Modeling gradient processes in Polabian vowel chain shifting and blocking

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This paper presents an analysis of two interacting sound changes in the extinct West Slavic language Polabian. Polabian is known to have two types of vowel innovations: (i) the incorporation of acoustic properties from consonant secondary co-articulations (either palatalization or velarization) and (ii) a systematic rotation of vowels (Timberlake 1995). This paper argues that the innovation in (ii) is a vowel chain shift similar to those analyzed in Labov (1994). Unlike the other languages surveyed in Labov (1994), Polabian has phonologically predictable exceptions to the general direction of vowel movement through the acoustic space. Unlike previous work on Polabian, this paper proposes that the vowel chain shift operated simultaneously with the innovation in (i) resulting in phonologically predictable exceptions. This paper tests Timberlake's (1995) proposal and the current proposal in a Harmonic Grammar (Flemming 2001) which uses Purcell's (1979) acoustic data from Russian as a proxy. The model only captures the correct distribution of vowel reflexes under the assumption that co-articulatory based innovations and vowel chain shifting were active at the same time.

Keywords: vowel chain shifting, sound change exception, predictive modeling, Slavic, extinct language, acoustic proxy

1. Introduction

Traditional approaches to modeling sound change often provide two options for temporal sequencing of multiple innovations when an absolute chronology cannot be established (Arlotto 1972; Bloomfield 1984; Campbell 2013; Crist 2001; Crowley & Bowern 2010; Lass 1997). In the first case, the innovations must be ordered in distinct temporal phases known as *relative chronology*. When innovations are sequenced relative to one another, the occurrence of a particular innovation during

https://doi.org/10.1075/jhl.18021.bur
Journal of Historical Linguistics 11:1 (2021), pp. 102–142. ISSN 2210-2116 | E-ISSN 2210-2124

an earlier phase directly impacts the items which can undergo a different innovation in a later phase. In the second case, innovations are unordered and may co-occur in overlapping temporal phases (Crowley & Bowern 2010: 58–62; Lass 1997: 241–243). When innovations are unordered, the co-occurrence of each innovation in the same phase has no direct consequence for other co-occurring innovations. This paper challenges the traditional view of temporal sequencing through an investigation of the interaction of two sound changes in the oral vowel system of the extinct language Polabian (West Slavic, Lechitic). All West Slavic languages have undergone changes from the Late Common Slavic (LCS) vowel system, but Polabian shows considerable innovation when compared to some of its closest relatives as exemplified with Polish in Table 1.[1]

Table 1. Late Common Slavic vowel reflexes in Lechitic

	Polabian (Polański & Sehnert 1967)	**Polish (Swan 2009)**	**LCS**	**Gloss**
Set A	<vaidlåi>	<vidły>	*vidlɯ	'pitchfork'
	<laună>	<łuna> 'glow'	*luna	'moon'
	<t'ölü>	<koło>	*kolo	'wheel'
	<pic>	<piec>	*pektĭ	'hearth'
	<coso>	<czasza> 'bowl'	*t͡ʃaʃa	'cup'
Set B	<zenă>	<żona>	*ʒena	'woman/wife'
	<gord>	<gród>	*gordŭ	'castle'
	<vål>	<wół>	*volŭ	'ox'

Table 1 shows that Polish vowel reflexes are generally more conservative than Polabian (see Set A), although this is not always the case (see Set B). As Set A illustrates, Polabian exhibits innovations such as diphthongization of LCS *i, *ɯ, *u, fronting of LCS *o, and raising of LCS *e, *o, *a. On the other hand as Set B demonstrates, Polabian vowel reflexes can at times be either conservative, i.e., they have not undergone changes from LCS, or they are lower in the vowel space.

Polabian exhibits context-sensitive mid vowel innovations not found in Polish. Timberlake (1995) attributes innovative Polabian mid vowel reflexes to the influence of post-vocalic consonants, which are either palatalized or velarized. For instance, secondary palatalization triggers raising of LCS *e in words like LCS *pektĭ 'hearth'→ Polabian <pic> while secondary velarization triggers lowering of

1. Polabian orthographic <ü> represents IPA [y], <ö> represents [ø], and <å> represents a low back rounded vowel, either [ɒ] or [ɔ].

that same vowel in words like LCS *ʒena 'woman' → Polabian <zenă> thus maximizing the phonetic difference between the two secondary co-articulations. According to Timberlake, a subsequent chain shift affected the vowel system after the co-articulated allophones emerged. All vowels underwent a chain shift which involved diphthongization of high vowels, fronting of back vowels, and raising of all non-high vowels. In this account, *ʒena 'woman' lowers to *z**e̞n**ᶭɐ due to co-articulation, and then subsequently rises back to its original position producing [zenɐ] <zenă>. In short, Timberlake's analysis accounts for the developments by proposing two separate stages of vowel changes, first new allophones arise from co-articulation, followed by a vowel chain shift which in some cases undoes the effects of the previous vowel changes.

In this paper, I propose instead that vowel chain shifting and secondary co-articulation innovations occur simultaneously in the history of Polabian. The vowel chain shift triggers raising in non-high vowels producing the reflexes shown in Set A but velarized co-articulation could either neutralize or reverse the direction of the shift resulting in predictable exceptions shown in Set B. This hypothesis allows for the possibility that the mid vowel reflex in Polabian <zenă> 'woman' is conservative, i.e., it has not undergone changes from the original vowel found in LCS *ʒena.

Timberlake's account of vowel innovations and the account presented here differ in two substantial ways. First, as already noted, Timberlake assumes that vowel innovations occurred in two separate stages: co-articulation followed by vowel chain shifting. Conversely, my analysis claims that co-articulation and vowel chain shifting are contemporaneous. According to my proposal that follows, the correct distribution of allophones cannot be derived unless co-articulation and chain shifting interact. The second difference concerns the role of secondary co-articulation. Timberlake stipulates that the co-articulatory innovations serve to maximize the phonetic difference between contrastive secondary articulations, thus maintaining a phonemic system with an equal but opposing dichotomy between each secondary articulation. My proposal will show instead that secondary velarization and segments with acoustic properties similar to velarization actively worked against the overall direction of vowel chain shifting. Secondary palatalization, meanwhile, had less influence on the overall outcome of the reflexes.

Both Timberlake's proposal and my own rely on phonetically gradient properties of secondary co-articulation to derive innovative allophones of LCS vowels. This work aims to test both proposals in a formal framework and identify the most parsimonious account of vowel innovations. The two proposals are compared in a gradient Harmonic Grammar (HG) model of Polabian based on acoustic data from Russian (Purcell 1979).

This paper finds that the new proposal provides the most parsimonious account of allophone clustering in the HG because all phonetic constraints put into the model correctly predict the distribution of modern Polabian reflexes. The constraint set based on Timberlake's proposed mechanisms is able to generate allophones in the HG, but the allophones do not have the distribution of modern Polabian reflexes. As such, the allophones generated by his proposal require an appeal to additional phonetic processes in order to account for the structure of modern Polabian.

The findings of this work suggest that over time, (i) multiple processes interacted at some point in the innovation and that (ii) co-articulation of secondary velarization left a more detectable mark on Polabian vowel reflexes than secondary palatalization. It should be noted, however, that these findings do not preclude an early stage of development akin to Timberlake's proposal that was later followed by interacting processes.

The findings of this study have broader implications for research on vowel chain shifts. Some scholars view chain shifting as a gradient process and thus support modeling of vowel chain shifting with scalar features (Labov 1994; Kirchner 1996; Minkova & Stockwell 2003; Parkinson 1996). Their models often lack external motivation for why a scale should be used or what objectively grounds the values and increments on the scale. The model proposed in this paper using HG is fully gradient, in keeping with the commonly accepted view that many regular sound changes start out as gradient phonetically natural processes (Ohala 1993; Garrett & Johnson 2013). By using a Hz-based scale, the approach advocated for in this paper is able to capture the interaction of three different phonetic processes (raising, lowering, and fronting) in a unified model.

The second implication of this study regards the core mechanisms of chain shifting. Polabian differs from other languages surveyed in the vowel chain shifting literature because the movements in the Polabian chain shift can be interrupted by regular phonetic processes such as velarization and palatalization. This suggests that the unconditioned raising frequently observed in vowel chain shifting deserves a more direct explanation rather than treating it as an incidental by-product of the structure-preserving properties of chain shifting. While it is the goal of this paper to call attention to this property, it falls beyond the scope of this paper to settle *why* raising is a property of vowel chain shifting.

Although this current work focuses on a case study of interacting phonological processes in a Slavic language, the methodology used to construct the HG has implications beyond Slavic. Scholars should not be limited to building acoustic models of gradient sound changes in living languages. Provided that there are audio recordings of other languages with similar phonological structures, acoustic models of extinct languages can be developed by using a proxy language.

The rest of the paper is organized as follows. The rest of Section 1 discusses the known mechanism of sound change involved in consonant co-articulation influencing vowel properties. Section 2 provides background to Polabian and the two competing accounts of vowel innovations. Section 3 briefly discusses the theoretical place of exceptions to vowel chain shifting and introduces the types of models which have been proposed to account for chain shifting. This Section ends by outlining the structure of the HG used in this study thus providing a methodology for building a HG for an extinct language. Section 4 implements the HG on mid vowels according to the two hypotheses and compares the results of each. Finally Section 5 closes with the findings and implications of this paper.

1.1 The structure of co-articulation as a sound change

The two proposals outlined above attribute restructuring of vowel reflexes to secondary consonant co-articulation. Consonant and vowel (C/V) gestural overlap produces formant transitions. The formant transition's structure is primarily determined by the adjacent consonant's place properties. Velars converge F2 and F3, retroflexes depress F4, coronals raise F2, labials depress all formants, and glottals lack formant transitions (Ladefoged & Johnson 2015; Zhou et al. 2008). Secondary articulations differing in place can also alter formant transition profiles as shown in Iskarous & Kavitskaya's (2018) analysis of Russian.

There are two sides to C/V transitions: production and perception. The production of C/V overlap can be gradient which is consistent with phonetically natural sound change. High degrees of C/V overlap have shorter formant transitions resulting in monophthongs that incorporate properties of the formant transition. Low degrees of C/V overlap have longer formant transitions resulting in diphthong-like vowels. Long vs. short transitions are gradient in the degree of C/V overlap, but perception of the overlap is not gradient. Compensation for co-articulation literature shows that listeners have a strong hand in restructuring categories associated with overlapping gestures (Yu & Lee 2014; Guion 1998). When presented with a series of acoustically gradient segment combinations, listeners will often partition the data into categories with abrupt divisions between each category.

