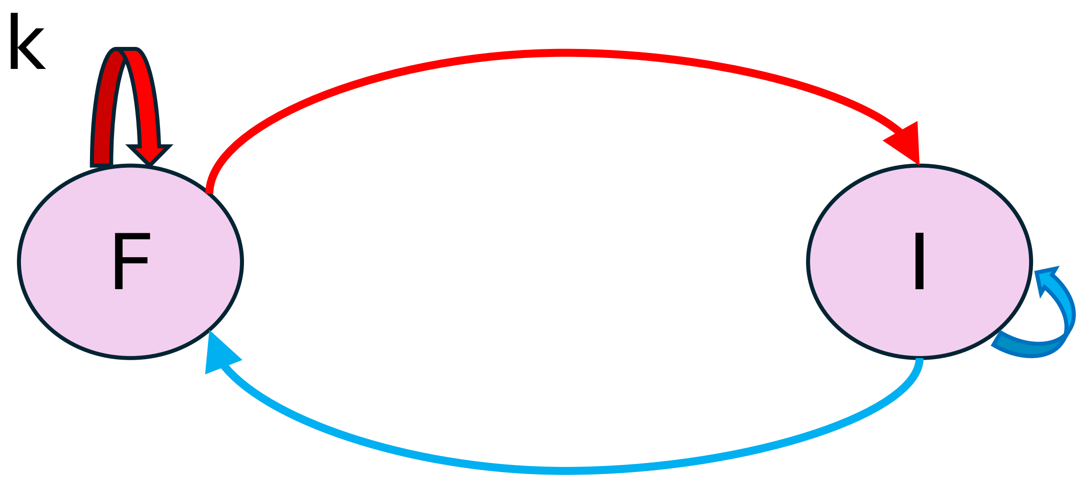
Full AE Tune Dynamics

- Phrase Accent and Boundary Tone are part of the *prosody* of language
- As many before us, we look at prosody as structure (Beckman, 1996)
- We interpret structure as dynamical modulation
- But the modulation doesn't come from a time-varying intelligent nonautonomous force; it is itself triggered by F and I via feedback: dependence of a coefficient on the state (S&G, 2016).



Current theory : <u>F and I tell F how to excite I</u>

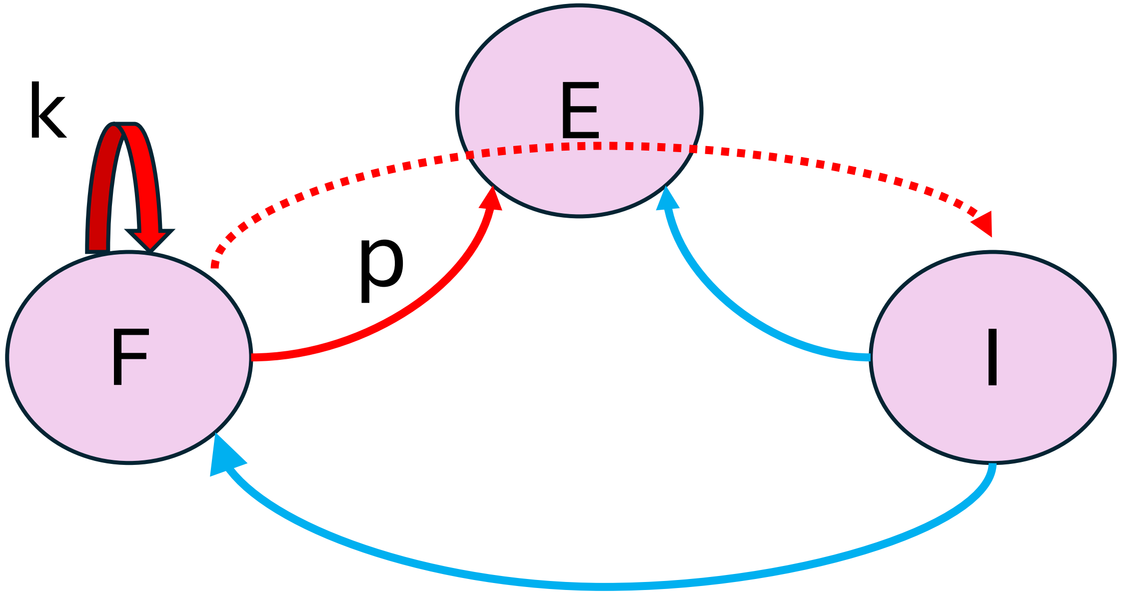
Pitch Accent Dynamics



$$\frac{dF}{dt} = kF - F^3 - I + .5$$
$$\frac{dI}{dt} = EF - I$$

Iskarous et al. (2024)

