Dynamical systems and integrated phonetics - phonology

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Outline of the talk

- Background on cognition & dynamics
- The transparency problem
- Experiments
- Dynamical model
- Conclusion

Qualitative and quantitative aspects of cognition

A theory of cognition must provide tools for studying …

the relation between the **qualitative** and **quantitative** aspects of cognitive systems

Phonetics - ? - Phonology

- How are the qualitative aspects of phonological competence related to their variable and continuous phonetic manifestation?

- This question is the defining theme of laboratory phonology (Cohn 90, Beckman & Kingston 90, Ohala 1990 and much subsequent work).

The derivational view

- The relation between qualitative and quantitative aspects of phonetics-phonology consists of a process of **translation** from discrete symbols to continuous physical properties of an articulatory and acoustic nature.

- This is the view in the background of most current work in phonetics, phonology and cognitive science in general, e.g., see the notion of transducer in Fodor & Pylyshyn 81, Harnad 90.

In terms of formal tools

- Use discrete math for the qualitative aspects. Use continuous math for the quantitative aspects.

- Example:

> “the realization component ... maps symbolic categories – things that can be described using discrete mathematics – onto physical parameters – things that can be described using continuous mathematics”; from Ladd 2002, LabPhon 8.

An alternative: nonlinear dynamics

A formal language that allows to:

(i) express **both** qualitative and quantitative aspects of a complex system within a unified framework; and

(ii) do away with the temporal metaphor of precedence between the qualitative and the quantitative, **without losing sight of the essential distinction between the two**.

Gafos (in press), Gafos & Benus (2005)

Precursors

- The dynamical (sub-symbolic) theory of cognition developed in work of Smolensky (1988) and known as harmony theory, itself a precursor of Optimality Theory.

- The dynamically based theory of phonological representations developed in the work of Browman & Goldstein (1986 *et seq*.) and colleagues, known as articulatory phonology.

- Petitot-Cocorda's (1985) «*Les catastrophes de la parole. De Roman Jakobson à René Thom*» using mathematical notions from Thom's catastroph theory and Stevens' quantal theory to elaborate the notion of distinctive features.

What do we mean by nonlinear?

A system exhibits nonlinearity when it meets the the following two conditions:

(i) There is little or no change in the behavior of the system, as a control parameter changes smoothly.

(ii) But, when the control parameter passes a critical value, a discontinuous change may be observed in the behavior of that system.

Examples

- Categorical perception (Liberman *et al*. 57)

- Biological coordination (Kelso 84) :

  Kelso observed that when adults are asked to move their index fingers in an anti-phase pattern (both fingers move to the left or the right at the same time), they can perform this task over a wide range of cycling frequencies.

  As frequency is increased, subjects show a spontaneous shift to an in-phase pattern, that is, to a pattern where the fingers move toward each other or away from each other at the same time.

- Abundant elsewhere in nature (see Haken 77; Winfree 80)

Dynamical model example

from first-order, autonomous dynamical systems

- A model is an explicit statement of rules or equations whose whose output or variables correspond to measurable quantities.

- Dynamical models are stated in terms of differential equations, referring to some variable x and its derivatives.

$$\dot{x} = f(x)$$

- x is the state of the system, which can be thought of as the position of a particle in an abstract 1-dimensional space, called the phase-space

- f(x) is the 'force'; for first-order systems, we can express the force as the derivative of a potential function V(x)

$$\dot{x} = f(x) = -dV(x)/dx$$

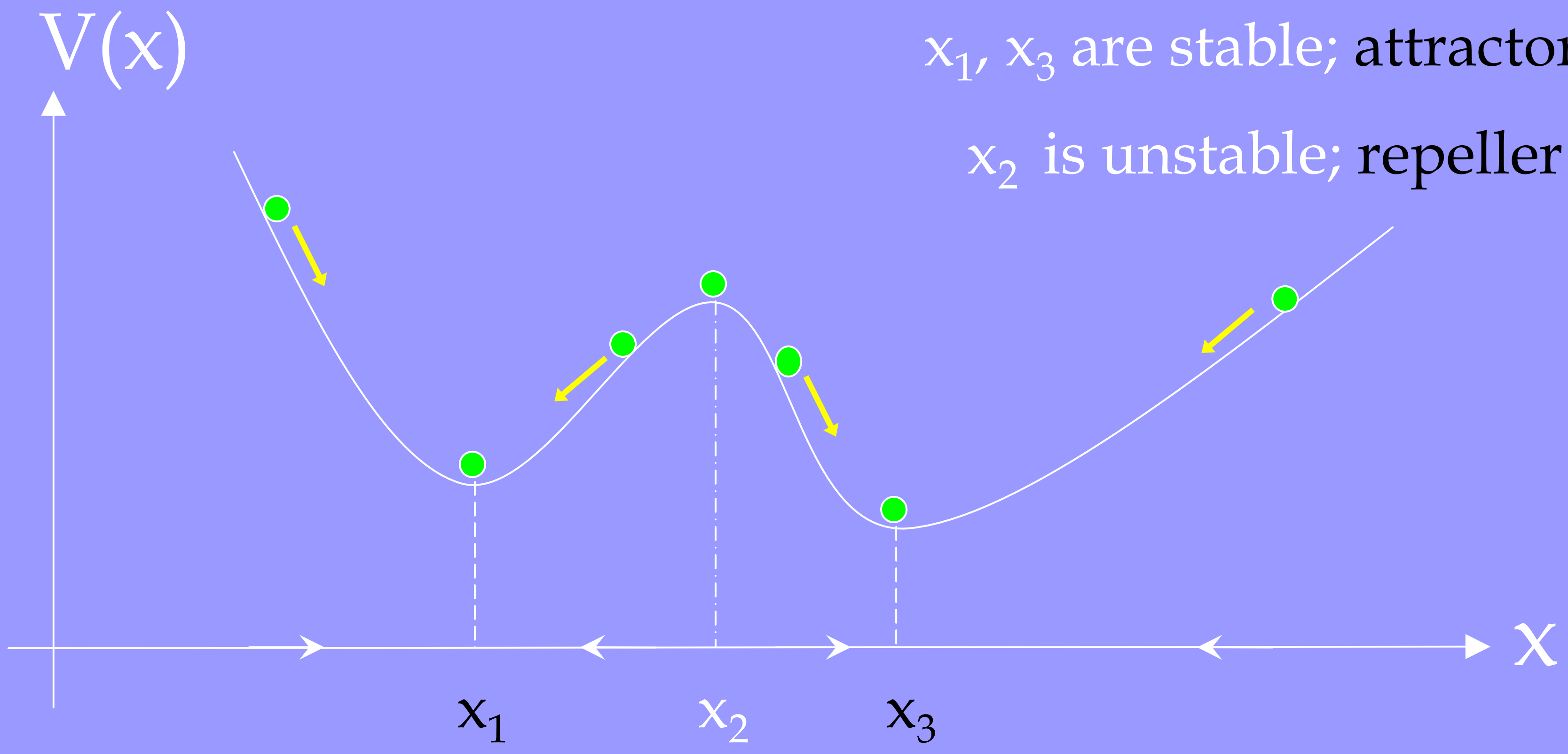
Attractor (stable fixed point)

- The points x_k where $f(x_k) = 0$ represent states of equilibrium – if a particle is placed initially at such a point it remains there for all time. Such points are called fixed points.

- Two types of fixed points: stable and unstable. Stable fixed points correspond to the minima of the potential $V(x)$. Unstable fixed points correspond to the maxima of the potential $V(x)$.

- Stable fixed points are also known as attractors; unstable fixed points as repellers.

Example with a bistable potential



x_1, x_3 are stable; attractors

x_2 is unstable; repeller

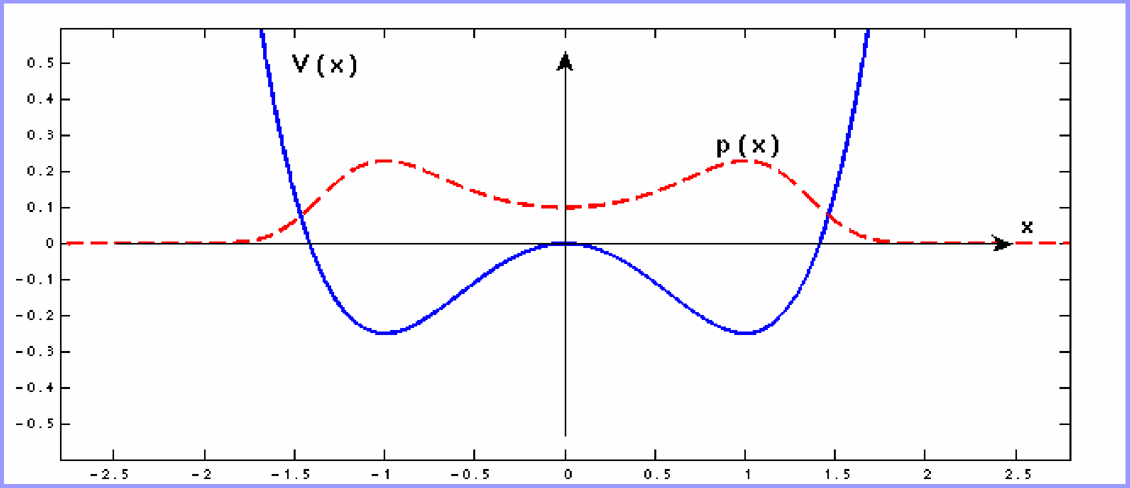
Dynamic stability
(term borrowed from B. Goodwin 1970)

- In natural systems, attractive states exhibit small fluctuations around their mean values
- Fluctuations are due to noise. Noise is due to the organizational complexity of behavior, i.e. parallel involvement of different faculties
- Mathematically, …

Stochastic dynamical systems

$$\dot{x} = f(x) + Noise = -dV(x)/dx + Q\sqrt{\xi_t}$$

- We can compute the probability of finding x within a given region of values using the probability density function p(x)