When consonant properties become categorically treated as salient vowel properties, it is due to a process known as *hypocorrection* (Ohala 1993). In hypocorrection, listeners fail to correctly identify the source of an otherwise naturally occurring acoustic perturbation (Ohala 1993). Consequently, the perturbations are assumed to be intentionally transmitted parts of the speech signal rather than surface motivated co-occurrences. Developments like vowel nasalization from /VN/ sequences, low tone from /VC̬/ sequences, and high tone from /VC̥/ sequences are well-known cases of hypocorrection involving co-articulated consonant properties being reinterpreted as vowel properties (Hombert, Ohala & Ewan 1979; Ohala 1993). When consonants influence place properties of a vowel, hypocorrection over-generalizes consonant place information (the transition) to the rest of the vowel in an abrupt fashion which is consistent with the effect observed in the compensation for co-articulation literature.

Recent developments in phonological theory seek to model the behavior of phonological units that are below the level of the segment (Shih & Inkelas 2014; Lionnet 2016; Operstein 2010; Schwartz 2016). Works which model the behavior of formant transitions treat them as a sub-segmental unit called an *intrasegmental* structure which is temporally situated between the C and V target (Operstein 2010).[2] Figure 1 shows the proposed intrasegmental structures for the vowel [o] followed by a velarized coronal plosive based on Operstein's consonant pre-vocalization framework (2010: 32–34, 68). The solid box represents consonant segment properties whereas the dashed box represents vowels segment properties. The bold line in the hierarchy represents the formant transition node.

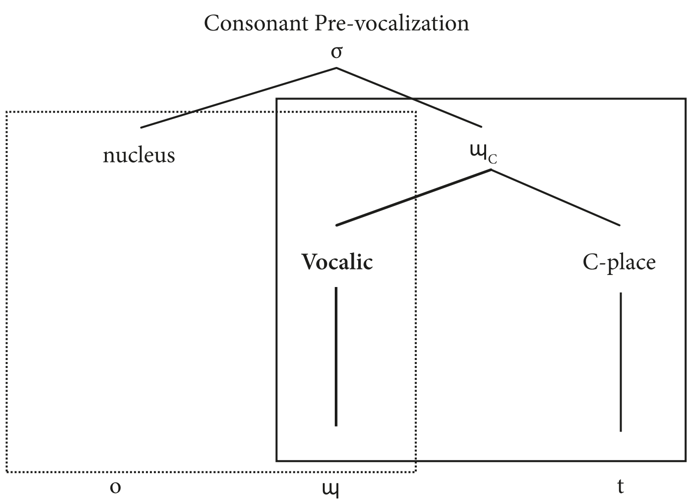

Figure 1. Phonological representations of formant transitions (based on Operstein 2010)

In Operstein's representation, the transition [ɰ] occupies a position that is neither exclusively consonant nor vowel. This leads to ambiguity in how listeners should interpret the transition node even though the phonetic properties of the consonant type determine the phonetic properties of the transition's structure as outlined above. According to the structure in Figure 1, hypocorrection involves the reinterpretation of the consonant's vocalic node as a purely vocalic element

2. I would like to thank a reviewer who suggested incorporating Schwartz (2016). Schwartz's (2016) proposal is similar to Operstein (2010), but Operstein's analysis incorporates a broader range of phenomena including, but not limited to, types of C/V overlap found in Polabian.

belonging in the nucleus. The reinterpretation results in a categorical shift in the mental representation of the vowel.

This paper focuses on consonant transitions associated with secondary palatalization and velarization, however it should be noted that not all Slavic languages have phonetic secondary velarization. Polish, Polabian’s closest relative, does not preserve phonetic velarization, but languages such as Russian and Bulgarian do (Iskarous & Kavitskaya 2018: 54). Polabian exhibits evidence that phonetic velarization was present (Timberlake 1995) and therefore it patterns with Russian and Bulgarian instead of Polish. For this reason, the HG model that I develop in this paper incorporates Russian formant transition data taken from Purcell (1979). For the sake of simplicity, when the F1xF2 value of any given vowel is provided in this work, the reader may assume that hypocorrection of the CV co-articulation has already occurred.

While this paper primarily focuses on secondary consonant articulations that become incorporated into a preexisting vowel target, it should be mentioned that nothing precludes the phonetic property of vowels from being incorporated into a consonant. Polabian velars frequently interact with the following vowel and incorporate vowel properties. For example, after the development of front rounded vowels, pre-vocalic velars incorporate information from the vowel resulting in a new set of palatalized coronal reflexes (e.g., [dʲørɐ] <d’öră> ‘mountain’ < *gʲørɐ < *gora).

2. The Polabian data

This section provides basic information about the synchronic LCS and Polabian vowel systems (insofar as it is relevant to understanding Polabian vowel reflexes). Additionally, this section develops the two competing proposals of Polabian vowel innovations: one based on Timberlake (1995) and the new analysis presented in this paper. Both proposals assume that at the time of the co-articulation based innovations, Polabian exhibited a property known as *contrast dispersion* (Lindblom 1986; Flemming 1995; Padgett 1991). Contrast dispersion is the addition of phonetic cues signaling the difference between phonemically contrastive categories thus reinforcing the perceptual distinctness of each category. In Slavic, contrast dispersion maximizes the difference between palatalized and non-palatalized consonants by actively velarizing non-palatalized consonants (Bolla 1981; Padgett 1991; Timberlake 1995; Padgett 2003; Operstein 2010; Litvin 2014).

2.1 From Late Common Slavic to Polabian

This section presents a broad summary of the vowel inventory differences between the Late Common Slavic period (also called Late Proto-Slavic) and Polabian. The LCS period began roughly around the 6th century when the unified Common Slavic population initially began to split apart. LCS continued for several hundred years until the attestation of regional eastern, western, and southern Slavic varieties between the 7th–11th centuries (Schenker 1993: 73; Carleton 1991: 120; Fortson 2010: 419). Polabian was first mentioned in 11th-century texts and was spoken on the western shores of the Elbe River alongside Low German until its extinction in the 18th century (Olesch 1962). The vast majority of Polabian documentation comes from the period of its decline in the late 17th and early 18th century (Polański & Sehnert 1967). Due to the short period of Polabian attestation, it is not clear when during the 1,200 year span that the innovations discussed in this paper occurred. Despite the fact that documentation of Polabian predated the development of standardized phonetic orthographies, linguists are fairly certain of the phonetic values in the sound system because of meticulous work by Kaiser (1968), Olesch (1962), Polański & Sehnert (1967), Schleicher (1967), and Trubetzkoy (1929) to name a few.

The Polabian oral vowel system developed from the nine vowel system of LCS shown in Table 2.

Table 2. LCS oral vowel system (based on Schenker 1993: 82)

			Back	
	Front	**Central**	**Unround**	**Round**
High	*i *ĭ		*ɯ	*ŭ *u
Mid	*e			*o
Low	*æ	*a		

All vowels in Table 2 could occur in either stressed or unstressed syllables.[3] The vowels *ĭ and *ŭ are romanizations of the super-short vowels which Slavicists call front yer <ь> and back yer <ъ> respectively. LCS had contrastive rounding in the high back vowel system, but not in the front vowel system. LCS had a two-way contrast in the low vowel system, but it is frequently lost in many daughter languages.

3. The seven other oral vowels could occur as either long or short, but LCS length variation is neutralized and reassigned in Polabian based on the position of stress.

The Polabian non-reduced oral vowel inventory contains nine monophthongs and three diphthongs. After innovations in the LCS accentuation system, Polabian non-reduced vowels in strong position (tonic and pre-tonic) underwent a set of innovations (Olesch 1974; Polański 1993: 200; Kortlandt 2010). The non-reduced Polabian inventory is presented in Table 3.

Table 3. Polabian oral vowel inventory (based on Polański 1993: 799)

		Front			
			Round	**Central**	**Back**
High		[i] <i>	[y] <ü>		[u] <u>
Mid	Raised*	[e̯] <ė>			
		[e] <e>	[ø] <ö>		[o] <o>
Low				[a] <a>	[ɒ] <å>
Diphthongs		[ai] <ai>		[ɒi] <åi>	[au] <au>

* Although Polański (1993) presents this as a separate vowel, Timberlake (1995) believes <ė> is a raised allophone of /e/. This work represents <ė>'s quality according to Polański's system.

Polabian has contrastive rounding, but unlike LCS, the contrast only exists in the front vowel system. Additionally, Polabian has a two-way contrast in low vowels whereas many of its closest relatives do not. The raised vowel [e̯] <ė> developed from yers following velar consonants.

2.2 Previous accounts of Polabian vowel innovations

There are several accounts of the Polabian qualitative innovations, the most recent being Polański (1993) and Timberlake (1995). Polański (1993) summarizes the qualitative vowel innovations from LCS calling special attention to the diphthongization of LCS high vowels (*i > [ai], *ɯ > [ɒi], *u > [au]) and the fronting of LCS *o > [y], [ø] (1993: 803). The innovations in the vowel system left a gap for /u/ which was eventually filled by loan words from Low German (e.g., [runtɐ] <runtă> 'round' < Middle Low German <runt>). Most reflexes of /a/ and /ɒ/ come from the lowering of the yers (*ĭ > a, *ŭ > ɒ).

The most comprehensive account of Polabian qualitative vowel innovations is Timberlake (1995). Timberlake divides Polabian into two stages, which I will call "Early Polabian" and "Late Polabian". Early Polabian is defined by co-articulation innovations which restructure LCS vowel allophones and Late Polabian is defined by step-wise vowel rotations. Table 4 shows the proposed Early Polabian oral vowel system (Timberlake 1995: 286, 291). The diacritic ◌̹ indicates rounding, ◌̟ indicates frontness, ◌̝ indicates raising, and ◌̞ indicates lowering. Allophones of the same phoneme are listed in round brackets. The LCS source vowel has been added for clarification.

Table 4. Early Polabian vowel system (based on Timberlake 1995: 286)

[i] < *i	[ɨ] < *ɯ	[u] < *u
([e̝] [e̞]) < *e		([o̝] [o̞]) < *o
	([ə̟], [ə̹]) < *ŭ, *ĭ	
[a̟] < *æ		[a] < *a

Some LCS vowels developed multiple allophones as a means of maximizing the acoustic cues of contrastive secondary articulations in post-vocalic consonants (1995: 284). Palatalized consonants raised F2 and lowered F1 consequently producing raised and fronted allophones, while velarized consonants lowered F2 and raised F1 which as a result produced lowered and retracted allophones. Table 5 shows the allophonic outcomes of secondary co-articulation according to Timberlake's proposal. Information about secondary co-articulation is provided only for Early Polabian.