AE Prosodic Dynamics

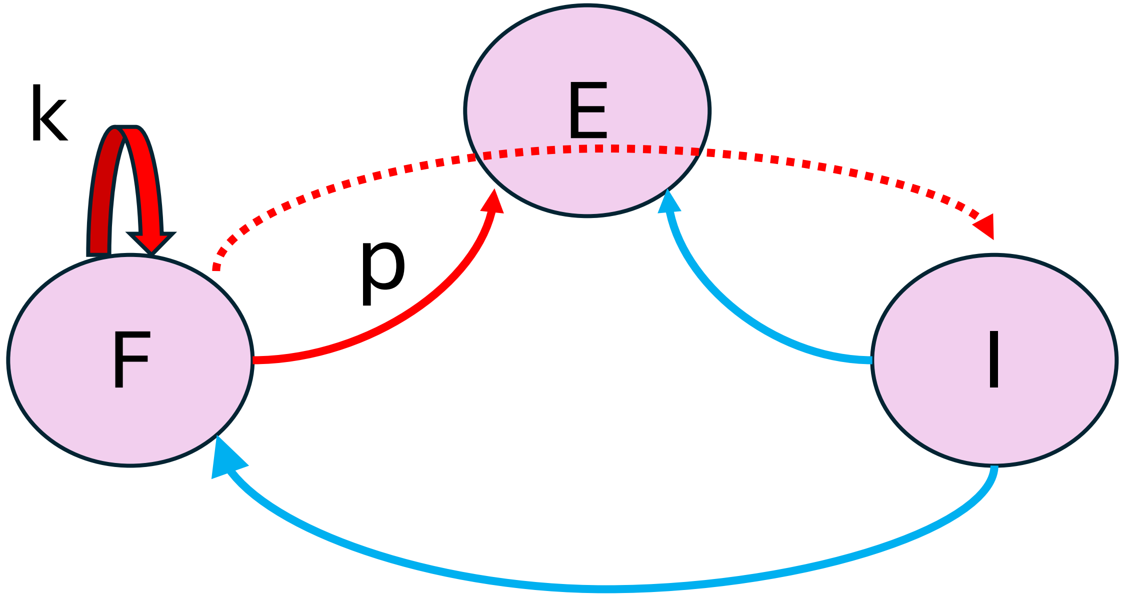


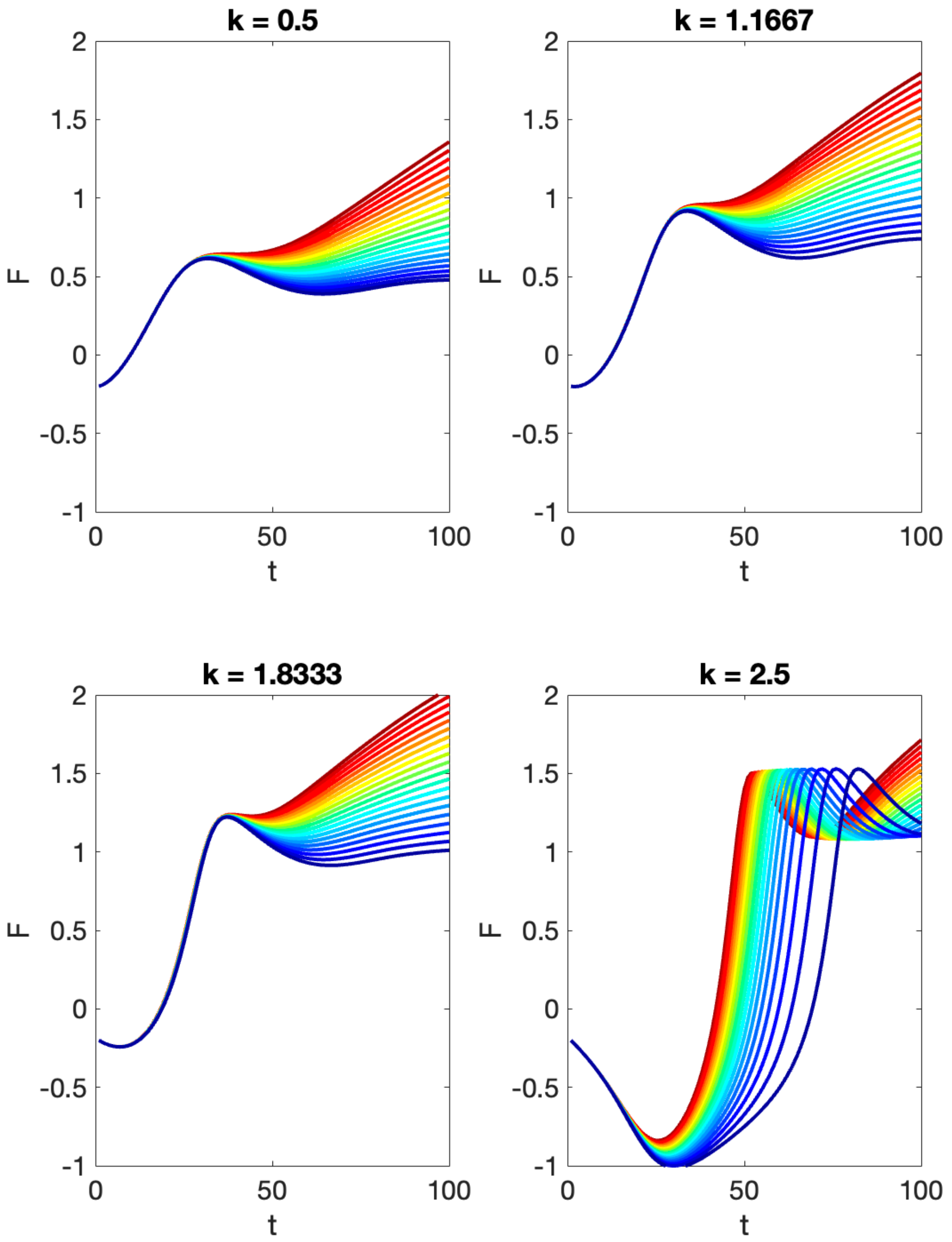
$$\frac{dF}{dt} = kF - F^3 - I + .5$$
$$\frac{dI}{dt} = 3EF - I$$
$$\frac{dE}{dt} = pF - .05I$$

