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Issues in Uyghur backness harmony: Corpus, experimental, and computational studies

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ABSTRACT OF THE DISSERTATION

Issues in Uyghur backness harmony: Corpus, experimental, and computational studies

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This dissertation investigates backness harmony in Uyghur (Turkic: China) from a variety of methodological and analytical perspectives. Backness harmony is a phenomenon where suffix forms must agree in backness with the roots to which they are attached. This dissertation demonstrates that the harmony system in Uyghur consists of a productive phonological core with many lexicalized components that have emerged as the result of sound change and extensive borrowing. That is, backness harmony in Uyghur has many of the properties of an inflectional class system with strong phonological correlates, rather than a purely phonological phenomenon. I explore the implications of this observation for theories of phonological opacity, phonetic biases in phonological learning, and the mathematical complexity of phonological patterns.

The first part of the dissertation presents corpus and experimental studies that investigate the role lexicalization plays in the backness harmony system. Chapter 3 looks at an opaque interaction between backness harmony and an independent process of vowel reduction. A large scale corpus study reveals that this opacity is of a type hitherto unattested, exhibiting gradient rates of opacity that are correlated with root frequency. I argue that this behavior is not predicted by standard theories that treat opacity as an ordering relationship between two phonological processes, and is best analyzed as a parallel interaction between general phonological markedness constraints on harmony and lexically-indexed constraints that specify the harmonic class of a root. Chapter 4 presents the results of an experiment that examines how Uyghur speakers generalize backness harmony to novel roots. Responses display sensitivities to the phonetic properties of backness har-

mony that are not evident in attested forms. I suggest that this discrepancy between attested and novel words can be explained by phonetically-driven learning biases whose effect is obscured by lexical listing of the harmonizing class of attested roots, but which become evident in novel roots for which no such listing exists. Finally, Chapter 5 is a phonetic study that evaluates whether roots with no harmonizing segments display evidence of a covert backness contrast in their vowels that drives their harmonizing behavior, as previously suggested in the literature. Although evidence of coarticulatory effects from neighboring segments is found, there is no correlation between vowel backness and harmonizing behavior. This again supports an analysis where the harmonizing behavior of these roots is lexically specified, rather than phonologically determined.

The second part of the dissertation, Chapters 6 and 7, look at Uyghur backness harmony from the perspective of formal language theory. Previous work suggests that patterns in segmental phonology tend to occupy a particular region of the *subregular hierarchy* (that is, they can be generated by mathematical models which are less powerful than finite-state automata). More complex patterns have been shown to pose learnability problems in artificial grammar learning studies. Chapter 6 demonstrates that Uyghur backness harmony exceeds an upper bound of complexity that has been proposed for segmental patterns. Chapter 7 presents a probabilistic extension of a language class commonly applied to phonological patterns, which is used to model the novel root data from Chapter 4. This model is used to test the hypothesis that the discrepancy between wug and corpus patterns presented in Chapter 4 results from a bias towards computationally simpler patterns. It is demonstrated that the productive pattern learned by speakers is not computationally simpler than the pattern found in attested words, presenting evidence against claims of learning biases towards computationally simpler patterns.

The dissertation of Connor Mayer is approved.

Kie Zuraw

Adam McCollum

Tim Hunter

Bruce Hayes, Committee Chair

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2021

For Courtney

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Finishing a dissertation while simultaneously looking for an academic job is a difficult situation to be in at the best of times, and I strongly recommend against doing it during a global pandemic. Suffice it to say that things would have been a lot more difficult if not for the support of many wonderful people in my life.

I have to first thank my committee members. I've worked with my chair, Bruce Hayes, more or less consistently throughout my time at UCLA, and it's difficult to overstate the influence he's had on my approach to phonology. Bruce is almost frighteningly insightful, with a natural ability to cleave through empirical, technical, and analytical complexity to get to the heart of the matter. Discussions with him have been incredibly valuable for refining my research questions and analyses. He has also been willing to entertain theoretical views he disagrees with, and has been gracious enough to show only a modest amount of glee when the data lead me back into his camp.

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CHAPTER 1

Introduction

This dissertation investigates the phonology and phonetics of Uyghur (ISO 639-3: uig) backness harmony from a variety of methodological and analytical perspectives. The broad goals of the dissertation are to better understand the empirical properties of backness harmony in Uyghur and related phonological phenomena, to explore how speakers internalize these properties in their mental grammars, and to explore the implications of these findings for phonological theory.

Harmony refers to phenomena where multiple segments in some phonological domain must agree for some feature, such as tongue backness, lip rounding, tongue root position, and so on (Hansson, 2001; Rose & Walker, 2011). Simple examples of backness harmony in Uyghur are shown in (1) and (2).

(1) **o**t-l**ɑ**r 'fire-PL'

(2) **ø**j-l**æ**r 'house-PL'

The plural suffix /-lAr/ surfaces in two forms: [-lɑr], with the back vowel [ɑ], or [-lær], with the front vowel [æ]. In the two examples above, the vowel in the root determines which form is used: /ot/ 'fire' has a back vowel /o/, and accordingly takes suffixes in their back forms, while /øj/ 'house' has a front vowel /ø/, and takes suffixes in their front forms. Thus the backness of the vowel in this suffix agrees or harmonizes with the backness of the vowel in the root.[1]

Harmony systems have posed longstanding issues for phonological theory, and have been a driving force behind many theoretical innovations, such as autosegmental theory (Goldsmith, 1976), Agreement by Correspondence (Hansson, 2001; Rose & Walker, 2004), and tier-based

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[1] I use the term "backness harmony" rather than the more conventional "vowel harmony" throughout this dissertation because of the role of consonants alongside vowels as both triggers and undergoers of harmony in Uyghur.

models of formal language phonology (Heinz, Rawal, & Tanner, 2011; McMullin & Hansson, 2016; de Santo & Graf, 2017; McMullin & Hansson, 2019). Many aspects of harmony systems remain topics of lively debate, such as the extent of their typological variation, the relationship between phonetics and phonology in such systems, the nature of locality and transparent segments, and so on. Enhancing our understanding of harmony systems, and phonological theory in general, requires data and insights that span a range of languages and methodologies. This dissertation will focus on some of the insights that backness harmony in Uyghur can provide into these issues.

Like most Turkic languages, Uyghur has both backness and rounding harmony. Uyghur's harmony system has been complicated by a number of historical changes, rendering it relatively more complex than harmony systems in other Turkic languages (R. F. Hahn, 1991a). These changes have led to the development *transparent* or *neutral* vowels, which do not participate in harmony processes, harmonizing consonants that do, and opaque interactions between harmony and other phonological processes in the language. The complexity of the harmony system appears to pose certain challenges for learners, and makes it particularly fertile ground for phonological study. The chapters in this thesis touch on important issues for the field such as phonological opacity and exceptionality, phonetic biases in phonological learning, and the computational complexity of phonological patterns.

The dissertation is divided broadly into three parts, which are outlined below.

1.1   Part 1: Background and empirical description

Chapter 2 presents some background on the Uyghur language and a high-level description of the two phonological processes in Uyghur that are most relevant for the remainder of the dissertation: backness harmony and vowel reduction. It also touches briefly on several other phonological processes that interact with vowel harmony but are not central to the dissertation. Additional detail on these processes is provided in the Appendices. I hope that these appendices will serve as a useful starting point for more detailed study of these phenomena.

1.2 Part 2: Corpus and experimental studies

Chapters 3, 4, and 5 describe results from several corpus and experimental studies. Broadly construed, these chapters focus on the role of lexical diacritics in the Uyghur harmony system: that is, the extent to which the harmonizing behavior of roots is governed not only by general phonological properties, but also by their participation in a morphological inflectional class system in which roots are categorized into one of two harmony classes depending on whether they take front suffixes or back suffixes.

Chapter 3 investigates the interaction between backness harmony and a process of vowel reduction that introduces opacity into the harmony system by reducing two vowels that differ in backness to the same transparent vowel. Elicitation and corpus study reveal Uyghur opacity to be a type hitherto unattested, with optionality and frequency-based lexical gradience. Although the prevalent pattern is to harmonize *opaquely* with the underlying form of the vowel, there are a substantial number of tokens that exhibit *surface-true* harmony. The rate of opaque harmony for a root is predicted by its token frequency. The existence of this gradient opacity poses problems for standard accounts that treat opacity as an ordering relationship between two phonological processes, which neither predict variation in opaque behavior nor the correlation with token frequency. I argue that this pattern should be analyzed as a case of phonological exceptionality governed by the parallel interaction between phonological pressures for surface harmony and lexical pressures to maintain the harmony class of a root across its allomorphs, even when this violates surface harmony. This analysis accounts for the gradient opacity and connection to frequency, and unifies this pattern with other aspects of the harmony system that require lexical specification of exceptional harmonizing behavior.

Chapter 4 presents the results of a wug test study that investigates how Uyghur speakers generalize backness harmony to novel roots. A comparison of wug test results against corpus frequencies shows that Uyghur speakers' harmony patterns differ from corpus patterns in several ways: they show a strong tendency towards distance-based decay as harmonizing vowel and suffix are separated by longer sequences of transparent vowels (see Hayes & Londe, 2006; Hayes et al., 2009; Kimper, 2011; Zymet, 2014), an increased effect of uvular harmony triggers, and a decreased ef-

fect of velar harmony triggers. I demonstrate that this discrepancy can be accounted for by positing certain learning biases that relate to the coarticulatory properties of the segments that participate in backness harmony, and are obscured by the lexicalization of the harmonic behavior of attested words. This chapter also bears on the issue of whether a correspondence or local spreading analysis is most appropriate for Uyghur backness harmony. I demonstrate that although a correspondence analysis seems motivated due to cases where suffixes will "jump over" an intervening harmonic consonant to harmonize with the previous vowel, a model that treats backness as a gradient, rather than categorical, feature can reconcile Uyghur harmony with a local spreading analysis, as well as capture the biases described above.

Finally, Chapter 5 uses evidence from a phonetic experiment to address an alternative account of Uyghur backness harmony. Previous analyses have suggested that the harmonizing behavior of these roots is driven by underlying [back] features that are neutralized on the surface (Lindblad, 1990; R. F. Hahn, 1991b). Such an analysis may predict subtle but systematic phonetic differences between vowels specified as [+back] and those specified as [–back], following Benus and Gafos (2007). This chapter finds no evidence for such a distinction, and suggests that an analysis using lexically-indexed constraints is more appropriate.

Chapters 4 and 5 are collaborative work with Travis Major and Mahire Yakup, who contributed to experimental design and data collection.

1.3   Part 3: Mathematical studies

Chapters 6 and 7 comprise the section of the dissertation that approaches Uyghur backness harmony from the perspective of formal language theory. Formal language theory attempts to provide mathematical characterizations of sets of expressions generated by combining symbols from an alphabet according to certain rules or processes. Formal language theory is foundational for modern generative linguistics (see, e.g., Chomsky, 1956), in that generative linguistics focuses on identifying the processes that constitute grammars that generate all and only the set of legal utterances in a language. Though generative linguistic theory does not generally work directly with formal language models, many commonly used frameworks can be directly related to such models (e.g.,

Johnson, 1972; Kaplan & Kay, 1994; Stabler, 2013; Lamont, 2021, to appear). Work in recent years has approached phonology explicitly from this perspective in an attempt to provide a more rigorous and restrictive characterization of phonological processes, to reason more explicitly about the generative capacity of different theoretical models, and to investigate typological generalizations that are most simply expressed using tools from formal language theory (see Heinz, 2018, for an overview). It is to this research program that the papers in this section contribute.

Chapter 6 provides a mathematical characterization of the complexity of backness harmony in Uyghur, and shows that its complexity violates the *weak subregular hypothesis*, which suggests that all segmental phonology can be generated by *tier-based strictly local* (TSL) grammars, a particular subregular class of grammars. This is typically attributed to a learning bias towards patterns that are TSL (e.g., Lai, 2015; Heinz, 2018). The chapter then sketches out the type of formalism required to capture the pattern (which is presented fully in Graf & Mayer, 2018), and explores several possibilities that can reconcile the pattern with the weak subregular hypothesis. This chapter was done in collaboration with Travis Major, and is a modified version of a previously published paper (Mayer & Major, 2018).

Chapter 7 presents an extension of the tier-based strictly local languages, *probabilistic tier-based strictly local languages*, or *pTSL*. These models allow the gradient patterns of production frequency and acceptability judgments commonly found in wug tests of long-distance phonological processes to be represented in a way that aligns well with the empirical data and has simple, easily interpretable parameters.

In addition to providing a useful tool for representing gradient phonological patterns using formal language models, this model allows us to directly test whether the gradient responses provided by Uyghur speakers in the wug tests in Chapter 4 provide evidence for a learning bias towards patterns that are TSL, as predicted by the weak subregular hypothesis. The results an analysis using this model demonstrate that, although speakers do display evidence for learning biases as described in Chapter 4, these biases do not lead to a formally simpler pattern, and hence do not provide evidence for a bias towards TSL grammars. This chapter is a slightly modified version of a previously published peer-reviewed conference paper (Mayer, 2021).

1.4   Takeaway points

In addition to the specific empirical and theoretical results described above, this dissertation has three broad takeaway points.

The first point is methodological: phonological theory has increasingly come to draw on many methodological and analytical perspectives, and it has been enriched by doing so. This dissertation uses a combination of traditional elicitation, corpus study, wug testing, acoustic measurement, and phonological and mathematical analysis. This breadth of perspectives allows a relatively comprehensive picture of backness harmony in Uyghur to be developed, and allows for insights that would not be possible with a more restricted approach. This is particularly important for Uyghur backness harmony, where the small set of anecdotal data points that has been used in the literature to drive foundational claims about the representation of phonological contrast are not an accurate characterization of opacity in the system (see Chapter 3).

The second point is that the patterns of Uyghur backness harmony are largely driven by lexical diacritics that dictate the harmonizing behavior of roots. Although Uyghur speakers internalize many phonological aspects of the harmony system, learning the kinds of phonotactic properties that are associated with roots that take front suffixes and those that take back suffixes, they also come to learn which harmonizing class each attested root falls into. This interaction between lexically-specified harmonizing behavior and the phonological generalizations is perhaps a consequence of the relative complexity of Uyghur backness harmony, and gives rise to many of the interesting properties that this dissertation investigates, such as gradient opacity, discrepancies between corpus and wug data, and the behavior of neutral and exceptional roots.

The third, related point is that the phonological intuitions of Uyghur speakers reveal a blend of inductive learning and phonetic bias. The existence of surface-harmonizing forms in Chapter 3 suggests a bias towards surface-true harmony, which is generally overruled by root-specific harmony knowledge. When lexical diacritics are stripped away in the wug test in Chapter 4, speakers' responses display both general inductive properties (e.g., a statistical preference for back suffixes) and phonetic biases that lead to divergence from patterns in the corpus. The role of phonetic naturalness in phonological learning is controversial: typological generalizations and experimental

results suggest biases towards phonetic naturalness (e.g., Hayes, Kirchner, & Steriade, 2004; Wilson, 2006; White, 2013; Martin & Peperkamp, 2020), while the relative prevalence of unnatural phonological patterns (Mielke, 2008) and many results from artificial grammar learning experiments (see Moreton & Pater, 2012, for a summary) suggest more general inductive mechanisms are used. The results here provide support for the idea that phonetic substance does indeed exert an important influence on phonological learning.

Finally, in addition to its value for linguistic theory, the study of Uyghur is important from a social and cultural perspective. Although Uyghur is not an endangered language in the narrow sense of the term, Chinese government policies towards the Uyghur people and their language have rendered its long-term survival uncertain. I see this dissertation as part of a larger project undertaken by other linguists and researchers in related disciplines to better understand and document Uyghur language and culture. I hope that my dissertation will make a modest contribution to raising awareness of Uyghur in the linguistic community, and to future studies of Uyghur. I refer readers interested in learning more about the Uyghur situation in China to work such as Bovingdon (2010), Byler (2018), and Zenz (2019), among many others, and to the Uyghur Human Rights Project.[2]

Code and data related to this dissertation will be available at `https://github.com/connormayer/dissertation_materials`.

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[2]`https://uhrp.org/`

CHAPTER 2

The Uyghur language

Uyghur is a southeastern Turkic language spoken by roughly 12 million people. Its speakers are located primarily in the Xinjiang Uyghur Autonomous Region in the People's Republic of China (Fig. 2.1), but there are also significant diasporic communities in neighboring regions in Central Asia such as Kazakhstan, Kyrgyzstan, and Uzbekistan, as well as smaller communities in Turkey, the United States, Canada, Australia, Russia, Saudi Arabia, Afghanistan, Pakistan, India, and Europe. There are an estimated 2 million diasporic speakers (Nazarova & Niyaz, 2013).

Figure 2.1: The Xinjiang Uyghur Autonomous Region (from `https://commons.wikimedia.org/wiki/File:Xinjiang_map.png`). Public domain.

Uyghur is a highly agglutinating language, almost exclusively suffixing, with SOV word order and a rich case marking and agreement system. It is typologically most similar to modern Uzbek (Engesæth, Yakup, & Dwyer, 2009/2010; Nazarova & Niyaz, 2013).

2.1 The segmental inventory of Uyghur

2.1.1 Vowels

The Uyghur vowel phonemes are shown in Table 2.1. The bolded vowels are those that serve as triggers of backness harmony processes, while the non-bolded vowels are harmonically neutral (see Section 2.5.1).

Although these are the standard symbols used to transcribe these vowels, they are somewhat inaccurate representations of their phonetic realization. In particular, these vowels are generally produced less peripherally than their transcriptions would indicate. The vowel transcribed as /æ/ is acoustically intermediate between cardinal [æ] and [ɛ]. The vowels transcribed as /u/, /y/, /o/, and /ø/ are generally produced more closely to [ʊ], [ʏ], [ɔ], and [œ] respectively.

	Front		Back	
	Unrounded	Round	Unrounded	Round
High	i	**y**		**u**
Mid	e	**ø**		**o**
Low	**æ**		**ɑ**	

Table 2.1: The Uyghur vowel system. Harmonizing vowels are in bold.

The neutral vowels, particularly /i/, display a much greater susceptibility to coarticulation than the harmonizing vowels. R. F. Hahn (1991b) describes no less than *fourteen* allophones of /i/, which range from [ɯ] to [ə] to [ɪ] to [i]. /e/ may surface as [ɛ], [e], or [i], with the latter a common allophone in initial syllables. Thus although these vowels are phonemically transcribed as non-low front vowels, the reader should keep in mind that their phonetic realization varies substantially. A plot of F1 and F2 for these vowels normalized to Z-scores is shown in Fig. 2.2. These measurements were made from the recordings of 23 native speakers of Uyghur living in Kazakhstan that are used in Chapters 4, 5, and 7. The materials used to elicit these recordings were not designed to map the Uyghur vowel space; nevertheless they may be useful for providing an impression of the quality of Uyghur vowels.
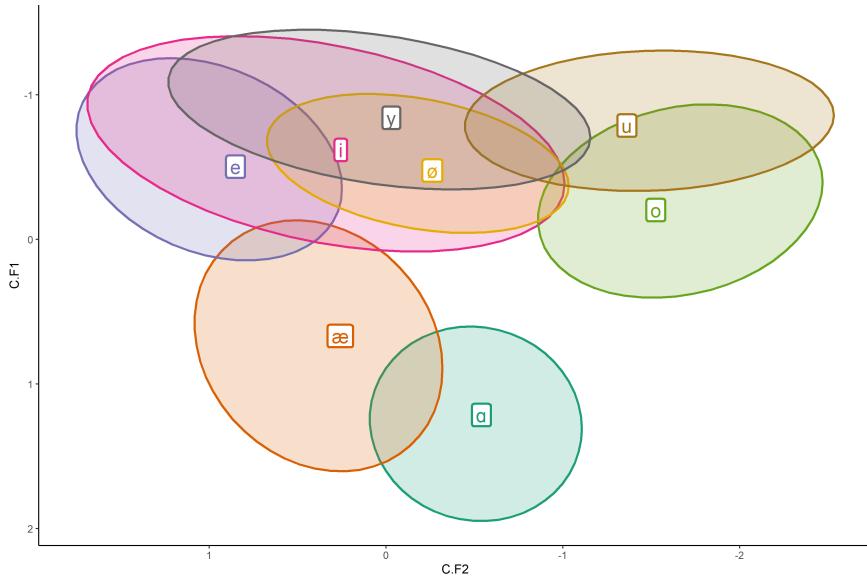
Figure 2.2: A plot of F1 and F2 of the Uyghur vowels normalized to Z-scores.

Some researchers have proposed underlying back phonemic counterparts to /i/ and /e/, /ɯ/ and /ɤ/ (e.g., Lindblad, 1990; R. F. Hahn, 1991a, 1991b). Although allophonic variation is clear both subjectively and empirically, evidence of a phonemic contrast that is not motivated by parsimonious phonological analysis of the harmony system has been more difficult to obtain. R. F. Hahn, though in favor of a phonemic distinction, admits that these front and back counterparts "share the same set of allophones and are orthographically represented alike" (R. F. Hahn, 1991b, p. 34). He proposes a post-lexical fronting rule whereby underlying /ɯ/ and /ɤ/ are fronted to /i/ and /e/ in all contexts after vowel harmony has applied. One challenge to this account is the total absence of homophones that differ in the backness of suffixes they take (i.e., underlying minimal pairs between /i/-/ɯ/ and /e/-/ɤ/), even though such pairs are easy to find for other vowel pairs (see Chapter 5). This is a canonical case of what Kiparsky (1973) called the "diacritic use of phonological features" (p. 16).

Acoustic studies have found that the backness of vowels in roots containing only the vowels /i e/ are not a reliable predictor of whether such roots take front or back suffixes (e.g., McCollum, 2021). My anecdotal experience has been that Uyghur speakers often have intuitions about whether a token of /i/ is a "front *i*" or a "back *i*", but these intuitions do not always conform with the expected harmonizing behavior of roots. For example, one of my consultants reports that the final

	Labial	Dental	Post-alveolar	Velar	Uvular	Glottal
Stop	p b	t d	ʧ ʤ	k g	q	ʔ
Nasal	m	n		ŋ		
Fricative	(f) (v)	s z	ʃ ʒ		χ ʁ	h
Trill		r				
Approximant		l	j	w		

Table 2.2: The Uyghur consonant inventory

/i/ in /qojʧi/ 'shepherd' is front, but attaches back suffixes to this root.[1] This issue is dealt with in greater detail in Chapter 5.

With these facts in mind, I assume the phonemic vowel inventory shown in Table 2.1, while acknowledging that it will be important to better understand the relationship between the phonetic realization of the transparent vowels and harmonic patterns with future phonetic study.

2.1.2 Consonants

The Uyghur consonant phoneme inventory is shown in Table 2.2.

The sound /f/ occurs only in loanwords (e.g., /telefon/ 'telephone', /fɑkit/ 'fact'), and is often realized as [p]. /ʒ/ occurs in loanwords (e.g., /ʒurnɑlist/ 'journalist') and in onomatopoeic words (e.g., /piʒpiʒ/ a sizzling sound), and as an allophone of /j/ before certain high vowels in some dialects. [v] is a common realization of /w/, particularly in dialects of Uyghur spoken in former Soviet countries. The sound /ʔ/ occurs intervocalically in certain loanwords (e.g., /soʔal/ 'question', /muʔællim/ 'teacher'). It is often elided in rapid speech. /ŋ/ may not occur word-initially.

The subset of dorsal consonants shown in Table 2.3 both trigger and undergo vowel harmony (see Section 2.5.1).[2]

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[1]Though this may be related to the observation that /i/ in open, final syllables does not undergo phonemic rounding harmony in modern Uyghur (Nadzhip, 1971), and Old Turkic apparently neutralized the distinction between /i/ and /ɯ/ in non-initial syllables (Erdal, 2004).

[2]Abdulla, Ebeydulla, and Raxman (2010) suggest that /χ/ also serves as a back trigger, but evidence for this is equivocal, and it is not an undergoer of harmony in the same way as /q/ or /ʁ/. The velar nasal /ŋ/ does not appear to participate in the harmony process, though it does have an allophonic backing effect on adjacent vowels (see

	Front	Back
Voiceless	k	q
Voiced	g	ʁ

Table 2.3: Harmonizing Uyghur consonants

2.2 Orthography and notation

2.2.1 Orthography

Uyghur has historically been written using a variety of different orthographies (Nazarova & Niyaz, 2013). Today, Uyghur in Xinjiang is written using a modified Perso-Arabic script, while in former Soviet countries it is written using a modified Cyrillic alphabet (though it is not commonly written in former Soviet countries outside of a small number of Uyghur districts; McCollum p.c.). Several Latin representation of Uyghur have also been developed: these, or informal variants, are commonly used by diasporic communities.

All official Uyghur orthographies are relatively good approximations of surface phonemic representations. In particular, the alternations conditioned by harmony and raising (see Sections 2.5.1 and 2.5.2 below) are reflected in the orthography.