Table 5. Co-articulated allophones of Early Polabian (data from Timberlake 1995)

Vowel	**Polabian**	**Early Polabian**	**LCS**	**Gloss**	**Polabian**	**Early Polabian**	**LCS**	**Gloss**
*e	[disãt]	< *dʲ**e̝sʲ**ẽtʲ	< *desẽtĭ	'ten'	[teply]	< *tʲ**e̞pᶭ**lᶭo	< *teplo	'warm'
*o	[gnüj]	< *gᶭnᶭ**o̝j**	< *gnojĭ	'manure'	[dʲørɐ]	< *gᶭ**o̞rᶭ**a	< *gora	'mountain'
*ŭ	[tʲe̝d]	< *kʲ**ə̟dʲ**	< *kŭde	'who'	[bɒz]	< *bᶭ**ə̹zᶭ**	< *bŭzŭ	'lilac'
*ĭ	[dan]	< *dʲ**ə̟nʲ**	< *dĭnĭ	'day'	[pʲɒs]	< *pʲ**ə̹sᶭ**	< *pĭsŭ	'dog'

In mid vowels, co-articulation resulted in height-differentiated allophones. In reflexes of the yers, co-articulation resulted in front and back (rounded) allophones. The development of *ŭ > [e̝] relies on the presence of a pre-vocalic velar (which would have been velarized) and a post-vocalic palatalized consonant. *ŭ does not front in any other context with a post-vocalic palatalized consonant.

Timberlake attributes some innovations to dissimilation followed by co-articulation. Coronals are inherently front segments, so velarization is exaggerated in order to maintain a perceptible difference between velarization and palatalization

(1995: 284). In turn, the exaggerated velarization becomes encoded in the co-articulation of the vowel (1995: 284). Although there is a phonetic difference between regular co-articulation and exaggerated co-articulation, phonologically Early Polabian has only one raised and one lowered allophone per mid vowel as shown in Table 4 (Timberlake 1995: 286, 291).

The distribution of lowered allophones sometimes varies based on the conditioning consonant's primary place of articulation and pre-vocalic glides [ʋ] < *v and [j] (Timberlake 1995: 283). Table 6 shows the distribution of raised allophones (light grey) and lowered allophones (dark grey) by context.

Table 6. Mid vowel reflexes (from Timberlake 1995: 284)

	*vo	*e	*je	*o
__C^{j}	ʋi < ʋy	i	ji	y
__#	ʋi < ʋy	i	ji	y
__C^{ɰ} (labial, velar)	ʋɒ	e	je	y
__C^{ɰ} (coronal)	ʋɒ	e	ja	ø

Most environments show a binary partition of raised and lowered allophones. Timberlake attributes the developments *je > ja and *o > ø to coronal velarization, but only *o > ø fits within his account of dissimilation. Timberlake ascribes the development of *je > ja to a different mechanism in which pre-vocalic [j] absorbs the initial part of the vowel. According to this mechanism, all vowels followed by a consonant have a transition determined by the following consonant's acoustic properties: Vɪ in palatalized contexts, Və in velarized contexts, and the compound transition Vəẹ in velarized coronal contexts. When the glide [j] absorbs the initial part of the vowel in the velarized coronal context, the transition [əẹ] becomes the nucleus because it is the only remaining portion of the vowel. The nucleus [əẹ] is lower than the original *e thus resulting in a lowered reflex as in [jadlɐ] <jadlă> 'fir' < *jəẹd^{ɰ}l^{ɰ}a < *jeəẹd^{ɰ}l^{ɰ}a < LCS *jedla (1995: 285). Timberlake does not explain why [jadɒn] <jadån> 'one' < *jed^{j}an^{ɰ} < *jedĭnŭ would lose its inherited palatalization and pattern like a segment with an inherited velarized consonant.

After Early Polabian, Timberlake proposes a rotational innovation (1995: 286, 291), which today we would call a *vowel chain shift*. A chain shift is a seemingly serial set of step-wise innovations which often preserve contrasts (e.g., *A → B, *B → C, *C → D). Table 7 summarizes the Late Polabian vowel system resulting from the chain shift.

Table 7. Late Polabian vowel system (based on Timberlake 1995: 286, 291)

[i] < *e̝, [y] < *o̝				
	[e] < *e̞, *a̟, [ø] < *o̞			[o] < *a
	[a] < *ə̟		[ɒ] < *ə̹	
	[ai] < *i	[ɒi] < *ɨ	[au] < *u	

The rotations include the diphthongization of high vowels, the raising of non-high vowels, and the fronting of back vowels. Because chain shifts are contrast-preserving structures, the distribution of the Late Polabian system is mostly structured prior to the chain shift. The one merger which occurs in the shift is when the vowel in [devɐ] <devă> 'girl' < *da̟vɐ < *dæva merges with the vowel in [led] <led> 'ice' < *le̞dɰ < *ledŭ (Timberlake 1995: 286).

The biggest take-aways from Timberlake's analysis are the ways that opposing contrastive secondary articulations structured the Early Polabian vowel system; palatalization triggers raising/fronting and velarization triggers lowering/backing. If a segment conflicts with inherent properties of secondary articulation, the conflict is counteracted by exaggerating formant transitions thereby maintaining perceptible acoustic cues of contrastive phonological categories in the vowel system.

Timberlake's analysis leaves many open questions concerning secondary articulation. First, it is not clear if exaggerated velarized transitions are the same as transitions bearing two co-articulations like the velarized coronal transition Vəe̞tɰ (where ə is a property of secondary velarization and e̞ is a property of the coronal). Second, Timberlake makes it clear that co-articulation restructures the distribution of allophones prior to chain shifting, but there is no account of how allophones associated with *ʊo > *ʊɒ* or *je > *ja* interact with the chain shift's rotation. Perhaps the largest open issue is why the word-final context behaves the way it does. Timberlake recognizes that the word-final context for mid vowels functions as part of an elsewhere class (1995: 282), but his analysis does not incorporate this fact, and instead relies only on co-articulation to account for raising (1995: 284).

The next section works towards a new account of vowel innovations by analyzing the questions posed in (1):

(1) a. Is there sufficient evidence to treat secondary articulations as equal but opposing influences?
  b. Why do reflexes in the word-final context pattern with reflexes in the palatalizing context?
  c. Are there any other processes which are relevant to the development of vowel reflexes?

The rest of this paper focuses on my analysis of how the co-articulation of phonological contrast restructures the Polabian vowel system. I will not address dissimilation in this article as it is the topic of a separate paper.

2.3 Towards a new account

From the outset of this work, I proposed that secondary articulations are not evenly balanced in their contribution to mid vowel reflex development. There are three pieces of evidence used to support this position outlined in (2).

(2) a. Additive enhancement of secondary co-articulation only occurs for velarized consonants. Additive enhancement is a type of interaction between two or more distinct segment types with similar acoustic or perceptual properties. All interacting segments contribute the sum of their shared acoustic/perceptual properties to the realization of a single target (Lionnet 2016: 65).

b. Word-final environments do not necessarily produce reflexes that pattern with the palatalizing context's reflexes. The behavior of different word-final reflexes requires an explanation independent of palatalization.

c. Behavior similar to secondary velarization can be observed with post-vocalic rhotics regardless of their secondary articulation.

First, additive enhancement of secondary co-articulation only occurs with velarization, not palatalization. Loanwords provide evidence that Timberlake's labial glide has velar properties and is [w] and *w, not [ʋ] and *v (cf., Polabian <ku**v**ål> 'ball' < Middle Low German <ku**g**el> 'ball'). The labio-velar glide produces lowered reflexes when paired with post-vocalic velarized segments as in [w**ɒ**l] <vål> 'ox' < ***wolᶭ** < *wolŭ and [w**ɒ**tʲy] <våt'ü> 'eye' < *wɒkʲy < ***wokᶭ**o < *oko. These data suggest that [w] adds to the effect of secondary velarization resulting in enhanced backing and lowering in vowels with shared place properties. Additive support of secondary palatalization triggered by [j] is absent. The reflex of *e in [jiz] <jiz> 'hedgehog' < *jeʒĭ does not get a bump in its co-articulation and as a result, it fails to diphthongize to [jaiz].[4]

4. The innovation *ŭ > [ẹ] is not additive enhanced secondary palatalization because the conditioning segments do not support each other's properties. All back vowels with weak labialization undergo a similar set of innovations (Timberlake 1995: 289) suggesting that * ŭ > [ẹ] develops because the preceding velar absorbs the initial part of the vowel similar to the development in *jedla 'fir' > [jadla] (e.g., [tʲẹd] <t'ėd> 'who' < *kɪdʲ < *kŭɪdʲ < *kŭde). In velarized contexts, absorption of the initial portion of the vowel still results in a back vowel because the velarized transition is also back (e.g., <nekåtü> 'no one' < *nekəẹtᶭo < *nekŭəẹtᶭo <*nekŭto). Low German loanwords with a velar followed by a syllabic consonant develop the syllabic element as the

Second, raising is found in both the palatalizing and word-final contexts ([d**i**vãt] <d**i**vąt> 'nine' < *d**e**vẽtĭ, [syl**i**] <sül**i**> 'salt' < *sol**e** 'salt GEN SG'),[5] but it isn't clear why these two should behave similarly. The process of word-final raising could be a reasonable explanation (Nobre & Ingemann 2011[1987]; Oliver-Rajan 2007; Law & Strange 2015), but as shown in Table 8, not all vowel classes which undergo co-articulation exhibit raised reflexes in word-final environments. Outputs which rise are in light grey, those that do not are in dark grey.

Table 8. Co-articulated and word-final vowel reflexes (data from Polański & Sehnert 1967)

	*e	*o	*ŭ	*ĭ
__Cᶭ	[n**e**by] 'heaven' < *n**e**bo	[l**ø**ny] 'bosom' < *l**o**no	[s**ɒ**lyv] 'nightingale' < *s**ŭ**lovĭ	[pʲ**ɒ**s] 'dog' < *p**ĭ**sŭ*
__Cʲ	[z**i**mʲɐ] 'earth' < *z**e**mʲa	[d**y**bre] 'well' < *d**o**bræ	[d**ɒ**ne] 'inside' < *d**ŭ**næ	[zar**ɐ**t] 'look INF' < *z**ĭ**ræti
__#	[wẹs**i**]' 'all NOM SG N' < *wĭsʲ**e** 'N'	[jautr**y**] 'morning' < *jutr**o**	[t**ɒ**] 'who REL' < *t**ŭ**	N/A

* The back realization of front yer is due to a Lechitic diphthongization process which occurs before velarized coronals. Polabian is unique among Lechitic languages in that yer also participated in the innovation in addition to the other vowels which underwent diphthongization. Although this is thought to be one of the defining innovations of Lechitic, this sub-branch remains a controversial phylogenetic group.

Table 8 shows that palatalization does not imply raising; all yer reflexes fall. Table 8 also shows that vowel reflexes in word-final contexts do not pattern exclusively with reflexes found in palatalizing contexts. In some cases word-final vowel reflexes rise (like in palatalization) and in other cases word-final reflexes fall (like in velarization). This means that while co-articulation can account for vowel behavior in contexts with post-vocalic consonants, word-final contexts require a separate explanation independent of palatalization and raising.

