

Modeling the Gradient Evolution and Decay of Harmony Systems

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1 Introduction

While vowel harmony processes are widespread and well-known, it remains unclear how vowel harmony emerges and decays. The most concrete proposals suggest that vowel harmony derives from coarticulation (Ohala 1994; Przedziecki 2005), but few works have focused on decay (Binnick 1991; Dombrowski 2013; McCollum 2015). Of those works, none formalize the decay process, leaving much unanswered. For instance, if harmony emerges from coarticulation, does it similarly decay into coarticulation? Stated differently, are the pathways of emergence and decline symmetrical?

These questions touch on the interface between phonology and phonetics. If vowel harmony is a cognitive process, as is often assumed, it is difficult to reconcile how phonological harmony diachronically interacts with phonetic implementation (cf. Ohala 1994), which is assumed to be physically rather than cognitively constrained. One possibility is to unify both phonology and phonetics in one formalism (Flemming 2001). This approach is adopted in herein. Like Flemming (2001), the analysis below uses weighted scalar factors to predict the degree of coarticulation in Kazakh labial harmony, where degree of coarticulation is a quantitative measure used to describe both variable and categorical assimilations.

The paper is organized as follows. In Section 2, I present data from contemporary colloquial Kazakh. In Section 3, I define the set of relevant forces and their formal implementation in the analysis. Insights from the synchronic analysis are extrapolated in Section 4 to address the evolution of vowel harmony more generally. Section 5 compares the model outlined herein with constraint-based grammars (Prince & Smolensky 1993; Legendre et al. 1990) and Articulatory Phonology (Browman & Goldstein 1986, 1992). In Section 6, I conclude the paper.

2 Gradient harmony in Kazakh

The Kazakh vowel inventory consists of at least the following eight vowels: /ɑ ɔ ʊ ʊ e ø ɪ ʏ/ (Kirchner 1998:319; Vajda 1994; Kara 2002; Bowman & Lokshin 2014). Up to three other vowels may be part of the underlying inventory, /æ i u/, but these vowels do not figure prominently in the harmony system, and therefore are not further discussed. Two harmony processes affect the distribution of vowels in Kazakh, palatal and labial harmony. Palatal harmony is almost always obeyed, but labial harmony is less pervasive.

2.1 Contemporary labial harmony In some early work labial harmony was reported to be co-extensive with the word in Kazakh (Menges 1947:59-64, Korn 1969:102-103). However, other writers have observed a reduced domain of application. For instance, Balakaev (1962:102) notes that second syllable vowels (excluding /ɑ/) systematically undergo harmony while third- and fourth- syllable vowels are realized with diminishing labialization (see also Dzhusisbekov 1980; Vajda 1994; Kirchner 1998:320-321; Muhamedowa 2015:282). Furthermore, McCollum (2015) reports even more reduced labial harmony in contemporary Kazakh. In (1) below observe first that while harmony was almost exceptionless in the older

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variety of the language reported in Korn (1969), in contemporary Kazakh harmony typically affects root-internal, but not suffix vowels (1a-h). Second, harmony affects high vowels only (1i-m), and lastly, [ɔ] does not regularly trigger harmony (1o).

(1)	Older	Contemporary	Gloss
a.	kʏn-dʏ	kʏn-dɪ	day-ACC
b.	kʏn-dø	kʏn-de	day-LOC
c.	øt-tʏ	øt-tɪ	gall.bladder-ACC
d.	øt-tø	øt-te	gall.bladder-LOC
e.	qʊs-tʊ	qʊs-tuɪ	bird-ACC
f.	qʊs-ta (*qʊs-tə)	qʊs-ta	bird-LOC
g.	qʊs-tø	qʊs-tuɪ	hut-ACC
h.	qʊs-ta (*qʊs-tə)	qʊs-ta	hut-LOC
i.	ʒʏzʏk	ʒʏzʏk	ring
j.	tʏløk	tʏlek	graduate
k.	køsyk	køsyk	desert.carrot
l.	tøbø	tøbe	hill
m.	qʊløn	qʊløn	colt
n.	qʊlɑq (*qʊlɔq)	qʊlɑq	ear
o.	qʊzʊ	qʊzʊ	lamb
p.	bʊlɑt (*bʊlɔt)	bʊlɑt	steel

It is evident from the examples above that some triggers more reliably initiate harmony than others in contemporary Kazakh. Following McCollum (2016), I treat varying degrees of trigger strength as a dispersion-related consequence for harmony. In short, the more dispersed a given vowel is from its unrounded harmonic counterpart, the less reliably it will initiate harmony (see also Kaun 1995, 2004 for a weakness-motivated analysis of labial harmony).