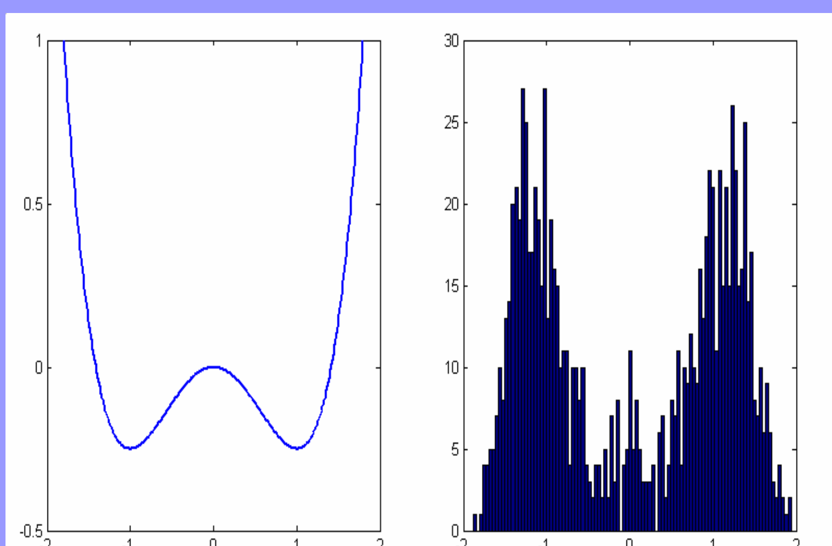


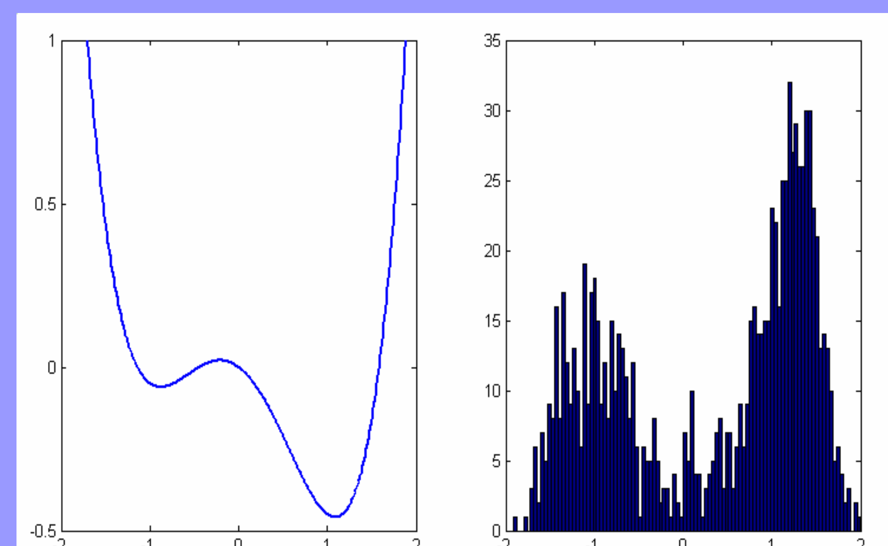
- There exist analytical methods for deducing the probability density function (Ch. 6, Freidlin & Wentzell 84)

Histogram estimation of pdf

- We can use the computer to numerically simulate the asymptotic behavior of parameter x and thus approximate the solutions to our equation by a histogram.

- Example with two potentials and simulation results:





Stability coexists with change

- These theoretical results and numerical simulations show that attractors are resistant to noise in a probabilistic sense.

- It is also true that in behavioral systems this stability in the presence of noise coexists with the flexibility to change.

- At a formal level, the ability to change in requires that we relax the notion of dynamic stability.

How to relax dynamic stability?

$$\dot{x} = f(x) + Noise = -dV(x)/dx + Noise$$

$$\big\downarrow \quad \text{via parameterization}$$

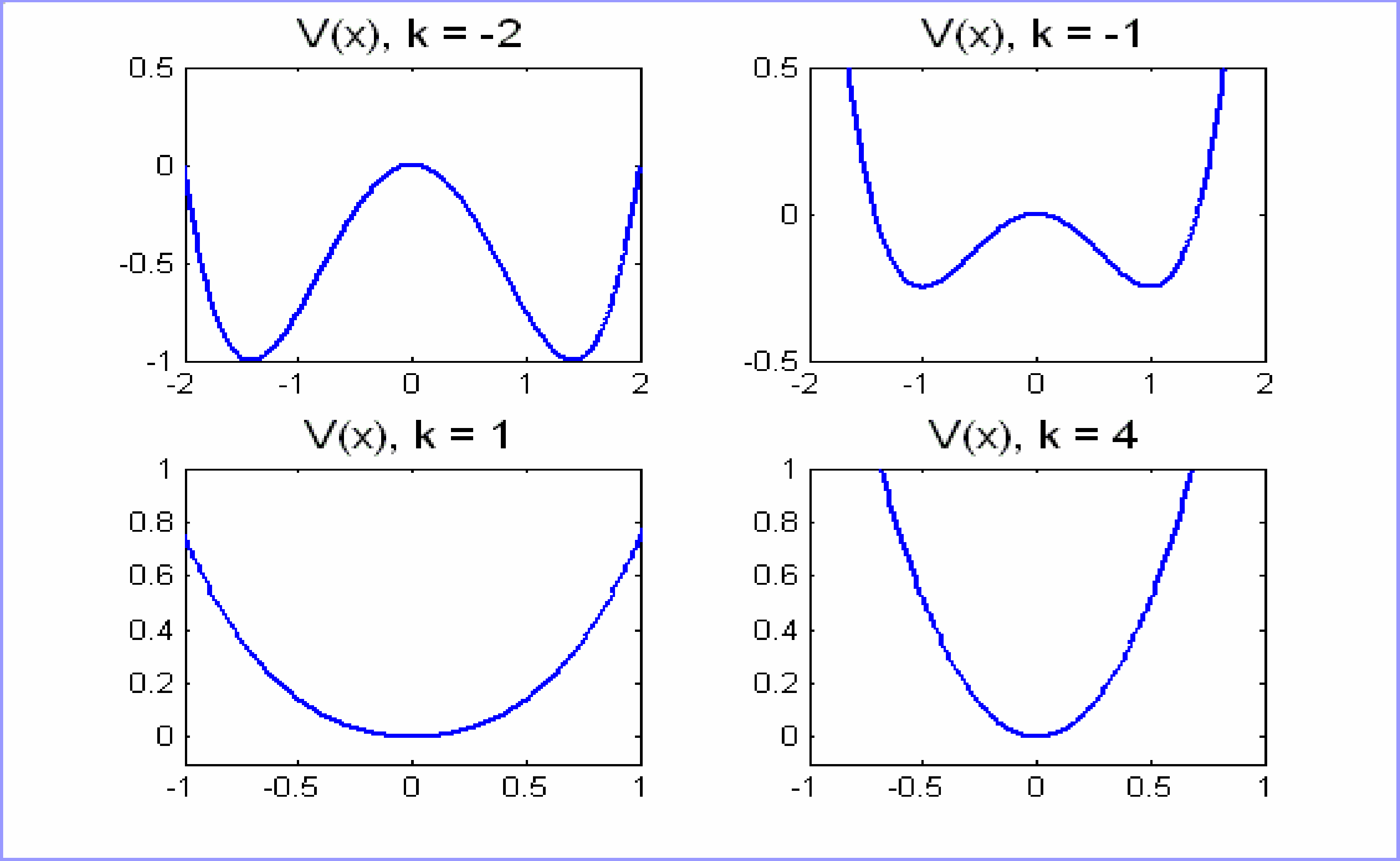
$$\dot{x} = f(x, P) + Noise = -dV(x)/dx + Noise$$

In general, as *P* changes continuously, the corresponding solutions to our equation also change continuously. But, when *P* crosses a critical value the system may change qualitatively or discontinuously.

Example

- Assume $f(x) = -k\,x - x^3$; then compute …
- $V(x) = -\int f(x)\,dx = k\,x^2/2 + x^4/4\ (+C)$
- What happens to our system as the control parameter k is varied?

Potential as a function of control k



Bifurcation

- As k is scaled smoothly beyond a certain critical value, there is a qualitative change in the behavior of the system, from a two-attractor landscape to a one-attractor landscape (a ‘pitchfork’ bifurcation).

With these basic concepts at hand, let us move on to the specific problem from the domain of phonetics – phonology …

Outline of what follows

- Basic facts of transparent vowels in Hungarian vowel harmony (”phonology”)
- Experimental methods and results (“phonetics”)
- Dynamic model of transparency – integrating the continuous “phonetics” and the categorical “phonology”

Hungarian vowel inventory
(as usually described)

	Front [–Round]	Front [+Round]	Back [–Round]	Back [+Round]
High	i[i] í[i:]	ü[y] ű[y:]		u[u] ú[u:]
Mid	é[e:]	ö[ø] ő[ø:]		o[o] ó[o:]
Low	e[ɛ]		á[ɑ:]	a[ɒ]

Hungarian vowel harmony

	Dative	Adessive	Notes
a. ház 'house'	ház-nak	ház-nál	regular harmony
b. tök 'pumpkin'	tök-nek	tök-nél	regular harmony
c. radír 'eraser'	radír-nak	radír-nál	/í/ is transparent
d. víz 'water'	víz-nek	víz-nél	TVs usually trigger front harmony
e. híd 'bridge'	híd-nak	híd-nál	TVs exceptionally trigger back harmony
f. nüansz 'nuance'	nüansz-nak	nüansz-nál	back vowels are opaque
g. parfüm	parfüm-nek	parfüm-nél	front round vowels are opaque

Transparency patterns

papír-ban/*ben ‘paper-Iness.’
mami-ban/*ben ‘mom-Iness.’
Acél-ban/*ben ‘Acel-Iness.’

A + {i, í, é}
↓
back suffix

---

hotel-ban/ben ‘hotel-Iness.’
Ágnes-ban/ben ‘Agnes-Iness.’

A + e
↓
vacillation

mami-csi-ban/ben ‘mom-Dim.-Iness.’
Acél-ék-ban/ben ‘Acel-Coll.-Iness.’

A+{i, í, é}+{i, í, é}
↓
vacillation

Summary & challenges

- The set of transparent vowels is {i, í, é, e}: common properties resulting in transparency, and differences within the set

- The notion of locality: front vowels in the back harmony domain, e.g. ‘radír-nak’

- Exceptions(?): transparent vowels may also select a back suffix, e.g. ‘víz-nek’ vs. ‘híd-nak’

- The nature of variation, e.g. ‘hotel-ban/ben’

Motivating the present study

- Over the past twenty-five years, lots of work on transparency in phonology; Partial list: Clements 77, Vago 80, Anderson 80, Smolensky 95, Ní Chiosáin & Padgett 97, McCarthy 98, Ringen & Vago 98, Gafos 99, Baković & Wilson 00, Krämer 01, Siptár & Törkenzy 01, Kiparsky & Pajusalu 02.

- Very little data exists on the phonetic side of transparency in vowel harmony (Fónagy 66, Gordon 99, Beddor *et al.* 01).

Experiments

- Well-accepted assumption in phonology:

  Transparent vowels do not participate in vowel harmony, at least on the surface.

- Question:

  What are the phonetic properties of these vowels in different harmonic contexts: AiA vs. EiE?