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vowel [e̝], despite the fact that the source language lacks secondary articulation (e.g., [swendʲe̝l] <svenďël> 'clapper' < MLG <swengel> and [ladʲe̝r] laďër 'camp' < MLG <lager>). This suggests that even though secondary palatalization produces formant transitions relevant to the innovation of [e̝], the innovation of the vowel does not rely exclusively on the presence of a palatalized consonant.

5. Although many Slavic languages have a nominative reflex which derives from the nominitive form *solĭ, the Polabian nominative form derives from the historical genitive singular (Derksen 2008: 461). The historical genitive singular usually has a reflex of *-i for a feminine i-stem genitive, but Upper Sorbian <sele>, like Polabian <süli> < *sole, derives from *-e common in consonant stems (Derksen 2008: 461; Polański & Sehnert 1967: 142).

In order to account for the patterns in Table 8, I propose that vowel chain shifting must have occurred simultaneously with co-articulation. While there are several ways to classify vowel chain shifting, this paper uses Labov's (1994) classification. His typology identifies three principles which characterize how vowels move in the acoustic space (Labov 1994: 122). The principles underpinning vowel shifts are defined in (3). Polabian examples are shown next to each type.

(3)

Principle 1: Peripheral (long/tense) vowels rise	[t͡s**o**s**o**] 'cup'	< *t͡ʃ**a**ʃ**a**	
	[lʲ**o**t**y**] 'summer'	< *lʲ**a**t**o**	< *l**æ**t**o**
	[sl**e**pə] 'blind'	< *sl**æ**pŭjĭ	
Principle 2: Non-Peripheral (short/lax) vowels fall	[s**ɒ**lyv] 'nightingale'	< *s**ŭ**lovĭ	
	[d**a**lã] 'length'	< *d**ĭ**lʲõ 'ACC SG'	< *d**ĭ**lʲi
2a: Nuclei of closing diphthongs fall	[z**ai**mɐ] 'winter'	< *z**i**ma	
	[t**ɒi**] '2SG'	< *t**ɯ**	
	[t**au**k] 'fat'	< *t**u**kŭ	
Principle 3: Back vowels front	[n**y**t͡s] 'night'	< *n**o**ktĭ	
	[n**ø**s] 'nose'	< *n**o**sŭ	

The principles identified in the Labovian typology are consistent with the Polabian innovations that cannot be explained by co-articulation such as final peripheral vowel raising in [pyl**i**] <püli> 'field' < *polʲ**e** and [jautr**y**] <jautrü> 'morning' < *jutr**o** and final non-peripheral vowel lowering in [t**ɒ**] <tå> 'who REL' < *t**ŭ**. The commonly observed movements could also account for the behavior of peripheral vowels in palatalizing contexts such [z**i**mʲɐ] <zimʹă> 'earth' < *z**e**mʲa and [d**y**bre] <dübre> 'well' < *d**o**bræ without appealing to co-articulation. Labov's principles can also account for the falling of the two non-peripheral vowels (yers) regardless of context. High vowel diphthongization is consistent with Principle 2a and is frequently found in Germanic and Baltic vowel chain shifts (Labov 1994: 282).

Front-rounded vowels tend to develop cross-linguistically due to vowel-vowel co-articulation, e.g., umlaut (Hock 1991: 66–71). Unlike umlaut, vowel chain shifts often occur independent of segmental conditioning. In Polabian, there is no triggering segment that fronts *o. The development in Polabian looks more like vowel chain shifting observed in Swedish (North Germanic), Plautdietsch (West Germanic), and Akha (Tibeto-Burman) among others. In Polabian, Swedish, Plautdietsch, and Akha, unconditioned fronting of back vowel classes with a higher position in the acoustic space is accompanied by raising of the vowel classes below them. Under a chain shift analysis, exceptionless innovations in Polabian would have the trajectory modeled in Figure 2. LCS vowels are outlined, Polabian reflexes are solid. An animated figure is provided in the digital version for those who are less familiar with vowel chain shift diagrams. The Polabian vowel /u/ is grey because it comes from Low German loans as mentioned in Section 2.1.

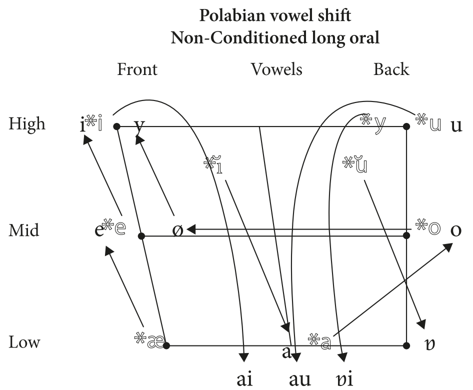

Figure 2. Vowel chain shift diagram (for moving image, see https://doi.org/10.1075/jhl.18021.bur.additional)

Assuming that Polabian exhibits unconditioned chain shifting, all peripheral vowels in strong positions (defined in Section 2.1) should rise and *o should front. Reflexes which do not conform to the movements in Figure 2, such as [n**e**by] <nebü> 'heaven' < *n**e**bo, [l**ø**ny] <lönü> 'bosom' < *l**o**no, and [w**ɒ**stɐt͡s] <våstăc> 'thistle' < *(w)**o**sŭtŭci, are all influenced by velarization. Consonants which naturally complement the properties of secondary velarization, such as [w], enhance the effects of velarization and result in reflexes that go against the expected direction of the vowel shift as in [w**ɒ**do] <vådo> 'water' < *w**o**da. This suggests that velarization has an active counter-shifting influence.

Secondary palatalization did little to alter the outcomes of the shift. As noted above, there are no processes associated with additive enhancement of secondary palatalization. This is notable because secondary palatalization would have supplemented peripheral vowel raising which was already underway. Additionally, palatalization does not counteract the effects of peripheral vowel lowering in either [l**ɒ**zə] <låze> 'lie 3SG' < *l**ŭ**ʒe or [z**a**rɐt] <zarăt> 'look INF' < *z**ĭ**ræti. Instead of conflicting with lowering, palatalization defaults to fronting which doesn't go against the general direction of the shift.

The final piece of evidence corroborating the claim that shift-blocking is an active process comes from the behavior of rhotics. Polabian rhotics have contrastive palatalization (Polański 1993: 799), but post-vocalic rhotics inhibit shifting independent of secondary articulation as shown in (4).[6]

(4)

Reflex		Source	Properties	
[zø.ri] (≠ zy.ri) <zöri> 'dawn'	←	*zo.rʲi	palatalized	Heterosyllabic
[tʲø.rɒi.tə] (≠ tʲy.rɒi.tə) <t'öråitě> 'trough'	←	*ko.rɯ.to	velarized	
[xor.nət] (≠ çyr.nət) <xorně t> 'feed INF'	←	*xor.ni.ti	palatalized	Tautosyllabic
[swor.ko] (≠ swyr.ko) <svorko> 'magpie'	←	*swor.ka	velarized	

In LCS *zorʲi 'dawn' → Polabian [zøri] and LCS *korɯto 'trough' → Polabian [tʲørɒitə], the vowel fronts but the post-vocalic rhotics block raising. Timberlake's analysis predicts that LCS *zorʲi 'dawn' should have a high front vowel reflex because the post-vocalic segment is a palatalized coronal. In LCS *xorniti 'feed INF' → Polabian [xornət] and LCS *sworka 'magpie' → Polabian [sworko], the post-vocalic rhotics share the rime with *o and fully block all processes related to shifting. Once again, Timberlake's analysis incorrectly predicts that the Polabian vowel reflex in LCS *xorniti 'feed INF' should be a high front vowel. While it is not the goal of this paper to propose a formal model for rhotics, their behavior, taken together with the facts of velarization, suggests that the role of secondary palatalization in structuring vowel reflexes was eclipsed by other processes.

2.4 Summary of proposals

In the preceding sections, I have presented two competing hypotheses to account for the development of LCS vowel reflexes in Polabian. Timberlake's proposal assumes two stages of development. In Early Polabian, secondary palatalization and velarization were co-articulated on the preceding mid vowel lowering *e in

6. Articulatorily, rhotics are complex segments made with multiple constrictions in the oral cavity, which may be part of the reason why they interact with the vowel. Walker & Proctor (2016) provide evidence that the complex articulation of the English rhotic is behind the reduction of vowel contrasts in tautosyllabic Vr sequences. While many Slavic languages do not have English-like rhotics, Polabian was in heavy contact with Low German, some varieties of which have English-like rhotics in the coda. Acoustically, many types of rhotics are associated with depressed F3 and F2, but not to the same extent as segments like [w]. Because rhotics have a less extreme formant depression, they may be more restricted in their ability to alter the trajectory of the shift. See Kavitskaya et al. (2009) for a survey of rhotics in Slavic languages.

*nẹbo 'heaven' < LCS *nebo and raising *e in *zẹmʲa 'earth' < *zemʲa. Contrast dispersion maximizes the acoustic cues signaling the difference between palatalization and velarization, but does so in a way that maintains an equal distribution of the contrastive categories. After the co-articulated allophones developed, vowel chain shifting swept over the vowel system raising both [neby] 'heaven' < *nẹbo and [zimʲɐ] 'earth' < *zẹmʲa.

Three issues in Timberlake's proposal drew attention to the need for a new analysis. First, it was unclear why reflexes in the word-final context patterned with reflexes in the palatalizing context. While there are phonological processes which could explain their shared patterning (e.g., word-final raising), these two environments do not always exhibit reflexes with the same properties. Word-final peripheral vowels rise ([pyli] 'field' < *polʲe), but word-final non-peripheral vowels fall ([tɒ] <tå> 'who REL' < *tŭ). Second, while contrast dispersion gives equal phonological status to secondary articulations, the phonetic information encoded into vowels reflects acoustic properties shared by velarization and acoustically similar segments. Features which support secondary velarization are able to exert extra influence on vowels ([wɒz] <våz> 'cartload' < *wozŭ), while features which support secondary palatalization do not ([jiz] 'hedgehog' (≠[jaiz]) < *jeʒĭ). Finally, other processes influence vowel reflexes which are incompatible with Timberlake's analysis. Post-vocalic rhotics, regardless of secondary articulation, inhibit raising and fronting of *o depending on syllable structure.

My account posits the development of chain shifting, which interacts simultaneously with co-articulation. Vowel chain shifting began, causing (i) all high vowels to diphthongize, (ii) non-high peripheral vowels to rise, and (iii) all non-peripheral vowels to lower. The articulatory properties of velarization conflicted directly with the mechanisms underlying the process of vowel chain shifting thus blocking its effects in words like [neby] 'heaven' < *nebo. In the case that a vowel was co-articulated with the glide [w], the effects of velarization overpowered the mechanisms underlying vowel chain shifting causing an apparent reversal in the expected direction of the vowel's movement as in [wɒsk] <våsk> 'wax' < *woskŭ. A similar blocking effect occurs with post-vocalic rhotics as in [gord] <gord> 'castle' (≠[gørd]) < *gor.dŭ. The two proposals are summarized in Table 9.