2.2 *Phonetic factors affecting harmony* In addition to the above three restrictions on harmony, several phonetic factors also modulate the application of labial harmony in Kazakh. The two factors most salient are intervening consonant duration and phonetic labialization. With regard to consonant duration, stops and liquids are shorter than nasals, which are shorter than fricatives. Specifically, the duration of intervening consonants is negatively correlated with labial harmony, such that an increase in consonantal duration is associated with diminished harmony. Thus, labialization is more likely to occur across a single lateral, as in (2a,c), than across a fricative, seen in (2b,d).

(2)	a.	øl-e-dɪ ~ øl-ø-dɪ	‘die-NPST-3’
	b.	øʂ-e-dɪ	‘grow-NPST-3’
	c.	kʏl-e-dɪ ~ kʏl-ø-dɪ	‘laugh-NPST-3’
	d.	tʏs-e-dɪ	‘descend-NPST-3’

As for phonetic labialization, the labial segments, [p b m w ʊ], typically trigger low-level lip rounding of nearby segments. The effect of these segments is asymmetrical, where [ʊ w] trigger more reliable rounding than [p b]. This could be tied to something more abstract like sonority, or to something more physical like duration. For our purposes, it is important to note that labial segments may trigger coarticulatory rounding that interacts with phonological harmony. In (3) below, non-initial round vowels are more likely to occur before [m] than before [ŋ].

(3)	a.	køl-ɪ-m ~ køl-ʏ-m	‘lake-POSS-1’
	b.	køl-ɪ-ŋ	‘lake-POSS-2’

In (3b), labialization of /ɪ/ is not ungrammatical, but once again, is less reliable than in (3a). In (4b), the high round vowel of the gerundial suffix, [ʊ], triggers regressive rounding of the passive morpheme, even

after [ɔ], which, as noted above, does not typically trigger harmony. The round vowel in GER thus triggers coarticulatory rounding on PASS

- (4) a. qɔs-ʉl-du ‘add-PASS-PST.3’
 b. qɔs-ʉl-ʉw ‘add-PASS-GER’

The effect of GER, the only round vowel that may occur independent of harmony in non-initial syllables, is schematized in (5) below. In (5a), the passive morpheme vowel is not rounded between an unrounded root vowel and GER. In (5b) the high vowel in the passive morpheme optionally undergoes rounding after round vowels. In (5c), however, the vowel of the passive morpheme is usually rounded if both surrounding vowels are round. This is an instance of what Lionnet (2014) calls “subphonemic teamwork.”

- (5) a. /- - +/ → [- - +] as-ʉl-ʉw ‘reach-PASS-GER’
 ter-ɪ-ɣw ‘gather-PASS-GER’
 b. /+ - -/ → [+ -/+ -] qɔr-ʉl-du ~ qɔr-ʉl-du ‘construct-PASS-PST.3’
 kɔr-ɪ-dɪ ~ kɔr-ɪ-dɪ ‘see-PASS-PST.3’
 c. /+ - +/ → [+ + +] qɔs-ʉl-ʉw ‘add-PASS-GER’
 kɔr-ɪ-ɣw ‘see-PASS-GER’

Coarticulatory rounding may also obtain when a high vowel is flanked by the GER morpheme and a labial consonant, as in (6c). Thus, both vowels and consonants may initiate coarticulatory rounding.

- (6) a. as-ʉw-ʉ ‘reach-GER-POSS.3’
 b. as-ʉw-ʉ-ŋ ‘reach-GER-POSS.2’
 c. as-ʉw-ʉ-m ‘reach-GER-POSS.1’

In summary, the most significant driving force in non-initial labialization is harmony. Secondly, non-initial vowels may be rounded under in the influence of proximate labial segments, as exemplified above in (5-6). These two forces, phonological harmony and phonetic coarticulation thus motivate labialization in the language. These forces are mitigated by intervening consonant duration, as well as by morphological constituency and vowel height. Tautomorphemic harmony is typically applied, but harmony across morpheme boundaries is decidedly variable, as in (1) above. Additionally, high vowels undergo harmony more often than non-high vowels, as in (1i-p). These factors will be used in Section 3 to construct an analysis of coarticulation in contemporary Kazakh.

