Qualitative and Quantitative Aspects of Vowel Harmony: A Dynamics Model

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Abstract

A fundamental problem in spoken language is the duality between the continuous aspects of phonetic performance and the discrete aspects of phonological competence. We study a specific instance of this problem in Hungarian vowel harmony. We present a model where continuous phonetic distinctions uncovered by our experiments are linked to the discreteness of phonological form using the mathematics of nonlinear dynamics.

Key words: vowel harmony; phonetics-phonology relation; non-linear dynamics; Hungarian.

1 Introduction

A primary aim in the cognitive science of language is to discover the computational principles underlying our ability to speak. A major problem is how to relate the symbolic or discrete aspects of our speaking competence to their continuous manifestation in terms of vocal tract action. The study of these two aspects of speech has traditionally been pursued under separate domains, the symbolic aspects being the domain of phonology and the continuous aspects being the domain of phonetics.

The problem of the phonology-phonetics relation is an instance of a fundamental problem in cognitive science, namely, the problem of relating the low-dimensional, discrete aspects of cognition to the high-dimensional, vastly detailed aspects of performance. At the heart of this problem one meets a methodological challenge. Computation is embedded in a continuously varying environment. To understand computation we must use inferences based on surface, performance data that have been extracted from specific contexts. Abstracting away from contextual or environmental factors requires an understanding of how computation adapts to different contexts, which in turn assumes an understanding of computation. Kosslyn has aptly dubbed this "the inference problem" for cognitive psychology and emphasizes that surface data are a function of competence with added noise, and both competence as well as the nature of the function mapping competence onto surface data must be studied (Kosslyn, 1978).

In this paper, we follow Kosslyn's approach, focusing on two central questions: How is the discreteness of a phonological system related to the continuity of the speech signal? What kinds of formal tools are best in dealing with this duality? We think that progress on these questions is best achieved when the relation between continuity and discreteness is formalized explicitly for representative language-particular cases. In this paper, we propose a model of how low-level spatial phonetic properties of vowels determine the high-level phonological behavior described as vowel harmony. Our model employs tools made available by the mathematics of non-linear dynamics. Building on previous theoretical and experimental work, we consider if and how changes in appropriate control parameters result in qualitative changes or phase transitions from one stable pattern to another. The key idea is that categorical aspects of linguistic grammars emerge from non-linear interactions of lower-level continuous dynamical systems.

2 Background Notions from Dynamics

We begin by a general mathematical formulation for the simplest class of non-linear dynamical systems, namely, first-order, autonomous dynamical systems (Percival & Richards, 1982). Any such system can be described by a differential equation $\dot{x} = f(x)$, where *f(x)* is a nonlinear function of *x*, *x* is the state of the system, which can be thought of as the position of a particle in an abstract one-dimensional space called the *phase space*, and *f(x)* is the force. For first-order systems, the force can be expressed as a function of the derivative of a *potential V(x)*, $\dot{x} = f(x) = -dV(x)/dx$. An intuitive grasp of the dynamics of our state variable *x* can be inferred by examining geometric properties of *f(x)* or its related potential *V(x)*. For example, consider the behavior of a particle placed in the potential of Figure 1, and assume that the position of our particle, its *x* value, corresponds to the state of the system. The points x_k where $f(x_k) = 0$ represent states of equilibrium – if our particle is placed initially at x_k it remains there for all time. Such points are called *fixed points*. There are two types of fixed points, *stable* and *unstable*. Stable fixed points correspond to the minima of the potential *V(x)* – x_1, x_3 in Figure 1. Around these points *f(x)* is a decreasing function of *x*, or intuitively, the arrows on the x-axis of Figure 1, which show the *flow*, point towards that point. Unstable fixed points correspond to the maxima of the potential *V(x)* – x_2 in Figure 1. Around such points, *f(x)* is an increasing function of x, and the arrows of the flow point away from that point. Stable fixed points are also called *attractors*, and unstable fixed points *repellers*.