My proposal identifies three distinct properties which converge to block the general directions of chain shifting (velarization, labio-velars, and rhotics). When distinct properties cannot be collapsed into a single statement but converge on a unified structural behavior, it is called a *phonological conspiracy* (Kisseberth 1970). Models of these types of interactions are more unified in constraint based frameworks like Optimality Theory (OT) as opposed to frameworks which draw on the assumption that each phonological operation must occur independent of others. The next section explores a range of issues concerning OT models of vowel chain shifting before implementing the HG analysis in Section 4.

Table 9. Summary of Polabian vowel development proposals

	Timberlake 1995	Current work
Stages in process	– Early Polabian: co-articulation of post-vocalic consonants – Late Polabian: Vowel chain shift	– Simultaneous vowel chain shift and co-articulatory changes
Contribution of co-articulation	– Secondary co-articulations hold equal status in the phonological system – Effects of secondary co-articulations can be enhanced by pre-vocalic glides	– Secondary velarization and enhancing glides counter effects of chain shifting – Secondary palatalization does not enhance chain shifting – Post-vocalic rhotics counter chain shifting solely based on syllable position

3. Modeling vowel chain shifting

This section focuses on the suitability of different frameworks for modeling vowel chain shifting. Many properties of vowel chain shifts which linguists try to account for involve a series of commonly observed movements, e.g., fronting or raising (see Labov 1994). Despite the common observation of these movements, we still do not know *why* vowels move in the direction that they do in a chain shift. Attempts to model chain shifting come with certain assumptions and claims about the underlying motivations and mechanisms of how the process occurs (Labov 1994; Miglio & Morén 2003; Parkinson 1996; Kiparsky 2016, among others) but the generalizability of these claims and the suitability of each model's theoretical framework are difficult to assess across case studies. Labov (1994) believed that by studying exceptions to chain shifting that arise due to regular sound change, scholars could eventually gain insight into what causes the principles in (3) to apply (1994: 137). Coming closer to understanding *what* perceptual and production properties a model needs to account for can eventually lead scholars to a broader consensus on what constitutes a suitable framework or model for vowel chain shifting in general.

Exceptions to chain shifting involving regular sound change (as opposed to borrowing) are rare.[7] Labov discusses two cases, New Zealand English and Middle Korean.[8] The New Zealand Chain Shift raises ɪ > ɨ, ɛ > ɪ, æ > ɛ going against

7. The Parisian Chain Shift exhibits movements going in the opposite direction of canonical chain shifting, but this is due to dialectal borrowing and hypercorrection instead of regular sound change (Labov 1994: 139–140).

8. Burns (2016) observed movements not described in (3), namely rising diphthong nuclei. She argues that these movements are not exceptions. In her view, the movements fit within the overall set of proposed movements because the diphthongs are opening rather than closing. In

Principle 2, but this may not be a true exception. The short vowels that rise in New Zealand English have undergone tensing, which means that the "long-short" distinction in New Zealand is purely quantitative and not based on peripherality (Maclagan & Hay 2007: 19; Labov 1994: 285). After tensing, the short vowels would be subject to Principle 1 which stipulates that peripheral vowels should rise. Tensing is also observed in the Northern Cities Shift development of æ > iᵊ. It is worth noting that all developments in the Northern Cities Shift are considered by Labov to fit within the expected set of chain shift behaviors.

The second exception is the controversial Middle Korean Chain Shift: ɔ > a, u > ɔ, ɨ > u, ə > ɨ, e > ə. Labov views this shift as violating Principles 1 and 3. Evidence for this shift comes from Middle Korean transcriptions of Mongolian and Chinese loanwords. Some scholars claim that the phonological features ascribed to some of the vowels in the loan words have been misinterpreted, thus the shift never happened (Ko 2013). Ahn and Iverson (2007) and Ko (2013) present data leading to analyses of Korean vowel innovations than diverge from Labov's analysis of vowel chain shifting. In their accounts, the merger of ɔ > a is independent of chain shifting. Ahn and Iverson (2007) claim that in addition to an ɛ > e merger, contemporary Korean exhibits incipient raising of a> ə, ə > ɨ, and o > u which all conform to Principle 1 (2007: 291).

The Polabian exceptions to Labov's principles are of high interest to research on vowel chain shifting because they are phonologically conditioned. Depending on the conditioning environment, the exceptions exhibit a range of behaviors including blocking (e.g., *p**e**ro 'feather' > [p**e**ry] <p**e**rü> ≠ [p**i**ry]) and reversal (e.g., *(w)**o**sa 'wasp' > [w**ɒ**sɐ] <v**å**să> ≠ [w**y**sɐ]/[w**i**sɐ]). Analyzing Polabian may not be able to answer the *why* of vowel chain shifting's directions, but it does bring us closer to understanding *what* is important to model (i.e., gradient acoustic values which can be acted upon by independent processes).

3.1 Previous chain shift models

As stated above, there is a lack of consensus on the appropriate framework and theoretical assumptions to build into vowel chain shift models. This subsection explores some of the variation that is commonly found in previous models of vowel chain shifting.

effect she claims that there is a subcomponent of Principle 1 in which nuclei of opening diphthongs rise just as there is a subcomponent of Principle 2 in which the nuclei of closing diphthongs fall.

Labov's typology is now regarded as descriptive in nature, but when it was first introduced, it was intended to be incorporated into a predictive gradient mathematical model of vowel chain shifting (Labov 1994: Chapters 7 & 8). Many linguists since Labov (1994) have attempted to build predictive models of vowel chain shifting in OT, but there are a range of different approaches. One of the most basic dichotomies is based on the treatment of vowel features as either scalar (existing along a single scale with intermediate values) or discrete (existing as independent individual values). Table 10 shows a range of feature representations in a hypothetical three vowel system.

Table 10. Representation of feature system types

	Scalar (Cumulative)		**Discrete (Binary)**	
	Labov (1994)	**Parkinson (1996)**	**Kiparsky (2016)**	**Miglio & Morén (2003)**
[i]	3 High	Close [+++]	[+high]	[+high]
[e]	2 High	Close [++]	[−high-low]	[+high+low]
[a]	1 High	Close [+]	[+low]	[+low]

The scalar vs. discrete feature dichotomy presented in Table 9 is important because it bears on whether a gradient or abrupt innovation is being modeled (see Section 1.2), although most work on chain shifting does not directly discuss the consequences of choosing a particular feature type. Because a gradient innovation is incremental, scalar features which exist along a single scale are best suited to model these types of innovations. Because discrete features represent individual properties which are not inherently connected to other properties, they are best suited to model abrupt innovations which rely on the existence of distinct categories. Some binary approaches assert the necessity for using binary features in phonological representations (Kiparsky 2016; Miglio & Morén 2003), while others propose binary features as stand-ins for gradient features (Ahn 2001, 2002). Most scalar approaches to vowel chain shifting (and chain shifting in general) use cumulative monovalent features like Parkinson's (1996) features represented in Table 10 (see also Minkova & Stockwell 2003; Kirchner 1996).

In OT, the underlying motivation for any given surface phenomenon is stated in terms of constraints. In light of this, it is interesting that many OT accounts of vowel chain shifting avoid accounting for the direction of vowel movements in the analysis. Some works make the assumption that the correct direction will occur because they focus on other issues such as merger vs. non-merger rather than the direction of the shift (Minkova & Stockwell 2003; Kiparsky 2016). Other works which do address directionality do so from one of two perspectives. In one group, scholars derive the movements of chain shifting by defining constraints which directly reference a scale and movements along a scale (Parkinson 1996; Kirchner 1996; Gnanadesikan 1997). Kirchner (1996) accounts for Principle 1 by directly appealing to a constraint called RAISING which penalizes vowels that fail to accumulate an additional height feature (1996: 344). In the other group, scholars present observed directions as epiphenomenal from markedness constraints governing other properties unrelated to the directionality of chain shifting. Miglio and Morén (2003) explain Principle 1 in the English Great Vowel Shift as the result of the conflict between height faithfulness and markedness constraints and constraints governing the identity of lengthened mid vowels.

Although Miglio and Morén (2003) attempt a more explanatory account of directionality in vowel chain shifts than Kirchner (1996), their model of chain shifting suffers from being over fit to the specific history of English, which is supported by the language's rich documentation. Not all languages with vowel chain shifts begin as Miglio and Morén (2003) claim the English Great Vowel Shift did with lengthening of mid lax vowels (e.g., the Plautdietsch vowel shift, which retains all length values for mid vowels in the early stages of the shift). There is no direct evidence that an English-like innovation triggered the changes in Polabian.[9] In light of these observations and the difficulty of identifying the initial catalyst of the Polabian shift, I adopt the position found in much of the non-English chain shift literature, by referencing the scale and direction of shifting in the definition of the constraints.

An additional problem in modeling vowel chain shifting is the question of what is actually being modeled, especially when OT is concerned. There are many OT models which aim to show inter-generational changes in a population via inductive learning (e.g., Boersma & Pater's (2008) Noisy Harmonic Grammar, Hayes & Wilson's (2008) MaxEnt, among others). These types of models aim to show the transmission of linguistic change from one generation to the next which is not the goal of this present article. As stated in Section 1, the goal of this article is to provide a parsimonious account by generalizing over the summary of the innovations, much like Timberlake's (1995) account of the changes which was not modeled in a formal framework. In the model adopted here, the input represents an LCS-like pronunciation and the output represents an intermediate stage between LCS and 18th century Polabian. In this respect, a raised version of *e will not necessarily represent the vowel [i], but it will exhibit some degree of raising divergent from the input value of *e. Fronted versions of *o will not necessarily represent the vowels [y] or [ø], but rather they will represent something which is developing in a direction consistent with those reflexes.

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9. At the outset of this project, I first suspected that lowering of super-short yers may have preceded and even triggered the chain reaction in other segments due to crowding of the low vowel space. This chronology is supported by the relative chronology proposed in Timberlake (1995: 187), but there is no external evidence to support this assumption.

3.2 A Harmonic Grammar of Polabian

Harmonic Grammar (HG) is a form of OT which has weighted constraints and measures violations in a cumulative fashion (Legendre, Miyata & Smolensky 1990). The type of HG used in this paper is suited for the phonetically gradient properties of inputs, candidates, and violations reflected in the data (Flemming 2001). Violations are incurred when there is a difference between a candidate and target value. The cost of any given violation is the squared difference between the candidate's value and target's value. The relative contribution that a constraint makes to the selection of the winning candidate is calculated via assigned weights rather than ranking. The sum of all weighted cost violations incurred by a given candidate is that candidate's total cost. (5) provides the formula for calculating the total cost of a candidate. Let *x* be the phonetic value of a candidate, *T* be the target value defined in the constraint, *w* be the weight of the constraint, and *C(x)* be the total cost of a given candidate.