3 Analysis

When the data presented in Section 2 is compared to previous accounts of Kazakh it is clear that labial harmony is decaying in the contemporary language. Earlier writers reported categorical (i.e. phonological) factors motivating and blocking harmony, whereas the description above and in McCollum (2015, 2016) casts harmony in more phonetic (i.e. gradient) terms. The question that arises is- how do phonetics and phonology interact in transitional harmony systems? It has been argued that harmony evolves from phonetic coarticulation (Ohala 1994; Przedziecki 2005; cf. though Nevins 2010:209 n.1). Similarly, it has been argued that phonetic similarity facilitates the acquisition of a vowel harmony pattern (Skoruppa et al. 2011). However, these suggestions do not account for the differing factors that modulate phonetic coarticulation and phonological harmony. In this Section, I present a unified analysis of coarticulation and vowel harmony by treating both processes as differing only in magnitude of effect (Przedziecki 2005), and by predicting that effect quantitatively.

3.1 The coarticulatory framework For the analysis presented below, it is of crucial importance to understand the way in which coarticulation is operationalized herein. While McCollum (2016) addresses the variable effects of harmony using frequency of attestation (e.g. [qɔzʉ] occurs nine of ten times), this paper frames gradience in acoustic terms. Moreover, I assume that round vowels that surface via harmony do not differ phonetically from underlyingly round vowels (Zsiga 1997:234-235). Thus, the output of

harmony should approximate the acoustic characteristics of underlying, in this case initial-syllable vowels. Labialization typically depresses both F2 and F3 (Ladefoged 2001:41,46), but McCollum (2015), found that the addition of F3 did not significantly improve vowel discrimination over a model that used only F1-F2. Therefore, coarticulation in non-initial syllables is defined herein as the difference between mean F2 of the relevant [\pm round] harmonic pair in initial syllables. Mean F1-F2 values in Hertz for initial-syllable vowels (N=2,496) were converted to ERB and then normalized (Labonov 1971). The resulting values are presented below in Table 1 with accompanying delta F2. Note below that [a] and [ɔ] were excluded. As previous studies report no labialization of /a/ to [ɔ] non-initially, this context was removed from the analysis. In this way the analysis focused only on the contexts where harmony has been attested in previous descriptions of the language.

Table 1: Mean normalized F1-F2 (in z-scores) with standard deviations

Vowel	Mean F1 (SD)	Mean F2 (SD)	Δ F2
u	0.117 (0.657)	0.103 (0.272)	.767
o	-0.007 (0.587)	-0.664 (0.353)	
e	-0.637 (0.375)	1.196 (0.265)	1.137
ø	-0.595 (0.399)	0.059 (0.482)	
ɪ	-0.542 (0.532)	0.745 (0.227)	0.373
ɣ	-0.788 (0.459)	0.372 (0.388)	

Throughout the analysis non-initial vowels are written according to Turkological convention, with I representing high vowels and E representing non-high vowels. Alongside this representation, the roundness of a vowel is represented by its degree of coarticulation, which is determined by subtracting the mean F2 of that vowel from the mean F2 of its unrounded harmonic counterpart in initial-syllable position. If the difference between mean F2 of a given vowel and its initial unrounded counterpart approximates the difference between the relevant [\pm round] harmonic pair in initial position, then the vowel in question is assumed to undergo full assimilation.¹ Treating the modulation of F2 in this manner results in a continuous scale of coarticulation that, while offering a test of the model's accuracy, is not that intuitively meaningful. Therefore, continuous variables were discretized on an integer scale between 0 and 5, where 0 represents no coarticulation and 5 indicates full assimilation. Despite discretizing the acoustic space, this still does not necessarily align with what is perceptually relevant. Given the lack of perceptual studies on Kazakh, these approximations must suffice for the present.

To illustrate the above procedure, take the second syllable vowel in [qɔzI]. The mean normalized F2 of this vowel (N=10) was -0.034z. Mean F2 of [u] was .103z and mean F2 of [o] was -0.664z. The difference between mean [u] and [o] was divided by 5, producing a value, .153z, that corresponds to 1 degree of coarticulation for this particular vowel pair. As the difference between the second vowel in [qɔzI] and [u] was .137z, this difference equaled .894 degrees of coarticulation. This value was rounded to 1, producing a coarticulatory representation for this vowel [qɔzI (1)]. This procedure was carried out for every word containing an initial round vowel (N=1,548) in the corpus, producing a list of 175 contexts, each represented by an average of 8.85 tokens per form. Average coarticulation for each second- and third-syllable vowel in a given context is exemplified in Table 2 below.

¹ Video and acoustic data for all vowels were further inspected to identify F2 depression due to centralization (for front vowels) or general backing that did not relate to labialization. All tokens with reduced F2 not due to rounding were removed.