Approximation I

Communication System hands constants *k* and *p* to the phonology

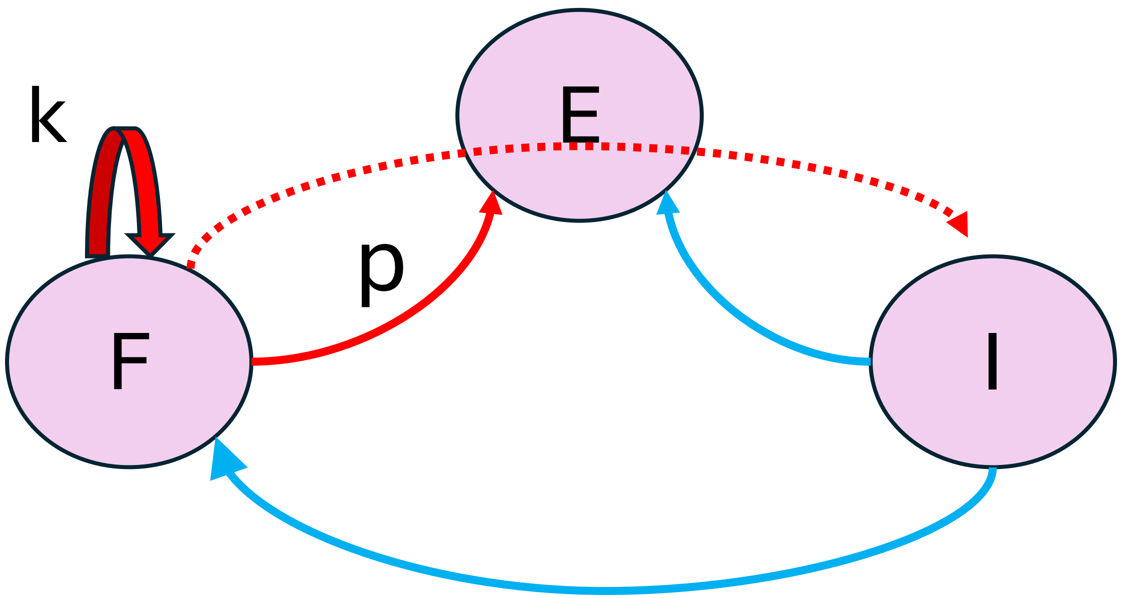
Predictions of the Prosodic Kinetic Theory Approx I