(5) $C(x)=w_1(x-T_1)^2+w_2(x-T_2)^2 \ldots +w_n(x-T_n)^2$

One of the differences between HG and classical OT is that it is unlikely to find a candidate without violations unless all of the constraints have the exact same target value. It is more likely that all candidates will incur violations and the winning candidate is the one with the lowest total cost. Because of how HG calculates violations and selects winning candidates, it is possible to solve for the winning candidate with only constraint targets and weights. In order to do this, the product of each weight and target pairing is summed and divided by the sum of all weights as shown in (6).

(6) $x=\Sigma(w_1T_1,w_2T_2,w_nT_n)/\Sigma(w_1,w_2,w_n)$

HG analyses rely on measurements from recorded acoustic data. As Polabian died before acoustic surveying was possible, I adopt the survey of modern Russian by Purcell (1979) as a proxy for measuring the effects of consonant co-articulation on vowel production. Purcell (1979) examines four native Russian speakers' productions of nonce VCV sequences ($M=2$, $F=2$). Each word consists of a voiced plosive that varies based on place of articulation (labial, coronal, or velar) and secondary articulation (velarized or palatalized). The vowels in the nonce word belonged to one of five phonemes: /i, e, a, o, u/. In total, 1,200 words were collected. Purcell reports the mean formant value of each vowel type both before and after each plosive (Types = 60, Tokens per Type = 40).

I will first define constraints and targets related to vowel chain shifting based on the Russian proxy. Following Kirchner (1996), the constraint RISE governs vowel raising. As this chain shift also involves vowel fronting, I propose a constraint called FRONT. Targets for these constraints are defined as the average distance from one vowel category to the next vowel in the shifting direction. On average, rising one height level lowers F1 by 82.81 Hz while fronting raises F2 by 328.04 Hz.[10] Thus we can define the constraints in (7).

(7) RISE: A long vowel must rise one height level. Target: F1 −82.81 Hz
FRONT: A long non-low back vowel must move one position forward. Target: F2 +328.04 Hz
IDENT(V): A vowel should not change from the input value. Target: 0 Hz.

Following the structure of co-articulatory constraints in Flemming (2001), I propose a series of constraints and targets governing secondary co-articulation. I define PALATALIZE and VELARIZE formant intrinsically across all vowels.[11] The targets for these constraints are defined as the distance between a formant's mean and the co-articulated formant's mean. The constraints are defined in (8).

(8) PALATALIZE(F1): A post-vocalic palatalized consonant must lower the preceding vowel's F1. Target: F1 −27.83 Hz.
VELARIZE(F1): A post-vocalic velarized consonant must raise the preceding vowel's F1. Target: F1 +27.83 Hz.
PALATALIZE(F2): A post-vocalic palatalized consonant must raise the preceding vowel's F2. Target: F2 +226.35 Hz.
VELARIZE(F2): A post-vocalic velarized consonant must lower the preceding vowel's F2. Target: F2 −226.35 Hz.

The final constraint that I propose, LABIALIZE, defines the effects of additive labio-velar enhancement on each formant. Russian lacks labio-velars, but the labial class exhibits comparable acoustic behavior. Labials do not have a homogeneous effect on vowel formants; rather, they break down into two classes based on their secondary co-articulation. (9) shows the equation used to derive the effects of labialization. Let f be a formant, s be a secondary articulation, l be a labial, and μ a mean value. Subscripts on the formants represent a consistent formant type (either F1 or F2) and subscripts on a secondary articulation represent a consistent type (either palatalized or velarized).

(9) $l\ \text{enhancement} = (\mu f_i - \mu f_i(ls_j))/(\mu f_i - \mu f_i(s_j))$

10. In Russian, the phoneme /a/ is central. Although the phonetic value of Polabian /a/ is unknown, it patterns phonologically as a front vowel.

11. Flemming (2001) uses a constraint called MINIMUM EFFORT, but this constraint is not used in this analysis because it stipulates an equal effect of both secondary articulations. While this is the type of effect suggested by Timberlake (1995), it is not the view of co-articulation in the present analysis. I therefore break down the effects of MINIMUM EFFORT into the individual effects of each co-articulation.

This formula provides a proportion of the relative strength of a secondary articulation to a labial of the same type. Palatalized labials exert only 35% of the average effect of palatalization on the neighboring vowel. Velarized labials exhibit nearly double (209%) the average effect of velarization on the neighboring vowel. The constraints and targets of LABIALIZE are defined in (10).

(10) LABIALIZE(F1): A pre-vocalic labio-velar must enhance F1 raising of a post-vocalic velarized segment. Target: F1 +58.16 Hz.
LABIALIZE(F2): A pre-vocalic labio-velar must enhance F2 lowering of a post-vocalic velarized segment. Target: F2 −473.07 Hz.

Now that the articulatory properties of all constraints and their targets have been defined, the only question remaining is: how should the different approaches weigh constraints? Timberlake's proposal suggests an even dispersal of co-articulated mid vowel allophones. In Early Polabian, the co-articulated allophones approach the boundaries of neighboring height classes but they cross the boundary only in Late Polabian after the chain shift. Because Timberlake's analysis presumes roughly equal statuses of secondary articulations, all weights in the Timberlake model are assigned an equal weight of 1. The novel proposal advanced in this paper seeks to replicate two properties of Timberlake's analysis (i) unique allophone clusters should be as evenly dispersed as possible and (ii) co-articulated allophones should fall close to the height boundary of neighboring vowel categories. Because the second analysis has multiple constraints which interact with the two properties separately, different weighting systems were constructed to see which ones converged on these two properties. The system with the lowest weights that comes the closest to meeting these two requirements is given in Section 4.

4. Analysis

The previous sections have presented two different accounts of Polabian vowel innovations and built a set of constraints to test the different proposals based on acoustic data from Russian. In Timberlake's (1995) proposal, different secondary co-articulations restructure the distribution of vowel allophones but in my proposal, vowel chain shifting which is counteracted by a subset of acoustic properties restructures the distribution of vowel allophones. This section implements the HG for LCS mid vowels according to both proposals and identifies the most parsimonious account. The LCS mid vowels are tested in the seven conditions shown in (11).

(11)

Condition	*e		*o	
__Cʲ	[z**i**mʲɐ] <ziḿă> ‘earth’	< *z**e**mʲa	[d**y**bre] <dübre> ‘well	< *d**o**bræ
__#	[pyl**i**] <püli> ‘field’	< *polʲ**e**	[rebr**y**] <rebrü> ‘rib’	< *rebr**o**
__Cᶭ	[z**e**nɐ] <zenă> ‘wife’	< *ʒ**e**na	[n**ø**s] <nös> ‘nose’	< *n**o**sŭ
w__Cᶭ	N/A		[w**ɒ**do] <vådo> ‘water’	< *w**o**da

These conditions are chosen because they exhibit sensitivity to co-articulation in both proposals. The tableaux in Section 4.1 are only presented for the sake of showing the evaluation of specific formants according to each analysis. A summary of the HG optimal candidates for both Timberlake’s account and my account are presented in a summary table and figure in Section 4.2 by using the formula in (6).

4.1 Harmonic Grammar implementation

The tableaux modeling Timberlake’s hypothesis will only model co-articulation constraints and IDENT(V) because chain shifting is a separate process entirely. Tableau 1 shows the evaluation of raised and lowered allophones of *e.[12] The input provides the average formant value of the mid vowel being modeled. The constraints provide the relative change in formant values according to the definitions in Section 3.2. The target value that would fully satisfy each constraint is provided in T. The weight of each constraint is provided in W. Because palatalization and velarization play equal but opposing roles in Timberlake’s account, each co-articulation constraint has a weight of 1. The number provided for a constraint violation is the squared difference of the candidate and the constraint’s ideal target value. Note that in the tableaux, if a co-articulation environment is not present in the input there will be no value in the cells measuring constraint violations. The total cost of all constraint violations are summed in the final column. The winning candidate is the one with the lowest sum.

In Tableau 1, the candidate with the lowest violation of IDENT(V) is the candidate closest to the input value of [e], candidate (d). This same candidate, however, fares poorly with respect to the requirement to palatalize. Candidate (c) provides the best satisfaction for the constraint PALATALIZE(F1), and as a consequence violates the identity constraint. Because the overall sum of violations for candidate (c) is 133.5 points lower than the sum for candidate (d), candidate (c) with a raised reflex of the vowel in *zemʲa ‘earth’ is selected as the winner.

12. For simplicity, all values are rounded to the nearest hundredth.

Tableau 1. Hypothesis 1 raised allophone of *e

Input: *zemʲa		IDENT(V)	PALATALIZE(F1)	VELARIZE(F1)	
		+0	−27.83	+27.83	
		T: 375.08	T: 347.25	T: 402.91	
[e] = 375.08		W:1	W:1	W:1	TOTAL COST
a.	300	5637.01 $=(300-375)^2$	2232.56 $=(300-347.25)^2$	–	7869.57 =5637.01+2232.56
b.	325	2508.01	495.06	–	3003.07
c.	350	629.01	7.56	–	636.57
d.	375	0.01	770.06	–	770.07
e.	400	621.01	2782.56	–	3403.57

Tableau 2 provides the derivation of *e lowering according to Timberlake's hypothesis.

Tableau 2. Hypothesis 1 lowered allophone of *e

Input: *ʒena		IDENT(V)	PALATALIZE(F1)	VELARIZE(F1)	
		+0	−27.83	+27.83	
		T: 375.08	T: 347.25	T: 402.91	
[e] = 375.08		W:1	W:1	W:1	TOTAL COST
a.	300	5637.01	–	10590.47	16227.48
b.	325	2508.01	–	6069.97	8577.98
c.	350	629.01	–	2799.47	3428.48
d.	375	0.01	–	778.97	778.98
e.	400	621.01	–	8.47	629.48

The violations for IDENT(V) are the same as in Tableau 1. The main difference is the candidate which best satisfies the target for VELARIZE(F1), candidate (e). The lowered vowel reflex for *ʒena is selected as the winner because the sum of violations for candidate (e) is 149.5 lower than the sum for the faithful candidate (d). Together, Tableaux 1 and 2 show that Timberlake's account properly derives raised and lowered allophones for *zemʲa 'earth' and *ʒena 'wife'. When the model is run for *polʲe 'field', the word-final condition, the winning candidate is the faithful candidate (d) instead of the observed reflex which should match Tableau 1's winner (c).

Timberlake's proposal is equally successful in deriving co-articulation effects on *o as shown in Tableau 3.