Stimuli I
(trisyllabic words: disyllabic stem - suffix)

Back context	**Front context**
[kaːbiː-tom] 'daze'	[reːpiː-tɛm] 'send'
[buli-val] 'party'	[bili-vɛl] 'pot'
[boːdeː-toːl] 'hut'	[bideː-tøːl] 'bidet'

…

Suffixes shown here: first singular possessive, instrumental, ablative

Stimuli II
(monosyllabic stems)

- Most 1-syllable stems take front suffixes

cím ‘address’	cím-nek ‘address.dat’
szél ‘wind’	szél-nek ‘wind.dat’

- A limited number (≈ 60) select back suffixes

síp ‘whistle’	síp-nak ‘whistle.dat’
cél ‘aim’	cél-nak ‘aim.dat’

- Comparisons of bare 1-syllable stems: cím vs. síp

Methods Used

- **Ultrasound**:

  to image the whole surface of the tongue

- **Electromagnetometry (Emma)**:

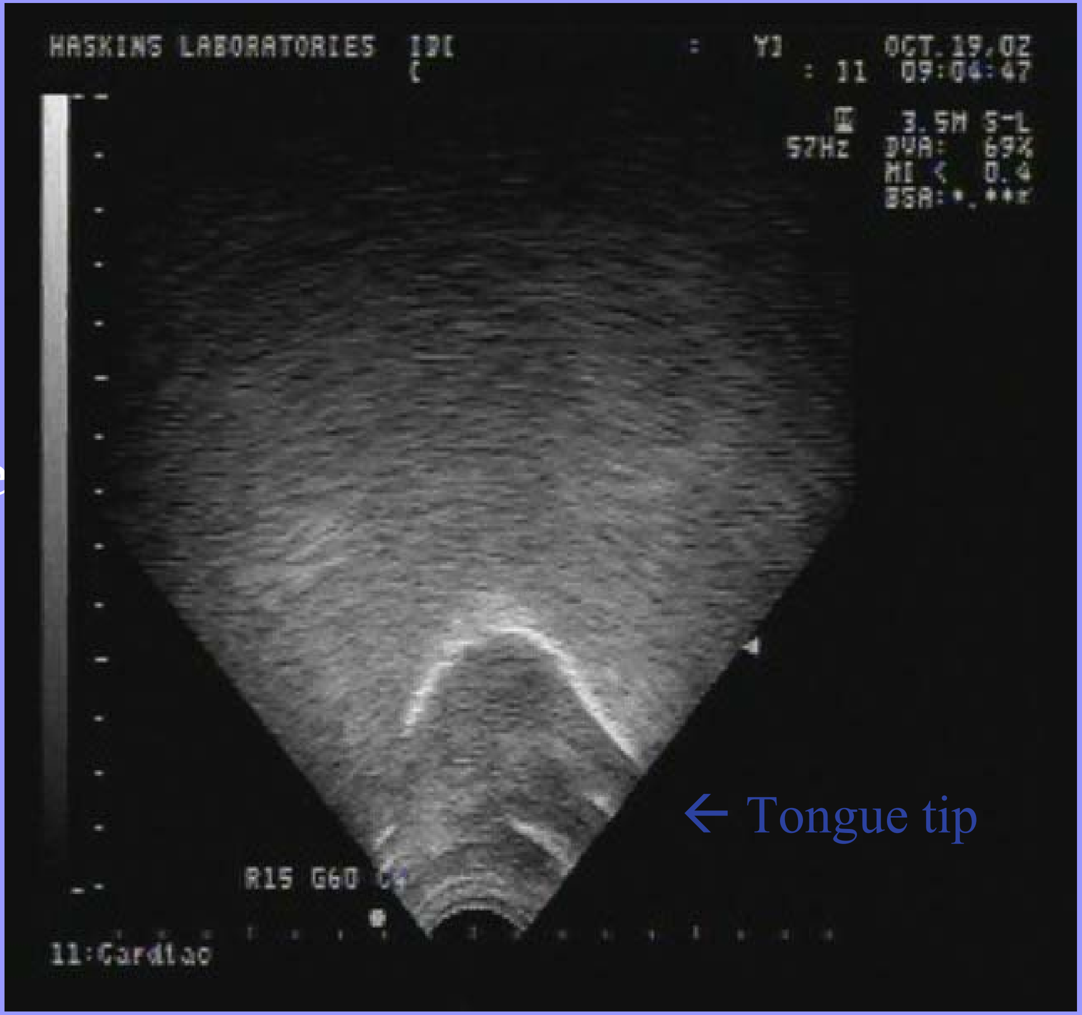
  to image individual points of the tongue

- **Acoustics**:

  to study the acoustic consequences of the articulatory configurations

Ultrasound

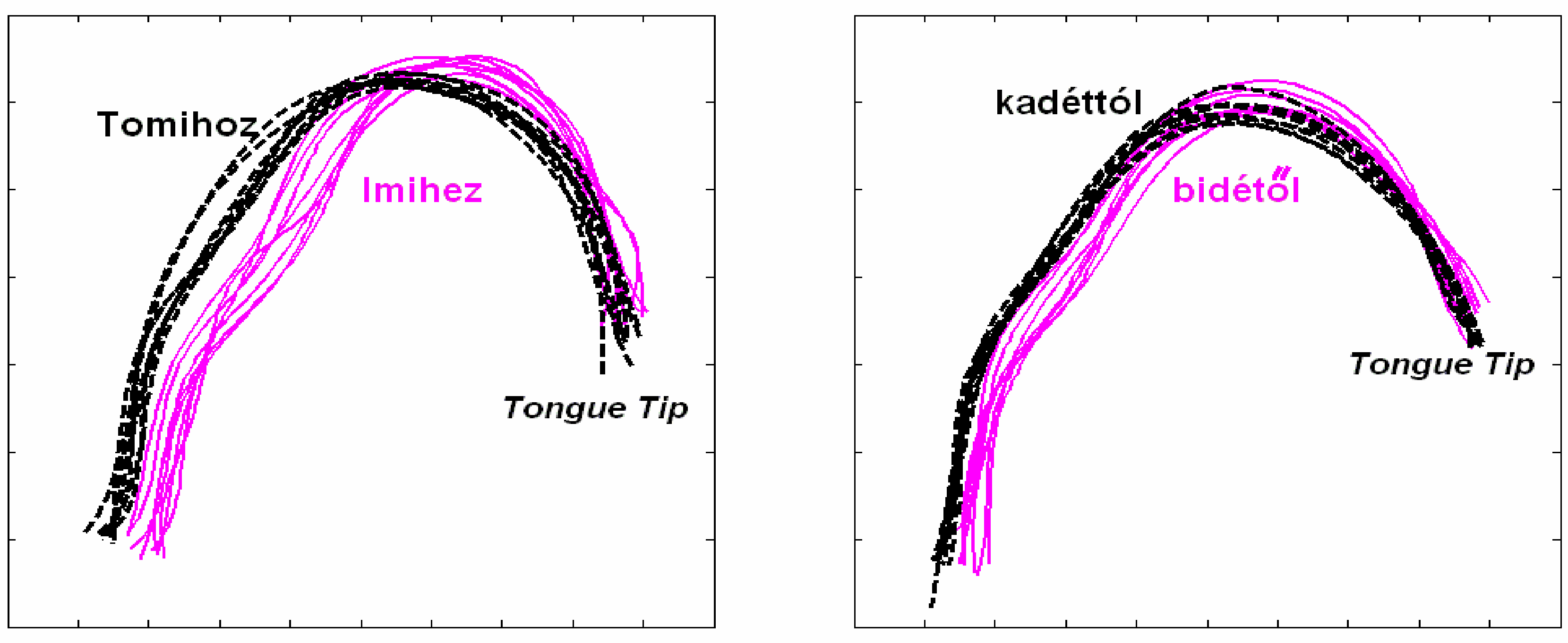
- Haskins Aloka SSD-1000 with a 3-5MHz (piezoelectric crystal) probe.
- Probe placed below chin in contact with the soft area surrounded by the jaw.
- UHF waves (traveling through the soft tissue) are reflected back by air or bony mass.