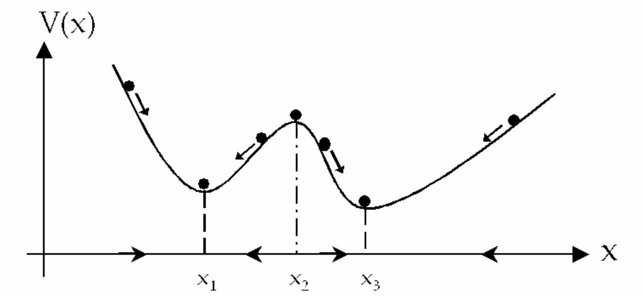

Figure 1 : Potential *V(x)*, attractors x_1, x_3, and repeller x_2 of a simple dynamical system.

At a high-level of description any behavioral pattern can be described by a few parameters whose dynamics are coupled to lower-level subsystems controlling the more specific components. For speech, the high-level description is specified by the macroscopic parameters of phonology (e.g., place and degree of oral constriction, laryngeal state, etc.) and the lower levels correspond to the neuronal, aerodynamic and myodynamic subsystems controlling the speech articulators. Due to the complexity of this organization, noise is inevitably a part of any behavioral phenomenon. Following Haken (1977), we describe noise as a small, random perturbation force pushing the representative point of the system *x*, the position of the particle, back and forth randomly. Mathematically, noise enters the dynamics of high-level parameters as shown in (1), with the additional factor representing Gaussian white-noise of strength *Q*.

$$\dot{x} = f(x) + Noise = -\frac{dV(x)}{dx} + \sqrt{Q}\,\xi_t \qquad (1)$$

The presence of noise introduces stochasticity in the dynamics of the state variable *x*. Consequently, we can only compute the probability of finding *x* within a given interval of *x* values. This probability is described by the probability density function *p(x)* multiplied by the length of the interval. For any first-order dynamical system, there exist methods allowing us to compute the probability distribution function by finding a stationary solution to the Fokker-Planck equation (see Haken 1977; Freidlin & Wentzell 1984). An example of a probability density function corresponding to a bi-stable potential (two attractors present) is shown below.

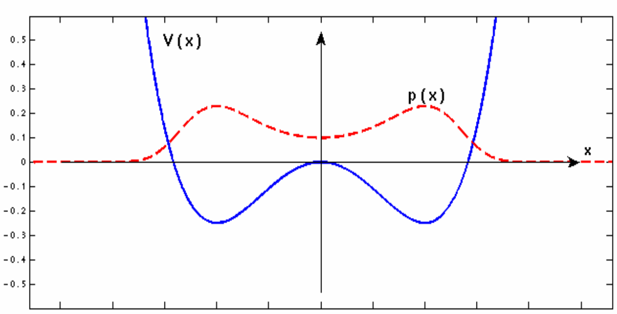

Figure 2 : *V(x)* and probability density function *p(x)*.

It can be seen that the probability of finding the system around the mean states of the two attractors is quite high. The probability to find the system at some other point decreases quickly as we move away from the mean states but it may not be zero. In short, the preferred modes of essential parameters, the attractors, are resistant to noise in a probabilistic sense.

A key notion of non-linear dynamics is non-linearity. A system exhibits non-linearity when large or discontinuous changes can be observed in the behavior of that system as some control parameter varies smoothly. In a prototypical example of this situation from speech, Stevens (1972) has argued that the relation between articulatory parameters and their acoustic/auditory output is 'quantal' in the following sense. There are certain ranges of articulatory parameter variation within which the acoustic output remains relatively stable. In other ranges, however, small variations in the articulatory parameter cause large (non-linear) changes in the quality of the acoustic output. Put differently, gradual changes in some articulatory parameters lead to qualitatively distinct acoustic outputs. In another example from biological coordination, Kelso (1995) 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. But 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. In these examples, then, scaling of a continuous parameter results in qualitative changes in the behavior of a dynamical system, the shift from one stable mode to another. Such qualitative changes are commonly referred to as bifurcations by mathematicians or phase transitions by physicists.