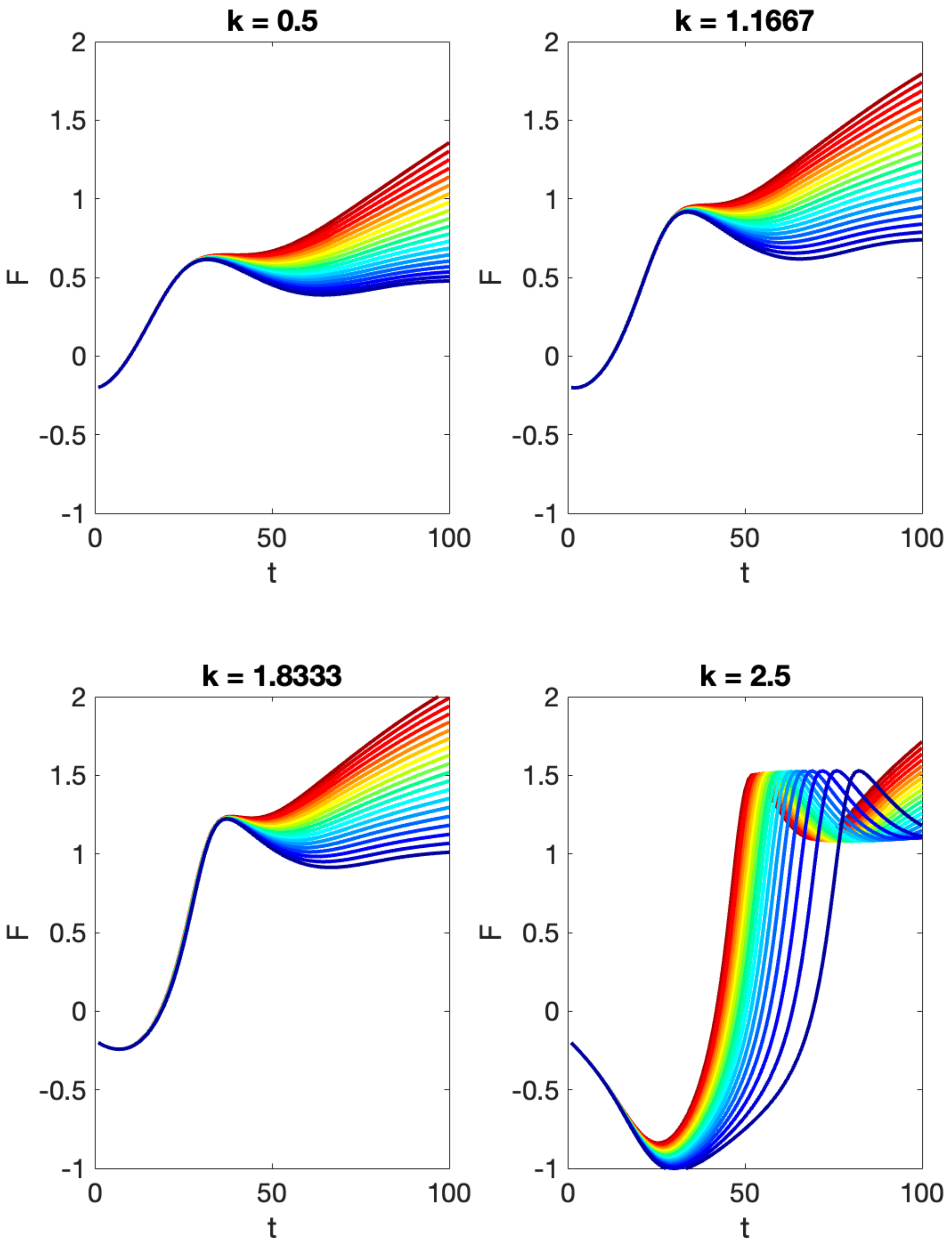




p choice allows F to leave its equilibrium value, and go higher, as in HH or lower than higher, as in LH.