Differences in tongue shape

Back environment

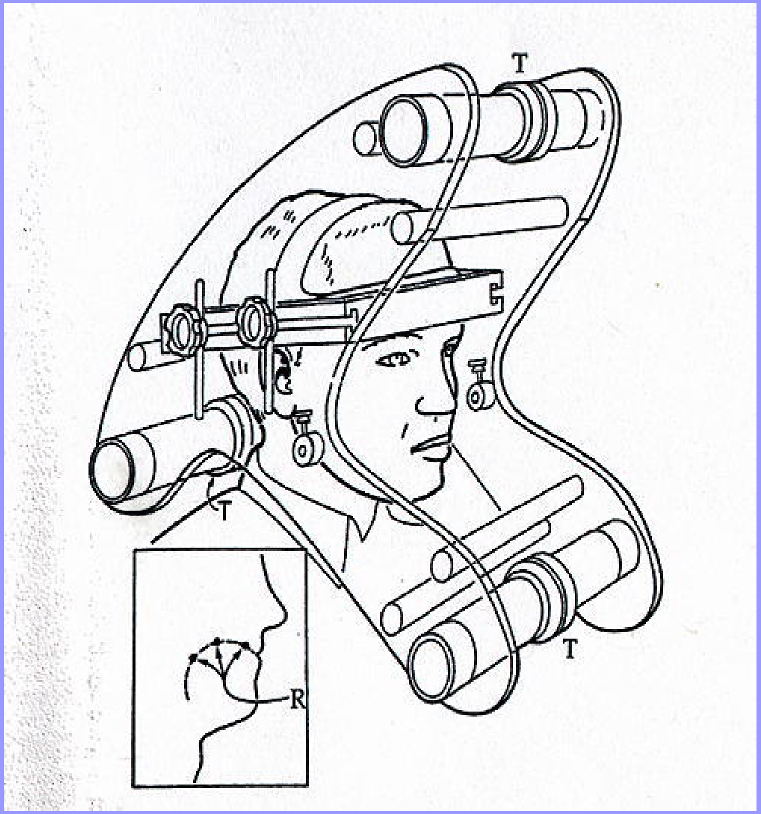
Front environment



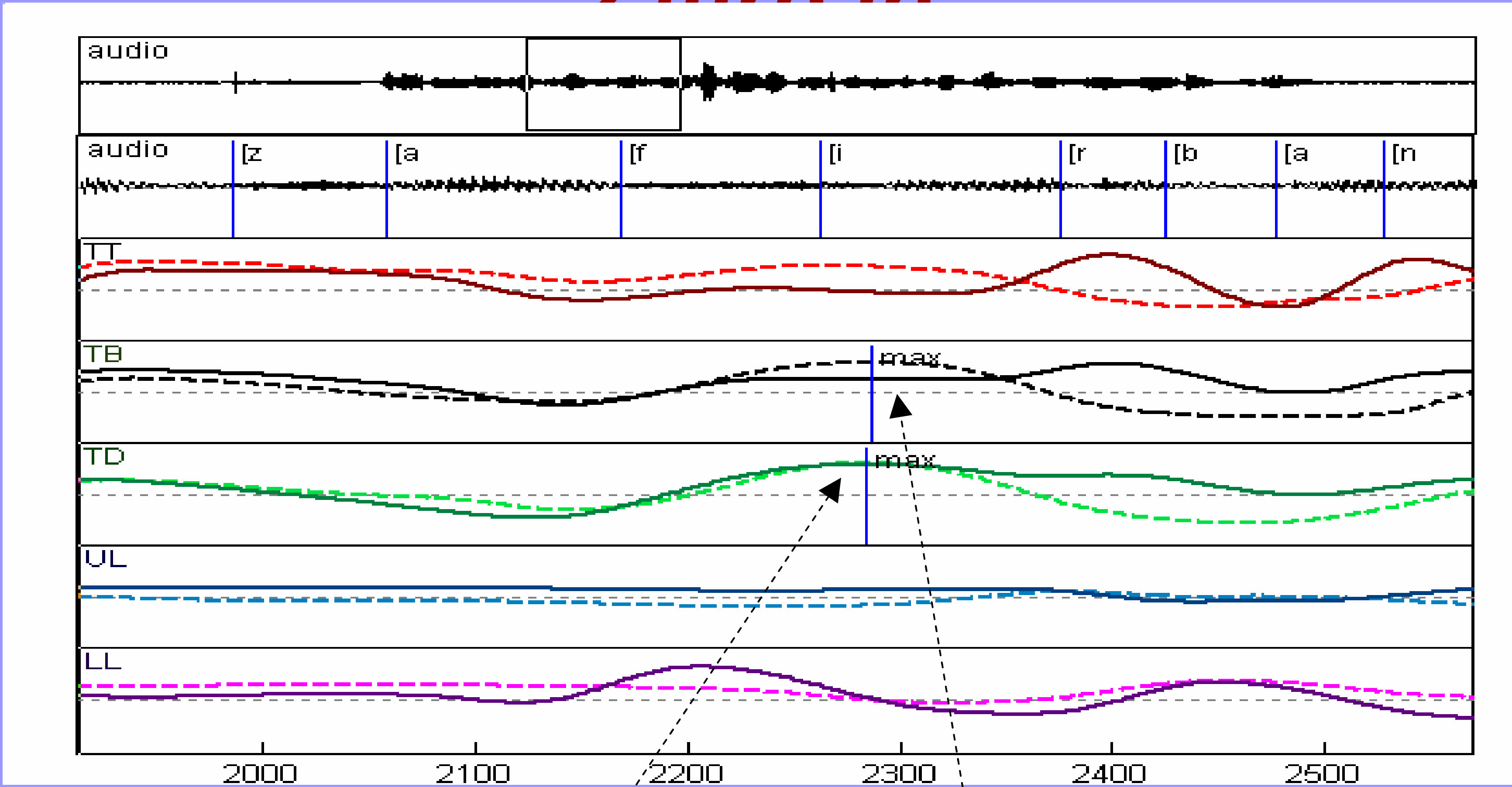
Transparent vowels in back harmony domains are articulated with tongue body retraction as compared to front harmony domains.

Electromagnetic midsagittal articulometry (Emma, Perkell *et al*. 1992)

- Three transmitter coils (T)
- Up to 8 receiver coils (R) placed on articulators
- Receivers: Tongue Tip (TT), Tongue Body (TB), Tongue Dorsum (TD), Upper Lip (UL), Lower Lip (LL), Jaw



Example of articulator kinematics recorded with emma token: *zafírban*



Measured spatial values: frontward horizontal extrema of receivers on tongue dorsum and body.

Example results (EMMA)

	Rec.	ZZ subject			BU subject			CK subject		
		Front	Back	MD	Front	Back	MD	Front	Back	MD
3-syll	TD	– 48.02	– 48.97	**0.95****	– 43.12	– 43.51	**0.39****	– 24.59	– 25.58	**0.99***
	TB	– 38.65	– 40.05	**1.40****	– 30.89	– 31.48	**0.59****			
	TT	– 23.41	– 24.73	**1.32****	– 21.68	– 22.07	**0.39****	– 21.83	– 22.08	**0.23**
1-syll	TD	– 46.67	– 46.93	**0.26**	– 42.08	– 42.61	**0.53****	– 22.25	– 22.94	**0.69***
	TB	– 36.17	– 36.81	**0.64***	– 29.54	– 30.38	**0.84****			
	TT	– 20.35	– 20.62	**0.27**	– 20.09	– 20.6	**0.51****	– 20.00	– 19.78	**– 0.22**

MD = Front - Back

Main observation: in back harmony domains ([buli-val], [tomi-hoz], [hi:d]), transparent vowels are produced farther back than in front harmony domains ([bili-vel], [imi-hez], [vi:z]).

Preview: dynamical model of transparency

- From the experiments, we saw that a discrete phonological alternation correlates with a continuous phonetic dimension: subphonemically retracted/advanced transparent vowels are followed by back/front suffixes.

- How can small, continuous phonetic differences be related to a categorical alternation in suffixes?

Nonlinear dynamics provides a formal language for linking the qualitative, phonological alternation in suffixes to continuous changes in the tongue body constriction location of the preceding vowel.

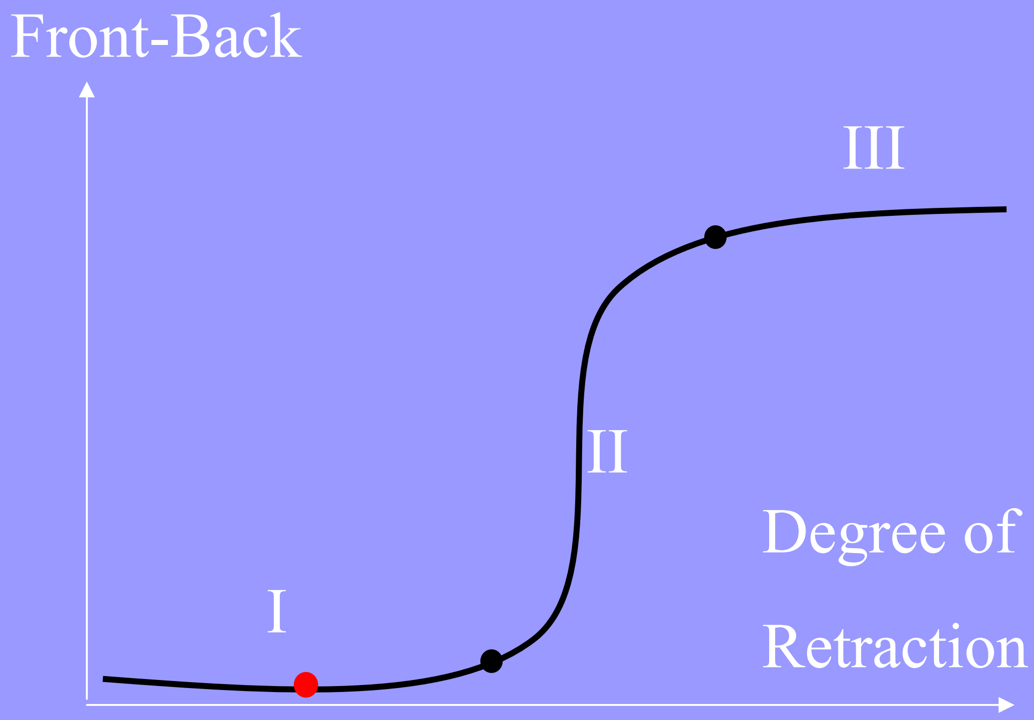
Phonetic basis of vowel harmony

- It has been proposed that a phonetic basis for vowel harmony can be traced to phonetic effects among vowels in consecutive syllables (Fowler 1983, Lindblom 1985, Ohala 1994).

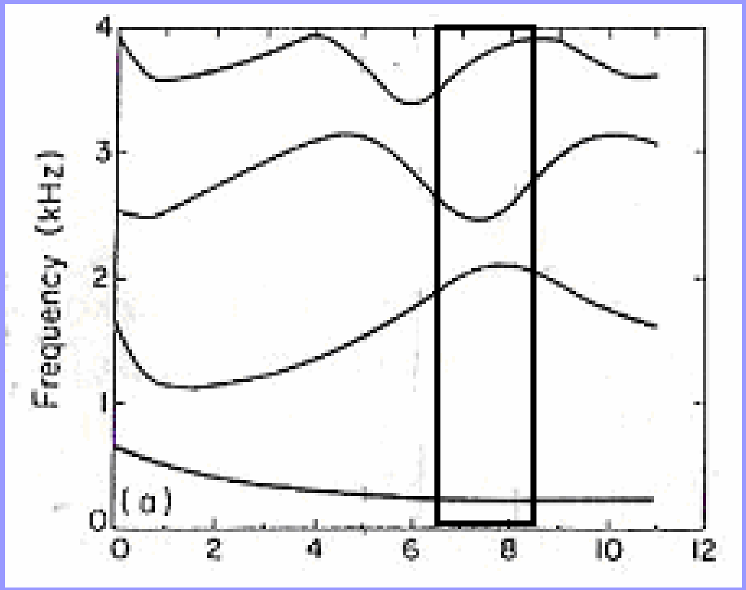
- The crucial fact is that vowels exert influences on neighboring vowels across intervening consonants, the so-called *V-to-V coarticulation* (Öhman 1966).

- However, it remains to be shown how the variable and quantitative coarticulation effects are to be linked to the binary [±back] character of suffix alternations (the continuous – discrete theme).