Throughout this dissertation, I will use a combination of the Latin orthography and IPA transcription. Phonemic IPA transcription will be used in all cases, except when dealing specifically with issues related to orthography, in which case the Latin orthography will be used. Fortunately, the Latin orthography is quite transparent, and resembles a phonemic IPA transcription. The few discrepancies between IPA and the Latin orthography are highlighted in Table 2.4 for the reader's convenience.

2.2.2 Archiphonemic notation

Many morphemes in Uyghur vary in their pronunciation depending on the backness, rounding, or voicing of preceding material. I assume for the purpose of the analyses in this dissertation that the

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Chapter 5).

Uyghur Latin Script	IPA		Uyghur Latin Script	IPA
e	æ		r	r/ɾ
é	e		sh	ʃ
gh	ʁ		ch	tʃ
j	dʒ		ü	y
ng	ŋ		y	j
ö	ø		zh	ʒ

Table 2.4: Correspondences between IPA and Uyghur Latin script. Characters not listed are (roughly) identical between the two.

alternating phonemes in these morphemes are underspecified for the relevant features (Archangeli, 1988). I use upper case letters to denote phonemes that are unspecified for a particular feature. /I/ and /E/ are used to represent unrounded high and mid vowels respectively that are unspecified for backness (/i/ or /ɯ/ and /e/ or /ɤ/ respectively). /A/ represents low unrounded vowels that are unspecified for backness (/æ/ or /ɑ/). /U/ is used to represent high vowels that are unspecified for both backness and rounding (/u/, /y/, or /i/)

/K/ represents a voiceless dorsal sound that is unspecified for backness (/k/ or /q/). /G/ represents a dorsal sound that is unspecified for both voicing and backness (/k/, /g/, /q/, or /ʁ/). /D/ represents a coronal stop that is unspecified for voicing (/t/ or /d/).

Harmonically invariant segments in roots and harmony-blocking suffixes are assumed to be fully specified for backness and roundness (see, e.g., Nevins, 2004).

2.3 Data sources

The data used in this dissertation come from a variety of sources:

- Grammars and pedagogical materials (e.g., Nadzhip, 1971; R. F. Hahn, 1991b; Engesæth et al., 2009/2010; Abdulla et al., 2010; Nazarova & Niyaz, 2013, 2016).

- Previous descriptions in the linguistics literature (e.g., Lindblad, 1990; R. F. Hahn, 1991a; Vaux, 2000), though these data are sometimes treated critically.

- Elicitation with eight native Uyghur speakers from the Xinjiang Uyghur Autonomous Region currently living in the United States.

- Personal language study. I initially began studying independently with the help of an Uyghur friend. I then took the intensive Intermediate Uyghur class at the University of Wisconsin Madison's Central Eurasian Studies Summer Institute.[3]

- Experimental work done with Uyghur participants living in Almaty, Kazakhstan (see Chapters 4, 5, and 7).

- Large-scale corpus study from two online Uyghur newspapers (see Chapters 3 and 4).

2.4   Phonological frameworks

Throughout the next two chapters of the dissertation, I will present analyses primarily using the Optimality Theory (OT) framework (e.g., Prince & Smolensky, 1993/2004), a model that proposes that the mapping from underlying to surface forms is governed by the optimal satisfaction of a set of (sometimes conflicting) ranked constraints that mandate either *faithfulness* to the properties of the underlying form, or the avoidance of certain *marked* structures in the output form. Because much of the data I work with are gradient, I specifically employ Maximum Entropy Optimality Theory (MaxEnt OT; Smolensky, 1986; Goldwater & Johnson, 2003). This is a variant of OT that assigns numeric weights to constraints, rather than a strict ranking, and uses these weights to calculate probability distributions over potential output candidates. Additional detail about MaxEnt OT is provided in Chapters 3 and 4.

Chapters 6 and 7 approach Uyghur backness harmony from the perspective of formal language theory, specifically the class of subregular grammars (Heinz, 2018). Details about the relevant models are presented in these chapters.

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[3]https://cessi.wisc.edu/

2.5   Phonological processes of Uyghur

This section will briefly outline some of the phonological processes of Uyghur that are relevant to this dissertation. Additional detail is provided in the chapters and appendices referenced in each section. In particular, the appendices go into detail about a number of exceptions or morphological interactions that are not directly relevant to this dissertation, but are interesting nonetheless. I include these appendices because the interactions they describe have not been fully presented in the linguistics literature.

2.5.1   Backness harmony

The central phenomenon to be addressed in this dissertation is backness harmony in Uyghur. Broadly speaking, backness harmony requires certain vowels and consonants in a word to agree for the feature [back]. Turkic roots tend to be harmonic, containing only [+back] or [–back] sounds. However, a large number of borrowings from Persian, Russian, Arabic, and Chinese, many of which are quite old, have resulted in a high degree of root-internal disharmony in language (that is, roots that contain a mixture of front and back vowel and/or consonants).

Because of this prevalence of disharmonic roots, backness harmony is most evident as a morphophonological process, where segments in many suffixes must agree in backness with the roots they attach to (e.g., Lindblad, 1990; R. F. Hahn, 1991a, 1991b; Engesæth et al., 2009/2010; Abdulla et al., 2010). Diachronic change has made the Uyghur harmony system more complex than similar systems in other languages. The development of transparent vowels led to consonants serving as triggers for harmony as well as undergoers (see Chapters 4 and 6), a class of roots that must be lexically specified for harmonizing behavior (see Chapter 5), and, via interaction with vowel raising processes, to opacity in the harmony system (see Chapter 3).

Because backness harmony is described extensively throughout the remaining chapters, I will not go into additional detail here. Some morphological exceptions to harmony that are not directly relevant to the dissertation are discussed in Appendix A.

2.5.2 Vowel raising

Uyghur has two independent, though similar, phonological vowel raising processes. These processes are quite productive in the language, but generally occur only in derived environments: that is, these processes are not generally observed as restrictions on root phonotactics (with a few exceptions shown in Appendix D), but are observed as alternations triggered by suffixation.

The first process, traditionally referred to as *vowel reduction*, raises the low vowels /ɑ æ/ to [i] in medial open syllables, as in /bɑlɑ-lAr/ → [bɑlilɑr] 'child-PL' or /sællæ-lAr/ → [sællilær] 'turban-PL'. This process is described in more detail in Chapter 3, Section 3.3.4. A number of additional morphological exceptions to vowel reduction are described in Appendix B, and a phonological analysis of raising is presented in Appendix E.

The second raising process is traditionally referred to as *umlaut* or *regressive assimilation*. This processes raises the low vowels /ɑ æ/ to [e] in initial open syllables when the vowel in the following syllable is /i/ (or sometimes /æ/). For example, /tɑʃ-i/ → [teʃi] 'stone-3.POS' or /bæʃ-i/ → [beʃi] 'head-3.POS'. This process does not factor heavily in the dissertation, but is described in some detail in Appendix C.

2.5.3 Other phonological processes

Uyghur also has a process of rounding harmony that applies only to high vowels. For example, compare the forms below involving the derivational suffix /-lUQ/.

(3) *Examples of rounding harmony*

/qorɑl-lUQ/	→ [qorɑl-liq]	'weapon-LIQ (armed)'
/tæm-lUQ/	→ [tæm-lik]	'taste-LIQ (tasty)'
/tuz-lUQ/	→ [tuz-luq]	'salt-LIQ (salty)'
/øz-lUQ/	→ [øz-lyk]	'self-LIQ (reflexive)'

The vowel in this suffix agrees for rounding and backness with the root while the consonant agrees in backness (though note that backness contrast on the vowel is only manifested when the epenthetic vowel is rounded, as there is no front-back contrast between high unrounded vowels).

Note that although rounding harmony overlaps with backness harmony, the interaction between the two is not important for the purposes of this dissertation. A more detailed description of rounding harmony is given in Appendix F.

CHAPTER 3

Gradient opacity in Uyghur backness harmony

3.1 Introduction

This chapter examines a phonological pattern in Uyghur whereby a vowel raising process converts harmonic vowels into transparent vowels, rendering the harmony pattern opaque. Opaque patterns are of interest to phonology because of the challenges they pose for learning and for certain classes of phonological models. In particular, opacity has been a perpetual difficulty for strictly parallel phonological models such as classical OT, which do not straightforwardly predict its existence.

This chapter has two primary goals. The first is to present new empirical data on this phenomenon based on a combination of elicitation and a large-scale corpus study. Specifically, this chapter will demonstrate that although opaque harmony is the majority pattern, there is variability in rates of opacity both within and between roots. The second is to argue based on the nature of this variability that the grammar underlying backness harmony in Uyghur has both a phonological component, which favors surface-true harmony, and a lexical component, which categorizes roots into one of two harmony classes: those that take front suffixes and those that take back. Opaque harmony results when lexical pressures mandating uniform suffix backness across allomorphs of the same root dominate phonological pressures for surface harmony. Variability in rates of opacity is attributed to variation in the strength of these lexical pressures across roots.

In addition to accounting for the patterns observed in the corpus data, this analysis allows opacity in Uyghur to be captured in a strictly parallel model, rebutting, at least in this case, the common criticism that such models are flawed because they cannot handle opacity.

Section 3.2 provides background on phonological opacity. Section 3.3 first describes the phonological processes of backness harmony and vowel reduction in Uyghur, and how they can

interact to produce a kind of opacity that is problematic for strictly parallel models. It then describes previous claims made about this opacity in the literature, but demonstrates that there are empirical problems with this work. In order to achieve more stable empirical footing, Section 3.4 presents the results of a large-scale corpus study looking at rates of opacity by root. Section 3.5 presents a strictly parallel analysis that characterizes opacity as an interaction between phonological pressures towards surface harmony and lexical pressures to maintain the harmony class of a root across its allomorphs. I argue that this analysis provides greater explanatory adequacy than serial analyses of the data. Finally, Section 3.6 discusses the implications of this claim for theories of opacity in general, and how future research on opaque phenomena might proceed.

3.2 Phonological opacity

Kiparsky (1971, 1973) defines phonological opacity as follows:

(4)   Assume a phonological rule $\mathbb{R}$ of the form A → B / C_D. $\mathbb{R}$ is *opaque* if there are surface forms with either:

   a.   *A* in the environment *C_ D* (underapplication opacity)

   b.   *B* derived from *A* in environments other than *C_ D* (overapplication opacity)

In other words, opacity arises when either a conditioned alternation appears not to occur despite its conditions being met, or appears to occur when its conditions have not been met.

Working in a rule-based framework, Kiparsky associated opacity of types (4a) and (4b) with *counterfeeding* and *counterbleeding* rule orders respectively. In the case of counterfeeding opacity, the structural conditions for rule $\mathbb{R}$ to apply are created by a different rule $\mathbb{P}$ that applies after $\mathbb{R}$: hence the necessary conditions are not met when $\mathbb{R}$ applies. Changing the rule ordering such that $\mathbb{P}$ applied before $\mathbb{R}$ would produce a *feeding* order where $\mathbb{R}$ applies transparently to the conditioning environment produced by $\mathbb{P}$.

In counterbleeding opacity, the conditions for $\mathbb{R}$ are met when it applies, but are subsequently altered by a different rule $\mathbb{Q}$ that applies after $\mathbb{R}$. Changing the rule ordering such that $\mathbb{Q}$ applies

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before $\mathbb{R}$ would produce a *bleeding* order where $\mathbb{R}$ transparently fails to apply because $\mathbb{Q}$ removes its conditioning environment.

Opacity has been a longstanding topic of interest in phonological theory since its definition by Kiparsky. In recent years, this interest has stemmed from debates on the merits of serial models such as *SPE*-style rules (e.g., Chomsky & Halle, 1968) vs. parallel models such as Optimality Theory (e.g., Prince & Smolensky, 1993/2004). Parallel models have difficulty correctly predicting cases of counterbleeding opacity, which generally produce faithfulness violations with no corresponding markedness repairs to motivate them. They also have difficulty with most types of counterfeeding opacity, which fail to repair a markedness violation whose repair is evident in other contexts. A number of solutions have been proposed to handle these cases, including solutions that incorporate some degree of serialism into OT, such as sympathy (McCarthy, 1999), stratal OT (Kiparsky, 2000; Nazarov & Pater, 2017), candidate chain theory (McCarthy, 2007), and serial markedness reduction (Jarosz, 2014), as well as purely parallel mechanisms, such as constraint conjunction (Kirchner, 1996), paradigm uniformity (Steriade, 2000), language-specific constraints (Pater, 2014), or indexed constraints (Nazarov, 2019, 2020). The need for such bespoke mechanisms has been seen as a point in favor of serial models, which handle these cases of opacity without issue (e.g., Vaux, 2008).

Although counterfeeding and counterbleeding orderings are the best known configurations that result in opacity, the typologies of opacity enumerated in Baković (2007, 2011) and Baković and Blumenfeld (2019) show that these orderings are neither sufficient nor necessary conditions for opacity as defined above. In particular, they identify a number of cases of overapplication opacity that are not predicted by SPE-style rule ordering, and some which are *only* able to be described by parallel models. Thus the characterization of opacity as a unique challenge for parallel models is a simplification, though perhaps accurate in broad strokes.

In light of the lack of a unified account of opacity from either serial or parallel theories, Baković suggests that the field focus on Kiparsky's claim that opaque patterns are more difficult to learn than transparent ones. The basic motivation for this claim is that phonological processes that interact in an opaque fashion make generalization about those processes difficult: opaque forms often appear on the surface to be counterexamples to generalizations that might robustly apply

elsewhere. Kiparsky (1971) supports this claim by presenting a number of cases of historical change where an opaque process is reanalyzed as a transparent one. Subsequent research has presented evidence that opaque processes are learned as either phonemic contrasts or lexicalized patterns rather than productive rules (e.g., Hooper/Bybee, 1976; Mielke, Hume, & Armstrong, 2003; Sanders, 2003; Sumner, 2003; Zhang, 2019; Bowers, 2019), though evidence also exists that some opaque processes are applied productively in language games and other contexts (e.g., Donegan & Stampe, 1979; Al-Mozainy, 1981; Vaux, 2011). This chapter will suggest that opacity in Uyghur falls into the former camp, resulting from a kind of lexicalization of the harmony pattern.

3.3 Opacity in Uyghur backness harmony

Uyghur is a southeastern Turkic language spoken by over 12 million people in the Xinjiang Uyghur Autonomous Region in the People's Republic of China, neighboring countries such as Kazakhstan and Kyrgyzstan, and various diasporic communities (Engesæth et al., 2009/2010; Nazarova & Niyaz, 2013). It has SOV word order with highly agglutinative morphology that is almost exclusively suffixing.

Opacity in Uyghur backness harmony arises from the interaction of two independent phonological processes: backness harmony and vowel reduction. I will introduce these processes separately before demonstrating how their interaction leads to opacity.

3.3.1 Segments involved in backness harmony

Like most Turkic languages, Uyghur has backness harmony. Borrowings from Persian, Russian, Arabic, and Chinese, many of which are quite old, have resulted in a high degree of root-internal disharmony, though roots of Turkic origin tend to be harmonic. As a consequence, backness harmony is most evident as a morphophonological process, where, broadly speaking, segments in many suffixes must agree in backness with the roots they attach to (e.g., Lindblad, 1990; R. F. Hahn, 1991a, 1991b; Engesæth et al., 2009/2010; Abdulla et al., 2010).

The segments that directly participate in backness harmony are shown in Tables 3.1 and 3.2.

	Front		Back	
	Unrounded	Round	Unrounded	Round
High	i	**y**		**u**
Mid	e	**ø**		**o**
Low	**æ**		**ɑ**	

Table 3.1: The Uyghur vowel system. Harmonizing vowels are in bold.

	Front	Back
Voiceless	k	q
Voiced	g	ʁ

Table 3.2: Harmonizing Uyghur consonants

The bolded vowels in Table 3.1 serve as harmony triggers, while the non-bolded vowels are transparent to harmony. This paper will focus primarily on harmony driven by vowels, but the role of consonants as harmony triggers will become important in Section 3.5.1. In addition to serving as triggers of harmony (that is, they serve to determine the backness of suffixes attached to roots containing them), the harmonizing vowels and consonants both emerge as the outcome of harmony in harmonizing suffixes.

3.3.2 A description of Uyghur backness harmony

In the examples of harmony below, I use nouns with the locative suffix /-DA/ (surface forms: [-tɑ], [-dɑ], [-tæ], [-dæ]), the plural suffix /-lAr/ (surface forms: [-lɑr], [-lær]), or the dative suffix /-GA/ (surface forms: [-qɑ], [-ʁɑ], [-kæ], [-gæ]).[1] I assume that the archiphoneme /A/ is unspecified for the feature [back], /D/ is unspecified for [voice], and /G/ is unspecified for both. Voicing alterna-

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[1]The dative suffix may also surface as [-qæ] when attached to a root with a front vowel that ends in a voiceless uvular, as in [χælq-qæ] 'people-DAT' (cf. [χælq-i-gæ] 'people-3.POS-DAT'). I consider this to be a case of place assimilation rather than harmony, though some previous work has ascribed greater significance to it (e.g., Pattillo, 2013). Additional evidence that this is assimilation rather than harmony comes from Standard Uzbek, which is closely related to Uyghur. Although Standard Uzbek has completely lost vowel harmony, an identical kind of place assimilation happens in the initial consonant of the dative suffix, which surfaces as [-qɑ] when attached to roots ending in a uvular, but [-kɑ] or [-gɑ] when attached to other roots.

tions in the initial segment are caused by voicing assimilation, and are orthogonal to harmony. All examples are attested tokens from the corpora described in Section 3.4.

The basic characterization of backness harmony is that suffixes must agree in backness with the final front (/y ø æ/) or back (/u o ɑ/) harmonizing root vowel.

(5) *Simple front harmonizing forms*

    t**y**r-d**æ**/*-dɑ   'type-LOC'

    p**æ**n-l**æ**r/*-lɑr   'science-PL'

    munb**æ**r-**gæ**/*-ʁɑ 'podium-DAT'

(6) *Simple back harmonizing forms*

    p**u**l-**ʁɑ**/*-gæ   'money-DAT'

    t**o**p-**qɑ**/*-kæ   'ball-DAT'

    ætr**ɑ**p-t**ɑ**/*-tæ 'surroundings-LOC'

The vowels /i e/ are *transparent* to harmony, meaning that they do not serve as harmony triggers for suffixes, but allow the harmonic value of preceding segments to "pass through" them.

(7) *Front roots with transparent vowels*

    m**æ**stʃit-t**æ**/*-tɑ 'mosque-LOC'

    ymid-l**æ**r/*-lɑr   'hope-PL'

    m**ø**min-**gæ**/*-ʁɑ 'believer-DAT'

(8) *Back roots with transparent vowels*

    st**u**dent-l**ɑ**r/*-lær   'student-PL'

    uniwersitet-t**ɑ**/*-tæ 'university-LOC'

    amil-**ʁɑ**/*-gæ   'element-DAT'

Uyghur also has a process of *rounding harmony* that applies to high vowels. I do not discuss this here as it is not directly relevant to the opaque pattern under discussion (but see Appendix F).

3.3.3 Diachronic origins of Uyghur backness harmony

Scholars generally agree that Old Turkic and Chagatay (the direct ancestor of Uyghur and Uzbek) had a phonemic contrast between /i/ and /ɯ/ in initial syllables (Lindblad, 1990; R. F. Hahn, 1991a, 1991b; Bodrogligeti, 2001; Erdal, 2004).[2] This contrast appears to have had a low functional load: the number of true minimal pairs differing only in this vowel contrast is small, with most of the pairs of roots differing in this vowel contrast also containing dorsals that differed in quality (Erdal, 2004).[3]

Thus no roots were harmonically neutral as is the case now, and front and back dorsals co-occurred with front and back vowels respectively. At some point in its history, Uyghur lost this distinction between /i/ and /ɯ/, which complicated the harmony system, introducing both transparent vowels, neutral roots, and consonants as harmony triggers.(see also Binnick, 1991, for discussion of the inherent instability of harmony systems, and how this results primarily from language-internal factors, rather than loanwords) Lindblad (1990) shows that the most frequent roots that previously had /i/ continued to take front suffixes (e.g., /biz/ 'we', /ilim/ 'science', /itʃ-/ 'drink'), the roots that previously had /ɯ/ continued to take back suffixes, and many less frequent roots that were underlyingly /i/ began to take the default back form of suffixes. Uyghur appears to be typologically unusual in that the default harmony value is [+back], despite the transparent vowels being phonetically [–back]. In languages such as Mongolian and Finnish, which have similar transparent vowels, transparent roots generally behave as [–back] (Lindblad, 1990).[4]

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[2]Though see e.g., Johanson (1998) for a critical perspective.

[3]Because /e/ occurs almost exclusively in loanwords or as the output of umlaut (see Appendix C), it is unlikely to have had a diachronic back correspondent.

[4]Though some might argue whether the characterization of the transparent vowels as phonetically [–back] in Uyghur is justified: in practice they range from central to front. See Chapter 2.

3.3.4 Vowel reduction

The primary phonological process that contributes to opacity in the Uyghur harmony system is *vowel reduction* or *raising*, which raises the low vowels /ɑ æ/ to [i] in medial open syllables.[5] Examples of vowel reduction are shown below.

(9) */ɑ/ vowel reduction*

bɑlɑ	'child'	bɑl**i**-ni	'child-ACC'
ɑpɑ	'mom'	ɑp**i**-si	'mom-3.POS'
ɑŋlɑ-ʃ	'listen-GER'	ɑŋl**i**-di	'listen-3.SG.PAST'
qɑrɑ-ʃ	'look-GER'	qɑr**i**-di	'look-3.SG.PAST'

(10) */æ/ vowel reduction*

ɑpæt	'disaster'	ɑp**i**t-i	'disaster-3.POS'
mewæ	'fruit'	mew**i**-si	'fruit-3.POS'
søzlæ-ʃ	'talk-GER'	søzl**i**-di	'talk-3.SG.PAST'
kytʃæ-ʃ	'strive-GER'	kytʃ**i**-di	'strive-3.SG.PAST'

This process generally applies only to derived environments. The root /mɑqɑlæ/ 'article', for example, surfaces as [mɑqɑlæ] rather than *[mɑqilæ].

Note that the underlying form cannot in general be predicted from forms where vowel reduction could have applied, as many words have underlying /i/ in these positions.

(11) *Roots with underlying /i/*

tɑksi	'taxi'	tɑksi-ni	'taxi-ACC'
æsli	'origin'	æsli-ni	'origin-ACC'
qeri-ʃ	'grow old-GER'	qeri-di	'grow old-3.SG.PAST'[6]
ɑʁri-ʃ	'become ill-GER'	ɑʁri-di	'become ill-3.SG.PAST'

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[5]The other vowel raising process in Uyghur, umlauting, only targets initial syllables, and thus does not in general produce opacity in the harmony system (although it may render underlyingly harmonic roots harmonically neutral on the surface). Accordingly, this chapter will focus on vowel reduction, but umlaut is described in more detail in Appendix C.

Even in derived environments, vowel reduction does not apply exceptionlessly. Certain roots resist raising categorically, though this appears to be more common when the potential raiser is /ɑ/.

(12) *Exceptions to vowel reduction with /ɑ/*

hɑwɑ	'weather'	hɑwɑ-si	'weather-3.POS'
dærjɑ	'river'	dærjɑ-si	'river-3.POS'
mɑkɑn	'place'	mɑkɑn-i	'place-3.POS'

(13) *Exceptions to vowel reduction with /æ/*

sæwæb	'reason'	sæwæb-i	'reason-3.POS'
mɑqɑlæ	'academic article'	mɑqɑlæ-lær	'academic article-PL'
wæqæ	'accident'	wæqæ-gæ	'accident-DAT'

Raising has been claimed to occur less frequently in loanwords (Nazarova & Niyaz, 2013), and to be sensitive to vowel length distinctions and/or stress, with long or stressed vowels failing to raise, though there has been limited phonetic evidence presented to support this (though see McCollum, 2020).[7] For the purposes of this chapter I assume a description of Uyghur stress that is broadly consistent with a number of existing papers (Yakup, 2013; Özçelik, 2015; Major & Mayer, 2018; McCollum, 2020): primary stress in Uyghur falls by default on the final syllable of a word, but certain roots are underlyingly specified for stress position. It is this class of roots with fixed stress locations that categorically fail to undergo raising. See Appendix E for a sketch of an analysis of vowel reduction.

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[6]The root /qeri/ is an instance of lexicalized umlauting, as discussed in Chapter 2: cf. Uzbek /qɑri/, Kyrgyz /qɑrɯ/.

[7]The status of phonemic vowel length and stress in Uyghur is somewhat unclear. R. F. Hahn (1991b) claims that Uyghur has phonemic vowel length which is not represented orthographically, as well as lexical stress reflected by increases in pitch, duration, and intensity. A series of production and perception experiments in Yakup (2013) suggest that lexical stress does exist, but is reflected only by increases in duration: however, Uyghur speakers frequently disagreed as to which syllables were stressed in many words. Major and Mayer (2018) reproduce and expand on these results, suggesting that phrasal prosody is responsible for pitch contours that have previously been attributed to stress. All Uyghur speakers I have worked with have some intuition that certain vowels are longer than others, but it is unclear whether this should be analyzed as underlying vowel length or lexically-specified stress (or both).