Predictions of the Prosodic Kinetic Theory Approx I

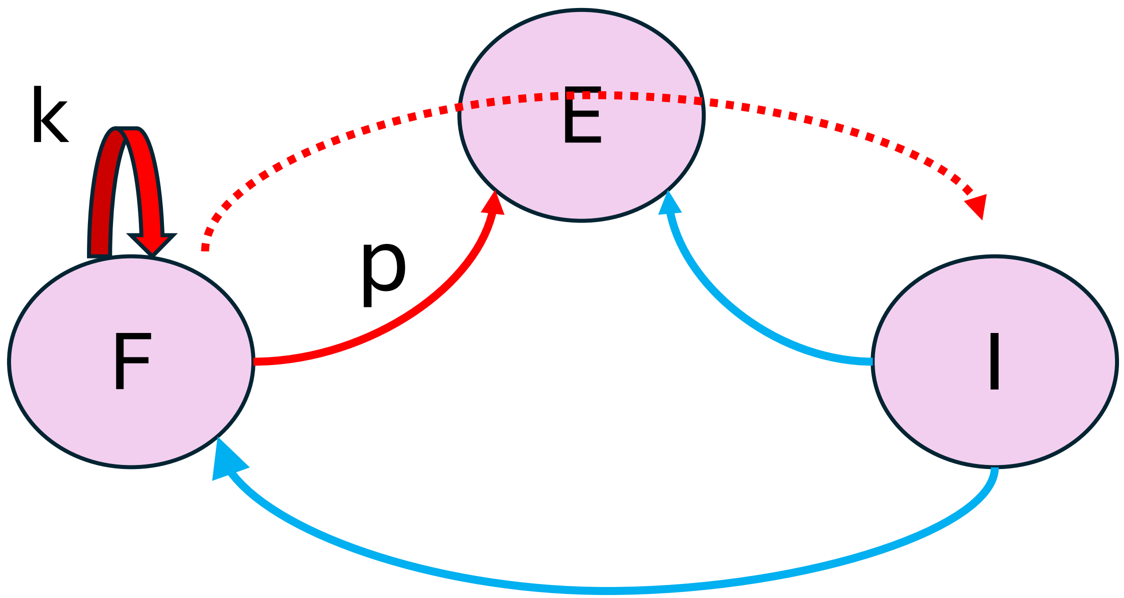


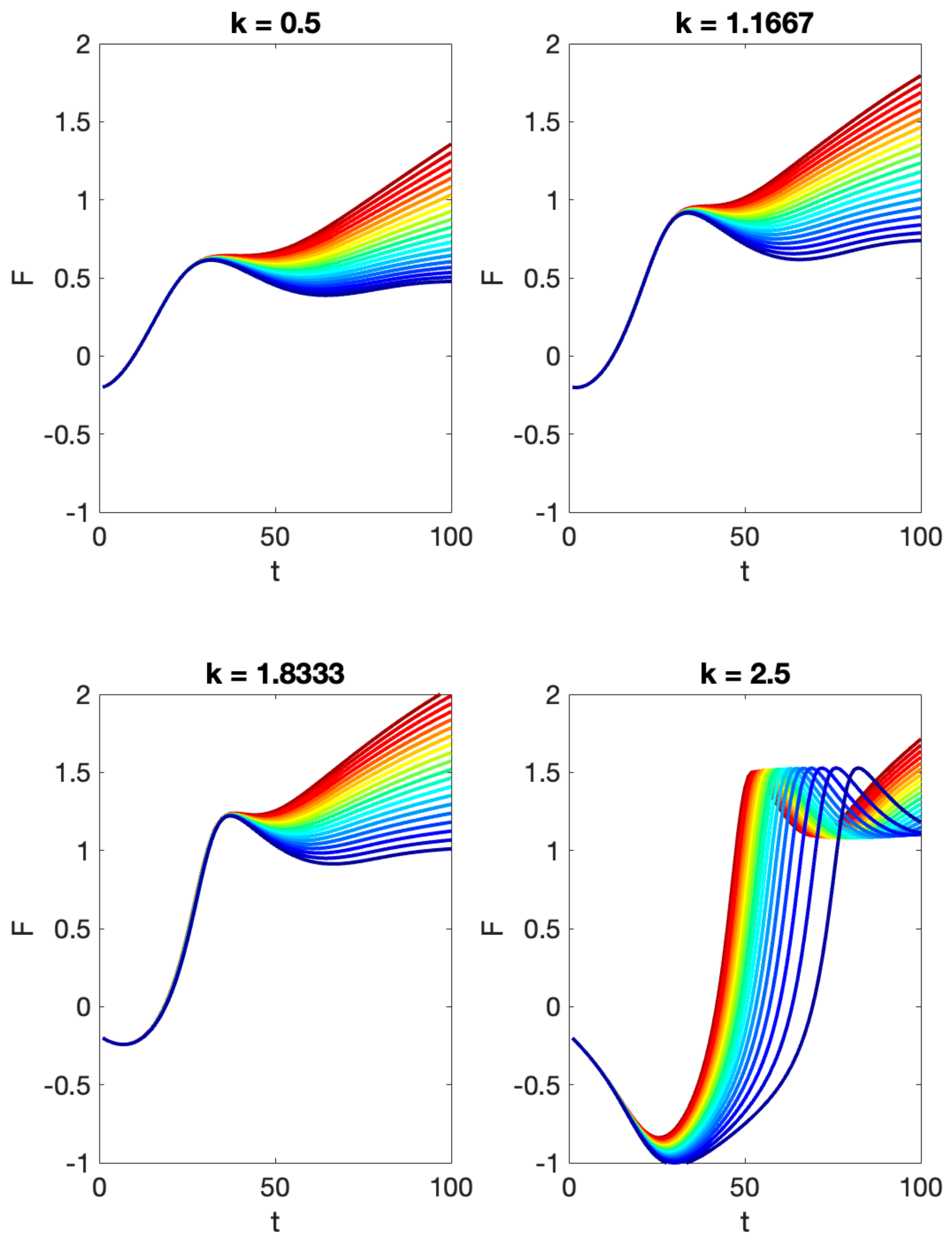


Problems → Approximation II:

- the L of LH is not sufficiently low, and we don't really get L-L%
- H-L% is already present in the Pitch Accent model alone—a problem for L* H-L%
- L* is too *excitable* (yet no oscillation)

Predictions of the Prosodic Kinetic Theory, II & III





Our ongoing work:
Loosening interactions to account for coarticulation between the pitch accent and "edge" regions of the tune

Where we are going…

- Continue work on the $\frac{dE}{dt}$ equation, resolving current limitations in a feedback-fashion (**not** nonautonomously)
- Following Kirkham (2024), we will try to infer the dynamics of F, I and E from our empirical F (f0) data, using SINDy regression (Brunto et al., 2016)
  - This type of regression can also model perception (Iskarous, 2016).
- Our current system is a type of 'winnerless competition' (Lauren, 2002):
  - Motor and cognitive systems perform tasks in sequence – no individual task 'wins', and 'targets' are modeled as temporary saddles.
  - One system of differential equations predicts both the **sequence** and **saddles**.
- Future extensions of this approach to model: Pre-nuclear pitch accents, downstep and interactions with speech timing, syllable, stress, systems without pitch accents, etc.

Where we stand: Local vs. Global Approaches

- Pierrehumbert (1980), Ladd (2008), Arvaniti (2011, 2021) criticize whole-tune global approaches of the IPO school and advocate a theory of local pitch events L and H that compose to form a tune.
- Our work supports the local approach, but is actually *hyperlocal*, as the circuit we propose applies at a far finer scale than the events H and L. It applies at every single point of time.
- However, like the AM theory it is able to predict a global tune.

Conclusions

- Kinetic Autonomy may allow us to *predict*, instead of *postulate,* many structural aspects of linguistic systems.
- Cognitive phonological and motor action can meet quite casually: phonology sets parameters of motor circuits, instead of through postulation of a cognitive dynamics separate, an execution dynamics, and a “translation” interface.
- Kinetic autonomy opens the road to thinking of syllables, words, and perhaps utterances as austonomous actions in and of themselves, not only as compositions of smaller actions.