We can illustrate the fundamental property of non-linearity with a simple mathematical example. Consider a force function parameterized by a so-called 'control' variable k and specified by $f(x,k) = -kx - x^3$. We are interested in what happens to x – ultimately the solutions to our equation – as the control parameter k is varied. The potential corresponding to our force function $V(x,k) = kx^2/2 + x^4/4 + (C)$ is plotted in Figure 3 for various values of *k*. For $k > 0$, as shown in the top row of Figure 3, the control parameter changes but the system retains a qualitative sameness of form. The minimum in the valley of *V(x)* represents the stable fixed point of *x*. This is the attractor, the preferred region within the continuum of *x* where the particle ends up. But as *k* passes through zero, suddenly a qualitative change occurs. The system changes to a bistable regime, showing two attractors – a bifurcation. Within the ranges $k > 0$ or $k < 0$, variation in k does affect smoothly the attractor landscape (this is known as scaling). For example, from $k = 4$ to $k = 1$ there is a change in the stability of the attractor, as is evident from the flattening of the walls in the attractor's basin.

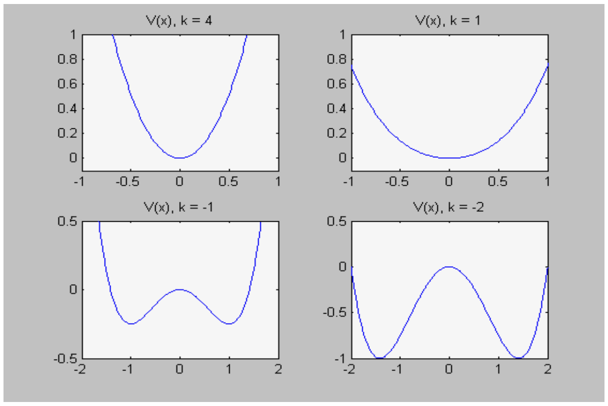

Figure 3: Potential as a function of a control variable k.

In the next two plots, as we move from $k = -1$ to $k = -2$, the stable points drift apart smoothly. But as long as k does not pass the critical value of *0*, that is, within the ranges $k > 0$ or $k < 0$, the macroscopic form of the system remains unaltered. It is only when variation in *k* passes a critical value (here, $k = 0$) that a qualitative change takes place.

Next, we consider how the concepts just introduced can be applied to our specific problem, the relation between continuous and discrete dimensions of speech patterns in vowel harmony.

3 Dynamics Applied to Vowel Harmony

Vowel harmony is a systematic regularity found in many languages by which vowels in a word must agree in terms of certain phonetic properties. For example, vowels in Hungarian words tend to be drawn either from the set of vowels articulated with a frontward movement of the tongue body ([i í e é ö ő ü ű]) or from the set of vowels articulated with a backward movement of the tongue body ([u ú o ó a á]). In our examples, we will be using Hungarian orthography where the acute accent denotes length, and the umlaut denotes front round vowels. In terms of phonological features, the 'front' vowels [i í e é ö ő ü ű] share the feature [–back], and the 'back' vowels [u ú o ó a á] share the feature [+back].

The phonological consequences of vowel harmony are most readily observed in suffix vowel alternations where the [±back] quality of the suffix vowel is determined by the [±back] quality of the stem vowel. For example, the Dative suffix alternates between a front /e/ and a back /a/ as a function of the stem vowel: *ház-nak* 'house-Dative' but *kéz-nek* 'hand-Dative'. Because the stem vowel determines the suffix form, it is called the trigger and the suffix vowel the target of the harmony process.

Phonetic investigations have shown that vowels exert influences on neighboring vowels across intervening consonants (Öhman, 1966). Such 'V-to-V coarticulation' effects are observed as quantitative, phonetic patterns whose degree varies depending on the quality of the intervening consonants, stress distribution, and other factors (e.g., Recasens, 1999). V-to-V coarticulation effects are generally assumed to provide a natural phonetic basis to vowel harmony, a categorical version of V-to-V coarticulation where the suffix vowels are maximally coarticulated with the stem vowels (Fowler, 1983; Ohala, 1994).