3.3.5 Opaque interactions between backness harmony and vowel reduction

Vowel reduction has the potential to introduce opaque behavior into the vowel harmony system. Consider, for example, the root /aʁinæ/ 'friend'. When suffixes with appropriate forms are attached, the final vowel raises without exception:

(14) /aʁinæ-ni/ → [aʁini-ni]/*[aʁinæ-ni] 'friend-ACC'

What will happen for forms such as /aʁinæ-DA/, where the vowel in the suffix must harmonize with the final vowel in the root?

I assume a serial analysis here for presentational purposes. Supposing we have a rule ordering where backness harmony precedes raising. We should expect to see the opaque form [aʁinidæ], produced via the derivation in (15):

(15) *Harmony precedes raising*

UR	/aʁinæ-DA/
Harmony	aʁin**æ**-d**æ**
Raising	aʁini-dæ
SR	[aʁini-dæ]

Note that this opacity is precisely the kind that classical OT has difficulty accounting for: we see an explicit markedness violation (failure to harmonize correctly), with no apparent motivation (cf. forms like /qojchi-DA/ → [q**o**jchid**ɑ**] 'shepherd-LOC'). According to the typology presented by Baković and Blumenfeld (2019), this is a case of *ambivalent opacity*, since whether it feeds or bleeds front/back harmony depends on the quality of the raised vowel.

Considering this interaction to be opaque relies on raising being *structure preserving*: that is, it does not introduce sounds not present in the language's inventory (e.g., Emonds, 1970; Kiparsky, 1985). If in Uyghur /æ/ raised to [i] and /ɑ/ raised to [ɯ], which is not a structure preserving transformation according to the inventory in Section 3.3.1, the interaction of harmony with raising would not longer be opaque, since suffixes would simply harmonize with the backness of the raised

vowel. I assume that structure preservation holds here.[8] Chapter 5 provides additional motivation for the inventory in Section 3.3.1, and Chapter 8 describes avenues of future research to more carefully explore this question.

If raising instead precedes backness harmony, we would expect the transparent form [ɑʁini-dɑ], shown in (16):

(16) *Raising precedes harmony*

UR	/ɑʁinæ-DA/
Raising	ɑʁini-DA
Harmony	**ɑʁini-dɑ**
SR	[ɑʁini-dɑ]

In addition to being an important empirical question, the presence or absence of opaque harmony is important from a theoretical perspective: opaque patterns such as the one in example (15) are not predicted to exist by many strictly parallel phonological models. The next section describes the problems such patterns pose for these models.

3.3.6 Modeling opacity in serial and parallel models

In this section I will present analyses of the opaque pattern in several serial and parallel models, illustrating the difficulties strictly parallel models have with capturing this pattern and presenting some solutions to this problem that have been proposed in the literature.

The kind of opacity shown in example (15) is straightforward to represent in serial rule-based models: the rule or rules driving harmony are simply ordered before the rule that drives raising. An analysis under such a model is essentially identical to the derivation in (15).

This pattern poses challenges for an analysis in classical OT. I will assume the following pair

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[8]Kiparsky (1985) suggests that structure preservation holds for lexical rules but not post-lexical rules. In a strictly parallel model such as the one presented in this chapter, this distinction becomes more tenuous. Were we to analyze raising in a stratal framework such as Lexical Phonology, its sensitivity to both morpheme identity and underlying morphological structure, as described above and in Appendix B, motivate positing it as a lexical rule. Thus the assumption of structure preservation is justified. Its limited optional application at the phrase level, described in Section 3.3.6, suggests that it may apply post-lexically as well.

of simple constraints that motivate vowel harmony.

(17)   VAGREEBACK: Assess one violation if a front suffix is attached to a root whose final harmonizing vowel is back.

(18)   VAGREEFRONT: Assess one violation if a back suffix is attached a root whose final harmonizing vowel is front.

These constraints are roughly a combination of the local and non-local AGREE constraints used in Hayes et al. (2009). The choice of the formulation these constraints is not intended to make a strong claim about the theoretical mechanisms of backness harmony in Uyghur: rather, they are employed simply to capture the generalizations that (a) the identity of any vowels preceding the final harmonizing vowel appears to be irrelevant to the harmonic behavior of real words; and (b) transparent vowels intervening between the final harmonizing vowel and the suffix do not appear to affect the harmonizing behavior of real roots. Other harmony frameworks may be substituted without significantly changing the analysis. Chapter 4 presents a more detailed study of the mechanisms of backness harmony in Uyghur.

I will use the following constraints to drive raising:

(19)   *UNREDUCED: Don't have low vowels in medial open syllables.

(20)   ID[HEIGHT]: Don't change the height of segments in the input.

These constraints may be considered shorthand for the analysis presented in Appendix E. I will not consider forms that exceptionally fail to undergo raising.

When relevant I will also employ an ID constraint that prevents already specified [back] values from being altered.

(21)   ID[BACK]: Don't change the backness of segments in the input.

Note that this constraint is not violated when a segment underspecified for backness in the input is assigned a backness value in the output, nor is it violated when /æ ɑ/ are raised to [i]: assuming that [i] is unspecified for backness, these processes violate DEP and MAX constraints respectively,

which are low-ranked and omitted from the tableaux below. ID[BACK] serves to prevent underlyingly specified vowels in roots and harmony-blocking suffixes such as /-wɑt/ 'PROG' from being altered.

/aʔilæ-lАr/	*UNREDUCED	VAGREEBACK	VAGREEFRONT	ID[HEIGHT]
☹ a. aʔili-lær		*!		*
💣 b. aʔili-lɑr				*
c. aʔilæ-lær	*!			
d. aʔilæ-lɑr	*!		*	

Table 3.3: Failed tableau for [aʔili-lær] 'family-PL'. The sad face indicates the candidate that should have won, and the bomb indicates that candidate that did win.

These constraints do not allow classical OT to derive opacity at all: only surface harmony is predicted, as shown in Table 3.3. Note that the desired candidate [aʔili-lær] is harmonically bound by the winning *[aʔili-lɑr], and so will never be the optimal candidate under any ranking of these constraints.

It is beyond the scope of this chapter to consider the application of all the proposed solutions to opacity in OT to this case, but I will show how an analysis using Stratal OT succeeds in capturing this opacity (Kiparsky, 2000; Bermúdez-Otero, 2003, 2018). Stratal OT divides the grammar into several strata (e.g., the stem, the word, the phrase) and assigns each of these levels a separate OT grammar, with differing constraint rankings/weights. The outputs of lower strata serve as the inputs to higher strata.

I choose this formalism as an example here because it is widely used in the contemporary literature, and because there is some evidence in Uyghur that raising applies across a larger domain than backness harmony the domain of backness harmony is the prosodic word (the root plus its suffixes), while the domain of raising is the *accentual phrase* (Major & Mayer, 2018, to appear).[9] For example, in the phrase *Adil Hesenge berdi* 'Adil gave it to Hesen', the dative *-ge* (IPA: [-gæ]) may raise to *-gi* in rapid speech. We can successfully capture the opaque pattern here by postulating

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[9]However, vowel reduction is sensitive to morphological structure in many cases (see, e.g., Chapter 2 and Appendix B), which may be a case for situating it at the word level as well.

that backness harmony occurs at the word level and raising occurs at the phrase level, resulting in derivations like that shown in Table 3.4.

Word level

/aʔilæ-lAr/	ID[BACK]	ID[HEIGHT]	VAGREEBACK	VAGREEFRONT	*UNREDUCED
a. aʔili-lær		*!	*		
b. aʔili-lɑr		*!			
☞ c. aʔilæ-lær					*
d. aʔilæ-lɑr				*!	*

Phrase level

/aʔilæ-lær/	ID[BACK]	*UNREDUCED	VAGREEBACK	VAGREEFRONT	ID[HEIGHT]
☞ a. aʔili-lær			*		*
b. aʔili-lɑr	*!				*
c. aʔilæ-lær		*!			
d. aʔilæ-lɑr	*!	*		*	

Table 3.4: Tableaux for the derivation of [aʔili-lær] 'family-PL' at the word stratum (top) and phrase stratum (bottom). At the word stratum, the constraint driving raising is ranked below its corresponding faithfulness constraint, meaning harmony applies but raising does not. The output from the word stratum serves as the input to the tableau for the phrase stratum. At this stratum, the constraint driving raising is now ranked above its corresponding faithfulness constraint, meaning raising can apply here.

Thus serial rule-based analyses predict opaque harmony straightforwardly, while strictly parallel analyses predict only surface-true harmony. Modifications to strictly parallel models that incorporate some degree of serialism, such as Stratal OT, also predict opaque harmony, though they differ in their attribution of the particular mechanism responsible for it. We will now turn to the question of whether Uyghur exhibits opaque harmony or surface-true harmony.

3.3.7 Previous work on opacity in Uyghur backness harmony

Previous work on the interaction between vowel raising and harmony has claimed that there is an asymmetry between vowels (Vaux, 2000; Halle, Vaux, & Wolfe, 2000; Hall & Ozburn, 2018):

raised /æ/ is opaque (i.e., serves as a front harmony trigger), while raised /ɑ/ is transparent. This claim has been based on eight data points from Vaux (2000), which I reproduce below.

(22) *Data on /ɑ/ raising opacity from Vaux (2000)*

UR	SR	Gloss
/æswɑb-i-GA/	[æswib-i-**gæ**]	'tool-3.POS-DAT'
/qæhwɑ-GA/	[qæhwi-**gæ**]	'coffee-DAT'
/æmmɑ-lAr/	[æmmi-**lær**]	'but-PL'
/ænʤɑn-i-GA/	[ænʤin-i-**gæ**]	'Änjan-3.POS-DAT'

(23) *Data on /æ/ raising opacity from Vaux (2000)*

UR	SR	Gloss
/ɑdæm-i-GA/	[ɑdim-i-**gæ**]	'man-3.POS-DAT'
/ɑpæt-i-GA/	[ɑpit-i-**gæ**]	'disaster-3.POS-DAT'
/roʃæn-i-GA/	[roʃin-i-**gæ**]	'Roshän-3.POS-DAT'
/ɑʁinæ-lAr/	[ɑʁini-**lær**]	'friend-PL'

In the forms in (22), the suffix harmonizes with the final harmonizing surface vowel, with the raised /ɑ/ behaving like a transparent vowel. In the forms in (23), however, the suffix harmonizes with the underlying form of the raised /æ/, even though it is neutralized on the surface. This apparent asymmetry has been used to drive claims about how contrasts are represented in phonological inventories (Vaux, 2000; Halle et al., 2000; Hall & Ozburn, 2018).

There are reasons to be suspicious of these data, however. I asked five native Uyghur speakers to judge the forms in (22) and (23). They found all the forms in (22) and one form in (23) to be ungrammatical, for the following reasons:

- The final vowels of the roots /æswɑb/ 'tool', /ænʤɑn/ 'Änjan', and /roʃæn/ 'Roshän' never undergo raising. The surface forms provided by all consultants were [æswɑb-i-**ʁɑ**], [ænʤɑn-i-**ʁɑ**], and [roʃæn-i-**gæ**], respectively, with expected surface-true harmony.

- The Uyghur word for coffee is /qæhwæ/, not */qæhwɑ/. In addition, the final vowel does not raise, giving the surface form [qæhwæ-**gæ**].

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- Four out of the five speakers rejected all forms of /æmmɑ-lAr/, which has the plural marker affixed to a conjunction. The one speaker who accepted it (under some duress) said they would say [æmmɑ-lɑr], without raising.

The realizations of Vaux's data according to my consultants are shown in (24) and (25), with '*' and '?' indicating forms which my consultants found ungrammatical or questionable, respectively.

(24) *My consultants' productions of /ɑ/ forms from Vaux (2000)*

Consultants' UR	Consultants' SR	Vaux UR	Vaux SR	Gloss
/æswɑb-i-GA/	[æswɑb-i-ʁɑ]	/æswɑb-i-GA/	*[æswib-i-**gæ**]	'tool-3.POS-DAT'
/qæhwæ-GA/	[qæhwæ-**gæ**]	*/qæhwɑ-GA/	*[qæhwi-**gæ**]	'coffee-DAT'
/æmmɑ-lAr/	[æmmɑ-lɑr]	?/æmmɑ-lAr/	*[æmmi-lær]	'but-PL'
/ænʤɑn-i-GA/	[ænʤɑn-i-ʁɑ]	/ænʤɑn-i-GA/	*[ænʤin-i-**gæ**]	'Änjan-3.POS-DAT'

(25) *My consultants' productions of /æ/ forms from Vaux (2000)*

Consultants' UR	Consultants' SR	Vaux UR	Vaux SR	Gloss
/ɑdæm-i-GA/	[ɑdim-i-**gæ**]	/ɑdæm-i-GA/	[ɑdim-i-**gæ**]	'man-3.POS-DAT'
/ɑpæt-i-GA/	[ɑpit-i-**gæ**]	/ɑpæt-i-GA/	[ɑpit-i-**gæ**]	'disaster-3.POS-DAT'
/roʃæn-i-GA/	[roʃæn-i-**gæ**]	/roʃæn-i-GA/	*[roʃin-i-**gæ**]	'Roshän-3.POS-DAT'
/ɑʁinæ-lAr/	[ɑʁin-i-lær]	/ɑʁinæ-lAr/	[ɑʁin-i-lær]	'friend-PL'

It is possible that the forms in (22) and (23) come from a different dialect of Uyghur, although at least one of my consultants felt that no native Uyghur speaker would produce them. In addition, data on these words from the corpora discussed below are consistent with my consultants' judgments. The forms that are accepted by my consultants suggest that raised /æ/ harmonizes opaquely, but the status of raised /ɑ/ is unclear based on these data points.

3.3.8 Elicitation on opacity in Uyghur backness harmony

Further elicitation revealed instances of raised /ɑ/ that *vary* in whether they harmonize opaquely or transparently. There are cases of raised /ɑ/ being consistently opaque, as in /ʃæjtɑn-i-GA/ → [ʃæjtin-i-ʁɑ] 'devil-3.POS-DAT'. There are also cases where both harmonizing forms may be acceptable such as in /ærzɑn-i-GA/ → [ærzin-i-**gæ**] or [ærzin-i-ʁɑ] 'cheap (one)-3.POS-DAT' or

/æzɑn-i-GA/ → [æzin-i-ʁɑ] or [æzin-i-gæ] 'call to prayer-3.POS-DAT'. My consultants generally prefer the former, but say the latter also sounds fine.

These data points suggest that opacity in Uyghur backness harmony may be more complicated than previously suggested. Rather than being consistently opaque or transparent, the same vowel may behave differently in different roots. The following section will present a corpus study to explore the harmonizing behavior of raised vowels across a large number of roots and tokens.

3.4   A corpus study of opacity in Uyghur backness harmony

In order to investigate the interaction of vowel raising and backness harmony, I performed a large scale corpus study using two corpora from different geographical areas. The first corpus was generated from the website of *Uyghur Awazi* (Uyghur Voice), an Uyghur-language newspaper published in Almaty, Kazakhstan (`http://uyguravazi.kazgazeta.kz/`). The second corpus was generated from the Radio Free Asia (RFA) Uyghur language website (`https://www.rfa.org/uyghur/`), which serves the Xinjiang region as well as diasporic communities. RFA is a US-sponsored non-profit news organization that focuses on serving regions of Asia where government censorship of news reports is pervasive.

Corpora were generated from the websites using *web scrapers*. A web scraper is software that, given a starting URL, instructions for how to navigate between pages, and instructions for which information to retrieve from each page, can download content from all pages on a site, or multiple sites. Such programs are useful for generating corpora from publicly available internet resources, in formats that are useful to researchers.

There are separate web scrapers for the Uyghur Awazi[10] and the RFA[11] websites. These scrapers were written by the author in collaboration with undergraduate research assistants at UCLA.[12] They are freely available for use in research. Information on how to run the scrapers can be found

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[10]`https://github.com/connormayer/uyghur_tools/tree/master/uyghur_awazi_scraper`

[11]`https://github.com/yzgncx/RFA-Scraper`

[12]Thanks to Daniela Zokaeim and Tyler Carson for their work on these programs.

at the links supplied in the footnotes.

The data presented in this chapter were retrieved from the Uyghur Awazi and RFA websites in January 2020. They consist of a complete scrape of both sites. The Uyghur Awazi corpus contains approximately 14,000 articles with a total of about 6.1 million words. The RFA corpus consists of approximately 30,000 articles with a total of about 9.6 million words. The scrapers stored the results in comma-separated value files containing the article text in both the original orthography and converted to standard Uyghur Latin, the author, the date, the URL, and some additional metadata.[13]

3.4.1 Uyghur orthography

Uyghur is spoken in a variety of countries and diasporic communities, and accordingly is represented by a variety of orthographies. Perso-Arabic script is typically used in China, while former Soviet countries tend to use Cyrillic script. Diasporic communities in the United States and elsewhere often use Latin orthography, of which there are several competing variants.

Despite this abundance of representations, all the official Uyghur orthographies map fairly closely onto pronunciation, which facilitates phonological research based on written corpora. In particular, the alternations conditioned by the raising and harmony processes are represented orthographically. The allophonic alternations in the transparent vowels discussed earlier are not represented, nor are other common processes like vowel devoicing.

3.4.2 Parsing the corpora

In order to extract information about the interaction between backness harmony and vowel raising from the corpus, I modified an existing Uyghur morphological transducer to detect the backness of suffix forms (`https://github.com/apertium/apertium-uig`; Littell et al., 2018; Washington et al., to appear). This transducer is part of Apertium, a free and open-source rule-based machine translation platform (`https://www.apertium.org`).

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[13]Note that articles on both Uyghur Awazi and RFA are often under totally or partially anonymous bylines, such as *admin* or *muxbirimiz Erkin* 'our reporter Erkin', which makes tracking authorship across the corpora difficult.

A morphological transducer maps between surface forms and underlying analyses that consist of roots plus morphological tags. This mapping may take place in either direction. For example, suppose we are mapping from surface forms to underlying analyses. If the input is the surface form *qizingizgha* "to your daughter" the output analysis will be *qiz<n><px2sg><frm><dat>* (I use Latin orthography throughout this section rather than IPA, since it more closely reflects the input to the transducer). This indicates that the root is *qiz*, a noun (<n>), and is suffixed with the 2nd person singular possessive marker (<px2sg>) in its formal form (<frm>) followed by the dative suffix (<dat>). The transducer can also carry out mapping in the opposite direction, from underlying analysis to surface form. In this case, the underlying input *qiz<n><px2sg><frm><dat>* produces the surface output *qizingizgha*.

I modified this transducer to work with the Cyrillic and Latin orthographies, and to detect the harmonic quality of suffixes when mapping from surface to underlying forms.[14] Under this modified system, the form *qizingizgha* presented above maps to *qiz<n><px2sg><frm><dat-b>*, indicating that the dative suffix surfaces in one of its back harmonizing forms (*-qa* or *-gha*) rather than one of its front harmonizing forms (*-ke*, *-ge*, or *-qe*). In addition, the restrictions the phonological component of the transducer imposes on harmony have been lifted. The original transducer, for example, would reject a form like **at-ler*, "horses", for being disharmonic. The modified transducer will instead simply interpret this as an instance of the front form of the plural suffix.

The vowel raising processes described in Section 3.3.4 can obscure the harmonizing quality of suffixes: for example, the surface realization of /dost-lAr-m/ 'friend-PL-1Sg.POS' is [dostlirim], which does not allow the backness of the plural morpheme to be determined. In such cases the modified transducer does not attempt to guess the backness of the suffix (i.e., to report either *<pl-f>* or *<pl-b>*), but will instead remain agnostic, simply reporting *<pl>*.

I also performed some manual error correction on the transducer: primarily removing or modifying invalid roots in consultation with an online Uyghur dictionary.[15]

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[14]The code for this modified transducer can be found at `https://github.com/connormayer/apertium-uig/tree/vowel_harmony`.

[15]`https://lughet.com/`

Additional details of the transducer are presented in Appendix G.

3.4.3 Interpreting the transducer output

Applying the transducer to the corpus will produce one or more possible analyses for each word that the transducer is able to recognize. We can use this output to calculate the frequency with which particular roots take front or back suffixes.

One challenge that arises is how to deal with multiple analyses in cases where they provide conflicting information about the root. The surface form *balilar*, for example, could correspond to underlying /bɑlɑ-lAr/ 'child-PL' or to /bɑl-i-lAr/ 'honey-3.POS-PL.' Although the transducers used in the Apertium system can be augmented with contextual information to determine the most likely analysis for ambiguous forms, this functionality is not yet available for Uyghur. I accordingly omit all roots with tokens that produce this kind of ambiguity: that is, roots for which there exists some token whose analysis may correspond to some other root. In the case described above, all tokens of both /bɑlɑ/ and /bɑl/ would be omitted.

A second challenge is how to treat forms that display conflicting harmony values among suffixes, such as the hypothetical form *qizlarge* "to the daughters", which contains the back form of the plural suffix /-lAr/ and the front form of the dative suffix /-GA/. I omit all tokens that produce at least one such analysis. That being said, these tokens are exceedingly uncommon (about 500 tokens from 13.24 million words) and frequently result from highly improbable, though logically possible, analysis. For example, the correct analysis of the string *orginida* is *orgin-i-da* 'organ-3.POS-LOC', but a possible analysis might be *or-gin-i-da* 'harvest-PERF-3.POS-LOC'. This analysis is unlikely because it requires that a front allomorph *-gen* (IPA [-gæn]) of the perfective morpheme /-GAn/ be attached to the verb root *or* (IPA: /or/), which is expected to take the back allomorph *-ghan* (IPA [-ʁɑn]), but it is accepted as a possibility by the transducer (vowel reduction causes the putative front allomorph here to surface as *-gin*, but it can still be identified as such by the presence of *g* rather than *gh*).

Thus the suffixes applied to a root almost always share the same backness values, unless one suffix is a harmony blocker. Such suffixes, like the continuous suffix /-wɑt/, block harmony by

failing to harmonize, and impose their own harmonic values on following suffixes: for example /søzlæ-wɑt-GAn/ → [søzlæwɑtqɑn] 'speak-PROG-PERF'. I omit tokens containing such suffixes.

3.4.4 Quantitative results

The morphological transducer was able to successfully analyze 4.55 million of the 6.13 million words in the *Uyghur Awazi* corpus (74.3%) and 8.69 million of the 9.58 million words in the RFA corpus (90.6%), resulting in a total of 84.3% of all words across the corpora being successfully analyzed. The poorer performance on the *Uyghur Awazi* corpus may be due to differences in the vocabulary of Uyghur spoken in Kazakhstan and in the content of the corpus. In addition, some articles contain sections of Kazakh text, which would fail to be analyzed.

Of the roots corresponding to tokens that were successfully analyzed, there were 232 that had the necessary structure to produce simple opacity. I divide these into two classes: BF roots ($n = 198$), whose final two harmonizing vowels are a back vowel followed by /æ/ (e.g., /ɑdæt/ 'custom', /sijɑsæt/ 'politics'); and FB roots ($n = 34$), whose final two harmonizing vowels are a front vowel followed by /ɑ/ (e.g., /ætrɑp/ 'area', /æhwɑl/ 'condition'). For simplicity, I omit roots containing harmonizing dorsals, though transparent vowels may be found in the roots I consider.

Subsequent text processing comparing the root identified by the transducer and the surface form shows that 195 of these roots displayed vowel reduction. Of the BF roots, 189 (97%) exhibited vowel reduction, while of the FB candidates, only six (18%) did.

Of the six FB roots, five contain the derivational morpheme '/-dɑʃ/', which means something similar to '-mate' in English. These roots are /χizmætdɑʃ/ 'coworker', /wætændɑʃ/ 'country-man', /qælæmdɑʃ/ '(fellow) writer', /kæsipdɑʃ/ 'colleague', and /søhbætdɑʃ/ 'interlocutor', with the vowel in /-dɑʃ/ raising (e.g., [kæsipdiʃ-i] 'colleague-3.POS'). The sole raising FB root in the corpus that does not contain this morpheme is /ærzɑn/ 'cheap' (see Section 3.3.8 for discussion of this root). Additional discussion of possible relationships between derivational morphology and opaque behavior is presented in Section 3.5.6.