Table 2: Average degree of coarticulation by context (target vowels are underlined)

Context	Gloss	Degree of coarticulation	Context	Gloss	Degree of coarticulation
kɔm <u>ɪ</u> r	coal	5	qɔs-t <u>ɪ</u> -m	add-PST-1S	2
kyl-d <u>ɪ</u>	laugh-PST.3	3	sɔj <u>ɪ</u> -p	speak-CVB	1
kyl-E-d <u>ɪ</u>	laugh-NPST-3	1	qɔs-ɪp-t <u>ɪ</u>	add-CVB-3	1
kyl-E-d <u>ɪ</u>	laugh-NPST-3	0	qɔs-ɪp-t <u>ɪ</u>	add-CVB-3	0
ɔl-E-d <u>ɪ</u>	die-NPST-3	1	kyn-n <u>ɛ</u> n	day-ABL	2
ɔl-E-d <u>ɪ</u>	die-NPST-3	0	kyl-s <u>ɛ</u> -d <u>ɛ</u>	laugh-COND-CONJ	0
ɔt-ɪ <u>ŋ</u>	gall.bladder-POSS.2	2	kyl-s <u>ɛ</u> -d <u>ɛ</u>	laugh-COND-CONJ	0
ɔt-t <u>ɪ</u> ŋ	gall.bladder-GEN	2	kyn-ɪ- <u>ŋ</u>	day-POSS-2	3
qɔs-ɪp	vomit-CVB	2	qur-ɪp-t <u>ɪ</u>	construct-CVB-3	3
qɔs-t <u>ɪ</u> -ŋ-ɪz	vomit-PST-2-FORMAL	1	qur-ɪp-t <u>ɪ</u>	construct-CVB-3	0
qɔs-t <u>ɪ</u> -ŋ-ɪz	vomit-PST-2-FORMAL	0	kyl-ɪn- <u>ɣw</u>	laugh-PASS-GER	5
tɔb <u>ɛ</u>	hill	1	bɔl-ɪn- <u>ɣw</u>	divide-PASS-GER	4
tɔb <u>ɛ</u> -nɪ	hill-ACC	1	qɔs-ɪt- <u>ow</u>	add-PASS-GER	4
tɔb <u>ɛ</u> -n <u>ɪ</u>	hill-ACC	0	qɔz <u>ɪ</u>	lamb	1
ɜyz <u>ɪ</u> m	grape	5	qɔs-t <u>ɪ</u> -q	add-PST-1P	1

3.2 *An analogy* Phonological vowel harmony is typically framed in abstract categorical terms that resemble, at least in spirit, derivational rules of the sort- A→B/C__D. If, however, a phonetic framework is used for understanding the degree of coarticulation, this categorical representation is no longer relevant. Rather, continuous variables may play a role in the degree of coarticulation observed in a given context. Phonetic coarticulation is gradiently affected by factors like consonantal constriction degree and place (Recasens 1984; Fowler & Brancazio 2000). In contrast, there are relatively few instances where consonantal place or manner block vowel harmony (see Rose & Walker 2011:§3.3.3). Additionally, as first proposed in Lindblom (1963), temporal factors play a significant role in the coarticulation of a given vowel (see also Pycha 2015), whereas temporal factors are not typically assumed to interact with phonological harmony.

To incorporate these kinds of factors in the analysis, I suggest a fundamental reconception of vowel harmony. If harmony is construed, not as abstract computation, but rather as a coarticulatory force that is attenuated by factors like distance and application then connecting harmony in both its categorical and gradient instantiations is possible. As an analogy, consider a wireless signal. One may not be able to access the signal for a variety of reasons, like distance from the router, intrinsic strength of the signal or intervening barriers (e.g. walls). Translated into labial harmonic terms, the strength of labial harmony could thus be construed as a physical signal that proceeds rightward throughout the word in Kazakh, and is attenuated by factors like consonant duration and morphological boundaries. Using this kind of analogical framework, in the following section I describe the factors promoting and preventing labialization in contemporary Kazakh.

3.3 *The factors* The elements that influence harmony are broadly, those that promote and those that prevent harmony (once again, operationalized as the depression of F2 approximating that of an underlying round vowel). Factors promoting harmony are divided into two types; phonological triggers and coarticulatory triggers. Initial-syllable vowels trigger reliable labialization of high vowels within roots, as compared to non-initial labial segments like [p, m, ʊ] that initiate gradient lip rounding. Initial triggers, under the analogy above, impart a particular force to harmony that proceeds rightward throughout the word.