In many languages with vowel harmony, however, one also finds vowels that disagree with their adjacent vowels. These vowels appear in so-called disharmonic stems and have been traditionally divided into two categories. Transparent vowels may intervene between the trigger and the target vowels even when they bear the opposite value for the harmonizing feature. For example, the /í/ in *papír* 'paper' is transparent because *papír* selects [+back] suffixes, e.g., *papír-nak* 'paper-Dative', in agreement with the [+back] value of the initial stem vowel and despite the intervening [–back] value of the /í/. Opaque vowels also show disagreement with the preceding stem vowel(s) but require a local agreement with the following suffix vowel. For example, the front rounded /ü/ in *parfüm* 'perfume' is opaque because it selects the [–back] version of the suffix, *parfüm-nek* 'perfume-Dative', and disagrees with the preceding [+back] stem vowel.

Hungarian transparent vowels, then, present a challenge to the proposal that vowel harmony has its basis in continuous V-to-V coarticulation effects between consecutive vowels. However, the assumption that transparent vowels do not participate in vowel harmony is based on impressionistic auditory observations. There has been no systematic investigation of the phonetic characteristics of these vowels. The experiments described below are aimed at filling this gap in our knowledge.

3.1. Experiments on Transparent Vowels

In Hungarian, the transparent vowels consist of the front unrounded vowels {/i/, /í/, /é/, /e/}. In addition to allowing agreement between vowels that are not in consecutive syllables (e.g., *papír-nak*), three stable distributional patterns have been observed in the phonology of transparent vowels (e.g., Vago, 1980; Kaun 1995; Benus, 2005). First, stems with only transparent vowels (T stems) may trigger both front and back suffixes. The majority of T stems trigger front suffixes (*cím-nek* 'address-Dative', *szél-nek* 'wind-Dative'), but approximately sixty monosyllabic T stems trigger back suffixes (*síp-nak* 'whistle-Dative', *cél-nak* 'aim-Dative'). Second, stems where a back vowel precedes one or two transparent vowels (BT and BTT stems respectively) may trigger vacillation in suffixes. For example, Hungarian speakers accept both *hotel-nek* and *hotel-nak* as acceptable renderings of 'hotel-Dative'. Finally, increasing the number of the transparent vowels that follow a back vowel decreases the likelihood of selecting back suffixes. For example, *kabin* 'cabin' selects back suffixes (*kabin-nak*) but *aszpirin* 'aspirin' vacillates (*aszpirin-nak*, *aszpirin-nek*).

To understand the nature of transparent vowels, we conducted for the first time a systematic study of their articulatory properties using two experimental techniques.

The first technique, EMMA (Electro-magnetic Midsagittal Articulometry, Perkell et al. 1992), uses an electro-magnetic field to track the movements of small receivers attached to the articulators.

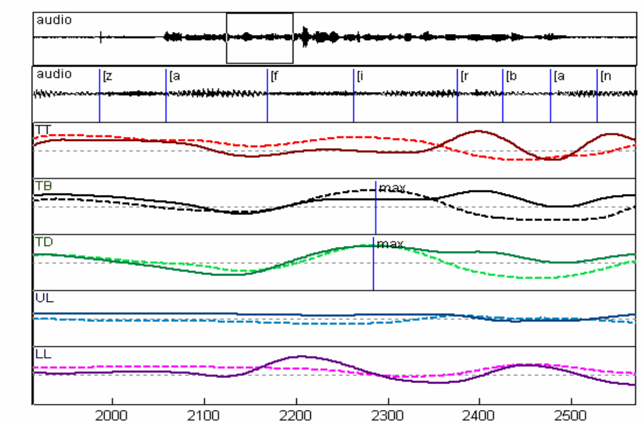

Figure 4: Articulator kinematics as recorded with EMMA.