Tableau 3. Hypothesis 1 raised and lowered allophones of *o

Input: *dobræ [o] = 367.66		IDENT(V) +0 T: 367.66 W:1	PALATALIZE(F1) −27.83 T: 339.83 W:1	VELARIZE(F1) +27.83 T: 395.49 W:1	TOTAL COST
a.	300	4577.88	1586.43	–	6164.31
b.	325	1819.88	219.93	–	2039.81
c.	350	311.88	103.43	–	415.31
d.	375	53.88	1236.93	–	1290.81
e.	400	1045.88	3620.43	–	4666.31
Input: *nosŭ [o] = 367.66		**IDENT(V) +0 T: 367.66 W:1**	**PALATALIZE(F1) −27.83 T: 339.83 W:1**	**VELARIZE(F1) +27.83 T: 395.49 W:1**	**TOTAL COST**
a.	300	4577.88	–	9118.34	13696.22
b.	325	1819.88	–	4968.84	6788.72
c.	350	311.88	–	2069.34	2381.22
d.	375	53.88	–	419.84	473.72
e.	400	1045.88	–	20.34	1066.22

Again, this proposal correctly produces different co-articulated reflexes of *o in *dobræ 'well' and *nosŭ 'nose', but it would still fail to group word-final reflexes with the palatalized candidate. The word-final reflex without co-articulation selects candidate (d) as the winner which is the same winner in the velarized context. The F2 reflexes exhibit similar outcomes as the F1 and will be discussed in the summary in Section 4.2. Timberlake's proposal can also accurately derive an enhanced reflex of lowered *o, but this reflex also exhibits a lack of clustering as will be shown in Section 4.2.

My account makes two novel claims. First, vowel shifting must be modeled with co-articulation properties. As vowel chain shifting is a general feature of this analysis, it will have a weight of 2, which is stronger than IDENT(V) and the general co-articulation effects seen in the Timberlake analysis. Second, there is a conspiracy that works against the normal direction of shifting, described in Section 2.3.

The constraints which enforce this property have an equal if not stronger effect than the effect of constraints favoring the general direction of the shift. Because of the second consideration, the constraint family VELARIZE has a weight of 2 rather than 1 when active. Tableau 4 provides the evaluation of vowels in the palatalizing and word-final contexts.

Tableau 4. Hypothesis 2 raised word-final and palatalized *e

		IDENT(V)	RISE	PALATALIZE(F1)	VELARIZE(F1)	
		+0	−82.81	−27.83	+27.83	
Input: *zemʲa		T: 375.08	T: 292.27	T: 347.25	T: 402.91	
[e] = 375.08		W:1	W:2	W:1	W:2	TOTAL COST
a.	300	5637.01	59.75	2232.56	–	7989.07
b.	325	2508.01	1071.25	495.06	–	5145.57
c.	350	629.01	3332.75	7.56	–	7302.07
d.	375	0.01	6844.25	770.06	–	14458.57
e.	400	621.01	11605.75	2782.56	–	26615.07
		IDENT(V)	RISE	PALATALIZE(F1)	VELARIZE(F1)	
		+0	−82.81	−27.83	+27.83	
Input: *polʲe		T: 375.08	T: 292.27	T: 347.25	T: 402.91	
[e] = 375.08		W:1	W:2	W:1	W:2	TOTAL COST
a.	300	5637.01	59.75	–	–	5756.51
b.	325	2508.01	1071.25	–	–	4650.51
c.	350	629.01	3332.75	–	–	7294.51
d.	375	0.01	6844.25	–	–	13688.51
e.	400	621.01	11605.75	–	–	23832.51

Under the co-articulated vowel shift analysis, both the palatalizing and word-final contexts select the same raised candidate, (b). As shown in Tableau 5, the velarizing context selects a candidate that is distinct from the one selected in Tableau 4.

The winning candidate in Tableau 5 is (c) which is distinct from the winning candidate in Tableau 3. These results are more consistent with the observed reflexes of Polabian and do not require stipulations of subsequent changes outside of the grammar. As shown in Tableau 6, the chain shift model is also effective in predicting raised allophones of *o in palatalizing and word-final contexts.

Unlike the palatalizing and word-final contexts of *e in Tableau 4, Tableau 6 selects different winning candidates of *o. This raises specters of a similar problem

Tableau 5. Hypothesis 2 lowered velarized *e

Input: *ʒena		IDENT(V)	RISE	PALATALIZE(F1)	VELARIZE(F1)	
		+0	−82.81	−27.83	+27.83	
		T: 375.08	T: 292.27	T: 347.25	T: 402.91	
[e] = 375.08		W:1	W:2	W:1	W:2	TOTAL COST
a.	300	5637.01	59.75	–	10590.47	26937.45
b.	325	2508.01	1071.25	–	6069.97	16790.45
c.	350	629.01	3332.75	–	2799.47	12893.45
d.	375	0.01	6844.25	–	778.97	15246.45
e.	400	621.01	11605.75	–	8.47	23849.45

Tableau 6. Hypothesis 2 raised word-final and palatalized *o

Input: *dobræ		IDENT(V)	RISE	PALATALIZE(F1)	VELARIZE(F1)	
		+0	−82.81	−27.83	+27.83	
		T: 367.66	T: 284.85	T: 339.83	T: 395.49	
[o] = 367.66		W:1	W:2	W:1	W:2	TOTAL COST
a.	300	4577.88	229.52	1586.43	–	6623.35
b.	325	1819.88	1612.02	219.93	–	5263.85
c.	350	311.88	4244.52	103.43	–	8904.35
d.	375	53.88	8127.02	1236.93	–	17544.85
e.	400	1045.88	13259.52	3620.43	–	31185.35
Input: *rebro		IDENT(V)	RISE	PALATALIZE(F1)	VELARIZE(F1)	
		+0	−82.81	−27.83	+27.83	
		T: 367.66	T: 284.85	T: 339.83	T: 395.49	
[o] = 367.66		W:1	W:2	W:1	W:2	TOTAL COST
a.	300	4577.88	229.52	–	–	5036.92
b.	325	1819.88	1612.02	–	–	5043.92
c.	350	311.88	4244.52	–	–	8800.92
d.	375	53.88	8127.02	–	–	16307.92
e.	400	1045.88	13259.52	–	–	27564.92

with Timberlake's HG analysis: there were three distinct candidates selected in the three different environments. The tripartite allophone issue is resolved by the relative frequency of the word-final allophone with respect to other allophones.

Unlike the word-final context in Timberlake's analysis, the word-final context of *o in Tableau 6 does not occupy an ambiguous position between the palatalizing and velarizing contexts' values. In Tableau 6, word-final *o is a higher vowel than the palatalizing context's vowel which means that it clusters with a raising context. The reflexes in Tableau 7 show the lowered allophones in velarizing contexts. The winning candidate for both velarizing contexts cluster below the threshold of the palatalizing context's reflex.

Tableau 7. Hypothesis 2 lowered velarized and enhanced velarized *o

		IDENT(V) +0 T: 367.66 W:1	RISE −82.81 T: 284.85 W:2	VELARIZE(F1) +27.83 T: 395.49 W:2	LABIALIZE(F1) + 58.16 T: 425.82 W:3	TOTAL COST
Input: *nosŭ [o] = 367.66						
a.	300	4577.88	229.52	4968.8401	–	23273.6
b.	325	1819.88	1612.02	2069.3401	–	14981.6
c.	350	311.88	4244.52	419.8401	–	12939.6
d.	375	53.88	8127.02	20.3401	–	17147.6
e.	400	1045.88	13259.52	870.8401	–	27605.6
Input: *woda [o] = 367.66		**IDENT(V) +0 T: 367.66 W:1**	**RISE −82.81 T: 284.85 W:2**	**VELARIZE(F1) +27.83 T: 395.49 W:2**	**LABIALIZE(F1) + 58.16 T: 425.82 W:3**	**TOTAL COST**
a.	300	4577.88	229.52	4968.8401	15830.67	70765.62
b.	325	1819.88	1612.02	2069.3401	10164.67	45475.62
c.	350	311.88	4244.52	419.8401	5748.67	30185.62
d.	375	53.88	8127.02	20.3401	2582.67	24895.62
e.	400	1045.88	13259.52	870.8401	666.67	29605.62

Under the co-articulated vowel shift analysis, velarization comes close to offsetting the effects of raising, but there is still slight raising that is observed in Tableaux 5 and 7. The reversal of the general direction of the shift in Tableau 7 is due to the effects of velarization and labialization overpowering the effects of raising.

The effects of shifting on F2 can also be derived in the novel account. The analysis does not require any modification to the weights used in the previous tableaux. Tableau 8 models fronting in the palatalizing and word-final contexts.

Tableau 8. Hypothesis 2 fronted word-final and palatalized *o

		IDENT(V)	FRONT	PALATALIZE(F2)	VELARIZE(F2)	
		+0	+328.04	+226.35	−226.35	
Input: *dobræ		T: 1450.5	T: 1778.54	T: 1676.85	T: 1224.15	
[o] = 1450.5		W:1	W:2	W:1	W:2	TOTAL COST
a.	1500	2450.25	77584.53	31275.92	–	188895.24
b.	1550	9900.25	52230.53	16090.92	–	130452.24
c.	1600	22350.25	31876.53	5905.92	–	92009.24
d.	1650	39800.25	16522.53	720.92	–	73566.24
e.	1700	62250.25	6168.53	535.92	–	75123.24
		IDENT(V)	FRONT	PALATALIZE(F2)	VELARIZE(F2)	
		+0	+328.04	+226.35	−226.35	
Input: *rebro		T: 1450.5	T: 1778.54	T: 1676.85	T: 1224.15	
[o] = 1450.5		W:1	W:2	W:1	W:2	TOTAL COST
a.	1500	2450.25	77584.53	–	–	157619.31
b.	1550	9900.25	52230.53	–	–	114361.31
c.	1600	22350.25	31876.53	–	–	86103.31
d.	1650	39800.25	16522.53	–	–	72845.31
e.	1700	62250.25	6168.53	–	–	74587.31

Both the palatalizing and word-final contexts of Tableau 8 select the same winning candidate, a centralized version of *o. In velarizing contexts, there is a definite split between the reflexes as shown in Tableau 9.

In Tableau 9, the simple velarizing context does not prevent the development of a centralized allophone, although the allophone is not as far forward as the one in the palatalizing and word-final context. The enhanced velarizing context, however, produces a clearly distinct back allophone which does not cluster with any of the other three contexts' allophones.