Phonetic basis of transparency



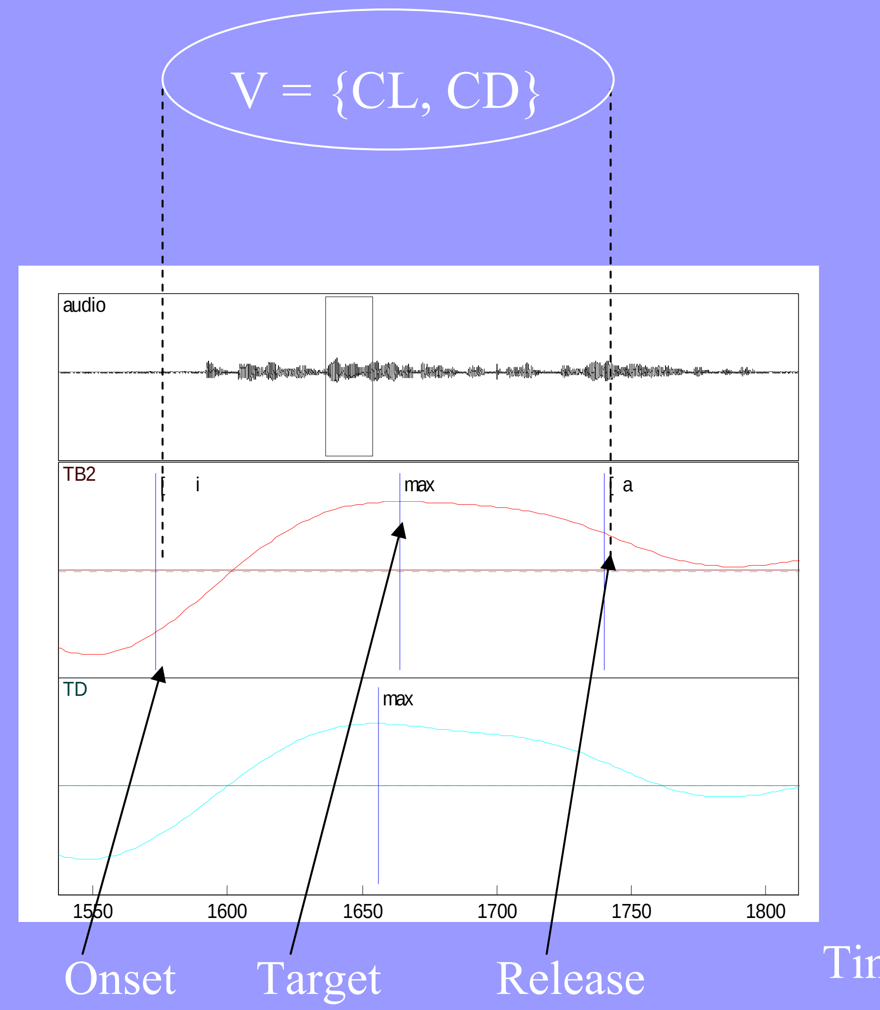
Non-low front vowels can be retracted articulatorily without corresponding acoustic consequences (Stevens 1972, Wood 1982)



Transparent vowels are those vowels that can be maximally retracted without losing their perceptual identity

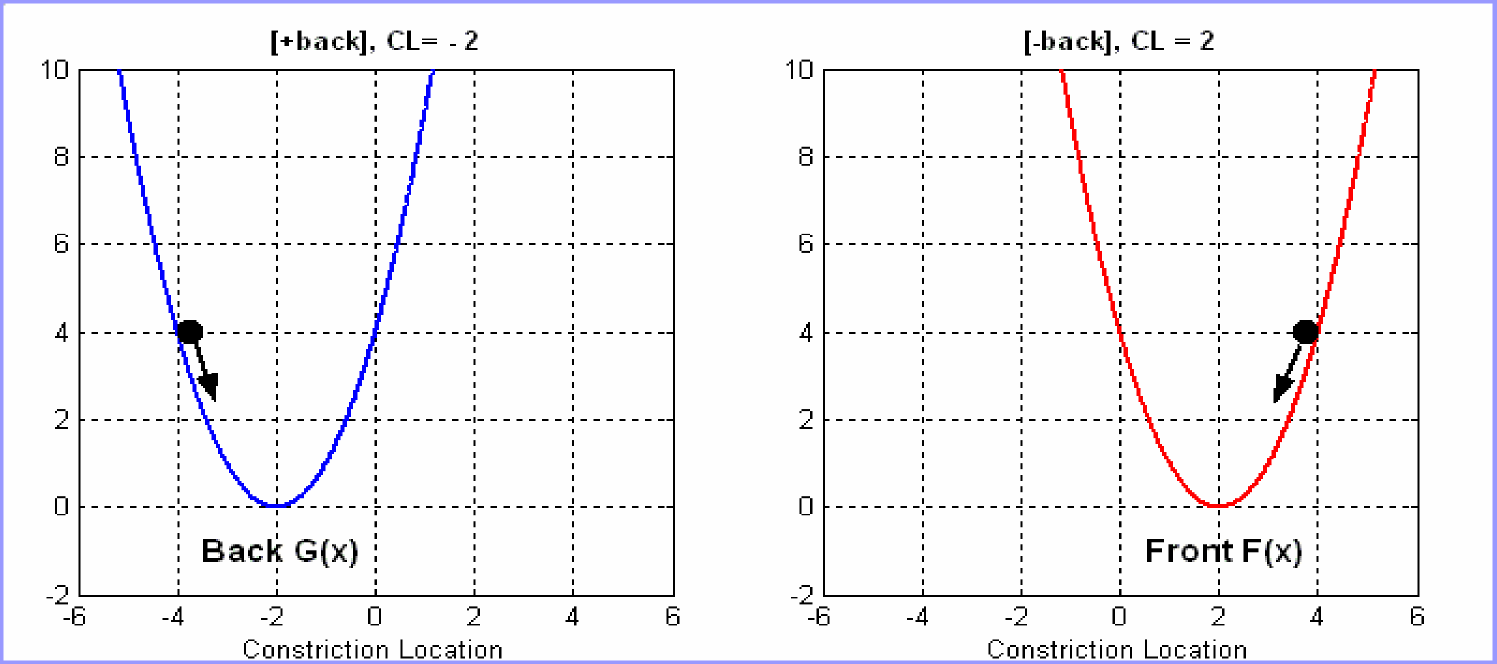
Representations

- Phonological representations are dynamically defined spatio-temporal gestures (Browman & Goldstein 1995).
- Each vowel is represented as a gesture with a specified constriction location (CL) and constriction degree (CD) variables (Wood 1986).



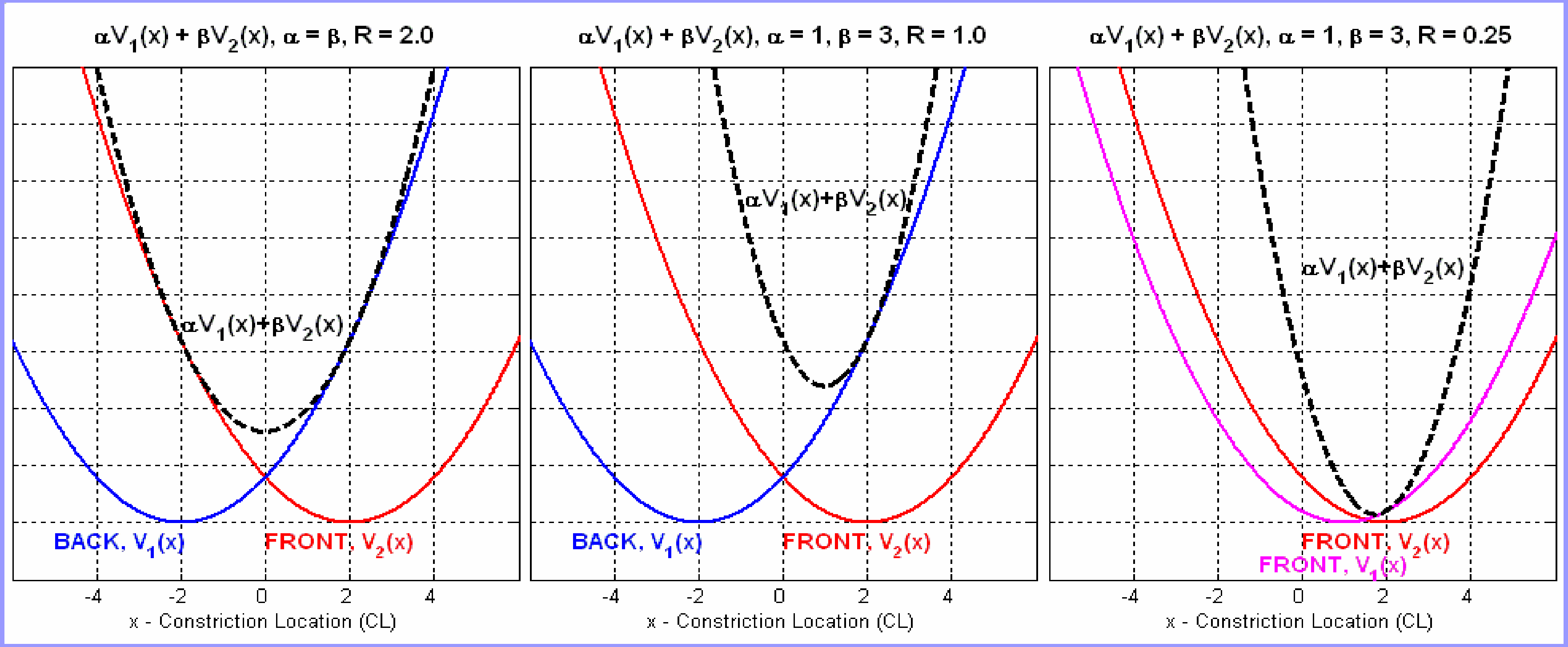
Dynamics of vocalic targets

- Monostable landscape $V(x) = \alpha (x - x_0)^2$, where x_0 represents the CL target value, front or back.



Articulatory blending formally
(Benus 2005)

- Simplest working hypothesis: linear combination of input potentials, αF(x) + βG(x), where α, β are the weights of the individual gestures.