Figure 4 shows the horizontal (dashed) and vertical (solid) trajectories of receivers attached on the tongue tip (TT), body (TB), dorsum (TD), and the upper and lower lips (UL, LL) during the production of *zafír-ban*. To quantify the spatial properties of transparent vowels (such as *í* in *zafír-ban*), we measured the maximal horizontal advancement of the TB and TD receivers during the production of the transparent vowel ('max' in Figure 4).

Our second technique uses ultrasound (Stone 1997) to provide 2D images of almost the complete surface of the tongue at its midline, during the production of transparent vowels. First, the frame with the most advanced tongue position was determined as the target frame (left, Figure 5). The tongue edge in this target frame was then traced using methods of Iskarous (in press) by determining the points of maximal contrast within the selected region (middle panel, Figure 5), and fitting multiple snakes into a curve that balances the distance of the points from the curve with the curve's smoothness (right panel, Figure 5).

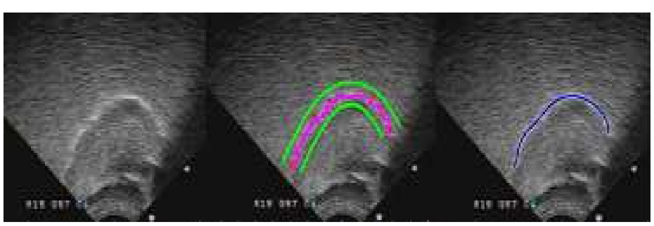

Figure 5: Static tongue surfaces captured with ultrasound, and extraction of tongue contours.

Stimuli consisted of carefully selected pairs of words where transparent vowels appear in similar consonantal environments and are followed by either front or back suffixes. For example, the /i/ in *Tomi-hoz* 'Tom-Diminutive-Allative' was compared to the /i/ in *Imi-hez* 'Imre-Diminutive-Allative'. EMMA data from three subjects and ultrasound data from one subject were analyzed.

For all subjects and both methodologies, the tongue position during transparent vowels in stems triggering back suffixes was slightly, but significantly, more retracted than the tongue position during transparent vowels in stems triggering front suffixes. The significant effect of harmonic environment ranged between 0.4 and 2.5 mm for various measurements. Figure 6 shows the effect of back harmony (darker, dotted shapes) vs. front harmony (lighter, solid lines) context with the ultrasound data.

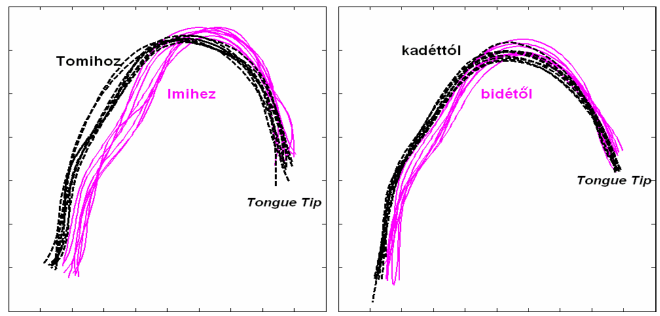

Figure 6: Effect of environment on /i/ (left) and /é/ (right).

In addition, transparent vowels in T stems produced in isolation (with no overt suffix) were more retracted in those stems that select back suffixes than in the stems selecting front suffixes. For example, /í/ in words like *síp* 'whistle' was more retracted than /i/ in words like *cím* 'address'; the former triggers back suffixes while the latter triggers front suffixes.

The overarching generalization from the phonetic and phonological data is that fine differences in articulatory retraction of transparent vowels are linked to an alternation in the suffix form. The advanced/retracted version of a transparent vowel selects the front/back suffix, respectively. This systematic correlation between the phonetics and phonology of transparent vowels argues for an approach in which the phonetic backness of the stem-final vowel plays a role in determining the phonological form of the suffix. More broadly, we require an approach that integrates continuous and discrete properties of transparent vowels within a unified system.