The rates of surface-true and opaque harmony for BF and FB roots in raised forms with harmonizing suffixes are shown in Fig. 3.1. Tokens of raised BF roots with front suffixes and tokens of
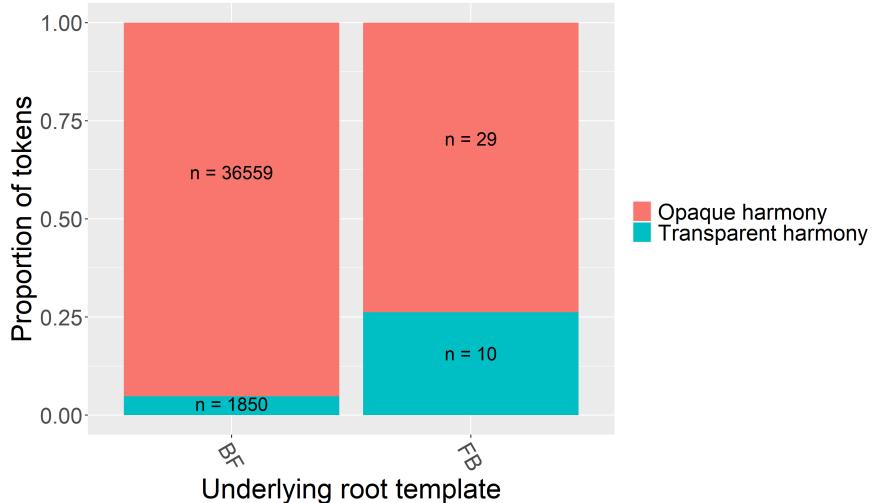
Figure 3.1: Proportion of opaque and transparent harmonizing tokens for BF and FB root types, with token counts overlaid. The tokens represented in this graph have roots with underlying BF and FB templates, display raising, and have one or more harmonizing suffixes attached. The token counts displayed in this graph correspond to 189 BF roots and 6 FB roots.

raised FB roots with back suffixes are considered opaquely harmonizing tokens. This figure shows that opaque harmony (that is, harmony with the underlying form) is the norm for raised roots in both classes. Of the 195 roots represented in this graph, 140 display opaque raising without exception (137 BF roots and 3 FB roots). 55 roots, however, vary in whether they display surface-true harmony or opaque harmony. The distribution of surface-true harmony across raised BF and FB roots are shown in Figs. 3.2 and 3.3 respectively.

In order to test for statistical and phonological predictors of opacity rates, I fit a linear regression model to these roots, with log token frequency, final underlying vowel identity (F or B), and proportion of raised tokens as predictors, and rate of opaque harmony as the dependent variable. The proportion of raised tokens is defined as the number of tokens of a root containing the raised allomorph divided by the total number of tokens: for example, the root /ɑpæt/ 'disaster' occurs 2201 times in the corpus. Of these tokens, 830 are in forms that exhibit raising (e.g., [ɑpit-i] 'disaster-3.POS', [ɑpit-i-ni] 'disaster-3.POS-ACC') and 1371 are in unraised forms (e.g., [ɑpæt] 'disaster', [ɑpæt-lær] 'disaster-PL'). Thus the proportion of raised tokens for this root is $830/2201 = 0.38$.
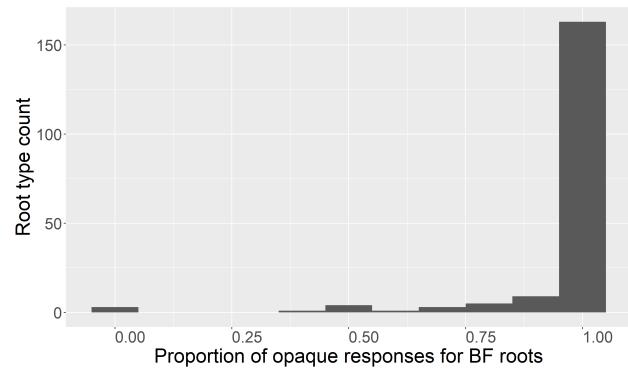
Figure 3.2: Histogram of back responses for BF roots in their raised forms.
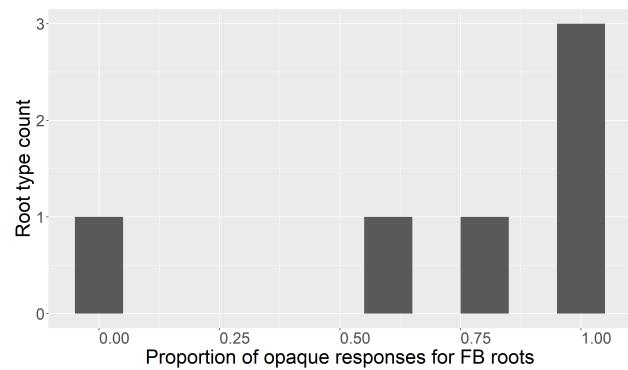
Figure 3.3: Histogram of back responses for FB roots in their raised forms.

The model shows that underlying vowel identity is a significant predictor of opaque harmony, with underlying back vowels being less likely to harmonize opaquely ($\beta = -0.23$, $t = -3.40$, $p < 0.001$). The proportion of raised tokens is a significant negative predictor of the rate of opaque harmony (Fig. 3.4; $\beta = -0.12$, $t = -2.94$, $p < 0.01$), and the overall log token frequency is a significant positive predictor of rate of opaque harmony (Fig 3.5; $\beta = 0.013$, $t = 2.28$, $p < 0.05$). In other words, the more frequently a root occurs in its raised form, and the less frequent it is overall, the more likely it is to display surface-true harmony. Fig. 3.6 shows this relationship for only roots that display variable opacity rates.
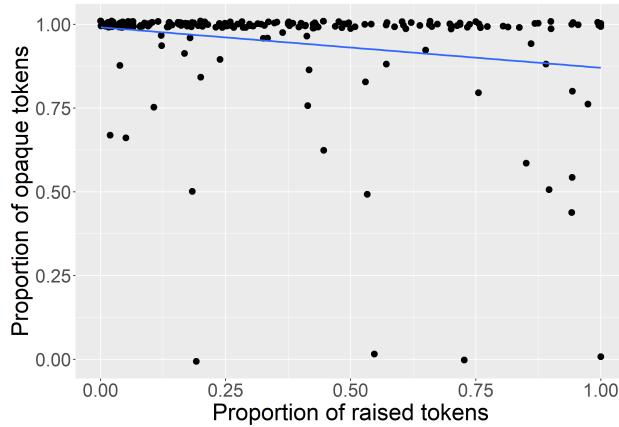
Figure 3.4: Proportion of harmony with the underlying form of the raised vowel (opaque behavior) plotted against the proportion of raised tokens ($r = -0.21$). Slight vertical jittering has been applied so the density of points around 100% opacity can be seen.

3.4.5 Gradient opacity within a single root

I will briefly illustrate examples of variation between opaque and surface-true harmony for a single root: /sɑhɑbæ/ 'Companion to the Prophet'. This word occurs in its raised form [sɑhɑbi] in 95% of tokens (65/69) and displays opaque harmony (i.e., takes front suffixes) 43% of the time in these raised forms. That is, we see the following surface realizations:

- Unsuffixed tokens: [sɑhɑbæ] ($n = 4$)
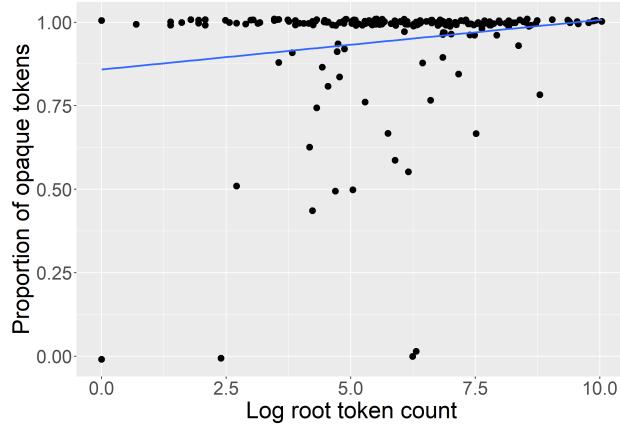
Figure 3.5: Proportion of harmony with the underlying form of the raised vowel (opaque behavior) plotted against overall frequency ($r = 0.18$). Slight vertical jittering has been applied so the density of points around 100% opacity can be seen.
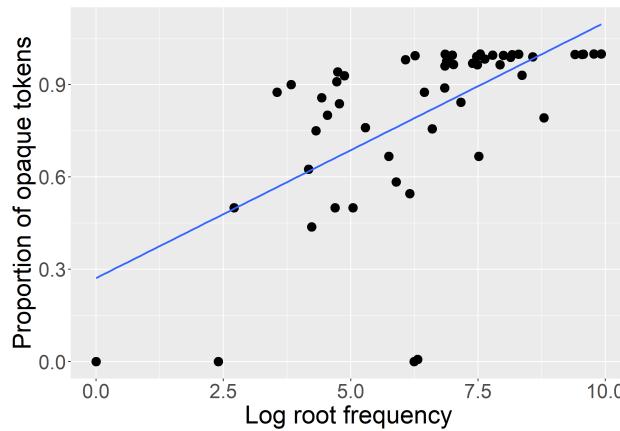
Figure 3.6: Proportion of harmony with the underlying form of the raised vowel (opaque behavior) of roots displaying opacity rates of < 1 plotted against overall frequency ($r = 0.32$).

- Opaque raised tokens: e.g., [sɑhɑbi-lær] ($n = 28$)

- Surface-true raised tokens: e.g., [sɑhɑbi-lɑr] ($n = 37$)

The high frequency of raised tokens has to do with the contexts in which this word is typically used: it is almost always produced with the plural suffix /-lAr/.

Below are a few examples of this root in its unsuffixed form and in its raised form with both

opaque and surface-true harmony. All examples come from the RFA corpus. Note that these examples are presented in Latin Uyghur orthography, rather than IPA, where /æ/ is notated as 'e' and /ʁ/ as 'gh'. Translations are my own.

(26) *Unsuffixed tokens of 'sahabe'*

⟨⟨*Xalid*⟩⟩ *dégen sözdin eqlimge islam tarixidiki meshhur **sahabe**, qabil qomandan Xalid Ibni Welid keldi.*

The word 'Khalid' brought to my mind the powerful commander Khalid Ibn Walid, a well-known Companion in the history of Islam.

(27) *Opaque tokens of raised 'sahabe'*

*Siyasetchiler üchün ereblerning wehhabiy bolghini bilen iranliqlarning **sahabilerni** tillishi otturisida perq yoq.*

For politicians, there is no difference between the Arabs' having become Wahhabi and the Iranians' insulting of the Companions.

*Andin **sahabilerning** hijret qilishigha ruxset qilghan.*

Then (he) allowed the Companions to emigrate (make the hijrah).

(28) *Surface-true tokens of raised 'sahabe'*

*Uni körgen **sahabilar** kütülmigen bu ehwalni körüp ghezeblinidu.*

The Companions who saw him were shocked to see this unexpected situation.

⟨⟨*Adaletlik bir padishah bar*⟩⟩ *dégen sözi **sahabilirigha** bergen bir kapalet idi.*

His words that 'there is a righteous king' were a promise given to his Companions.

3.5 Phonological analysis of corpus results

Chomsky (1965) enumerated a hierarchy of adequacy for evaluating grammatical theories: summarized briefly, a theory is *observationally adequate* if it correctly enumerates the observed data, *descriptively adequate* if it corresponds to the intuitions of native speakers and correctly expresses generalizations that underlie regularities in the language, and *explanatorily adequate* if it provides a principled basis for choosing it over other descriptively adequate grammars.

Given the quantitative results described above, a descriptively adequate grammar must be able to account for the following four properties:

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- Although opaque harmony is the majority pattern in raised tokens, cases of surface-true harmony also exist.

- The rate of opaque harmony varies across roots.

- The rate of opaque harmony for a root is positively correlated with the (log) token frequency of the root.

- The rate of opaque harmony for a root is negatively correlated with the proportion of raised tokens.

In the remainder of this chapter, I will argue that the opacity in Uyghur backness harmony should be analyzed primarily as a type of *exceptionality* driven by an inflectional class system that underlies backness harmony, rather than as the result of an opaque serial interaction between independent phonological processes. That is, in addition to learning phonological generalizations about the patterns of harmony, speakers also treat harmonizing behavior as a diacritic morphological property of roots. Roots are categorized into an inflectional class system based on the backness of suffixes they take, analogous to the classification of nouns into masculine and feminine classes in French, for example. This aligns with the treatment of Hungarian vowel harmony in Rebrus and Törkenczy (2017), which argues that sensitivity to this inflectional class system can override expected phonological effects.

The analysis presented in the following sections proposes that the gradience observed in rates of opaque harmony is the result of conflict between these phonological and morphological pressures. The phonological component is sensitive to the surface properties of harmony and prefers surface-true harmony, while the morphological component mandates that different allomorphs of a root should maintain the same inflectional class (that is, take suffixes of the same backness). This morphological component is independently necessary because of the relative pervasiveness of exceptionality in Uyghur backness harmony: a large class of exceptional roots harmonize in a way that violates general phonological patterns. The harmonizing behavior of such roots is determined according to their morphological class.

Such an analysis not only accounts for each of the properties listed above, but independently

motivates them based on the general properties of the Uyghur harmony system, the nature of exceptional morphemes, and the interaction between general and exceptional patterns. In particular, the connection between token frequency and opacity rates is straightforwardly predicted if opacity is treated as a type of exceptionality.

Both serial rule ordering and extensions of OT such as Stratal OT can generate categorical opacity in Uyghur backness harmony, but neither straightforwardly predict the four properties above. In fact, these properties are quite surprising under a stratal analysis, since variation in the order in which stratal derivations occur is not expected (i.e., if backness harmony occurs at the word level and raising at the phrase level, then raising should never precede harmony). Although it is likely possible to produce a descriptively adequate serial analysis that captures these properties by introducing the necessary theoretical machinery, such modifications are essentially ad hoc. Thus I will argue that it is not only possible to model the opaque pattern using a strictly parallel model, but necessary to achieve explanatory adequacy.

3.5.1 Exceptionality and the need for morphological diacritics

There are at least four different cases of exceptionality found in the backness harmony system that require the use of morphological diacritics. First, although roots without any harmonizing segments typically take back suffixes (Example 29), there are a number of exceptional forms that take front suffixes (Example 30). Chapter 5 demonstrates that whether such roots take front or back suffixes cannot be predicted from their acoustic or segmental properties, and must be memorized.

(29) *Neutral roots that take back suffixes*
      sir-lɑr/-*lær   'secret-PL'
      din-ʁɑ/*-gæ   'religion-DAT'
      hejt-tɑ/*-tæ   'festival-LOC'
      peʔil-lɑr/*-lær   'verb-PL'
      tip-qɑ/*-kæ   'type-DAT'

(30) *Exceptional neutral roots that take front suffixes*

    biz-**gæ**/*-ʁɑ   'us-DAT'

    bilim-**gæ**/*-ʁɑ   'knowledge-DAT'

    welisipit-**lær**/*-lɑr   'bicycle-PL'

Second, if a root contains no harmonizing vowels, the front dorsals /k g/ and back dorsals /q ʁ/ may serve as front and back harmony triggers respectively (Examples 31 and 32).

(31) *Roots with only front dorsals*

    kishi-**lær**/*-lɑr   'person-PL'

    ne**g**iz-**gæ**/*-ʁɑ   'basis-DAT'

(32) *Roots with only back dorsals*

    qiz-**lɑr**/*-lær   'girl-PL'

    ji**ʁ**in-d**ɑ**/*-dæ   'meeting-LOC'

There are, however, a small number of irregular roots containing front dorsals and only neutral vowels that take back suffixes, and represent exceptions to this general pattern (Example 33). To my knowledge these are all relatively recent loanwords.

(33) *Exceptional front dorsal roots with back suffixes*

    ingliz-l**ɑ**r   'English person-PL'

    etnik-l**ɑ**r   'ethnic group-PL'

    rentgen-**ʁɑ**   'x.ray-DAT'

    gips-**qɑ**   'plaster-DAT'

Third, it is generally the case that in roots containing a harmonizing vowel followed by a conflicting harmonizing dorsal, the vowel takes precedence (Example 34). There is a small class of roots, however, that harmonize with the intervening uvulars (Example 35).

(34) *Roots with conflicting vowels and dorsals where the vowel takes precedence*

mæntiq-q**æ** 'logic-DAT'

æqil-**gæ** 'intelligence-DAT'

rɑk-l**ɑr** 'cancer-PL'

pɑkit-l**ɑr** 'fact-PL'

(35) *Exceptional roots with conflicting front vowels and uvulars where the uvular takes prece-dence*

tæsti**q**-**qa** 'approval-DAT'

tæʃwi**q**-l**ɑr** 'publicity-PL'

tætqi**q**-l**ɑr** 'research-PL'

Finally, there are a small number of forms that can (optionally) violate harmony with the final harmonizing vowel in the same way opaque forms do (Example 36). These forms are relatively rare.

(36) *Harmony exceptions*

sowet-lær/-lɑr 'soviet-PL'

deŋiz sɑhil-i-gæ/-ʁɑ 'ocean-shore-3.POS-DAT' (cf. [sɑhil-ʁɑ] 'shore')

3.5.2 Exceptionality and frequency

The cases above show that lexical exceptionality is necessary to handle a number of corners of the harmony system where harmonizing behavior does not align with phonological generalizations. For these exceptional roots, knowledge of their morphological harmony class supersedes phonological considerations and drives the harmonizing behavior we observe. I propose that opaque harmony is driven by the same morphological pressure. In addition to unifying the treatment of opacity with other areas of exceptionality, it also accounts for the relationship between rates of opaque harmony and token frequency.

Frequency is known to be an important driver of phonological exceptionality (e.g., Bybee, 1985; Morgan & Levy, 2016; Moore-Cantwell, 2018, in prep). Items that are exceptional tend to be most stable when they are high frequency. That is, we memorize the exceptional properties of

high frequency items as a function of exposure, while we refer to general grammatical properties for low frequency items. Examples of this include English past tense morphology, where the forms that have maintained irregular past tenses tend to be highly frequent (e.g., Bybee, 1985), and "X and Y" vs. "Y and X" constructions (e.g., "salt and pepper" vs. "pepper and salt"), where the order of high frequency pairs tends to be memorized, but the order of low frequency pairs may be predicted from general grammatical properties (Morgan & Levy, 2016).

Because of the relationship between rates of opacity and root token frequency that is characteristic of exceptional patterns, I suggest that opacity in Uyghur backness harmony should also be modeled as a case of phonological exceptionality. In addition to predicting this relationship, treating opacity as a type of exceptionality also unifies its treatment with the exceptional cases presented above.

In the next section, I will show how this exceptionality can be modeled using *lexically indexed constraints*.

3.5.3 Representing exceptionality/opacity in OT

When a learner encounters a token of a root plus a harmonizing suffix, they learn both something about the phonological properties of harmony (e.g., front vowels should be followed by front suffixes) and something about the morphological class of the root (e.g., /ɑʔilæ/ is in the class of roots that take front suffixes). It is usually the case that these observations align, but in exceptional forms they do not: the opaque raised form [ɑʔili-lær], for example, satisfies the observation about the root, but not about the phonological grammar. There are also additional clues for the morphological class of a root beyond simply observing which suffixes it takes: for example, the class membership of unsuffixed roots can be inferred from their phonological structure (e.g., roots ending in front vowels tend to be in the class of front harmonizers).

One proposal for modeling the idiosyncratic behavior of particular lexical items is *indexed constraints* (e.g. Kraska-Szlenk, 1997, 1999; Fukazawa, 1999; Ito & Mester, 1999; Pater, 2010; Moore-Cantwell & Pater, 2016, a.o.). These are constraints that bear an index, and may only be violated by morphemes that bear the same index. That is, they are vacuously satisfied by morphemes

that do not bear the index. The use of these constraints allows general phonological knowledge to be separated from lexically-specific knowledge in the grammar. Increased exposure to exceptional forms leads to an increased ranking of an indexed constraint that captures the exceptional behavior.

I propose the following pair of indexed harmony constraints to capture the harmonizing behavior of roots that is driven by their inflectional class. These constraints effectively represent the strength with which a particular root can be placed in the class of back or front harmonizers respectively.[16]

(37) HARMONIZEBACK$_i$: A harmonizing suffix must be back if the immediately preceding morpheme bears the index i.

(38) HARMONIZEFRONT$_i$: A harmonizing suffix must be front if the immediately preceding morpheme bears the index i.

I will abbreviate this pair as HARMONIZE in discussions below. Note that these constraints are not violated in the presence of harmony blocking suffixes such as the progressive /-wɑt/ in forms like [søzli-wɑt-qɑn] 'speak-PROG-PERF', since although the harmony value of the suffix [-qɑn] (UR: /-GAn/) does not match that of the root /søzlæ/, it does match that of /-wɑt/. That is to say, harmony blocking suffixes are not exceptions in the same sense as raising opacity.

Similar to the rule-based analysis of Nez Perce in SPE (Chomsky & Halle, 1968), I propose that these constraints are indexed to individual roots. I also assume that these constraints are posited by the learner only when necessary to resolve inconsistency (that is, roots that never harmonize in a way that is not predicted by the general phonological grammar will not have a corresponding indexed constraint; Pater, 2010; Moore-Cantwell & Pater, 2016), and that these constraints are strengthened (i.e., ranked or weighted more highly) by exposure to exceptional forms (Moore-Cantwell, 2018, in prep). In practice this means that only roots that display phonologically exceptional behavior will have a corresponding HARMONIZE constraint, and whether this constraint

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[16]An analogy might be made to English irregular plurals: the plural of the highly frequent 'child' is consistently realized as 'children' rather than 'childs', while less frequent irregular forms such as the plural of 'deer' show variability between the irregular plural 'deer' and the default plural 'deers'.

mandates front or back harmony depends on the harmony class of the root.[17]

The tableau below shows how such a constraint can be used to correctly generate the opaque form [ɑʔili-lær] 'family-PL'. The purely phonological AGREE constraints prefer the surface-true candidate *[ɑʔili-lɑr], but this pressure is overwhelmed by the higher-ranked HARMONIZE constraint, which requires /ɑʔilæ/ to take front suffixes according to its morphological harmony class.

/ɑʔilæ$_k$-lAr/	*UNREDUCED	HARMONIZEFRONT$_k$	VAGREEBACK	VAGREEFRONT	ID[HEIGHT]
☞ a. ɑʔili-lær			*		*
b. ɑʔili-lɑr		*!			*
c. ɑʔilæ-lær	*!				
d. ɑʔilæ-lɑr	*!	*		*	

Table 3.5: Tableau for the opaque form [ɑʔili-lær] 'family-PL'. The opaque outcome is generated by the lexically indexed constraint HARMONIZEFRONT$_k$, which mandates that the root /ɑʔilæ$_k$/ must take front suffixes, where k is an arbitrary index shared by the root and constraint. Note that if this constraint were ranked below VAGREEBACK, the surface-true form would be generated.

3.5.4 Capturing gradience using Maximum Entropy Harmonic Grammar

Finally, I will model the gradience observed in the corpus using Maximum Entropy Harmonic Grammar (henceforth MaxEnt; Smolensky, 1986; Goldwater & Johnson, 2003), a variant of Optimality Theory (Prince & Smolensky, 1993/2004) with numeric constraint weights (see also Pater, 2009). MaxEnt is able to generate probability distributions over output candidates for a given input, making it well-suited to capturing phonological gradience of the kind we see in Uyghur. Because it is a numerical model that is able to assign likelihood values to a data set, it is also straightforward to learn constraint weights that optimize fit to the data (see Hayes & Wilson, 2008, for more detail on this learning procedure).

In a MaxEnt grammar, each constraint is associated with a real-valued weight that represents

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[17]Though Chapter 4 presents evidence that these lexical constraints are more pervasive in the harmony system.

its strength. In a grammar with N constraints, the weight of the ith constraint can be notated w_i. The function $C_i(x, y)$ returns the number of times an output candidate y for the input x violates the ith constraint. The *harmony* of an output candidate y given the input x is:

$$H(x, y) = \sum_i^N w_i C_i(x, y)$$

where higher values of $H(x, y)$ are associated with more severe constraint violations. The probability of an output candidate y given input x is

$$P(y|x) = \frac{\exp(-H(x, y))}{\sum_{z \in \Omega} \exp(-H(z, y))}$$

where Ω is the set of all possible output candidates given the input x.

A MaxEnt OT model was fit to the subset of the corpus data consisting of roots whose final two harmonizing vowels fall into one of the following four templates: FF, BB, FF, and BB, where the final vowel will always be one of /æ ɑ/. No regularization was used (see Chapter 4 for a discussion of regularization in MaxEnt models). As above, I do not consider roots that categorically resist raising, and I omit roots with harmonizing consonants for simplicity's sake. Appropriate HAR-MONIZE constraints were defined for each root with the structure necessary to produce opaque harmony (that is BF and FB roots). This data set contains $1,393$ roots corresponding to $235,372$ tokens. I consider only suffixes that trigger raising and do not model suffix identity, which does not appear to affect harmonizing behavior.

3.5.5 Analytical results

The optimal constraint weights and log likelihood for the model are shown in Table 3.6.

This model is sufficient to produce an almost perfect fit to the corpus data, as shown in Fig. 3.7. This is unsurprising given the number of parameters that directly correspond to rates of opacity for each root.