(7) SPREAD-R- the initial rightward coarticulatory force of harmony

As noted in 2.1, initial-syllable vowels differ in their intrinsic goodness as triggers of harmony (see McCollum 2016). This difference depends on the perceptual distance between each round vowel and its unrounded harmonic counterpart. Less dispersed vowels are more needy for harmony (Kaun 1995), and accordingly, are better triggers. I use the scaled weightings in McCollum (2016) to formalize this trigger strength asymmetry. The force of SPREAD-R is, therefore scaled by the weights shown in Table 3.

Table 3: Trigger force scaling (McCollum 2016)

Round harmonic pairs	Perceptual Distance	Scaling
ʏ-ɪ	0.365	1
ʊ-ɯ	0.568	0.894
ø-e	0.823	0.762
ɔ-ɑ	1.451	0.435

In essence, the initial force of harmony is smaller for those round vowels that are more dispersed (i.e. more perceptible) from their unrounded counterpart. The relationship between perceptual distance and scaled force is linear (see Zymet 2014 for relating findings).

The other force that promotes the depression of F2 is COARTICULATE. COARTICULATE differs from SPREAD-R in that any labial segment can initiate this force while only initial-syllable vowels can trigger SPREAD-R. This force is bidirectional, whereas SPREAD-R is pre-defined for directionality.² The weight of COARTICULATE is similarly scaled, but according to sonority, where more vowel-like triggers place more pressure on adjacent vowels to be round than less vowel-like segments.

- (8) COARTICULATE- the bidirectional coarticulatory pressure of labial segments, [p b m w ɔ ø ʊ ʏ]

The above two factors drive phonological and phonetic coarticulation. In addition to these harmony-driving forces, a number of harmony-blocking forces are necessary for the analysis. As noted above, the depression of F2 is affected by both temporal and abstract factors. On the temporal side, the duration of intervening consonants significantly affects degree of coarticulation. For instance, in the words [qorɪp], and [qosɪp], the degree of coarticulation is 3 for the second-syllable vowel after [r] but 2 after [s]. Therefore, I propose a force that diminishes the force of harmony across intervening consonants. The scaling of COARTICULATE by sonority is as follows: 1=obstruents, 2=nasals, 3=glides, and 4=vowels.

- (9) *SPANC- the resistance to harmony associated with spanning an intervening consonant

This restriction on harmony is potentially irrelevant for non-local harmony processes, but factors significantly in local harmony processes, like in Kazakh, and Turkic more generally (Dzhunisbekov 1980; Boyce 1990). Like the above forces, this constraint is scaled in the present analysis due to the inherent durational differences between consonant types in Kazakh. The scaling factor associated with consonant type is as follows: 1=stops and liquids, 2=nasals and glides, and 3=fricatives.

As for abstract factors, morphology appears to play a role in Kazakh, where harmony is more likely in tautomorphemic contexts. Across suffix boundaries, even in the case of the converbial suffix, CVB, which has an adjacent labial to increase coarticulation, F2 is less strongly depressed than in root-internal contexts. Compare the degree of coarticulation in [køsɪk] ‘desert carrot’, 5, with the degree of coarticulation across a morpheme boundary in [øɪɪp] ‘die-CVB’, 2. This parallels Cho’s (2001) finding that palatalization in Korean was significantly diminished in heteromorphemic contexts.

- (10) *SPANMORPH- the resistance to harmony associated with spanning a morphological boundary

The final force relevant to the analysis is vowel-internal resistance to coarticulation. This force is similar to Optimality Theory’s (Prince & Smolensky 1993) set of input-output IDENT constraints (McCarthy & Prince 1995) in that assimilation is dispreferred. The present analysis, though, does not

² It is not unreasonable to suppose a bidirectional SPREAD, but since Kazakh does not have harmonizing suffixes, and moreover because this study did not investigate leftward harmony (Kaun 1999; cf. Bellik 2016), this was not investigated.

distinguish between assimilation of underlying and epenthetic vowels, treating them as one unified phenomenon in the language.³ Since high vowels are far more likely to undergo harmony than non-high vowels, this factor is also scalar.

- (11) *ASSIMILATE- the intrinsic resistance of a target vowel to being assimilated

3.4 The synchronic model To illustrate the interaction of these forces for predicting the degree of coarticulation on a given vowel, see the schema below in (12), exemplified for [kyn-I(3)-ŋ] ‘day-POSS-2’. The initial force of harmonic spreading is 13.1, which is reduced by spanning a nasal stop on its way rightward. This attenuates the force of harmony by 1.64, the weight of *SPANC multiplied by the appropriate scaling factor associated with consonantal duration. The residual force of harmony, 11.46, is further attenuated by the resistance associated with crossing a morpheme boundary. After this additional reduction, the residual strength of the harmonic imperative is 7.66, which is less than the cost associated with fully assimilating a high vowel, 11.12. Therefore, the ratio of residual strength to necessary cost is multiplied by five to provide the predicted degree of coarticulation, which in this case is 3.44. This value is rounded to the nearest integer, 3, which provides the discretized degree of coarticulation.