3.3. Dynamic Model of Suffix Selection

Formally, the relation obtained between degree of retraction and suffix selection is nonlinear. Small changes in degree of retraction can cause large (nonlinear) changes in suffix form. In other words, we require a formal language that expresses this nonlinear nature of the relation between retraction degree and suffix selection. This is the language of nonlinear dynamics.

In the proposed dynamic model, the two discrete forms of an alternating suffix (e.g., Dative *-nak* vs. *-nek*) are mapped to attractors of a single dynamical system. To model the dependence between the continuous parameter of retraction degree R of the stem-final vowel and the discrete form of the suffix, we require that the choice of the suffix attractor be modulated by variation in R. Following the discussion in section 2, these ideas can be stated in the form of equation $\dot{x} = f(x, R) + Noise$. This equation expresses the temporal evolution of the suffix vowel constriction location, denoted by x, as a nonlinear function f of the current state x and the control parameter of retraction degree R.

What determines *f(x,R)*? An appropriate dynamical system for the suffix alternation is required to have (at least) a bistable (two-attractor) potential to capture the presence of two stable forms of a suffix, front and back. A polynomial of degree less than three allows for at most one attractor (Arnold 2000). Hence, the simplest model for suffix choice can be specified by a cubic polynomial. A good candidate for *f(x,R)* is the 'tilted' anharmonic oscillator, whose dynamics are described by $f(x,R) = (1-R) + x - x^3$ (Gafos, in press). Since $\dot{x} = f(x,R) = -dV(x,R)/dx$, we can compute the potential landscape $V(x,R) = (R-1) - x^2/2 + x^4/4$, by integrating *f(x,R)*. Using concepts from section 2, the value of the constriction location for a suffix vowel is interpreted by the position of a particle running downhill in this potential and the asymptotic behavior of x in this equation can be visualized by looking at the simulations shown Figure 7. For exposition purposes, in our simulations we (arbitrarily) map the back form of the suffix (*–nak*) to an attractor around $x = -1.4$, and the front form (*–nek*) to an attractor around $x = 1.4$. The control parameter R varies between 0 and 2, corresponding to minimal and maximal retraction, respectively.

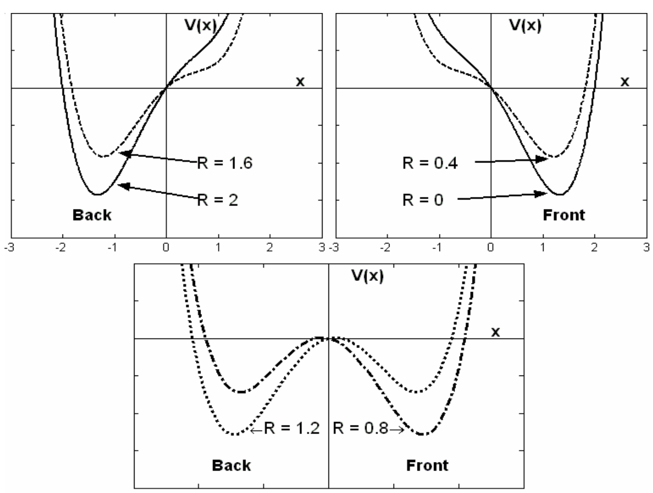

Figure 7: Suffix form as a function of retraction degree R.

The graph in the upper left simulates suffix selection in stems like *Tomi–*, which select back suffixes. We observed experimentally that in such stems, the transparent vowel is retracted. In our model, retraction enters the dynamics via R. The function *f(x,R)* for a range of R values, $R \approx 2$ (significant retraction), provides a potential *V(x,R)* with an attractor close to the value of constriction location $x = -1.4$ (BACK), corresponding to the back variant of the suffix. The probability that a particle left in this potential ends up in the vicinity of the BACK attractor is very high. Because the position of the particle represents the [±back] form of the suffix, it is predicted that the suffix is back, e.g., *Tomi-hoz.*

The graph in the upper right panel shows how the potential *V(x)* changes for stems whose final vowels show minimal or no retraction like *Imi–*. For minimal retraction, modeled as $R \approx 0$, a qualitative change is evident in the shape of *V(x)*. The BACK attractor has been replaced by a FRONT attractor that corresponds to the front variant of the suffix. A stem with minimal retraction of its final vowel is thus predicted to select front suffixes, e.g., *Imi-hez*.