The learned weights for the indexed HARMONIZE constraints are the driving force behind predicting rates of opacity for each root. To test whether the learned weights of these constraints can be predicted from statistical properties of roots in the corpus, I fit a linear regression model

VAGREEBACK	VAGREEFRONT	ID[HEIGHT]	*UNREDUCED	HARMONIZEBACK$_i$/ HARMONIZEFRONT$_i$	LL
7.37	7.82	0	31.02	[0, 25.19]	$-3,475$

Table 3.6: The optimal constraint weights and log likelihood of the model. The reported weights for HARMONIZEBACK$_i$/HARMONIZEFRONT$_i$ are the range of optimal weights across indexed roots.
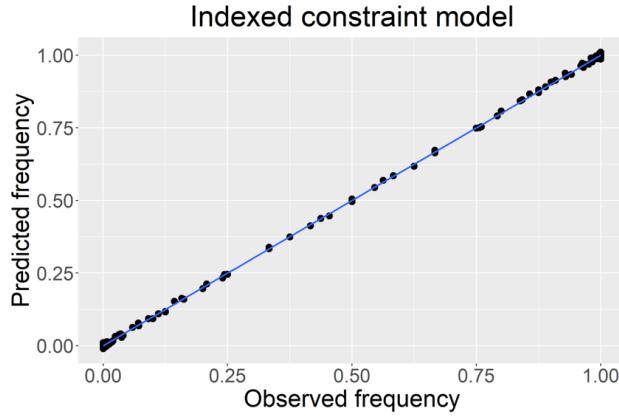
Figure 3.7: Observed candidate frequencies in the corpus plotted against frequencies predicted by the model.

with log token frequency, final underlying vowel identity (F or B), and proportion of raised tokens as predictors, and learned HARMONIZE constraint weight as the dependent variable. The model showed a significant effect for underlying final vowel identity, with roots ending in underlying back vowels having lower learned weights weights ($\beta = -4.92, t = -2.56, p < 0.05$), and for log token frequency, with more frequent roots having higher learned weights ($\beta = 0.44, t = 2.66, p < 0.01$) and roots with more raised tokens having lower learned weights ($\beta = -2.37, t = -2.1, p < 0.05$). Thus the learned weights directly reflect root token frequency and the proportion of raised tokens, confirming the connection between these properties and rates of opacity predicted by the grammar.[18] These relationships are shown in Figs. 3.8 and 3.9.

I will illustrate the learned weights and the calculation of predicted probabilities using three

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[18]Note that this is not guaranteed to be the case: if a highly frequent root has a low rate of opacity, the weight of the corresponding indexed HARMONY constraint will be low.
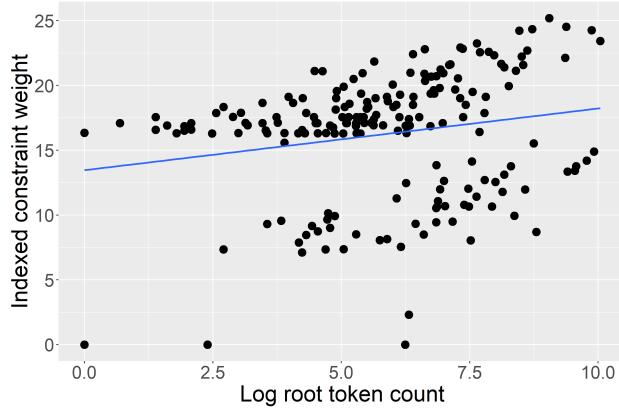
Figure 3.8: Optimal indexed constraint weights plotted against log token count.
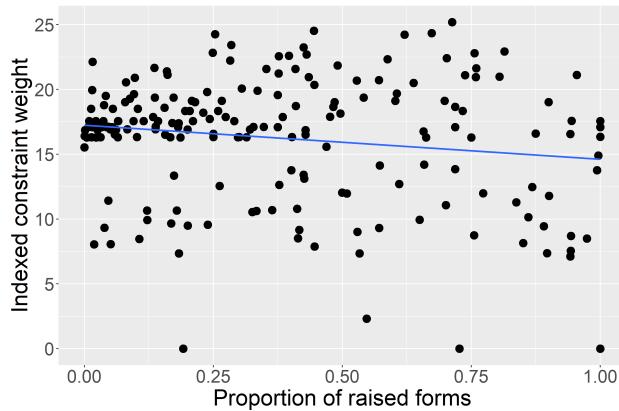
Figure 3.9: Optimal indexed constraint weights plotted against the proportion of raised tokens.

prototypical roots: one with a strong tendency towards opaque harmony, one with strong tendency towards surface-true harmony, and one that is intermediate. I omit ID[HEIGHT] since with a weight of 0 it does not play a role in frequency calculation.

The tableau for calculating possible surface realizations of the input /ɑʔilæ-lAr/ 'family-PL' is shown in Table 3.7. The predicted frequencies by the model match the observed frequencies in the corpus. Because the subset of the corpus I examine contains only tokens that undergo raising, the weight for *UNREDUCED is accordingly high, proving fatal to all candidates that do not raise. The final two rows of Table 3.7 compare raised candidates that harmonize opaquely and transparently respectively. Although the opaque candidate [ɑʔili-lær] is surface-disharmonic and violates VAGREEBACK, this violation is overshadowed by the transparent candidate [ɑʔili-lɑr]'s

/ɑʔilæ$_k$-lAr/	Pred. Freq.	Obs. Freq.	H	VAGREEB $w = 7.37$	VAGREEF $w = 7.82$	*UNREDUCED $w = 31.02$	HARMFRONT$_k$ $w = 25.19$
ɑʔilæ-lær	0	0	31.02			1	
ɑʔilæ-lɑr	0	0	64.03		1	1	1
ɑʔili-lær	1	1	7.37	1			
ɑʔili-lɑr	0	0	25.19				1

Table 3.7: Tableau for the strongly opaque form /ɑʔilæ-lAr/ 'family-PL'. The token count for this root is 8477, and the proportion of raised tokens is 0.71. k is an arbitrary indexed shared by the root and HARMONIZE constraint.

violation of the highly weighted HARMONIZEFRONT.

Table 3.8 shows possible surface realizations of the input /sɑhɑbæ-lAr/ 'disciple-PL', which has a large number of tokens exhibiting surface-true harmony. Note that although these candidates have exactly the same violation profiles as /ɑʔilæ-lAr/'s candidates in Table 3.7, the lower weight for HARMONIZEFRONT makes the transparent candidate [sɑhɑbi-lɑr] roughly as harmonic as the opaque candidate [sɑhɑbi-lær], and producing similar predicted frequencies.

/sɑhɑbæ$_k$-lAr/	Pred. Freq.	Obs. Freq.	H	VAGREEB $w = 7.37$	VAGREEF $w = 7.82$	*UNREDUCED $w = 31.02$	HARMFRONT$_k$ $w = 7.11$
sɑhɑbæ-lær	0	0	31.02			1	
sɑhɑbæ-lɑr	0	0	45.95		1	1	1
sɑhɑbi-lær	0.44	0.44	7.37	1			
sɑhɑbi-lɑr	0.56	0.56	7.11				1

Table 3.8: Tableau for the strongly transparent form /sɑhɑbæ-lAr/ 'companion-PL'. The token count for this root is 69 and the proportion of raised tokens is 0.94. k is an arbitrary indexed shared by the root and HARMONIZE constraint.

Finally, Table 3.9 shows an intermediately opaque form /kæsipdɑʃ-i-lAr/ 'colleague-3.POS-PL' (the presence of the possessive morpheme here is necessary to produce the environment for raising). The violation profiles for output candidates are similar to the previous two tableaux (modulo the differing backness of the final vowel), and the weight of the HARMONIZEBACK constraint,

which is intermediate between those of the previous two tableaux, accordingly produces an intermediate degree of opaque harmony.

/kæsipdɑʃ$_k$-i-lAr/	Pred. Freq.	Obs. Freq.	*H*	VAGREEB $w = 7.37$	VAGREEF $w = 7.82$	*UNREDUCED $w = 31.02$	HARMBACK$_k$ $w = 9.49$
kæsipdɑʃ-i-lær	0	0	47.88	1		1	1
kæsipdɑʃ-i-lɑr	0	0	31.02			1	
kæsipdiʃ-i-lær	0.15	0.15	9.50				1
kæsipdiʃ-i-lɑr	0.85	0.85	7.82		1		

Table 3.9: Tableau for the intermediate root /kæsipdɑʃ-i-lAr/ 'colleague-3.POS-PL'. The token count for this root is 1293 and the proportion of raised tokens is 0.2.

To summarize, this analysis is not only able to correctly predict the root-specific rates of opacity observed in the corpus, but also accounts for the relationship of these rates to factors such as log token frequency and the proportion of raised tokens. The weights of the indexed HARMONIZE constraints directly reflect the confidence with which speakers categorize a root into a particular morphological harmony class. Factors that contribute to this confidence, such as exposure to the root, particularly in its unraised form, directly correlate with the weights of the HARMONIZE constraints.

Note that the use of these constraints does not imply that backness harmony is a simply stipulated for all roots independently of their phonological properties. Aside from the cases discussed in this chapter, the harmonizing behavior of Uyghur roots can be effectively predicted from their phonological properties, and the variation presented here indicates that speakers are clearly sensitive to these properties. Previous work has assumed that constraints capturing exceptional behavior are posited only when necessary, and that general phonological constraints are used in the majority of cases, and when generalizing to new data (Zuraw, 2000; Pater, 2010; Moore-Cantwell & Pater, 2016). The roots that have the structure necessary to generate opacity due to raising are relatively few, and constitute exceptions to the general pattern of backness harmony in the language. The use of indexed constraints is a natural way to capture this exceptionality. However, the next chapter provides evidence from a wug test study that suggests that indexed harmony constraints play a

more pervasive role in the harmony system than might be expected.

Note as well, however, that this account does not necessarily predict that Uyghur speakers should demonstrate surface-true harmony across the board when generalizing to new roots, since the unraised form of a root also offers clear phonological cues to its harmonizing class. We might expect, however, that wug-tests would show a higher rate of surface-true harmony than inflections of similar attested forms.

3.5.6 Suffix opacity

In addition to the behavior of roots, variability in rates of opacity between certain suffixes supports this analysis. Certain suffixes in Uyghur have attracted attention in the literature because they behave idiosyncratically with respect to the opaque process described above (Vaux, 2000; Halle et al., 2000). The best known of these is the diminutive suffix /-ʧæ/. Unraised forms of /-ʧæ/ display harmony with the vowel in the diminutive.[19]

(39)   *Unraised occurrences of /-ʧæ/*

UR	SR	Gloss
/næj-ʧæ-m-DA/	[næjʧæmdæ]	'flute-DIM-1Sg.POS-LOC'
/kitɑb-ʧæ-m-DA/	[kitɑpʧæmdæ]	'book-DIM-1Sg.POS-LOC'
/ziχ-ʧæ-m-GA/	[ziχʧæmgæ]	'skewer-DIM-1Sg.POS-DAT'
/bɑʁ-ʧæ-m-DA/	[bɑʁʧæmgæ]	'park-DIM-1Sg.POS-LOC'

However, the vowel in /-ʧæ/ always becomes transparent to harmony when raised.

—————————————————————

[19]Although Uyghur is generally tolerant of disharmonic roots, several of the stems above can be optionally repaired to be internally harmonic, such as [bɑʁʧɑ] 'garden' or [ziχʧɑ] 'short skewer, needle' (though not, e.g., *[kitɑpʧɑ]). These repairs mean that raising does not change the harmonic behavior of the stem.

(40) *Transparent raising of /-tʃæ/*

UR	SR	Gloss
/næj-tʃæ-DA/	[næjtʃidæ]	'flute-DIM-LOC'
/kitɑb-tʃæ-DA/	[kitɑptʃidɑ]	'book-DIM-LOC'
/ziχ-tʃæ-GA/	[ziχtʃiʁɑ]	'skewer-DIM-DAT'
/bɑʁ-tʃæ-DA/	[bɑʁtʃiʁɑ]	'park-DIM-LOC'

Such suffixes, which are both harmonically invariant and undergo raising, are generally uncommon in the language. Suffixes that raise tend to be harmonizing suffixes (e.g., the plural /-lAr/), while suffixes that do not harmonize also tend to not raise (e.g., the progressive /-wɑt/).

The fact that /-tʃæ/ always behaves transparently when raised is predicted if there is no corresponding HARMONIZE constraint that mandates consistent harmony across its unraised and raised forms. This claim consists of two components:

1. The indexed HARMONIZE constraints mandate uniform harmonic behavior of *roots*.

2. /-tʃæ/, perhaps due to its productivity, is treated as a harmonically-invariant suffix, rather than part of the root.

A sample tableau for the form [kitɑp-tʃi-dɑ] 'book-DIM-LOC' is shown below.

/kitɑb-tʃæ-DA/	*UNREDUCED	VAGREEBACK	VAGREEFRONT	ID[HEIGHT]
☞ a. kitɑp-tʃi-dɑ				*
b. kitɑp-tʃi-dæ		*!		*
c. kitɑp-tʃæ-dɑ	*!		*	
d. kitɑp-tʃæ-dæ	*!			

Table 3.10: Simple surface harmony in the presence of raising for [kitɑp-tʃi-dɑ] 'book-DIM-LOC'.

It is instructive to compare /-tʃæ/ with the suffix /-ijæ/, which derives country names from names of ethnicities. This suffix is not generally productive (even among names of countries), and may be considered somewhat analogous to English -ia, as in 'Bulgaria', 'Russia', 'Estonia', etc.

(41)   *Uses of /-ijæ/*

finlɑnd	'Finnish person'	finlɑndijæ	'Finland'
rus	'Russian person'	rusijæ	'Russia'
ispɑn	'Spanish person'	ispɑnijæ	'Spain'

Forms with a back vowel followed by /-ijæ/, such as those shown above, show opaque harmony 97% of the time (e.g., /finlɑndijæ-DA/ → [finlɑndiji-dæ], not *[finlɑndiji-dɑ]).

The difference in harmonic behavior between these two similar suffixes can be accounted for by positing that certain derivational morphemes such as /-ijæ/, by virtue of their lack of productivity, may be considered part of the root, while others such as /-ʧæ/, which are more productive, are not treated as part of the root, and thus do not exert pressure to harmonize with their underlying vowels in the face of raising. This is demonstrated in the following tableau.

/finlɑndijæ$_k$-DA/	*UNREDUCED	HARMFRONT$_k$	VAGREEB	VAGREEF	ID[HEIGHT]
a. finlɑndiji-dɑ		*!			*
☞ b. finlɑndiji-dæ			*!		*
c. finlɑndijæ-dɑ	*!	*!		*	
d. finlɑndijæ-dæ	*!				

Table 3.11:   Opaque harmony in the presence of raising for [finlɑndiji-dæ] 'book-DIM-LOC', where *k* is an arbitrary index.

This analysis predicts that less productive suffixes should generally exhibit higher degrees of opacity in their raised forms. I leave this as an area of exploration for future research.[20]

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[20]It is worth noting that the suffixes [-wær] (a contraction of /-p bær/) and [-wɑl] (a contraction of /-p ɑl/) , are harmonically invariant, but display opaque harmony in the face of raising (in this case umlauting rather than vowel reduction). For example, in /ɑŋlɑ-p bær-ʃ-GA/ → [ɑŋlɑ-wer-iʃ-kæ] 'hear-WER-GER-DAT', we see the front form of the dative despite the final surface harmonizing vowel being back. An analysis of this opacity is beyond the scope of this chapter, but it could be accounted for by proposing that [-wær] and [-wɑl] are roots in their own rights, and have corresponding HARMONIZE constraints, or serve as the beginning of a new harmony domain. Both these analyses are in keeping with the underlying morphological structure of these forms.

3.5.7 A comparison with serial models

The preceding sections have demonstrated that opacity in Uyghur can be represented in a strictly parallel model of phonology if we assume that, rather than being the product of a particular order of application of the harmony and vowel reduction processes, opacity results from the parallel interaction of phonological harmony, vowel reduction, and root-specific harmony that is driven by the inflectional class of the root. In addition to being able to produce opacity, this account also unifies opacity with other types of exceptionality in the Uyghur harmony system and accounts for the relationship between rates of opacity and the token frequency and proportion of raised tokens of a root.

In principle a descriptively adequate analysis can also be produced in a serial model. However, I will argue that any such analysis will have less explanatory adequacy than the analysis presented above. It is beyond the scope of this chapter to address every serial extension of OT that might be applied to this pattern, so for simplicity's sake I consider only a serial rule-based analysis here (a brief argument against a Stratal OT analysis was provided earlier in the chapter). I suspect many of the issues raised here will be relevant for other serial frameworks.

Whether harmony is opaque or surface-true in a rule-based model is determined by the order of rule application. If the rule driving harmony (which I will notate as rule $\mathbb{H}$) applies before the rule driving raising (notated as $\mathbb{R}$), harmony will be opaque; if they apply in the opposite order, harmony will be surface-true. In order to produce gradient opacity within a single root, we must have some mechanism that allows probabilistic rule ordering: that is $\mathbb{H}$ will apply before $\mathbb{R}$ with some probability p, and $\mathbb{R}$ will apply before $\mathbb{H}$ with probability $1 - p$. To my knowledge no such mechanism for probabilistic rule reordering has been proposed, but it is not difficult to imagine in broad strokes how one might be implemented.[21] In order to capture the root-specific opacity evident in the corpus, this model will need to allow for p to vary across individual roots.

Given appropriate choices of p for each root, a serial model organized along these lines would

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[21]The lack of such a model is likely due more to historical accident than to any principled reason: by the time phonologists began engaging with probabilistic models in a serious way, the field had moved away from rule-based analyses to OT. The exception to this is found in sociolinguistics, where models of variable rule application were proposed (e.g., Cedergren & Sankoff, 1974; Sankoff & Labov, 1979). These models allowed rules to probabilistically apply or fail to apply, so they are not directly applicable to the data here.

be descriptively adequate to model the data presented in this chapter. From the perspective of explanatory adequacy, however, there are several problems.

The most pressing of these concerns is that such models do not provide an adequate account of why surface-true forms should exist at all, and, given that they do, why their occurrence should be more common in low frequency roots with a high proportion of raised tokens. Vaux (2008) writes that in serial rule-based models, opacity is "a straightforward product of process ordering" (p. 27) and "the acquisition scenario for opacity ... is simple" (p. 32): the learner identifies two independent generalizations (in this case harmony and raising) and subsequently learns that they are ordered with respect to one another in a particular way. In other words, opacity has no special status in serial rule-based models.

Why then should tokens exhibiting surface-true harmony exist at all? The model presented in this chapter accounts for their existence as the consequence of tension between phonological pressures that favor surface-true harmony and lexically stipulated harmonizing behavior, which favors opacity. These lexical pressures are generally strong enough to make opacity the majority pattern in the language, but they begin to break down in less frequent roots or roots with weaker clues to their harmony class (such as roots that occur frequently in raised forms). In this sense, the difficulty parallel OT has with representing opacity is a positive feature, and corresponds directly with speakers' default preference for surface-true harmony.

Serial rule-based models, on the other hand, have no single mechanism for expressing this preference, and accordingly no way to straightforwardly account for the variability in rates of opacity across roots and why this variability should be related to token frequency and the proportion of raised tokens. One might postulate a prior bias favoring non-opaque rule orderings that can be overridden given sufficient evidence of an opaque interaction (this aligns with the claim in Kiparsky, 1971, that opaque rule orderings tend to revert to transparent orderings over time). Leaving aside how a learner might determine whether a particular ordering produces opacity, this still leaves open the question of why rates of opacity should vary on a root-by-root basis rather than uniformly across the language.

Finally, even if gradient opacity is treated as a consequence of variable rule order, a rule-

based analysis will still need something like root-specific harmony classes in order to capture the harmonizing behavior of exceptional forms like those described in Section 3.5.1. A parallel, exceptionality-based account of opacity does not introduce additional complexity into the analysis, but relies on a property of the harmony system that is independently motivated in other cases.

Based on these considerations, the strictly parallel model presented in this chapter better accounts for the patterns in the corpus data than serial models that treat this opacity as an ordered application of two processes.

3.6 Discussion

Based on the results of the corpus study and general consideration of the properties of the Uyghur harmony system, this chapter suggests that the opacity observed in Uyghur backness harmony is best analyzed as an interaction between phonological pressures towards surface-true harmony and lexical pressures that mandate the harmony class of a root. I suggest that this relationship can be modeled using lexically indexed constraints mandating that the suffixes attached to a root should maintain the same backness value across all of its allomorphs.

3.6.1 Principles underlying opaque harmony

Why should this kind of disharmony be tolerated in Uyghur phonology? For one, backness harmony is an ancient property of Turkic languages (e.g., Clauson, 1972), while raising is a relatively new phenomenon in Uyghur, originating within the past 100–150 years (G. Eziz p.c.). Thus opaque harmony in the face of raising maintains historical patterns of root backness, while cases of surface-true harmony constitute a more recent innovation by Uyghur speakers.

There may also be biases towards the maintenance of this kind of opacity in harmony systems. The idea that there is pressure for roots to maintain the same harmonic class across allomorphs is closely related to a principle based on vowel harmony in Hungarian stated by Rebrus and Törkenczy (2017), which they call *Harmonic Uniformity*:

(42)   The harmonic class of a [suffixed] form is identical to that of its root (= monomorphemic

base) (p. 142)

Hungarian has a similar vowel harmony system to Uyghur, with front and back vowels as well as a set of transparent vowels, though, unlike Uyghur, transparent vowels skew towards front suffixes. Rebrus and Törkenczy note that roots whose final harmonizing vowel is back are more likely to take front suffixes when they have transparent vowels intervening between the final harmonizing vowel and the suffix, and that this tendency increases with the number of transparent vowels. This is called a *count effect* or *distance-based decay* (Hayes & Londe, 2006; Hayes et al., 2009; Kimper, 2011; Zymet, 2014).

(43)
 mɑdrid-uŋk/*-yŋk 'Madrid-1.PL.POS'
 mɑrtinik-uŋk/-yŋk 'Martinique-1.PL.POS'

Here /mɑdrid/, which consists of a back vowel followed by a single transparent vowel (BN) invariably takes back suffixes, while /mɑrtinik/, which has an additional transparent vowel (BNN), can take either form. In general, the ranking of the harmonic templates of roots by their likelihood of taking back suffixes is B ≫ BN ≫ BNN ≫ . . . .

When similar configurations are produced by suffixation, however, the suffixed stem does not become more likely to take front suffixes.

(44)
 hɒmiʃ-ɒbː/*-ɛbː 'false-COMPAR (Adjective)'
 hɒmiʃ-iːt-otː/*-ɛtː 'false-PAST (Verb)'

Here the stem /hɒmiʃ/, like /mɑdrid/, has a single back vowel followed by a transparent vowel (BN), and consistently takes back suffixes. When the suffix /-iːt/ is added, however, the stem continues to take only back suffixes despite its similarity to the root /mɑrtinik/ (both are BNN). In general, forms like B, B-N, B-N-N, . . . (where '-' is a morpheme boundary) will all consistently take back suffixes. Thus the count effects observed in monomorphemic roots do not emerge when similar structures are derived from suffixation. Under the analysis presented above using indexed constraints, this suggests that the index of the root is shared by its affixes (with the exception of harmony blockers such as /-wɑt/).

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The idea of lexically indexed HARMONIZE constraints mandates a similar property: the harmonic class of a morpheme should remain identical across its allomorphs, even when doing so produces surface disharmony.

This property may be related to the suggestion that rounding harmony serves to enhance the perceptibility of vowels in the root by spreading their rounding feature through the word Kaun (2004). Assuming the same is also true for backness, if harmony in Uyghur were not generally opaque in the face of raising, this would mean that the same root could take suffixes of differing backness in its different forms, which could potentially render harmony's perceptual benefits less effective.[22]

Under this analysis, backness harmony in Uyghur may be thought of as analogous to an inflectional class system like grammatical gender. In languages with grammatical gender there are often strong phonological clues to which gender a noun is: in Spanish, for example, masculine nouns often end in -o and feminine nouns in -a. There are also frequent exceptions to these generalizations: for example, Spanish *mapa* 'map' is masculine despite ending in -a. Just as we should not expect a morphological property such as gender to change across the allomorphs of a word, we may similarly expect the harmonic value of a root to remain constant, even when allomorphy renders its surface form disharmonic.

3.6.2 Implications for phonological theory

This chapter has shown that although serial models of phonology such as serial rule-ordering and Stratal OT can successfully represent opaque harmony in Uyghur, they do not predict gradient rates of opacity across roots, nor the relationship between root frequency and opacity rates. These properties are both predicted by an analysis that treats opaque harmony as a case of phonological exceptionality, which in turn connects it to other properties of the harmony system.