(12)

Input: /kyn-I-ŋ/	SPREAD-R	*SPANC	*SPANMORPH	*ASSIMILATE
Weights	+13.10	-0.82	-3.80	-11.12
	13.10	-0.82*2 = -1.64		
		13.10 - 1.64 = 11.46	-3.80*1 = -3.80	
			11.46 - 3.80 = 7.66	-11.12
				7.66 - 11.12 < 0
Degree of coarticulation				5*(7.66/11.12) = 3.44
Output:				[kyn-I(3)-ŋ]

To further illustrate the model, consider a more complicated example, like [qɔs-I-ɔw] ‘add-PASS-GER’ in (13) below. In this example, the spreading imperative must be scaled according to the perceptual distance between [ɔ] and [ɑ] in Table 3, resulting in an initial harmonic force of 5.7. This is reduced, as in (12) above, by spanning a consonant and a morpheme boundary. In (13), though, coarticulation from a subsequent round vowel, [ɔ], cooperates with the initial trigger to compel coarticulation of the high vowel in the passive morpheme. This coarticulatory force is scaled according to its sonority, resulting in a coarticulatory force of 9.04. The residual force of coarticulation after spanning a morpheme boundary and a consonant is 4.42. This is added to the residual force of the harmonic force initiated by the first-syllable vowel. Since the coarticulatory force of the initial vowel, [ɔ], is less than zero, the only coarticulatory effect on the second syllable derives from the following [ɔ], which has a residual assimilatory force of 4.42. As above, the degree of coarticulation is found by multiplying the ratio of residual to necessary force by 5, producing 1.99. In this case, though, the assimilatory force is less than the attested force, 4. The model thus incorrectly predicts second-degree coarticulation rather than the attested fourth-degree coarticulation. In this instance, this likely results from the fact that the model predicts no coarticulatory effect from root [ɔ]. Generally, note that the model works much like a statistical regression, using the above-mentioned factors to predict the dependent variable, the degree of assimilation.

³ This choice, though, is in no way crucial for the analysis. A variety of possible perspectives are perfectly compatible with the framework developed herein. This work assumes that epenthetic vowels are by default unrounded, and thus undergo harmony in the same way than an underlyingly unrounded vowel does.

(13)

Input: /qɑs-ɪ- ɔw/	SPREAD-R	*SPANC	*SPANM	*ASSIM	*SPANC	*SPANM	COART
Weights	+13.10	-0.82	-3.80	-11.12	-0.82	-3.80	+2.26
	13.10*0.435 = 5.70	-0.82*3 = -2.46				-3.80	2.26*4 = 9.04
		5.70 - 2.46 = 3.24	3.80*1 = -3.80		-0.82*1 = -0.82	9.04 - 3.80 = 5.24	
			3.24 - 3.80 < 0	-11.12	5.24 - 0.82 = 4.42		
				4.42 - 11.12 < 0			
Degree of coarticulation				5*(4.42/ 11.12) = 1.99			
Output:				[qɑs-ɪ(2)ɪ- ɔw]			

Total error was calculated by adding the difference between attested and predicted degrees of coarticulation for each of the 175 forms input to the model. To find the weights for the model, I used Microsoft Excel's Solver add-in (Fylstra et al. 1998) to minimize the total error in the model. This produced the weights used in (12) and (13) above. Scaling factors were manipulated manually. The mean error for the continuous model (non-discretized) was 0.385. The mean error for the discretized model was 0.372. This means that each model, on average, predicts the degree of coarticulation (from 0 to 5) to within 0.4 degrees of the attested mean coarticulation for that particular context. Overall, the model performs well, accounting for most of the variance in the data. A correlation between non-discretized predictions and the attested values indicates a high degree of accuracy ($t(173)=31.14$, $r=0.92$, $r^2=0.85$). When the discretized (rounded) model was compared to the data, a similarly high amount of variance was explained by the model ($t(173)=28.80$, $r=0.91$, $r^2=0.83$). Thus, the synchronic model accurately predicts the fine-grained degree of coarticulation on target vowels in contemporary Kazakh.