The graph in the bottom panel of Figure 7 shows the behavior of the system for intermediate values of the parameter R ($R \approx 1$). In nonlinear dynamics, a change from one macroscopic state of the system to another implies an intermediate stage of fluctuation. We see that there are now two minima representing the presence of two stable states, FRONT and BACK. For intermediate values of R thus our model predicts that the suffix can vary between a front and a back version. To see this, we must consider the effects of noise and initial position of the particle. For example, consider a particle at a position around (0,0) in any of the potentials of the bottom panel. Due to the random kicks introduced by the fluctuations, the particle will end up either in the FRONT or BACK attractor, and thus both front and back suffix are possible. As discussed earlier, we do in fact find two sources of suffix vacillation in Hungarian: stems where a back vowel is followed by the low /e/ (e.g., *hotel*) and stems where a back vowel is followed by two transparent vowels (e.g., *aszpirin*).

Figure 7 illustrates the fundamental property of non-linearity: equal changes in the control parameter (degree of retraction) do not always effect proportionately equal changes in the essential parameter (quality of the suffix). For example, both $R = 2$, and $R = 1.6$ result in qualitatively the same potential, with the single BACK attractor, albeit with different stability. But as R changes from $R = 1.6$ to $R = 1.2$ or from $R = 0.4$ to $R = 0.8$ the potential changes qualitatively from a mono-stable regime (upper panels) to a bi-stable regime (lower panel). Hence, a change of R by $\Delta = 0.4$ leaves the qualitative form of the system unaltered within a certain region of the control parameter space. But within a different region of control parameter values, a change of the same magnitude causes a qualitative change in the behavior of the system.

Our model then provides a qualitative match to the Hungarian data by predicting that stems with minimal retraction of their final vowel trigger front suffixes (e.g., *Imi* and *parfüm*), stems with intermediate degree of retraction trigger vacillation (e.g., *hotel* and *aszpirin*), and stems with significant retraction trigger back suffixes (e.g., *Tomi* and *papír*). These differences in stem-final vowel retraction among the different stem classes have been explicitly derived in a model of coarticulation between adjacent stem vowels (Benus 2005). For example, the differences in retraction degree of /i/, /e/, and /ü/ when they follow a back vowel are linked to quantal properties of these front vowels. More specifically, the low and somewhat retracted position of /e/'s tongue body and the lip-rounding of /ü/ allow for only limited retraction when these vowels coarticulate with a preceding back vowel. With respect to stems where a back vowel is followed by multiple transparent vowels, Benus (2005) argues that the retraction degree of the stem-final vowel in *aszpirin* is smaller than that of the stem-final vowel in *Tomi*. This is based on the fact that the transparent vowel in the stems like *Tomi* is directly preceded by a back vowel while the stem-final transparent vowel in stems like *aszpirin* is adjacent locally to a slightly retracted front vowel and only non-locally to a back vowel.

Given the lawful relationship between retraction degree and suffix form, our model thus accounts for the patterns of suffix selection in stems like *Tomi* (back suffix) vs. *Imi* (front suffix). The model also makes plausible and testable predictions for the patterns of opacity (*parfüm*) and vacillation (*hotel*, *aszpirin*). Currently, we are designing an experimental paradigm to test these predictions. Overall then, the proposed model builds on rigorous phonetic methods for phonological research, provides an explicit link between the quantitative and qualitative aspects of the relevant speech patterns, and makes specific predictions leading to new experimental studies.