A consequence of this analysis is that it can capture the data using a strictly parallel model supplemented with lexically indexed constraints: the various kinds of serial machinery that have

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[22]Though note that if backness harmony compensates for perceptual weakness, we might expect to see pairs of vowels with the least salient backness contrast behave as stronger triggers of harmony. To my knowledge there is no such variation between front-back vowel pairs in Uyghur.

been proposed to handle opacity in OT are unnecessary in this case, and indeed, do not predict the observations in the corpora. This is not meant, however, to suggest that all cases of opacity should be analyzed as exceptional behavior. As previous literature has pointed out, opacity is a variegated phenomenon (Baković, 2007, 2011; Baković & Blumenfeld, 2019), and there may not be a single theoretical mechanism that is adequate to describe in its entirety. That being said, however, I suggest following Nazarov (2019, 2020) that there may be a fundamental connection between exceptionality and at least some forms of opacity, and that this relationship should be studied more closely in the future.

Adopting Baković's suggestion, we might focus on the learnability and productivity of this pattern. In particular, an explicit model of how the weights of the indexed HARMONIZE constraints are set based on exposure to language data would be valuable. Studies of harmonic errors in Uyghur children may be informative: for example, if opaque harmony is learned as a type of exceptionality, we might expect a period of overregularization where children apply surface harmony more broadly than they should, similar to the overregularization observed in other cases (e.g., Pinker & Prince, 1991).

Wug testing and other perceptual studies on adult speakers may also be informative for this purpose. This chapter makes the specific prediction that opaque harmony in Uyghur is essentially driven by classification of roots into front-harmonizing and back-harmonizing classes, and the weights of the lexically indexed constraints mandating consistent harmonizing behavior within classes reflect the confidence with which roots can be assigned to a particular harmonizing class. This is a function of the phonological properties of the root, root token frequency, the proportion of raised forms, and doubtless other factors as well. As mentioned above, it is not necessarily the case that a wug-test of opaque harmony would produce entirely surface-true behavior, since the unraised form of a root also offers clear phonological cues to its harmonizing class. We might expect, however, that wug-tests would show a higher rate of surface-true harmony than inflections of similar attested forms.

Perceptual experiments, such as eye-tracking or reading time studies could be used to probe how surprising cases of surface-true harmony are to participants: the model presented here predicts that instances of surface-true harmony in low frequency words should be less surprising for

participants than in high frequency words. This in turn should result in increased reading time or backtracking in the latter case. Another prediction based on the relationship between the proportion of raised tokens and rates of opaque harmony is that priming speakers with raised vs. unraised forms of a root should influence their production: priming a speaker with the unraised form of a root (e.g., [ɑʔilæ] 'family') should lead to more instances of opaque harmony than when they are primed with a raised form (e.g., [ɑʔilini] 'family-ACC'). This technique could be applied to both wug and attested words.

Beyond Uyghur, artificial grammar learning experiments (e.g., Moreton & Pater, 2012) that test learners' sensitivity to token frequency when learning opaque patterns could provide valuable insights into how these patterns are learned.

Given these considerations, we might wonder whether Uyghur will display a shift to surface-true harmony as predicted by Kiparsky (1971) for opaque patterns in general. It is probably too early to tell at the time of this writing: raising is a relatively new process in Uyghur, and the phonological system may not have fully absorbed its consequences.[23] The analysis presented above predicts that we may see a shift towards surface-true harmony beginning from less frequent words. The very existence of innovative surface-true forms supports this claim. However, it may also be the case that pressures towards Harmonic Uniformity (Rebrus & Törkenczy, 2017) and stability of perceptual clues to root identity (Kaun, 2004) will make opaque harmony a stable outcome. It will be interesting and informative for phonological theory to see how the Uyghur backness harmony system evolves over subsequent generations.

An important limitation of the current study is that it relies on a specific genre of text: newspaper articles. This is a limitation for two reasons: the first is that it has a significant effect on word frequencies, as newspaper articles tend to be about specific topics. Thus it will be important to compare the relationships between opacity and token frequency in other corpora. Second, newspapers generally use prestige varieties of the languages they are written in. My consultants, who are generally highly educated, see opaque harmony as the 'correct' behavior, despite their acknowledgment of some areas of variability. It will be valuable to look at opacity in more conversational

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[23]It is worth noting that in neighboring languages like Kazakh, raising is a subphonemic process, while in Uyghur it appears to have had a more dramatic effect on the morphophonological system (McCollum p.c.).

corpora of Uyghur, where surface-true harmony could potentially be more prevalent. Although there are online Uyghur language forums that use less formal language,[24] these are frequently written using non-standard, phone-friendly Latin orthographies that eliminate the distinctions between some front and back vowels (e.g., /y/ and /u/ may both be written as *u*), making corpus study difficult.

In addition to its empirical and theoretical contributions, this chapter demonstrates the value of taking a more holistic and comprehensive empirical approach to linguistic data collection and analysis. Although the interaction between vowel raising and backness harmony in Uyghur has been studied in the past (e.g., Vaux, 2000; Halle et al., 2000; Hall & Ozburn, 2018), this work has relied on a small number of data points which, I have contended, incorrectly represent the two patterns and their interaction, at least in standard dialects of Uyghur. The internet has allowed for the proliferation of large amounts of textual data, even for smaller languages. Computational tools such as morphological transducers, when applied with discretion and a knowledge of the language under study, can allow us to marshal the complexity inherent in such large data sets, and provide access to new types of empirical data that allow us to supplement other data sources and measure phonological patterns writ large. I anticipate that such tools will become increasingly important as phonology continues to develop.

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[24]For example, `http://forum.uyghuramerican.org/forum/index.php`.

CHAPTER 4

Phonetic biases in the learning of backness harmony: Comparing corpus and wug test results

4.1 Introduction

Although the statistical patterning of sounds in a language is an important source of information to the learner about a language's phonology, previous work has shown that listeners are not equally sensitive to all statistical patterns. For example, Turkish displays devoicing of stops and affricates in coda positions, neutralizing underlying voicing distinctions in this environment.

(45) *Voicing alternations in Turkish root-final obstruents*
ʤop 'club' ʤobu 'her club'
sop 'clan' sopu 'her clan'

Whether a root displays alternation in the voicing of the final segment under suffixation can be analyzed by postulating particular underlying forms, such as /ʤob/ and /sop/ for the forms above. Final devoicing changes /b/ to [p] in unsuffixed contexts for the root /ʤob/, but applies vacuously to the root /sop/. In principle, seeing only the unsuffixed form of a root is not informative about whether it will display this kind of voicing alternation, since we cannot know whether the voiceless form of the final consonant is also present in the underlying form, or is derived from an underlyingly voiced stop via final devoicing.

Becker, Ketrez, and Nevins (2011) demonstrate, however, that whether a root undergoes this alternation can be effectively (though not definitively) predicted from its phonological properties: the height and backness of the final vowel in the root, the place of articulation of the final conso-nant, and the length of the root are all predictive of whether alternation will occur. When speakers

are asked to inflect novel words that control for these properties, however, they display sensitivity to root length and the place of articulation of the final consonant, but not the height and backness of the final vowel. Thus although the quality of the preceding vowel is an effective predictor of alternations in real words, it is not used by speakers when generalizing to new data.

These kinds of discrepancies provide evidence that speakers exhibit *learning biases* that guide their attention towards certain kinds of patterns and away from others: that is, when generalizing patterns in observed data to unobserved data, speakers may rely on certain assumptions more than others.[1] Previous studies have proposed several different types of biases. One proposal is a preference for "natural" patterns, where, for example, one sound has a clear biomechanical or acoustic influence on the pronunciation of another: this is the explanation given by Becker et al. to account for the failure of Turkish speakers to use vowel height and backness as predictors for voicing alternations, because there is no clear relationship between the two, whereas ease of voicing and place of articulation are clearly related.[2] Other studies have found similar results, though some have suggested that speakers may attend to phonetically unnatural cues in a more limited way, rather than disregarding them completely (e.g., Hayes et al., 2009; Zhang & Lai, 2010).

The goal of this chapter is to explore a similar discrepancy in Uyghur between statistical patterns in the backness harmony behavior of attested words and speakers' generalizations of this pattern to new words. I will suggest that this discrepancy can be understood as a learning bias that is sensitive to the coarticulatory properties of sounds that participate in the backness harmony system, at the expense of internalizing robust statistical regularities in the learning data. In addition to showing how biased learning can be implemented for a standard set of AGREE constraints, I will show how a model of gradient backness informed by the phonetic properties of segments that participate in the harmony system can also incorporate similar biases, while providing a local

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[1]It is worth noting here that the notion of a completely 'unbiased' learner is untenable (see, e.g., Mitchell, 1980). Any learner that is able to generalize from previously observed data to novel cases must do some according to some bias. Every theoretical framework and model presented in this chapter (and indeed, anywhere) necessarily implies certain learning biases. The question is really what kinds of biases we have evidence for, rather than whether biases are present or not.

[2]The sensitivity of speakers to root length is attributed to positional faithfulness constraints targeting initial syllables.

account of Uyghur backness harmony that is more consistent with our typological knowledge of harmony patterns.

Section 2 will provide an overview of the pattern of backness harmony in attested words and substantiate this description using corpus data, as well as providing a simple phonological model that accounts for these patterns. Section 3 will describe an experiment that asked Uyghur speakers to inflect novel words. The results of this study demonstrate that speakers deviate from corpus patterns in certain ways when inflecting novel words. Section 4 will propose some phonetically-driven learning biases that give rise to these discrepancies. These biases are then implemented in a pair of phonological models, one of which uses AGREE constraints and one which is phonetically-based and provides a local interpretation of backness harmony. Section 5 will discuss how the 'unnatural' pattern arose in Uyghur attested words, and explore some implications for the role of phonetic naturalness in phonological learning.[3]

4.2 Backness harmony in attested words: Corpus patterns

This section describes the basic pattern of backness harmony as attested in standard descriptions of the language, and substantiated by corpus data.

4.2.1 Corpus construction and parsing

See Chapter 3 as well as Appendix G for details on how the corpus was constructed and parsed. The only substantial difference in the data presented here is that tokens exhibiting raising were omitted, since they display idiosyncratic harmonizing behavior.

4.2.2 Overview of backness harmony

Like most Turkic languages, Uyghur has backness harmony. Borrowings from Persian, Russian, Arabic, and Chinese, many of which are quite old, have resulted in a high degree of root-internal disharmony, though roots of Turkic origin tend to be harmonic. As a consequence, backness

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[3]This chapter is a collaboration with Travis Major and Mahire Yakup.

harmony is most evident as a morphophonological process, where, broadly speaking, segments in many suffixes must agree in backness with the roots they attach to (e.g., Lindblad, 1990; R. F. Hahn, 1991a, 1991b; Engesæth et al., 2009/2010; Abdulla et al., 2010).

	Front		Back	
	Unrounded	Round	Unrounded	Round
High	i	**y**		**u**
Mid	e	**ø**		**o**
Low	**æ**		**ɑ**	

Table 4.1: The Uyghur vowel system. Harmonizing vowels are in bold.

	Front	Back
Voiceless	k	q
Voiced	g	ʁ

Table 4.2: Harmonizing Uyghur consonants

The segments that directly participate in backness harmony are shown in Tables 4.1 and 4.2.

In the examples of harmony below, we use nouns with the locative suffix /-DA/ (surface forms: [-tɑ], [-dɑ], [-tæ], [-dæ]), the plural suffix /-lAr/ (surface forms: [-lɑr], [-lær]), or the dative suffix /-GA/ (surface forms: [-qɑ], [-ʁɑ], [-kæ], [-gæ]). Note that in suffixes like /-GA/, both the vowel and consonant are undergo harmony. I assume that the archiphoneme /A/ is unspecified for the feature [back], /D/ is unspecified for [voice], and /G/ is unspecified for both. Voicing alternations in the suffix-initial segment are caused by voicing assimilation, and are orthogonal to harmony.

4.2.3 Basic vowel harmony

The basic characterization of backness harmony is that suffixes must agree in backness with the final front (/æ ø y/) or back (/u o ɑ/) harmonizing root vowel.

(46)   *Simple front harmonizing roots*

       t**y**r-d**æ**/*-dɑ   'type-LOC'

       p**æ**n-l**æ**r/*-lɑr   'science-PL'

       munb**æ**r-**gæ**/*-ʁɑ   'podium-DAT'

(47)   *Simple back harmonizing roots*

       p**u**l-**ʁɑ**/*-gæ   'money-DAT'

       t**o**p-**qɑ**/*-kæ   'ball-DAT'

       ætr**ɑ**p-t**ɑ**/*-tæ   'surroundings-LOC'

Figs. 4.1 and 4.2 show histograms of roots from the corpus whose final harmonizing element is a front (1875 roots, about 700k tokens) or back (3146 roots, about 1.17 million tokens) vowel respectively. Note that these data include both roots with conflicting vowels, such as /ætrɑp/ 'surroundings' or /munbær/ 'podium', as well as roots with transparent vowels intervening between the final harmonizing vowel and suffix (these roots will be discussed more in the following section). These results demonstrate that in roots containing harmonizing vowels, the backness of the final harmonizing vowel almost invariably determines the backness of the suffix form used.
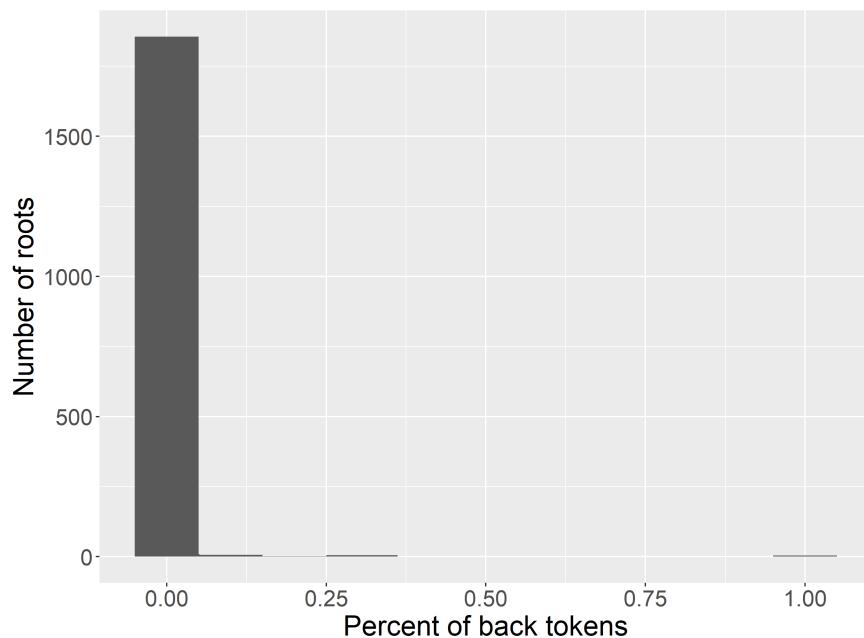
Figure 4.1: Roots whose final harmonizing element is a front vowel (F roots), such as /tyr/ 'type'.
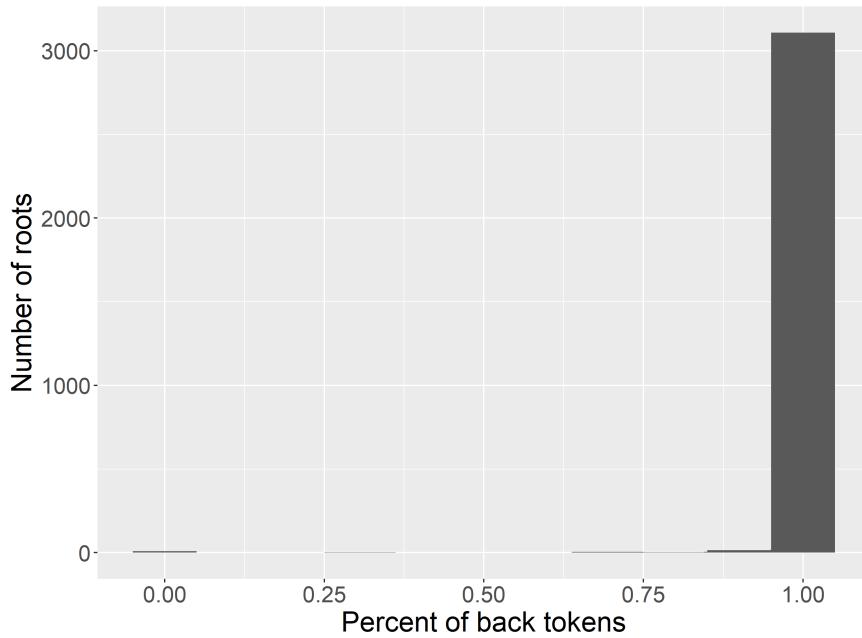
Figure 4.2: Roots whose final harmonizing element is a back vowel (B roots), such as /pul/ 'money'.

4.2.4 Transparent vowels

The vowels /i e/ are *transparent* to harmony, meaning that they do not serve as harmony triggers for suffixes, but allow the harmonic value of preceding segments to "pass through" them.

(48) *Front roots with transparent vowels*

      m**æ**estʃit-**tæ**/*-tɑ   'mosque-LOC'

      ymid-**lær**/*-lɑr   'hope-PL'

      m**ø**min-**gæ**/*-ʁɑ   'believer-DAT'

(49) *Back roots with transparent vowels*

      st**u**dent-**lɑr**/*-lær   'student-PL'

      uniwersitet-**tɑ**/*-tæ   'university-LOC'

      ɑmil-**ʁɑ**/*-gæ   'element-DAT'

Figs. 4.3 and 4.4 show corpus rates of back suffixes in roots whose final harmonic vowel is front or back, respectively, with increasing spans of transparent vowels between the final harmonizing vowel and the suffix. Note that increasing spans of transparent vowels do not affect the harmonic

behavior of these roots: that is, we do not see evidence of *distance-based decay*, a phenomenon where the strength of a phonological constraint decreases as more irrelevant segmental material intervenes between two participating segments (Hayes & Londe, 2006; Hayes et al., 2009; Kimper, 2011; Zymet, 2014).[4]
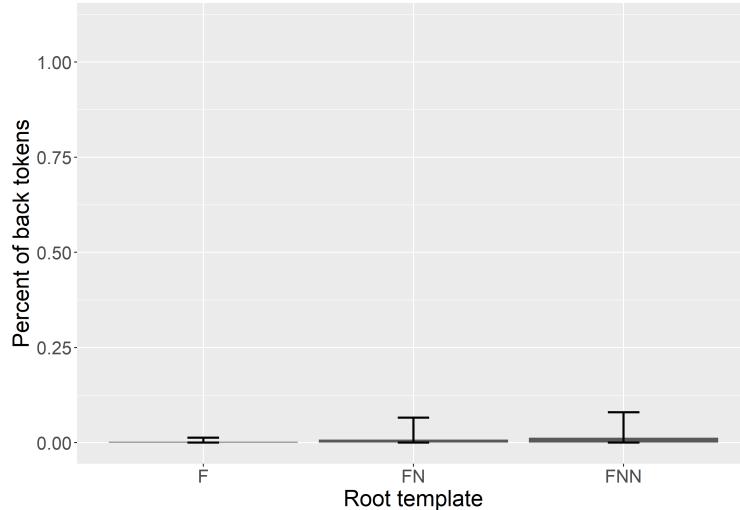
Figure 4.3: Rates of back suffixation in F roots with increasing spans of transparent vowels. Examples are the roots /tyr/ 'type' (F), /ymid/ 'hope' (FN), and /sædditʃin/ 'Great Wall' (FNN). Error bars are +/– one standard deviation of back suffixation rates across roots.

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[4]This phenomenon is also referred to as a *count effect*.
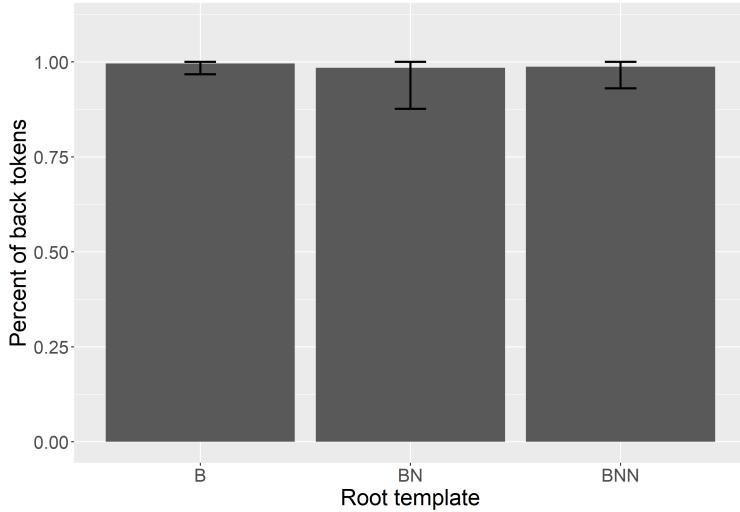
Figure 4.4: Rates of front suffixation in B roots with increasing spans of transparent vowels. Examples are the roots /top/ 'ball' (B), /ɑmil/ 'element' (BN), and /mojsipit/ 'elderly person' (BNN). Error bars are +/– one standard deviation of back suffixation rates across roots.

4.2.5 Dorsal consonant harmony

If a root contains no harmonizing vowels, the front dorsals /k g/ and back dorsals /q ʁ/ may serve as harmony triggers. Front dorsals behave as front triggers, while back dorsals behave as back triggers.

(50) *Roots with only front dorsals*
      kishi-lær/*-lɑr   'person-PL'
      ne**g**iz-**g**æ/*-ʁɑ   'basis-DAT'

(51) *Roots with only back dorsals*
      qiz-lɑr/*-læer   'girl-PL'
      ji**ʁ**in-dɑ/*-dæ   'meeting-LOC'

Figs. 4.5 and 4.6 show histograms of roots whose final harmonizing element is a back or front dorsal respectively, and which contain no harmonizing vowels. Roots containing only the back dorsals /q ʁ/ (165 roots, about 136k tokens) almost invariably take back suffixes. Roots with only the front dorsals /k g/ (151 roots, about 40k tokens) tend to take front suffixes, but there are

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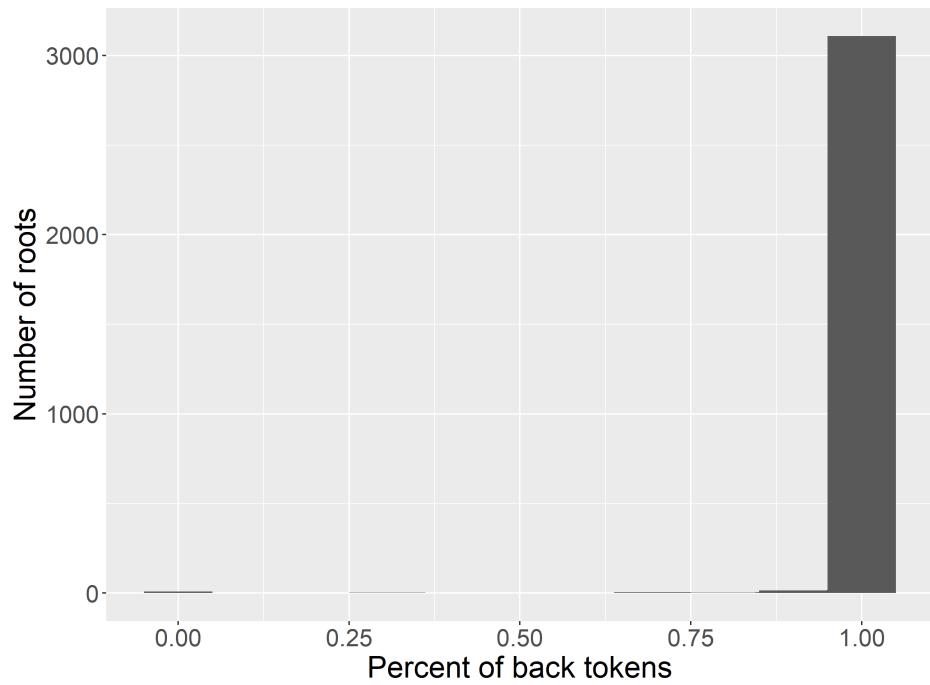
Figure 4.5: Roots whose final harmonizing element is a back dorsal /q ʁ/ and contain no harmonizing vowels (Q roots), such as /qiz/ 'girl'.
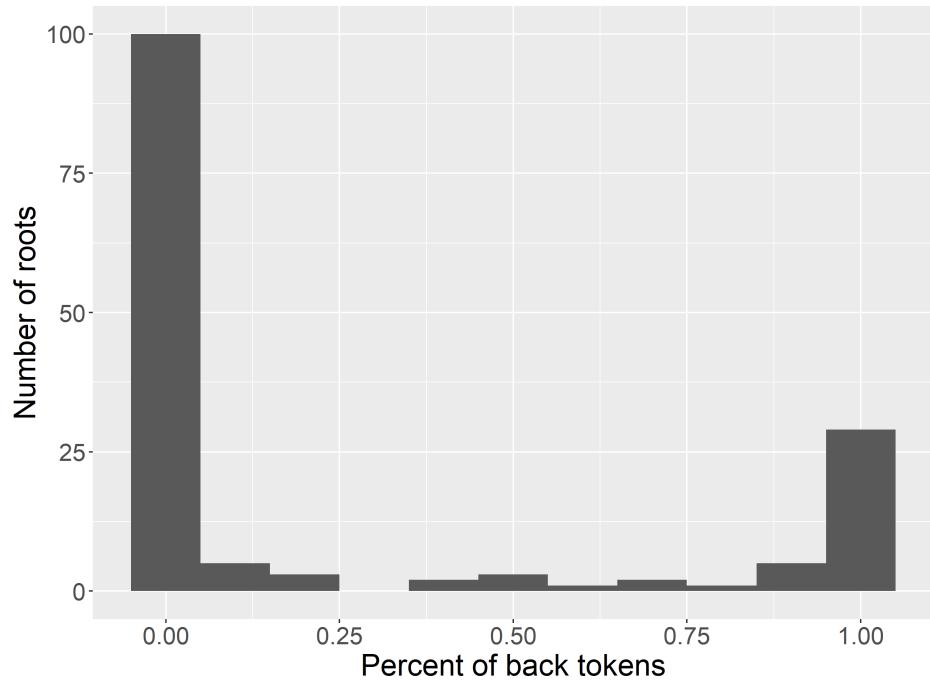
Figure 4.6: Roots whose final harmonizing element is a front dorsal /k g/ and contain no harmonizing vowels (K roots), such as /kir/ 'dirt'.

numerous exceptions to this pattern. 29 of these roots exclusively take back suffixes. Examples of these roots are shown in Example (52).