- Perturbations of vowel constriction location due to blending are captured with the degree of retraction **R**

Model for suffix selection

$$\dot{x} = f(x, R) + Noise$$

- x is the **order parameter**, the constriction location of the suffix vowel
- R is the **control parameter**, a function of the retraction degree R of the preceding stem vowel
- f(x, R) is a nonlinear function over x, R

Working hypothesis for suffix dynamics

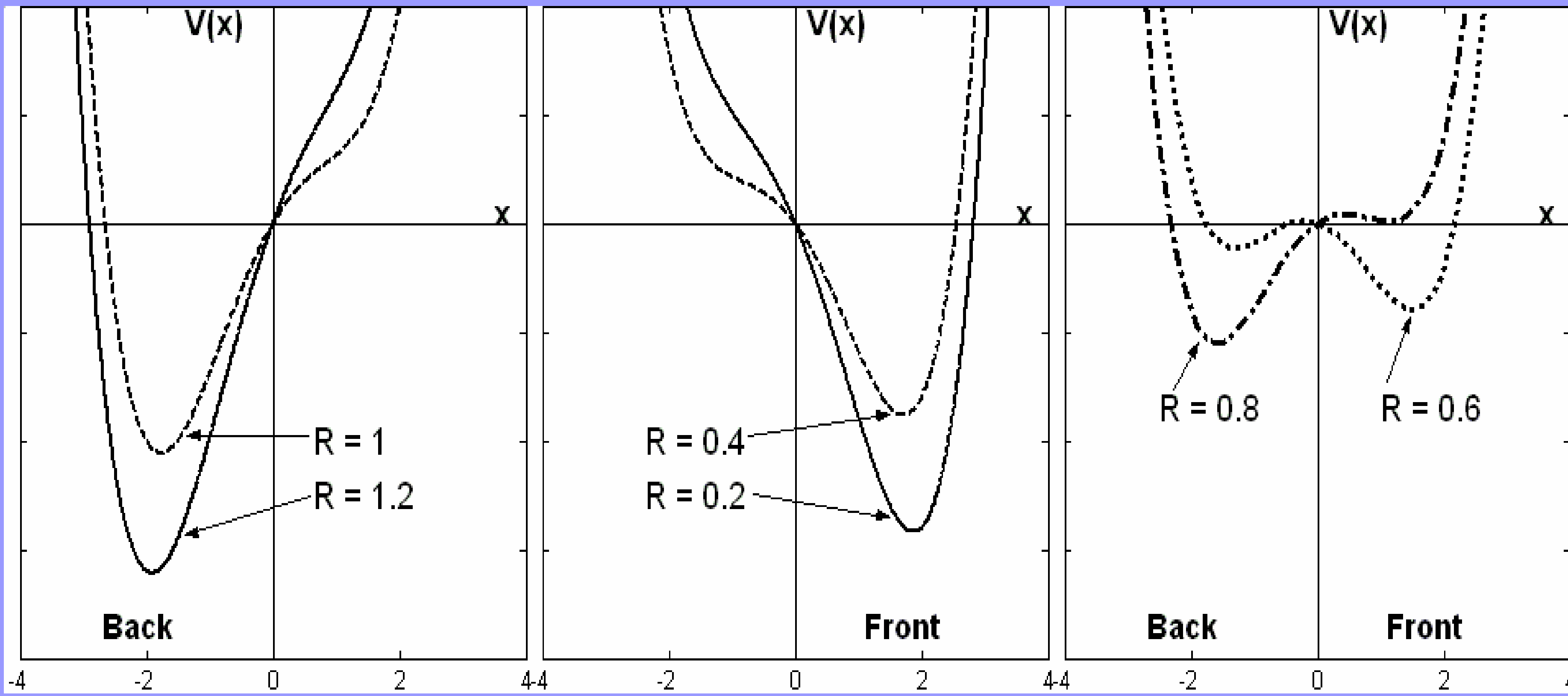
- Since suffixes alternate between a front and a back version, the suffix dynamics must afford at least two attractors.

- Given this requirement (Arnold 2000), a good candidate for f(x, R) is the function

$$f(x, R) = R + x - x^3$$

Suffix form as a function of *R*

maximal (*papír-nak*) | minimal (*emir-hez*) | intermediate (*aszpirin–nak/nek*)



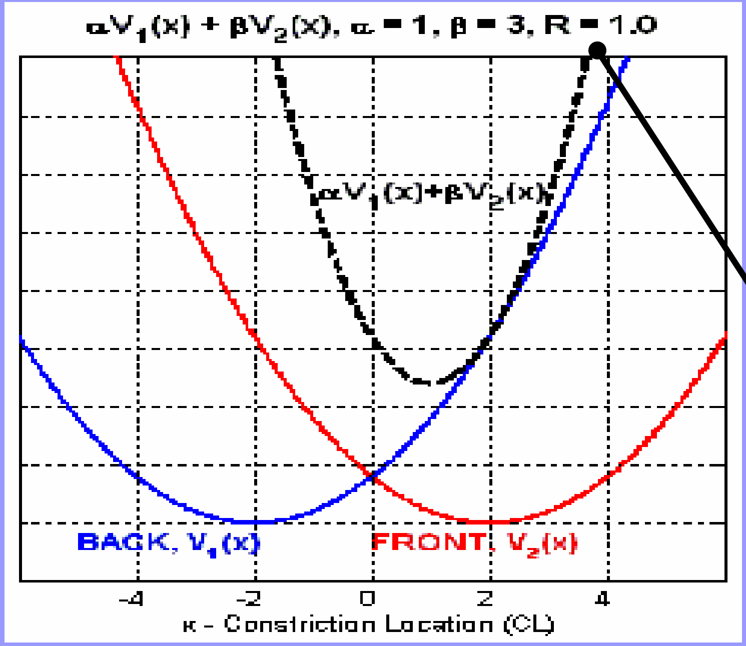
Transparent í, significant retraction

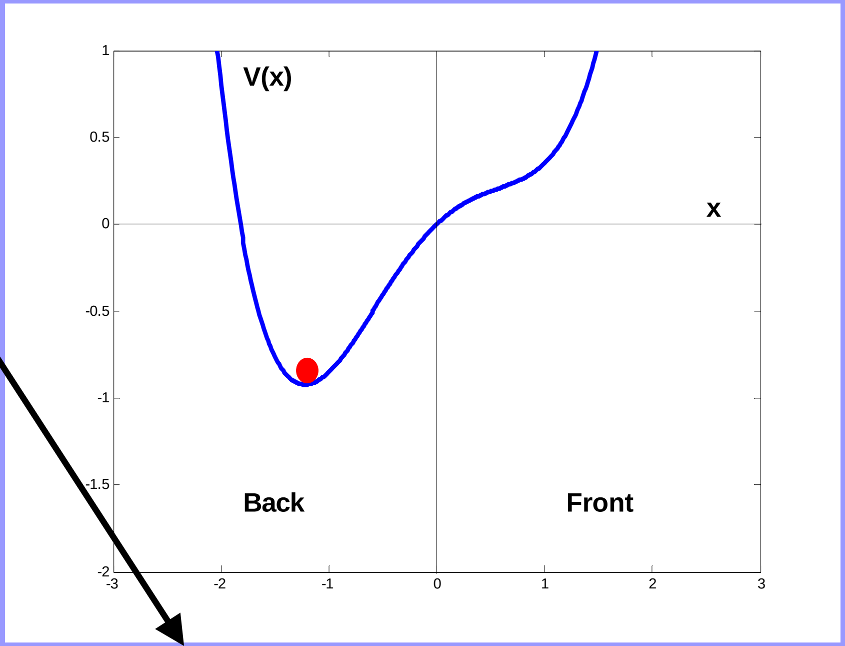
papír - nak

a={uvul wide}
CL_a = -2

í={pal nar}
CL_i= 2

V={__ wide}
CL = ?(a/e)

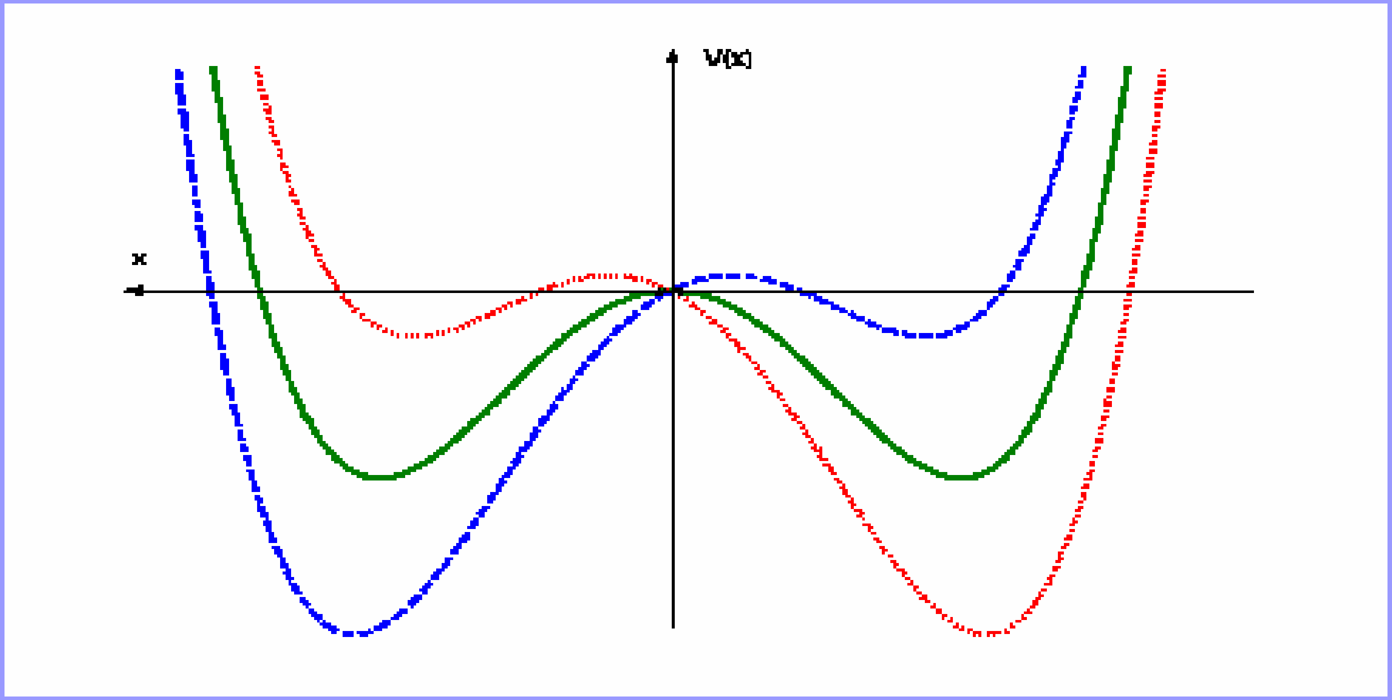




$$V(x) = -Rx - x^2/2 + x^4/4$$

Intermediate retraction => bistability

As the control parameter is smoothly decreased below a certain critical value, there is a qualitative change in the behavior of the system, from a one attractor landscape to a two attractor landscape.