4 Conclusion

We presented a model that allows one to relate continuous phonetic distinctions to discrete phonological form using the mathematics of nonlinear dynamics. In Hungarian transparent vowels, small changes in tongue body constriction location are related to qualitative changes in the form of the suffix. This is the fundamental property of nonlinearity, a hallmark of complexity in natural systems in general and in phonetics-phonology in particular. In the language of nonlinear dynamics, it is possible to model the relation between the discreteness of phonological form and the continuity of phonetic substance in which that form is embedded.

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References

Arnold, V. I. (2000). Nombres d'Euler, de Bernoulli et de Springer pour les groupes de Coxeter et les espaces de morsification: le calcul de serpents. In É. Charpentier & N. Nikolski (Eds.), *Leçons de Mathématiques d'Aujourd'Hui* (pp. 61-98). Paris: Cassini.

Benus, S. (2005). *Dynamics and transparency in vowel harmony*. Doctoral dissertation, Department of Linguistics, New York University.

Fowler, C. (1983). Converging sources of evidence for spoken and perceived rhythms of speech: cyclic production of vowels in sequences of monosyllabic feet. *Journal of Experimental Psychology*, 112, 384-412.

Freidlin, M. & Wentzell, A. (1984). *Random perturbations of dynamical systems*. New York: Springer-Verlag.

Gafos, A. (In press). Dynamics in grammar: Comments on Ladd and Ernestus & Baayen. In L. Goldstein, D. Whalen, C. Best (Eds.), *Varieties of Phonological Competence (Laboratory Phonology 8)*. Berlin, New York: Mouton de Gruyter.

Haken, H. (1977). *Synergetics, an introduction*. Heidelberg: Springer-Verlag.

Iskarous, K. (In press). Edge detection and shape measurement of the edge of the tongue. *Clinical Linguistics and Phonetics.*

Kaun, A. (1995). *The typology of rounding harmony: An Optimality Theoretic approach*. Doctoral dissertation, UCLA. [Published as UCLA Dissertations in Linguistics, No. 8.].

Kelso, S. (1995). *Dynamic patterns: the self-organization of brain and behavior*. Cambridge, MA: MIT Press.

Kosslyn, S. M. (1978). Imagery and internal representation. In E. Rosch & B. Lloyd (Eds.), *Cognition and categorization* (pp. 217-257). Hillsdale, NJ: Erlbaum Associates.

Ohala, J. (1994). Towards a universal, phonetically-based, theory of vowel harmony. In *Proceedings of International Conference on Spoken Language Processing* (pp. 491-494).

Öhman, S. (1966). Coarticulation in VCV utterances: Spectrographic measurements. *Journal of the Acoustical Society of America*, 39, 151-168.

Percival, I. & Richards, D. (1982). *Introduction to dynamics*. Cambridge: Cambridge University Press.

Perkell, J., Cohen, M., Svirsky, M., Matthies, M., Garabieta, I., & Jackson, I. (1992). Electromagnetic midsaggital articulometer (EMMA) systems for transducing speech articulatory movements. *Journal of the Acoustical Society of America*, 92, 3078-3096.

Recasens, D. (1999). Lingual coarticulation. In W.J. Hardcastle & N. Hewlett (Eds.), *Coarticulation: Theory, Data and Techniques in Speech Production* (pp. 78-104). Cambridge: Cambridge University Press.

Siptár, P. & Törkenczy, M. (2000). *The phonology of Hungarian*. Oxford: Oxford University Press.

Stevens, K. (1972). The quantal nature of speech: evidence from articulatory-acoustic data. In E. David & P. Denes (Eds.), *Human Communication: A Unified View* (pp. 51-66). New York: McGraw-Hill.

Stone, M. (1997). Laboratory techniques for investigating speech articulation. In J. Hardcastle & J. Laver (Eds.), *The Handbook of Phonetic sciences* (pp. 11-32). Oxford: Blackwell.

Vago, R. M. (1980). *The sound pattern of Hungarian*. Washington: Georgetown University Press.