(52) *Front dorsal roots that exclusively take back suffixes*

      ingliz-lɑr   'English person-PL'

      etnik-lɑr   'ethnic group-PL'

      rentgen-**ʁɑ**   'x.ray-DAT'

      gips-**qɑ**   'plaster-DAT'

Another group of 22 roots vacillate in their rate of back suffixation, showing a rate of between 0.05 and 0.95 back tokens. These include the roots shown in Example (53).

(53) *Front dorsal roots that vary in suffix backness*

      gezit-lɑr/-lær   'newspaper-PL'

      kirizis-**qa/-kæ** 'crisis-DAT'

      sergej-**ʁɑ/-gæ** 'Sergey-DAT'

Thus although both front and back dorsals in roots with no other harmonizing elements serve as triggers for front and back suffixes respectively, the velars are weaker triggers than the uvulars. Note that words where the velars fail to serve as front triggers tend to be more recent loanwords.[5]

4.2.6 Neutral roots

In the absence of any harmonizing elements, roots are lexically listed for backness, with a strong statistical tendency towards back suffixes (see also Chapter 5).

(54) *Neutral roots that take front suffixes*

      biz-**gæ**/*-ʁɑ   'us-DAT'

      bilim-**gæ**/*-ʁɑ   'knowledge-DAT'

      welisipit-**lær**/*-lɑr 'bicycle-PL'

---

[5]This might be considered something like a natural wug test, with recent borrowings serving as the wug words.

(55) *Neutral roots that take back suffixes*

    sir-lɑr/-*lær   'secret-PL'

    din-ʁɑ/*-gæ   'religion-DAT'

    hejt-tɑ/*-tæ   'festival-LOC'

    peʔil-lɑr/*-lær   'verb-PL'

    tip-qɑ/*-kæ   'type-DAT'

Fig. 4.7 shows a histogram of roots with no harmonizing elements at all (389 roots, about 165k tokens). These roots tend to take back suffixes, but a number take exclusively front suffixes, and a smaller number vary.[6]
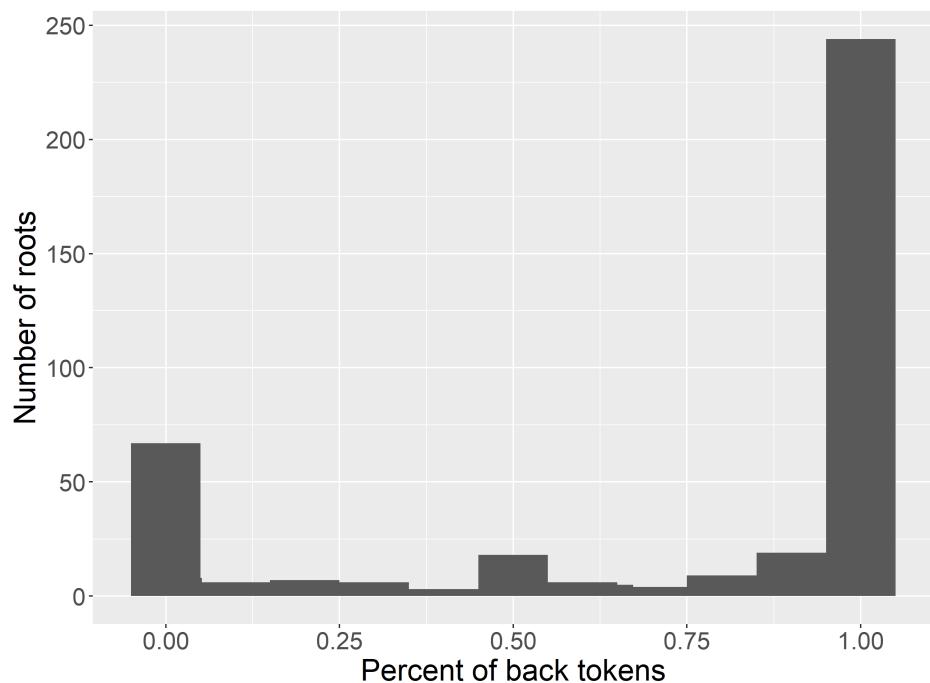
Figure 4.7: Roots with no harmonizing elements (N roots), such as /tiz/ 'knee'.

4.2.7 Vowel-dorsal conflicts

In roots where the final harmonizing vowel is followed by a dorsal that conflicts in backness, the final vowel generally takes precedence.

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[6]Within-root variance in neutral roots is attested in Old Turkic as well (see, e.g., Erdal, 2004).

(56)   *Conflicting vowels and dorsals, vowel takes precedence*

mæntiq-qæ   'logic-DAT'

æqil-**gæ**   'intelligence-DAT'

rɑk-lɑr   'cancer-PL'

pɑkit-lɑr   'fact-PL'

Figs. 4.8 and 4.9 show histograms of roots whose final harmonizing vowel conflicts in backness with a following harmonizing consonant. Figs. 4.8 shows roots where the final harmonizing vowel is front, and a subsequent harmonizing consonant is back (43 roots, about 32k tokens). In these cases, suffixes are almost exclusively front: the exceptions to this are the three roots /tæʃwiq/ 'publicity', /tæstiq/ 'sanction', and /tætqiq/ 'research', which almost always take back suffixes.
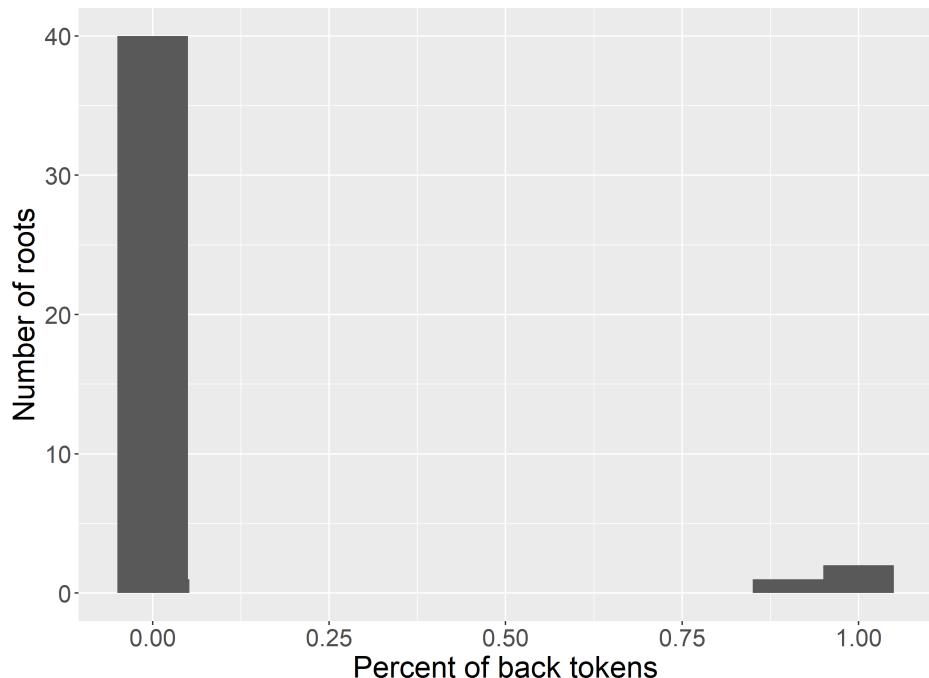
Figure 4.8: Roots whose final harmonizing vowel is front, followed by a back dorsal (FQ roots), such as /mæʃq/ 'exercise'.

Roots where the final harmonizing vowel is back and the final intervening harmonizing consonant is front (109 roots, about 14k tokens) show more variability. While the tendency is for such forms to take back suffixes, 11 roots variably take front suffixes. These roots always contain some number of transparent vowels, and fall into three broad categories: loanwords like

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/olimpik/ 'Olympic', /χɑrɑkter/ 'character', or /diʔɑlekt/ 'dialect'; proper names, like /ɑbdukerim/ 'Abdukérim' or /ɑlptekin/ 'Alptékin', and derived words like /bɑʤgir/ 'tax collector' (derived from /bɑʤ/ 'tax' and /-gir/ 'holder').
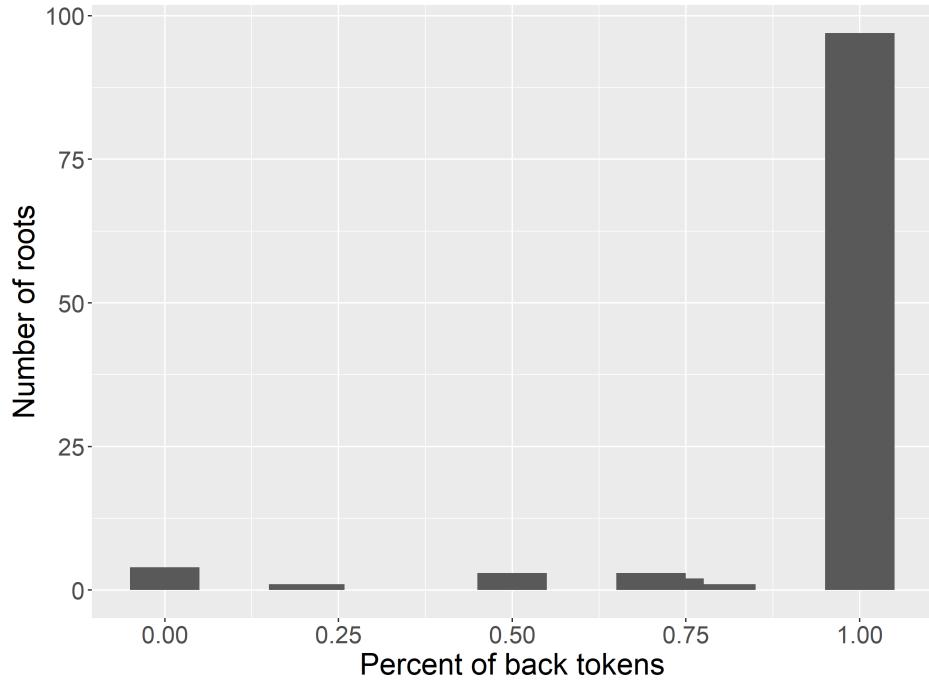
Figure 4.9: Roots whose final harmonizing element is a back, followed by a front dorsal (BK roots), such as /rɑk/ 'cancer'.

Roots with both harmonizing vowels and harmonizing dorsals, shown in Figs. 4.10 and 4.11, show some evidence of distance-based decay as more transparent vowels intervene between the conflicting vowel and dorsal triggers, unlike roots with no harmonizing consonants. This tendency to harmonize with local dorsals over distal vowels does not manifest uniformly across roots, however. Rather, exceptional roots that show harmony with local dorsals become more common when there are larger spans of transparent vowels separating the dorsal and final harmonizing vowel, but the behavior of individual roots is still largely categorical.
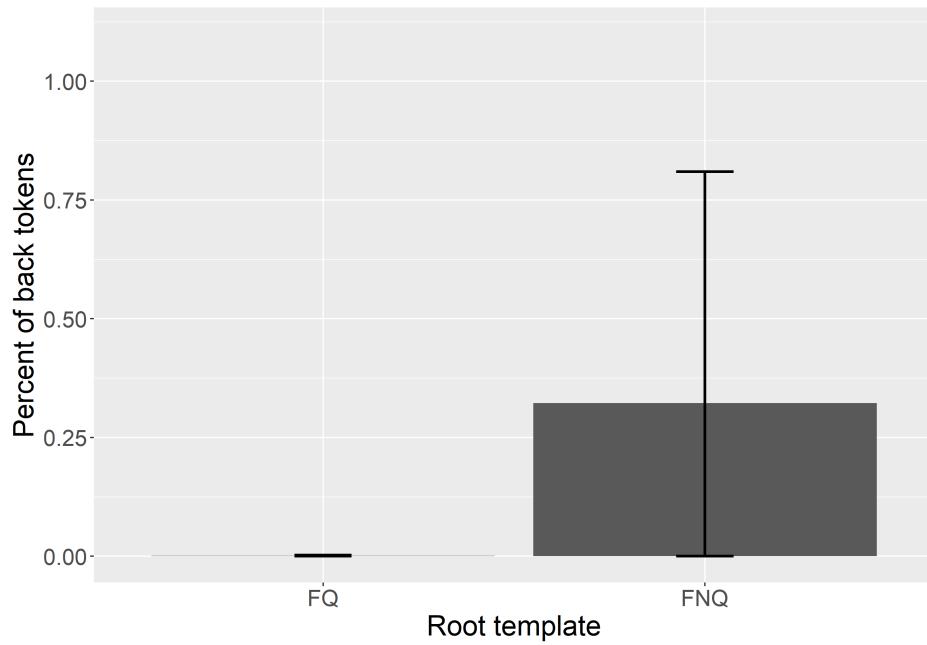
Figure 4.10: Rates of back suffixation in FQ roots with increasing spans of transparent vowels between the harmonizing vowel and following harmonizing dorsal.
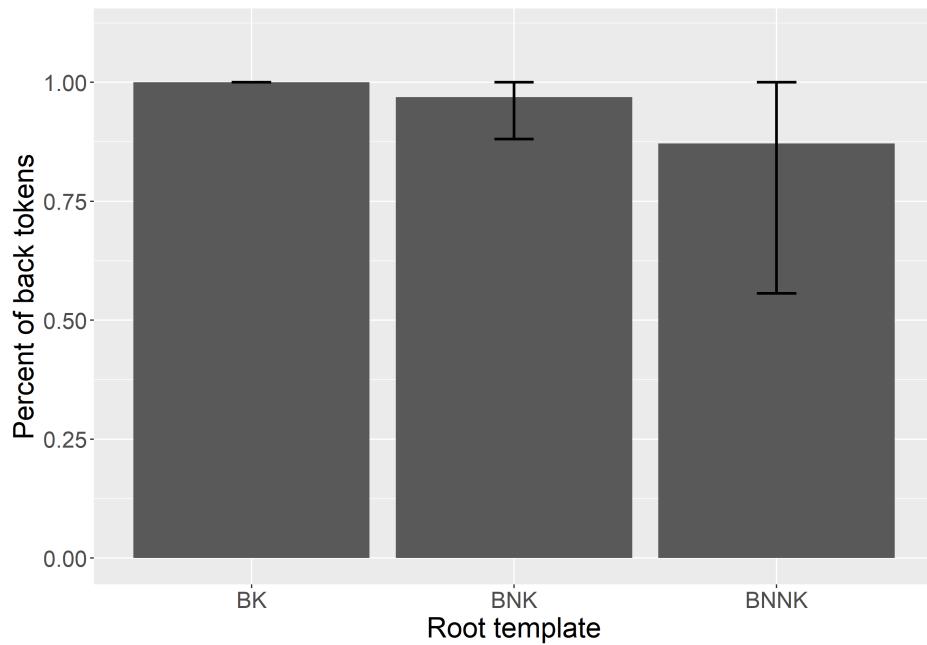
Figure 4.11: Rates of front suffixation in BK roots with increasing spans of transparent vowels between the harmonizing vowel and following harmonizing dorsal.

4.2.8 Summary of corpus results

Fig. 4.12 shows the overall rates of back suffixation for each of the categories discussed above.
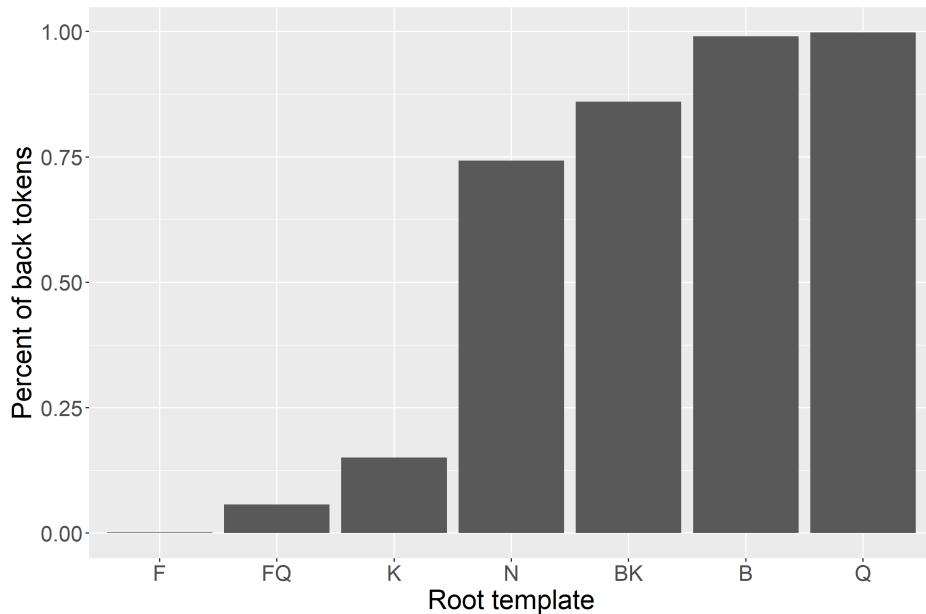
Figure 4.12: Summary of rates of back suffix forms across various root types. F: roots whose final harmonizing element is a front vowel; B: roots whose final harmonizing element is a back vowel; K: roots whose final harmonizing element is a front dorsal and contain no harmonizing vowels; Q: roots whose final harmonizing element is a back dorsal and contain no harmonizing vowels; FQ: roots whose final harmonizing vowel is a front vowel with a following back dorsal; BK: roots whose final harmonizing vowel is a back vowel with a following front dorsal; N: roots with no harmonizing elements.

These results show that the corpus data essentially corroborate the qualitative description of Uyghur backness harmony given in the previous chapter, although with some additional quantitative details: front and back vowels call for front and back suffixes respectively, as do front and back dorsals. Cases of a vowel followed by a dorsal that conflicts in backness generally take harmony from the vowel, with some exceptions, and completely neutral roots tend to take back suffixes.

An overall summary of decay rates in the corpus (that is, the extent to which expected harmony patterns are violated as the distance between trigger and target increases) by root type is shown in

Fig. 4.13.
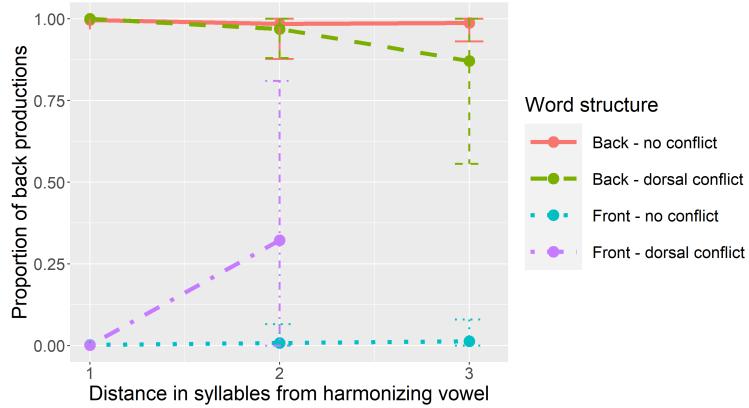
Figure 4.13: Summary of decay rates in the corpus by root type. Note that distance-based decay is evident across roots only in the presence of a conflicting harmonizing dorsal that intervenes between the final harmonizing vowel and suffix.

4.2.9 Analyzing corpus results

Setting aside exceptional forms and distance-based decay for the moment, the general pattern of backness harmony in the corpus may be captured by the following constraints:

(57) *FRONTSUFFIX: Assess one violation for each front suffix. This constraint captures the overall bias towards backs suffixes in neutral roots.[7]

(58) VAGREEBACK: Assess one violation when a front suffix follows a back harmonizing vowel at any distance (with no other harmonizing vowels intervening).

(59) VAGREEFRONT: Assess one violation when a back suffix follows a front harmonizing vowel at any distance (with no other harmonizing vowels intervening).

(60) CAGREEBACK: Assess one violation when a front suffix follows a back harmonizing dorsal at any distance (with no other harmonizing dorsals or vowels intervening).

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[7]This constraint can be thought of as shorthand for a pair of constraints: ID-[back] ≫ *[–back]. The highly ranked ID-[back] constraint prevents segments that are underlyingly specified for backness from changing their backness (that is, segments in roots and in harmony-blocking suffixes), while *[–back] exerts pressure on segments unspecified for backness (i.e., segments in harmonizing suffixes) to be realized as [+back].

(61) CAGREEFRONT: Assess one violation when a back suffix follows a front harmonizing dorsal at any distance (with no other harmonizing dorsals or vowels intervening).

I assume the existence of highly ranked root faithfulness constraints that prevent vowels in roots from being changed to facilitate harmony.

The general pattern of falling back to harmonizing dorsals only when no harmonizing vowels are present can be captured by the following ranking:

(62) VAGREEBACK, VAGREEFRONT ≫ CAGREEBACK, CAGREEFRONT ≫ *FRONTSUFFIX

The effects of this ranking are shown in Tables 4.3 to 4.9 using several representative roots. Note that for the purposes of the tableaux below, the pairs of VAGREE and CAGREE constraints could be collapsed into single general VAGREE and CAGREE constraints respectively. The separation of these constraints will be important for the weighted models presented later in the chapter, and so I leave them separated here.

/at-lAr/	VAGREEBACK	VAGREEFRONT	CAGREEBACK	CAGREEFRONT	*FRONTSUFFIX
☞ a. ɑt-lɑr					
b. ɑt-lær	*!				*

Table 4.3: Tableau for B root /at-lAr/ 'horse-PL'

/χæt-lAr/	VAGREEBACK	VAGREEFRONT	CAGREEBACK	CAGREEFRONT	*FRONTSUFFIX
a. χæt-lɑr		*!			
☞ b. χæt-lær					*

Table 4.4: Tableau for F root /χæt-lAr/ 'letter-PL'

/qiz-lAr/	VAGREEBACK	VAGREEFRONT	CAGREEBACK	CAGREEFRONT	*FRONTSUFFIX
☞ a. qiz-lɑr					
b. qiz-lær			*!		*

Table 4.5: Tableau for Q root /qiz-lAr/ 'girl-PL'

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/kiʃi-lAr/	VAGREEBACK	VAGREEFRONT	CAGREEBACK	CAGREEFRONT	*FRONTSUFFIX
a. kiʃi-lɑr				*!	
☞ b. kiʃi-lær					*

Table 4.6: Tableau for K root /kiʃi-lAr/ 'person-PL'

/blog-lAr/	VAGREEBACK	VAGREEFRONT	CAGREEBACK	CAGREEFRONT	*FRONTSUFFIX
☞ a. blog-lɑr				*	
b. blog-lær	*!				*

Table 4.7: Tableau for BK root /blog-lAr/ 'blog-PL'

/mæʃq-lAr/	VAGREEBACK	VAGREEFRONT	CAGREEBACK	CAGREEFRONT	*FRONTSUFFIX
a. mæʃq-lɑr		*!			
☞ b. mæʃq-lær			*		*

Table 4.8: Tableau for FQ root /mæʃq-lAr/ 'exercise-PL'

/mæʃq-lAr/	VAGREEBACK	VAGREEFRONT	CAGREEBACK	CAGREEFRONT	*FRONTSUFFIX
☞ a. sir-lɑr					
b. sir-lær					*!