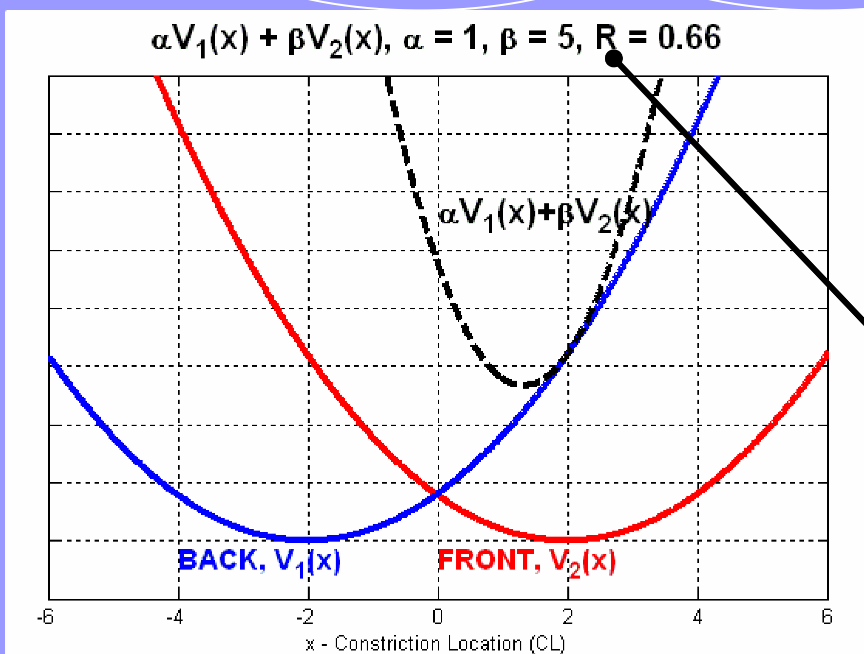
Less transparent e, intermediate retraction ($\beta_e > \beta_i$)

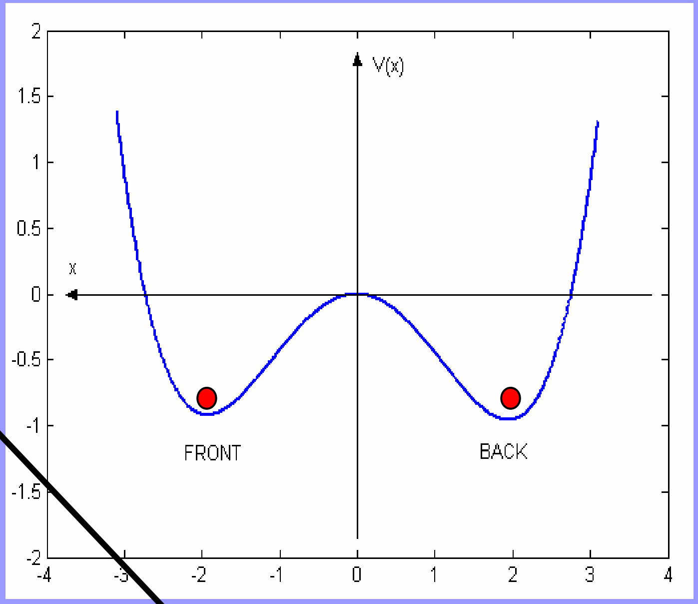
hárem-nak/nek

á={uvul wide}
$CL_a = 2$

e={pal wide}
$CL_e = -2$

V={__ wide}
$CL_0 = ??(a/e)$

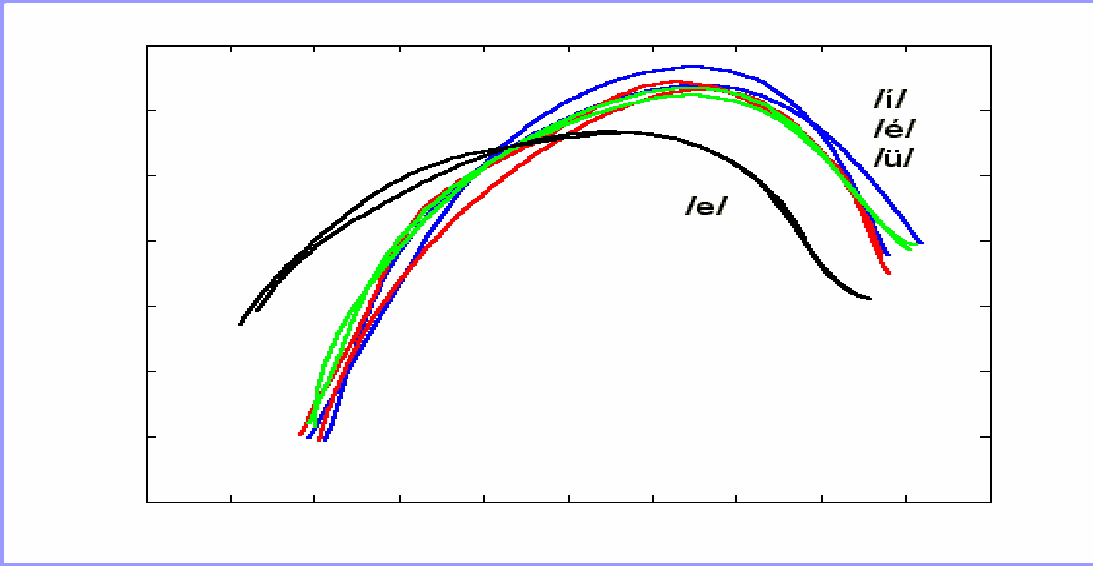




$V(x) = -Rx - x^2/2 + x^4/4$

Medial retraction degree of e: converging evidence

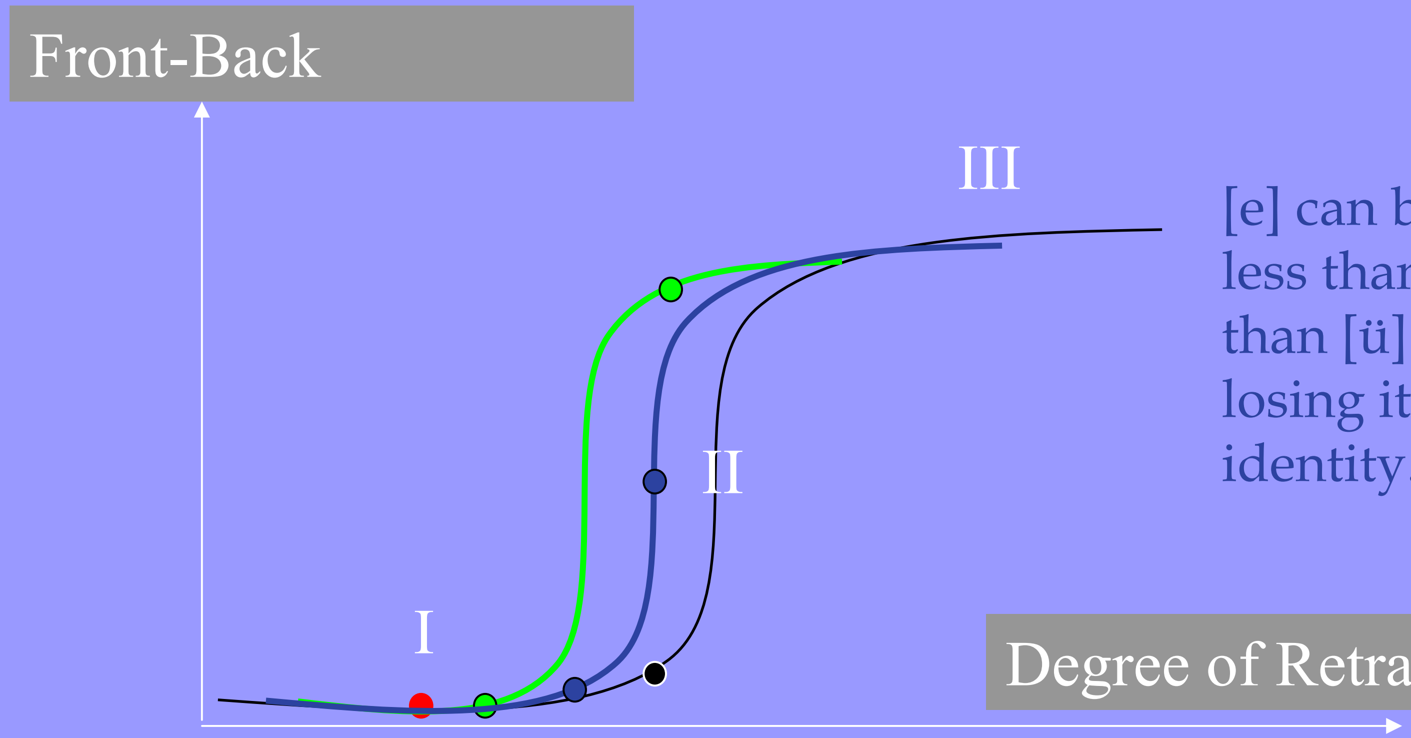
- No reliable experimental data for e
- Acoustic stability (insensitivity to articulatory retraction) only applies to non-low front unrounded vowels (Stevens 1972, Wood 1982). Hungarian /e/ is a low front vowel.



- Degree of articulatory retraction for /e/ is limited to allow for perceptual recoverability of its front quality.

Relation between height and acoustic stability

- Assuming a continuous relationship between acoustic stability and height, lower vowels are less acoustically stable than higher vowels



[e] can be retracted less than [i] but more than [ü] without losing its perceptual identity.

- Via our model we then predict that [e] is less transparent than [i].

Relation between height and transparency

- Western Hungarian dialects: /e/ has two allophones
  - high-mid [ë] – transparent – selects back suffixes
  - low-mid [e] – opaque – selects front suffixes

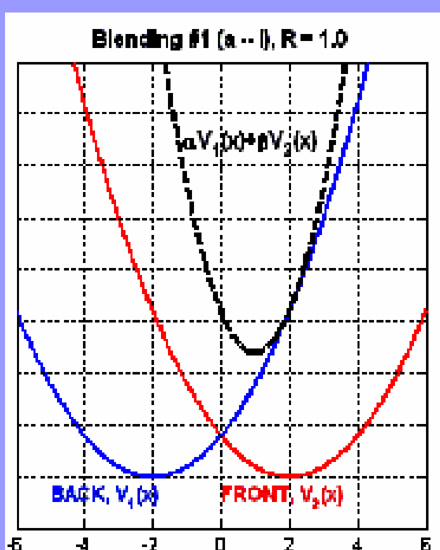
- Cross-linguistic generalization
  - if [e] is transparent, [i] must be also but not vice versa (L. Anderson 1980).