4 The diachronic trajectory of harmony

The goal of the analysis presented herein is not just to predict the fine-grained degree of coarticulation in a variety of morphological contexts. Additionally, this paper is interested in a parsimonious analysis of both diachronic and synchronic harmony. As with other weighted models, modeling change via re-weighting is unproblematic. Thus, if the initial force of harmony were increased one would be able to predict iterative harmony because the initial force would be sufficient, not only to assimilate one vowel across multiple consonants, but to assimilate several vowels across various morphological and consonantal boundaries. It seems implausible, though, to exponentially increase the strength of SPREAD-R to account for iterativity in the phonological grammar. One might need an initial harmonic strength of a large number well above 100 to do so, assuming other weights remain constant. Instead, I propose that iterative harmony is driven by an additional force, ITERATE.

(14) ITERATE- the force compelling recursion of an existing spreading force

Recall that harmonic force is monotonically reduced by temporal and morphological factors, as well as assimilation of target vowels. If a function like ITERATE is able to increase harmonic strength after assimilation, then it would be possible to produce iterative harmony without unduly inflating SPREAD values. Returning the analogy above, ITERATE would function like a wireless extender, taking the pre-existing signal and expanding its reach recursively throughout the word (or any other domain).

When the three harmony-driving forces, COARTICULATE, SPREAD, and ITERATE are considered together, their interaction can model the evolution and decay of harmony systems. If COARTICULATE is a

pre-existing force in a language, with some assumed weight based on the state of a language at Stage 1, SPREAD can be considered a superimposition of harmonic pressure on that pre-existing pressure to coarticulate. Thus, at Stage 2 the combined forces of COARTICULATE and SPREAD drive harmony within a non-iterative domain. At Stage 3, if parasitic ITERATE function is added to the two non-iterative forces, resulting in harmony throughout a given domain.⁴ In decay scenarios, Stages 4-5, the reverse occurs, where ITERATE is first lost, then SPREAD, and finally the weight of COARTICULATE is diminished. The evolutionary time course of harmony is depicted below in Table 4.

Table 4: The proposed taxonomy of vowel harmony by domains

Stage	Emerging harmony			Declining harmony	
	1	2	3	4	5
Forces at work:	COART	COART + SPREAD	COART + SPREAD + ITERATE	COART + SPREAD	COART
Harmony type:	phonetic coarticulation	non-iterative harmony	iterative harmony	non-iterative harmony	phonetic coarticulation
Attested languages:	Moba Yoruba	Asia Minor dialects of Greek	Turkish, Kyrgyz	Kazakh, Central Crimean Tatar	Uzbek, Northern Crimean Tatar

In the above evolutionary taxonomy of harmony, the majority of languages shown are Turkic, including the well-known iterative harmony patterns in Turkish (Lewis 2000) and Kyrgyz (Hebert & Poppe 1963), the decaying labial harmony pattern in the Central dialect of Crimean Tatar (Kavitskaya 2013), and the now-extinct harmonies in Uzbek (Sjoberg 1963) and the Northern dialect of Crimean Tatar (Kavitskaya 2013). These languages were chosen only to relate Kazakh to its phylogenetic relatives. Outside of Turkic, Przewdziecki (2005) argues that harmony is emerging in the Moba dialect of Yoruba (among others). Also, van Oostendorp and Revithiadou (2005) describe disyllabic harmony patterns that have recently emerged in varieties of Greek spoken in Turkey, presumably through contact with Turkish. This taxonomy does not assume any theological goal of word-extensive harmony. Many systems are stable with harmony operating within a smaller domain, and additionally, systems are noted that extend beyond the word (Archangeli & Pulleyblank 2002). Broadly, this taxonomy predicts that the extent of harmony is limited either to some morpho-prosodic domain, or to a two-syllable window. Thus, no three- or four-syllable patterns are predicted to occur. This prediction is currently under investigation, and of the 355 vowel harmony patterns recorded thus far, no languages exhibit syllable-defined domains other than the two-syllable window predicted above.⁵ At this point, the lack of these larger syllable-defined domains appears to support this general perspective on the diachrony of vowel harmony.

5 Discussion

In Section 5.1, I discuss the model developed as a model of coarticulation. Then in Section 5.2, I briefly discuss the similarities and differences between the model developed herein and two other formal models applied to vowel harmony, constraint-based models (both ranked and weighted versions) and Articulatory Phonology (Browman & Goldstein 1986, 1992).

5.1 Further improvements There are at least two specific ways in which the model could be improved. First, speech rate does not factor into the current model. There is varying evidence for the role of speech rate in coarticulation generally (Lindblom 1963; Moon & Lindblom 1994; Guenther 1995; Pycha

⁴ The most promising way to define domains seems to associate a certain resistance with spanning a domain, say a prosodic word. In this way, iterative harmony is unbounded intrinsically, but is blocked by morphological and prosodic boundaries.