Tableau 9. Hypothesis 2 velarized and enhanced velarized *o

Input: *nosŭ [o] = 1450.5		IDENT(V) +0 T: 1450.5 W:1	FRONT +328.04 T: 1778.54 W:2	VELARIZE(F2) −226.35 T:1224.15 W:2	LABIALIZE(F2) −473.07 T: 977.43 W:3	TOTAL COST
a.	1300	22650.25	229000.53	5753.22	–	492157.76
b.	1350	10100.25	183646.53	15838.22	–	409069.76
c.	1400	2550.25	143292.53	30923.22	–	350981.76
d.	1450	0.25	107938.53	51008.22	–	317893.76
e.	1500	2450.25	77584.53	76093.22	–	309805.76
Input: *woda [o] = 1450.5		IDENT(V) +0 T: 1450.5 W:1	FRONT +328.04 T: 1778.54 W:2	VELARIZE(F2) −226.35 T:1224.15 W:2	LABIALIZE(F2) −473.07 T: 977.43 W:3	TOTAL COST
a.	1200	62750.25	334708.53	583.22	49537.4	881945.97
b.	1250	40200.25	279354.53	668.22	74294.4	823128.97
c.	1300	22650.25	229000.53	5753.22	104051.4	804311.97
d.	1350	10100.25	183646.53	15838.22	138808.4	825494.97
e.	1400	2550.25	143292.53	30923.22	178565.4	886677.97

4.2 Harmonic Grammar summary

The previous section modeled the basic implementation of the HG according to the two hypotheses. This section summarizes the HG's function by presenting information about each input's F1xF2 optimal candidate using the formula first presented in (6). The formula is presented again in (12) for convenience. In this formula, let *x* represent the optimal candidate, *w* represent the weight of a constraint and *T* represent the target value.

(12) $x = \Sigma(w_1T_1, w_2T_2, w_nT_n)/\Sigma(w_1, w_2, w_n)$

Timberlake's proposal does not evoke chain shifting to differentiate mid vowel allophones from each other. In the model of his proposal, the burden lies exclusively on co-articulation constraints which have equal weights of 1. This structure produces reflexes which are evenly dispersed from each other for every distinct environment as shown in Table 11.

Although Timberlake's proposal successfully produces allophones, the even dispersal of reflexes in each context is a weakness in an otherwise well motivated

Table 11. Hz reflexes for the Timberlake model

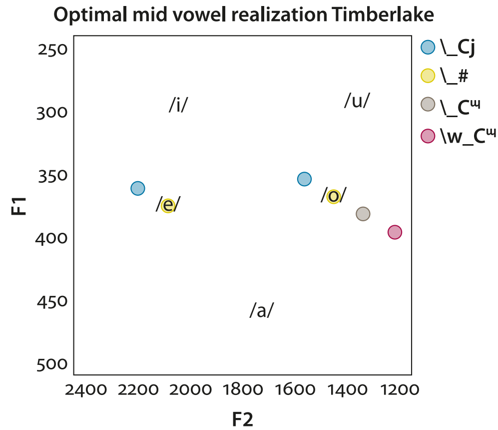
	*e			*o		
		F1	F2		F1	F2
__C^j	<ziḿă> ‘earth’ < *zem^{j}a	361.17	2199.93	<dübre> ‘well’ < *dobræ	353.75	1563.68
__#	<püli> ‘field’ < *pol^{j}e	375.08	2086.75	<rebrü> ‘rib’ < *rebro	367.66	1450.5
__$C^{ɰ}$	<zenă> ‘wife’ < *ʒena	389.0	1973.58	<nös> ‘nose’ < nosŭ	381.58	1337.33
w__$C^{ɰ}$	N/A	–	–	<vådo> ‘water’ < *woda	396.32	1217.36

analysis. The analysis proposed in this paper, stipulates that chain shifting and co-articulation innovations happened at the same time. It also stipulates that constraints governing shifting have a higher weight than constraints governing palatalization and vowel identity (2:1), and constraints governing velarization properties are either equal to or outweigh shifting in the case of enhancement. The resulting reflexes form distinct clusters as shown in Table 12.

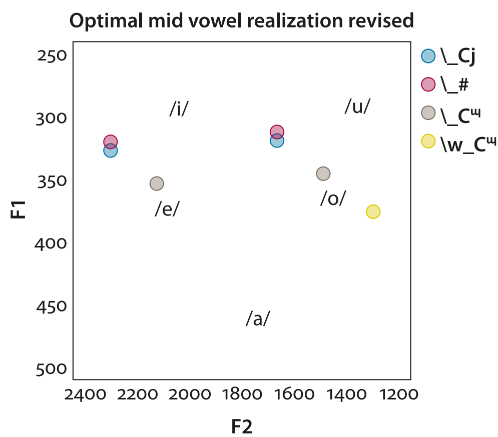
Table 12. Co-articulated vowel chain shift Hz reflexes

	*e			*o		
		F1	F2		F1	F2
__C^j	<ziḿă> ‘earth’ < *zem^{j}a	326.72	2307.36	<dübre> ‘well’ < *dobræ	319.3	1671.11
__#	<püli> ‘field’ < *pol^{j}e	319.87	2305.44	<rebrü> ‘rib’ < *rebro	312.45	1669.19
__$C^{ɰ}$	<zenă> ‘wife’ < *ʒena	353.09	2127.43	<nös> ‘nose’ < nosŭ	345.67	1491.18
w__$C^{ɰ}$	N/A	–	–	<vådo> ‘water’ < *woda	375.73	1298.52

The structure of allophones under the new proposal clusters palatalizing and word final reflexes together to the exclusion of other classes. Figure 3 shows a side-by side comparison of the allophone development according to the two proposals. Purcell’s vowel measurements are listed as phonemes and the co-articulated allophones are semi-transparent.



a.



b.

Figure 3. Visualization of vowel innovation hypotheses: (a) Timberlake, (b) Co-articulated Chain Shift

Under Timberlake's proposal, without more defined clustering in the vowel space at some point prior to the vowel shift, it remains to be explained why the word-final vowels cluster with the palatalized vowels and why the velarized context of *o didn't ultimately collapse with the enhanced velar context. Yet another possibility not ruled out by Timberlake's reflexes is the merger of the word-final and velarized contexts to the exclusion of palatalization and enhanced velarization. My account produces reflexes conforming to the basic observances made by Timberlake (1995), but also accounts for the clustering of the palatalizing and word-final contexts to the exclusion of other contexts. Even though the constraints produce a near even distribution of the three allophones of *o, the effect of fronting is captured by the relative closeness of F2 in the velarized and palatalized/word-final contexts of *o.

It should be reiterated at this point that these findings do not in any way preclude an earlier stage of allophony like that proposed by Timberlake. It is possible that co-articulation produced some allophones of *e and *o like those in Table 11, but subsequent introduction of vowel chain shifting while co-articulation was ongoing modified *e and *o in a way that is consistent with the dispersal patterns in Table 12.

5. Conclusion

This paper has presented an analysis of two interacting sound changes in a Harmonic Grammar of Polabian. Qualitative evidence presented in this work pointed toward the need to revisit Timberlake's widely accepted account of Polabian vowel developments because his proposal failed to account for three phenomena outlined in (13):

(13) a. Additive enhancement relies on acoustic and perceptual properties consistent with secondary velarization. There is no additive enhancement for acoustic and perceptual properties related to secondary palatalization.
b. Raising is not an inherent property of the word-final context. Without some other active process, word-final reflexes will lie in the acoustic space between velarized and palatalized reflexes.
c. Rhotic influence on neighboring vowels, regardless of the secondary articulation, most closely resembles the effects of velarization as opposed to palatalization. Variation in the degree to which rhotics influence vowels is determined by the degree of co-articulation of the rhotic with the preceding vowel (i.e., coda rhotic vs. the onset of a neighboring syllable)

Quantitative evidence also supported the need to develop a new account of Polabian vowel innovations. The implementation of Timberlake's proposed mechanisms in the HG model was able to develop differentiated allophones, but it is not clear what additional mechanism allowed for the resulting allophones to cluster into groups consistent with the modern Polabian reflexes.

In my account, the Polabian innovations are the result of a chain shifting process which operated simultaneously with secondary consonant co-articulation. According to this hypothesis, all peripheral non-high vowels were in the process of rising unless otherwise blocked by velarization and related processes (e.g., depending on their degree of co-articulation with the preceding vowel, rhotics also slow or block the progress of the shift). All non-peripheral vowels were in the process of lowering. My account's model produces mid vowel allophones consistent with the distribution of modern Polabian reflexes. This is because the relative strength of chain shifting constraints overpower the effects of palatalization and as a result word-final and palatalized reflexes cluster together. This model also captures the behavior of velarizing contexts which can neutralize or overpower the effects of chain shifting thus producing the shift reversal effect.

My analysis supports the view that Polabian is unique when compared to the languages surveyed in Labov (1994) due to its phonologically predictable exceptions to vowel chain shifting. The ability to model the blocking and reversal of the Polabian vowel shift has three consequences for our understanding of vowel chain shifting. First, the success of the model supports the view held by Labov (1994), Parkinson (1996), Minkova and Stockwell (2003), and Kirchner (1996) that vowel chain shifting can be succinctly modeled using a scalar feature set rather than arbitrarily inflating the number of binary features in an attempt to account for the same phenomenon. This parsimonious account is highly desirable, since many sound changes start out as phonetically gradient processes, even if they are subsequently reinterpreted as categorical (as discussed in Section 1.1).

Second, the results of this investigation suggest that physical directions frequently observed in vowel chain shifting may not be accidental or epiphenomenal. The ability to successfully model contexts which block and reverse chain shifting suggests that raising plays a more central role in vowel chain shifting than something which is an inconsequential by-product of other constraints.

Finally, this investigation helps identify which aspects of vowel chain shifting should be incorporated into a model. As discussed in Section 1.1 innovations can have gradient phonetically motivated characteristics or abrupt perceptually driven characteristics. Section 1.1 focuses on how gradient and abrupt mechanisms interact in C/V co-articulation innovations, but Section 3.1 calls attention to the lack of consensus regarding the gradient or categorical nature of vowel chain shifting. The literature often makes use of phonological feature sets without motivating the use of such features independent of the chain shift itself. Although this paper does not claim to delineate a boundary between the relative contribution of production and perceptual factors involved in vowel chain shifting, the production-based model accurately captures the exceptions to chain shifting. This suggests that vowel chain shifting is a process whose mechanism cannot lie purely in perception alone; there must also be a physical mechanism which can be interrupted by counteracting physical processes.

To conclude, this study found that co-occurring innovations do not necessarily act independent of one another. Polabian presents a case study in which at least two separate innovations co-occur and influence each other's outcomes. The methodology used to build the model showing this interaction can be extended to other languages, either living or extinct. In order to model extinct languages that lack audio recordings, the scholar will need to identify a language (or languages) with extant audio data and comparable phonological structures. The acoustic data from the languages with audio records can be used as a proxy for the language without audio records in the model.

Acknowledgments

I would like to thank Bruce Hayes, Maria Gouskova, Darya Kavitskaya, Laura Catharine Smith, Kie Zuraw, and the two anonymous reviewers for input on this project through its various stages of development. As always, I would like to thank my advisor, Gary Holland for his support on this project and many others.

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