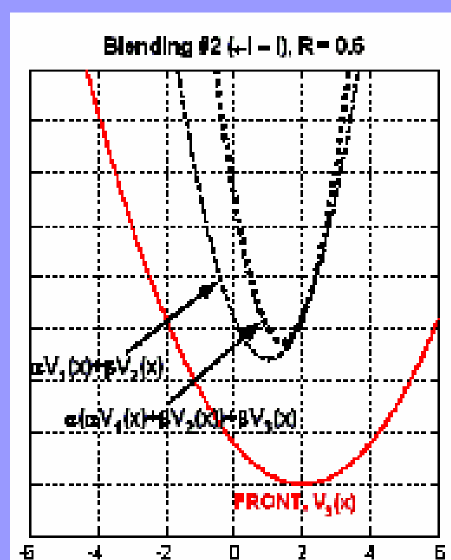
Multiple transparent vowels

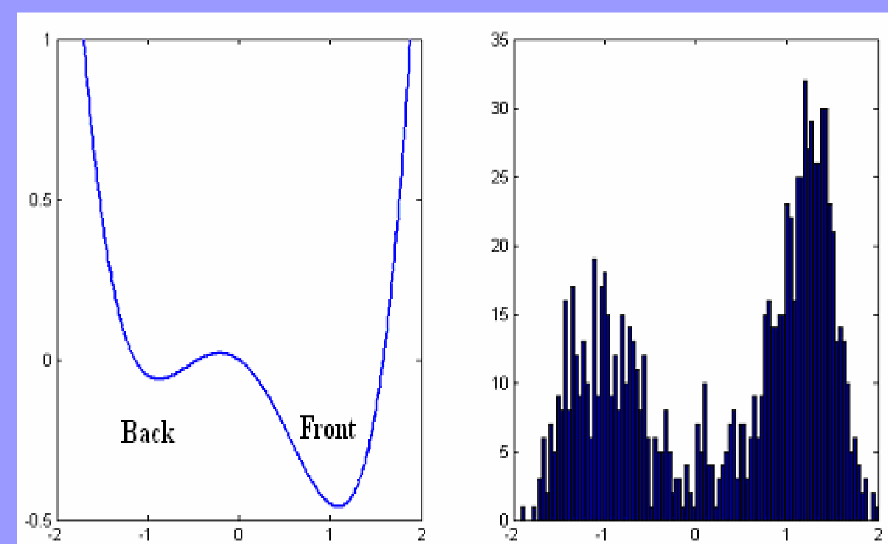
- Generalization: increasing the number of the TVs decreases transparency. Thus BTT stems are more likely to vacillate or take front suffixes than BT stems: *aszpirin – nak / nek*

- This is predicted in our model.

a={uvul wide} $CL_a = 2$	i={pal nar} $CL_i = -2$	i={pal nar} $CL_i = -2$	V={__ wide} CL = ?(a/e)

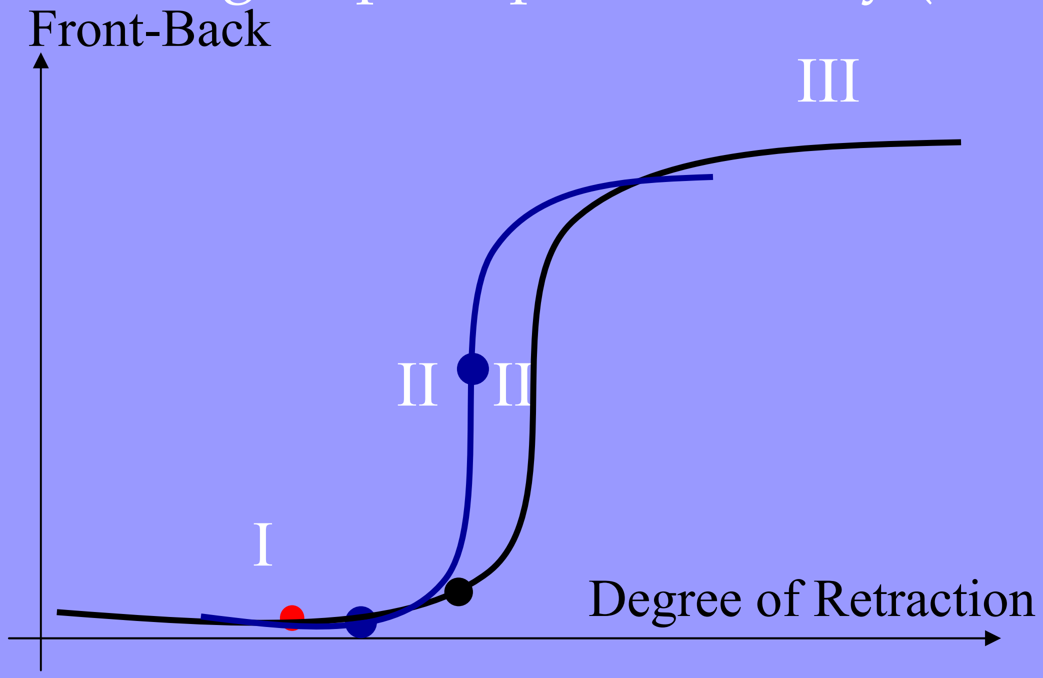


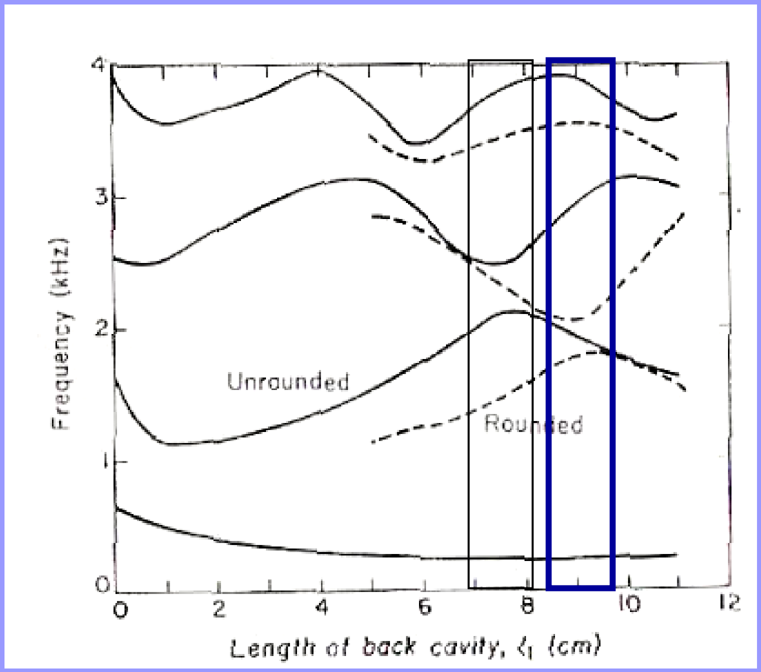




Opacity: minimal retraction

- Generalization: stems with front vowels or front rounded vowels always trigger front suffixes (*emir-hez, parfüm-nek*).
- /ü/cannot be retracted to the same degree as /i/ without losing its perceptual identity (Wood 1986).





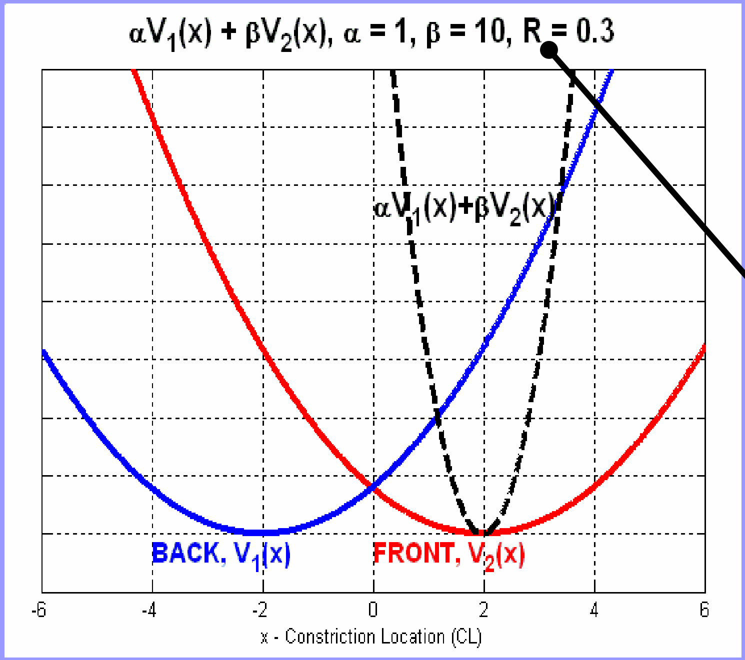
In our model, minimal retraction implies front suffix

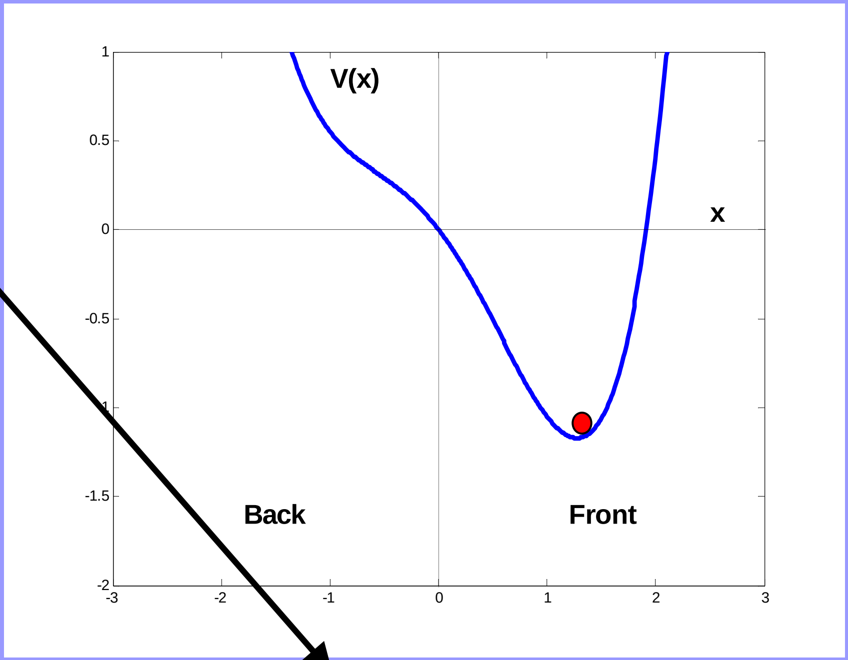
parfüm-nek

a={uvul wide} $CL_a = -2$

ü={pal nar} $CL_i = 2$

V={__ wide} CL = ?(a/e)





$$V(x) = -Rx - x^2/2 + x^4/4$$

Specific conclusions

- The set of transparent vowels is {i, í, é, e}: non-linearity between articulation and perception.
- The notion of locality: respected in the articulatory dimension – experimentally observed retraction.
- Transparent vowels in monosyllabic stems can trigger front and back suffixes: observed sub-phonemic retraction is part of speakers knowledge and can thus have phonological consequences.

Conclusion

- The hypothesis that language is (at least in part) biologically determined (e.g. Lindblom 83, 85; but see also Anderson 81, Ladefoged 83) suggests the use of the mathematics employed by physicists (Haken 77) and biologists (Yates 84) to study complex systems.

- As a small step in that direction, I hope have shown some of the promise of nonlinear dynamics in providing a powerful formal method for addressing the central issue here, the relation between the discreteness of phonological form and the continuity of phonetic substance in which that form is embedded.

Thank you !

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