⁵ One might object that two-syllable domains are typically foot-bounded, making harmony domain-delimited. While some instances of foot-bounded systems are attested, as in Kera (Pearce 2007), cases like Central Crimean Tatar are not amenable to this interpretation. Stress is word-final in Crimean Tatar. Therefore in a tri-syllabic word stress would fall outside the domain of harmony.

2015). Interestingly, in the data examined, the number of syllables was an important factor in the degree of coarticulation. For instance, see Table 5 below for the effect of syllable-count on the coarticulation of the high back vowel in /qɔzI/ ‘lamb.’ As the number of syllables increases, the rate of coarticulation also increases. The duration of the intervening fricative, [z], decreases from over 150 ms in two-syllable contexts to less than 100 ms in four-syllable contexts.

Table 5: Syllable count and coarticulation

Word (token count)	Gloss	Number of syllables	Mean Rate of Coarticulation
qɔzI (N=11)	lamb.NOM	2	0.89
qɔzI-dɑ (N=8)	lamb-DAT	3	1.57
qɔzI-ɪAr-dI (N=10)	lamb-PL-ACC	4	2.87

It seems reasonable that syllable count serves as general indicator of speech rate, and that as temporal obstacles (i.e. spanning a consonant) are reduced, coarticulation increases. At present, though, there is no mechanism with which to model this. It seems reasonable to propose a global scaling that corresponds to speech rate, where increases in speech rate would correspond with decreases in the resistance associated with spanning intervening consonants.

As for a second issue with the current model, some evidence from English suggests that partial coarticulation may proceed semi-iteratively (Magen 1997). In essence, if a string of vowels is concatenated, [x...y...z], where [x] triggers coarticulation and both [y] and [z] are potential targets for coarticulation, then [x] may exert a coarticulatory effect on [z] without fully assimilating intervening [y]. This contrasts with the simplifying assumption made in the model, namely that the full assimilation of [y] is prerequisite for any coarticulation on [z]. There are some instances in the data that seem to support Magen’s findings. Specifically, there are cases where a third-syllable vowel will show slight F2 depression despite the incomplete assimilation of the second syllable vowel. However, generally coarticulation appears to follow the assumption that coarticulation on a given vowel requires the full assimilation of the previous vowel. I hope that future work can clarify this issue.

5.2 Comparisons The model most dissimilar from the quantitative model above is canonical Optimality Theory, which, by using strict rankings, limits the possibility of capturing variable data like that presented above (though see Anttila 1997; Boersma & Hayes 2001). Within constraint-based grammars, weighted (harmonic) grammars (Legendre et al 1990; Goldwater & Johnson 2003; Pater 2009) are much more amenable to the spirit of the above analysis. The most problematic issue, though, is the proposed interaction of the three harmony-driving forces. In constraint-based grammars it is generally impermissible to allow one constraint to be parasitic upon another. More concretely, the application of SPREAD assumes the pre-existing application of COARTICULATE, and ITERATE similarly depends on the application of SPREAD. Apart from constraint conjunctions it seems problematic in the extreme to assume that constraints may reference one another in the grammar.

In Articulatory Phonology (AP), both the formal apparatus and the use of dynamical modeling (Saltzman & Munhall 1989) make AP a more similar model. However, as with constraint-based grammars AP is a model of all of phonology, broadly defined, and the above model makes no attempt to fit other types of phonological or phonetic processes. Thus, one possibility is to subsume the analysis presented herein within AP. However, the problem related to harmony-drivers noted above persists in AP although Smith (2016) proposes that harmony is a gesture that does not self-deactivate, which could be re-interpreted along the lines argued above. One very clear benefit of contextualizing the analysis in AP, is as Smith demonstrates, the ability to model transparency, which the above model cannot do at present.

6 Conclusion

This paper argues that the current application of labial harmony in Kazakh is best analyzed in phonetic terms. In transitional systems, like Kazakh, it is unclear where phonology ends and phonetics begins, and it is herein proposed that analyzing both in one phonetically-oriented formalism is preferable. More specifically, this paper proposes a quantitative analysis of phonological and phonetic coarticulation that is based on statistical regression models. Using this kind of model allows for both categorical and gradient effects to emerge synchronically and diachronically. The interaction of the mechanisms proposed here,

COARTICULATE, SPREAD, and ITERATE, is able to predict the typologically-attested domains of harmony found among the world's languages without overgenerating unattested syllable-defined domains. Thus, the combined ability of the model to accurately predict the degree and extent of synchronic coarticulation as well as the typologically-attested pathways for harmonic change are both promising results for the further study of diachronic change in vowel harmony systems.

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