Table 4.9: Tableau for N root /sir-lAr/ 'secret-PL'

4.2.10 Interpreting AGREE constraints

Long-distance phonological harmony processes are typically described as falling into two distinct categories: *local spreading*, where the domain of a single feature extends across neighboring segments (e.g. Clements, 1976; van der Hulst, 1985) and *correspondence*, where two segments are required to agree in some feature, without that feature necessarily occurring on intervening segments (e.g., McCarthy & Prince, 1995; Hansson, 2001, 2010; Rose & Walker, 2004); see Rose and Walker (2011) for an overview. Local spreading is generally considered to have been born out of coarticulation that subsequently becomes phonologized. Many instances of vowel and consonant harmony have been analyzed as local spreading (e.g., Gafos, 1999): under such analyses, so-called transparent segments that intervene between two segments in a harmony relationship are able to

bear the spreading feature (and its associated movement) without explicit acoustic consequences. These include cases such as vowel backness and rounding (see also Kaun, 2004) harmony, sibilant anteriority harmony, and retroflex harmony (e.g., Walker, Byrd, & Mpiranya, 2008; Ryan, 2017). This kind of harmony is shown schematically in Example (63), which illustrates a hypothetical case of vowel harmony via spreading.

(63) $[V_{+back}]CV \rightarrow [VCV_{+back}]$

Correspondence relationships, on the other hand, capture agreement between distal segments that cannot be explained by local spreading, such as agreement in place of articulation or various laryngeal properties. Previous literature has argued that correspondence restrictions may develop on the basis of constraints on speech planning, perception, and memory (Gafos, 2021). This kind of harmony is shown schematically in Example (64), which illustrates a hypothetical case of vowel harmony via correspondence.

(64) $[V_{+back}]CV \rightarrow [V_{i\ +back}]C[V_{i\ +back}]$

The AGREE constraints defined above are largely amenable to an interpretation as local spreading. However, FQ and BK roots become problematic under this interpretation. It is reasonable to assume that both front vowels and velars bear the feature [–back], while back vowels and uvulars bear the feature [+back]. Evidence for this assumption comes from both the behavior of these segments as harmony triggers described above, and their behavior as undergoers of harmony. That is, just as the vowel quality in the plural suffix /-lAr/ varies between [-lær] and [-lɑr] in the presence of front or back triggers respectively, so does the dorsal quality in suffixes like the elapsed past marker /-Gili/, which varies between front forms [-kili]/[-gili] and back forms [-qili]/[-ʁili], and both vowel and dorsal quality in suffixes like the infinitival marker /-mAQ/, which varies between front [-mæk] and back [-mɑq] in the same environments).

FQ and BK roots are problematic for local spreading because of the strong tendency for suffixes to harmonize with the vowel rather than the final dorsal. This suggests something like the correspondence relationship shown in Example (65), where *S* represents a suffix form.

(65) $[V_{-back}][C_{+back}] S \rightarrow [V_{i\ -back}][C_{+back}][S_{i\ -back}]$

A spreading analysis predicts that the intervening dorsal should either block the spread of the [back] feature from the vowel (Example 66), or assimilate to it in backness (Example 67), neither of which is the most prevalent pattern.

(66)   [V $_{-back}$][C $_{+back}$] S → [V $_{-back}$][C S $_{+back}$]

(67)   [V $_{-back}$][C $_{+back}$] S → [VCS $_{-back}$]

Due to the behavior of these conflicting roots, backness harmony in Uyghur aligns most closely with a correspondence analysis: thus we may for the time being think of these AGREE constraints as essentially correspondence constraints mandating both that (a) suffixes correspond to particular segments in the root; and (b) suffixes agree in backness with those segments. This point will be returned to later in the chapter.

4.3   Wug testing Uyghur backness harmony

Although the corpus data presented above is a useful source of information about the kinds of data available to the learner, the possible influence of lexical factors, such as those described in the previous chapter, means they are not necessarily an accurate characterization of speakers' phonological grammars. This section of the chapter aims to test whether speakers generalize to new data in a way that is consistent with these corpus patterns. We focus specifically differences in the strength of front/back vowel triggers and front/back dorsal triggers, particularly in cases of conflict, and to count effects of transparent vowels. This will allow us to learn something about the kinds of biases that guide phonological learning, and to address the question of locality in the harmony system. The stimuli were designed in consultation with, and the data collected by, Travis Major and Mahire Yakup. Elements of this section were presented in Mayer et al. (2019) and Mayer, Major, and Yakup (2020).

Wug tests (Berko, 1958) have long been used as a method for investigating phonological and morphological productivity, and for controlling for lexical effects on phonological patterns. They are used here to investigate the basic productivity of Uyghur backness harmony in the absence of lexical influences. This is particularly important given past analyses (Lindblad, 1990; R. F. Hahn,

1991b) which require a large degree of lexical specification in the form of diacritic phonological features to account for the pattern, but provide little insight into the productive capacity of speakers.

4.3.1 Methodology

We elicited data from 23 native speakers of Uyghur living in Almaty, Kazakhstan (ages 19–62; mean 40). All speakers grew up in Almaty province. Stimuli were presented in one of two random orders. Participants were recorded reading frame sentences containing each target word in both unsuffixed (nominative) and suffixed (the locative /-DA/) forms. The choice of the front vs. back form of the locative (i.e., /-Dæ/ vs. /-Dɑ/) were coded.

We created a custom Python script[8] to generate a large set of Uyghur wug words matching the 15 word templates in 5 categories shown in Table 4.10. These templates match those discussed in the previous section, except that wug roots containing only harmonizing dorsals (K and Q roots) were not tested.

A native Uyghur speaker (Mahire Yakup) selected four words per template that were judged to be phonologically plausible and contained a balance of vowel qualities. Consonants aside from the harmonizing dorsals were not carefully controlled. This resulted in a total of 60 wug words. The words for each template are shown in Table 4.10.[9]

We embedded wug words in one of three frame paragraphs, shown below. "Orun kélish" in the Uyghur indicates that the preceding target word should be produced with locative case marking.

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[8] `https://github.com/connormayer/uyghur_tools/blob/master/uyghur_wugger.py`

[9] Due to human error, the CBK template has 5 associated forms, while the CBC template has only 3.

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Category	Template	Words
No harmonizers (N)	CNC	[des], [nir], [wiw], [ref]
	CNCNC	[fedʒit], [limef], [sipen], [weŋif]
	CNCNCNC	[zelehip], [hitilidʒ], [ʃebipim], [tipidʒib]
Front vowel (F)	CFC	[tʃød], [døm], [zym], [læŋ]
	CFCNC	[pyhim], [næniʒ], [ræχidʒ], [læsih]
	CFCNCNC	[lyjeʃir], [mæʃidʒil], [χøwidʒel], [pæpedew]
Back vowel (B)	CBC	[tʃof], [nat], [nop]
	CBCNC	[tʃodip], [noditʃ], [ʒuzil], [zaŋiχ]
	CBCNCNC	[mubemes], [luwilin], [wasirem], [bupiŋed]
Front vowel & back dorsal (FQ)	CFQ	[dʒøʁ], [ryq], [møʁ], [pæq]
	CFCNQ	[dæwiq] [tʃædiq], [jyniq], [tʃymiʁ]
	CFCNCNQ	[løneʒiq], [søpiteq], [dætʃeŋeq], [dʒøpimeʁ]
Back vowel & front dorsal (BK)	CBK	[tug], [mok], [zak], [nuk], [fok]
	CBCNK	[fodʒik], [dapik], [wawik], [ʃotik]
	CBCNCNK	[dʒabedʒig], [maχetʃik], [waretik], [moʒiʃeg]

Table 4.10: Uyghur wug word templates. F: front vowel; B: back vowel; K: front dorsal; Q: back dorsal; C: transparent consonant; N: transparent vowel.

(68)   Ular _____ bir kona sheher dédi. Hazir kishiler _____ (orun kélish) yashimaydu.

"They say _____was an old city. Nowadays, people don't live in _____."

(69)   Kitupxanidiki _____ biz yazghan kitab. Méningche _____ (orun kélish) yaxshi hikayiler bar.

"In the library, _____ is a book that we wrote. In my opinion, there are many great stories in _____."

(70)   Ular bultur bir yoghan _____ sétiwaldi. Ular _____ (orun kélish) tamaq pishurghan.

"Last year they bought a massive _____. They cook food in _____."

We elicited 1/3rd of the words in each frame.

Significance testing was done by fitting a linear-mixed effects models using the *lme4* package in *R*. The dependent variable was suffix choice. The independent variables were distance in syllables from trigger to suffix, word template (one of B, F, BK, FQ), and the interaction of the two. Neutral roots were omitted from this model because distance from trigger to suffix is not meaningful for this class of roots. Random intercepts were included for participant, to account for idiosyncratic behavior across speakers, and root identity, to account for root-specific factors not explicitly coded here. Post-hoc pairwise comparisons were done using the *emmeans* package, and *p*-values were calculated using the *lmerTest* package using Satterthwaite's degrees of freedom method (Kuznetsova, Brockhoff, & Christensen, 2017).

4.3.2 Wug word results
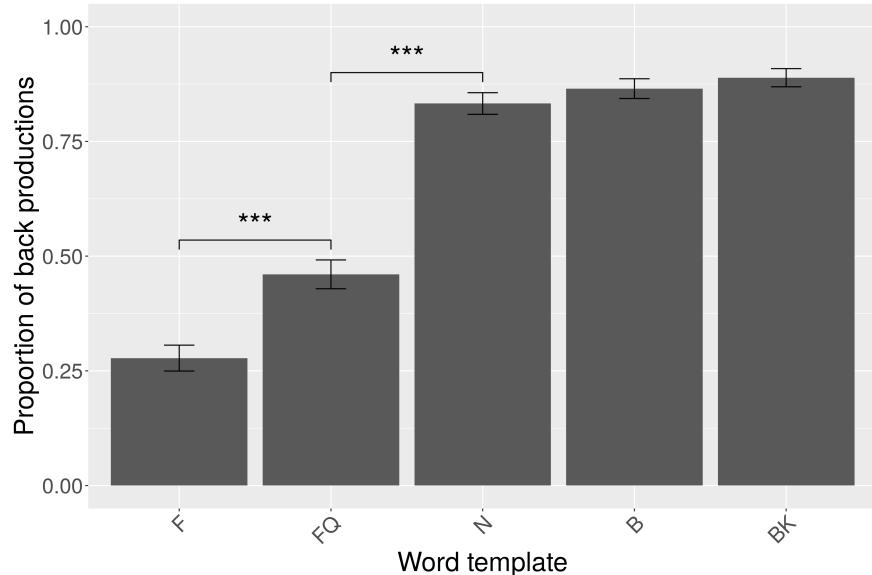
Figure 4.14: Wug results by template. Error bars are +/− one standard deviation.

The by-template results for wug word responses collapsed across distances are shown in Fig. 4.14. Generally, there is a strong preference for back suffixes across the board. The presence of conflicting uvulars in front vowel roots significantly increases the proportion of back responses. B, and BK roots have significantly more back responses than either the F and FQ roots, and FQ roots have significantly more back responses than F roots. However, there are no significant differences in

backness responses between B, and BK roots.

A similar model that includes neutral roots but omits distance from trigger to suffix as a predictor indicates that N roots produce significantly more back responses than both F and FQ roots, but do not different significantly in proportion of back responses from B and BK roots.
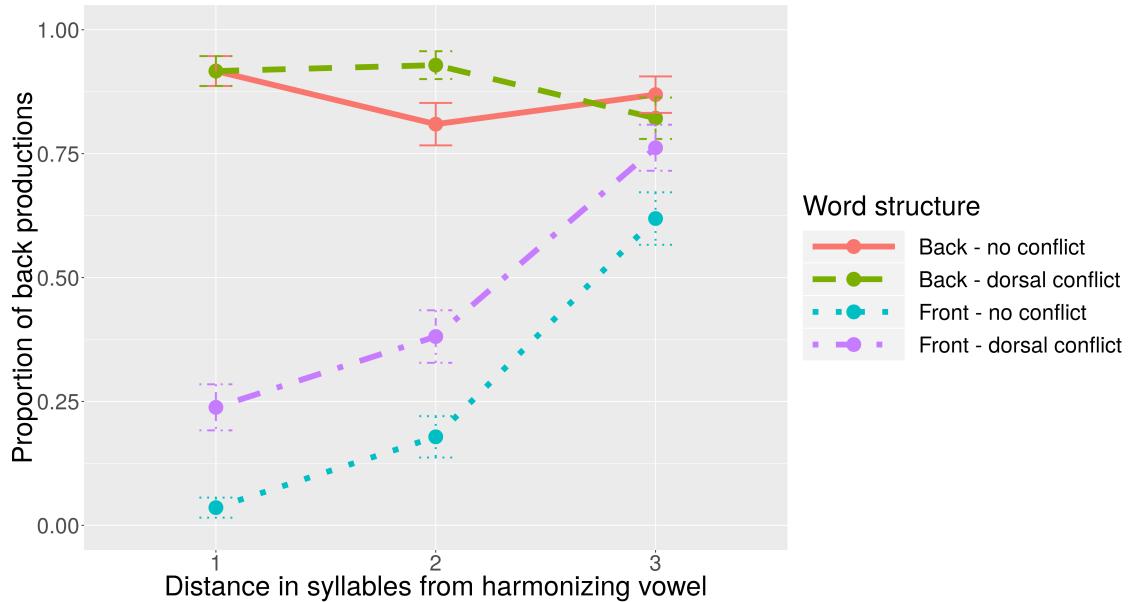
Figure 4.15: Proportion of back suffixes chosen across speakers, as a function of distance between harmonizing vowel and suffix, and root structure. "Back" and "Front" indicate the backness of the harmonizing vowel in the root, and "dorsal conflict" and "no conflict" indicate the presence or absence of a conflicting dorsal root-finally (/q/ or /ʁ/ for front vowels, and /k/ or /g/ for back vowels). Error bars are +/– one standard deviation.

The results broken down by both template and distance are shown in Fig. 4.15. The responses for the front vowel roots show that as transparent vowels intervene between the harmonizing vowel and suffix, the proportion of back suffix responses increases. With two intervening harmonic vowels (a distance of 3 syllables between harmonizing vowel and suffixes), back responses become the majority response. The presence of a root-final uvular skews suffix choice towards back responses at all distances.

The responses for back vowel roots show a different pattern. The large majority of responses

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are back, even as distance between vowel and suffix is increased. In addition, the presence of a conflicting velar sound does not appear to increase the number of front suffix responses (in fact, roots with a conflicting velar get slightly more back responses across the board).

Fig. 4.16 shows the proportion of back responses for B and BK roots broken down by distance between the harmonizing vowel and suffix. No distance effects are significant.
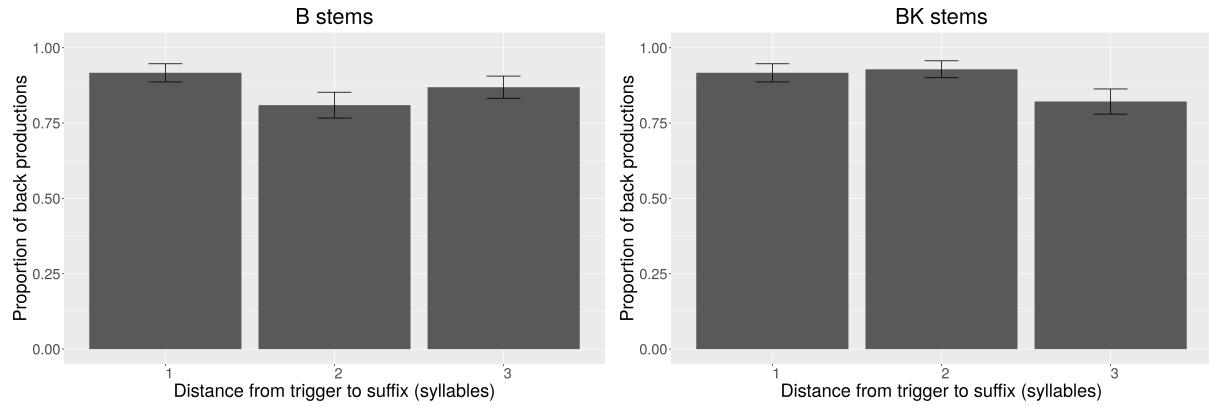
Figure 4.16: Back wug root results by distance between harmonizing vowel and suffix. Error bars are +/− one standard deviation.

Fig. 4.17 shows the proportion of back responses for F and FQ roots broken down by distance between the harmonizing vowel and suffix. Here each increase in distance between the harmonizing vowel and suffix results in an increase in back responses: the difference between 1 and 2 syllable distances is not significant for either root type, however.
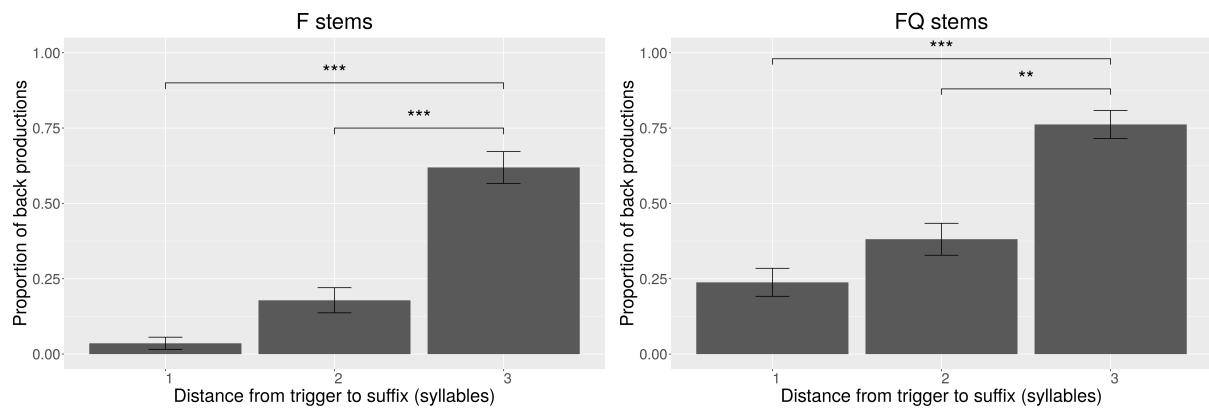
Figure 4.17: Front wug root results by distance between harmonizing vowel and suffix. Error bars are +/− one standard deviation.

These results show that:

- There is an overall bias towards back suffixes, which manifests most clearly in neutral roots.

- Trigger distance effects are only significant for front vowel triggers.

- When the final two harmonizing elements in a root are a front vowel followed by a uvular, the trigger strength of the front vowel is weakened (that is, participants were more likely to use back forms of suffixes). No such weakening is observed in cases where the final two harmonizing elements are a back vowel followed by a velar.

Wug responses broken down by individual word can be found in Appendix H.

4.4 Comparing wug and corpus words

The two most salient differences between the patterns of harmony in the corpus and in the wug tests are (a) the presence of distance-based decay in the wug responses following front vowels, and (b) the increased tendency for FQ roots to take back suffixes. These differences are reflected in Fig. 4.18.
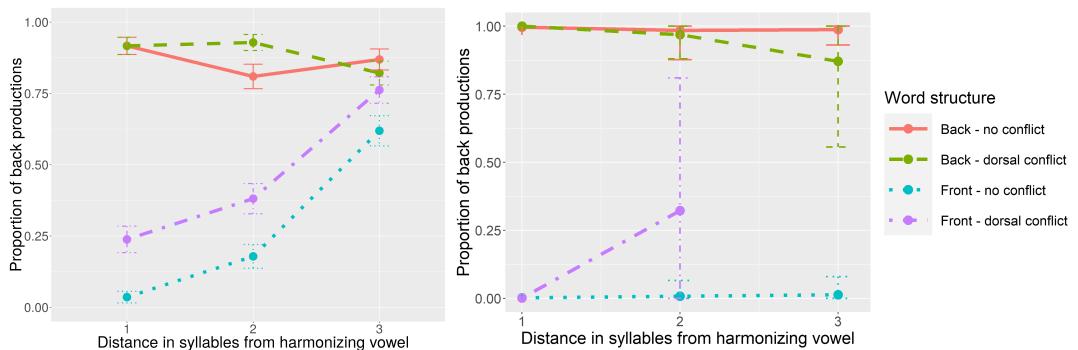
Figure 4.18: Wug (left) and real (right) results by template. Error bars are +/– one standard deviation.

These results show that Uyghur speakers generalize to wug words in a way that is not completely consistent with corpus data. In the next section, I will show that the constraints learned from patterns in the surface data are unlikely to have generated the observed behavior in wug tests.

4.5 Comparing corpus and wug models

The patterns in the corpus and wug data are compatible in broad strokes: their most salient differences lie in the extent to which factors such as conflicting velars and intervening transparent vowels influence backness choices. In order to model these differences, I will use Maximum Entropy Harmonic Grammar (henceforth MaxEnt; Smolensky, 1986; Goldwater & Johnson, 2003).

4.5.1 Maximum Entropy Optimality Theory

MaxEnt is a variant of Optimality Theory (Prince & Smolensky, 1993/2004) with numeric constraint weights (see also Pater, 2009). A MaxEnt model is able to generate probability distributions over output candidates for a given input, making it well-suited to capturing the gradient distinctions evident between the corpus and wug data. Because it is a numerical model that is able to assign likelihood values to a data set, it is also straightforward to learn constraint weights that optimize fit to the data (see Hayes & Wilson, 2008, for more detail on this learning procedure).

In a MaxEnt grammar, each constraint is associated with a real-valued weight that represents its strength. In a grammar with N constraints, the weight of the ith constraint can be notated w_i. The function $C_i(x,y)$ returns the number of times an output candidate y for an input form x violates the ith constraint. The *harmony* of an output form y given an input form x is:

$$H(x,y) = \sum_i^N w_i C_i(x,y)$$

where higher values of $H(x,y)$ are associated with more severe constraint violations. The probability of an output candidate y is

$$P(y|x) = \frac{\exp(-H(x,y))}{\sum_{z \in \Omega} \exp(-H(z,y))}$$

where Ω is the set of all possible output candidates given the input x.

The likelihood of a corpus $\hat{L}$ under a MaxEnt model can be calculated as follows

$$\hat{L} = \prod_{i=1}^n P(y_i|x_i)$$

where n is the number of tokens, x_i is the underlying form of token i, and y_i is the winning candidate for token i.

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4.5.2 Constraints

A MaxEnt OT model was fit to the subset of the corpus data that matched the templates used in the wug tests, using the same set of constraints described above: VAGREEBACK, VAGREEFRONT, CAGREEBACK, CAGREEFRONT, and *FRONTSUFFIX.

Because the wug responses displayed strong evidence of distance-based decay, I split the VAGREEBACK and VAGREEBACK constraints into sets of three distance-specific constraints: VAGREE-1, VAGREE-2, and VAGREE-3, with back and front variants. These constraints are violated at distances of exactly 1, 2, and 3 syllables between harmony trigger and harmony target respectively. Because the wug tests included only root-final harmonizing dorsals, distance-specific CAGREE constraints were not included.

	Corpus raw	Wug raw	Raw ratio	Corpus norm.	Wug norm.	Norm. ratio
VAGREEBACK-1	4.52	0.95	4.76	0.14	0.08	1.85
VAGREEBACK-2	3.12	0.35	8.91	0.10	0.03	3.47
VAGREEBACK-3	3.15	0.05	62.99	0.10	0.004	25.96
VAGREEFRONT-1	7.35	4.14	1.78	0.23	0.33	0.69
VAGREEFRONT-2	5.64	3.17	1.78	0.17	0.25	0.69
VAGREEFRONT-3	5.38	1.31	4.11	0.17	0.10	1.59
CAGREEBACK	1.34	1.08	1.24	0.04	0.09	0.48
CAGREEFRONT	0.94	0	n/a	0.03	0	n/a
*FRONTSUFFIX	1.06	1.55	0.68	0.03	0.13	0.27
Log likelihood	$-112,052$	-610		-0.142	-0.443	
r	0.98	0.99				

Table 4.11: Constraint weights and model fit for the MaxEnt OT model fit to the corpus and wug data. Raw values and normalized values are shown on the left and right respectively. Normalized weights are divided by the sum of all constraint weights, and thus reflect the share of the total weight assigned to each constraint. Normalized log likelihood values are divided by the number of tokens, and reflect the mean log likelihood per token.

Table 4.11 shows the learned weights from fitting this model to the corpus data and wug data, as well as the log likelihood assigned to the data under each model and the correlation between predicted and observed frequencies. No regularization terms were used (see Section 4.7.1).

Some salient differences jump out immediately. First, all constraints are somewhat lower in the wug test data. Hayes et al. (2009) make a similar observation, and attribute it to the less polarized output distribution in the wug tests: higher weights tend to produce more categorical outcomes, while lower weights allow for more variation. Second, the *FRONTSUFFIX constraint is weighted higher in the wug model than in the corpus model, which in turn drives the weights of the VAGREEBACK constraints down and the VAGREEFRONT constraints down (since these now have to do less and more work respectively to combat this general backness bias). This difference is driven largely by the responses to neutral roots, which take back suffixes about 85% of the time in the wug data, but only 75% of the time in the corpus data. Third, the relationships between the distance-specific constraints differ between the corpus: the corpus AGREE weights treat violations at distances 2 and 3 as less severe than violations at distance 1, and roughly equivalent to one another, while the wug weights decrease exponentially with distance. Finally, CAGREEFRONT receives a weight of zero in the wug model.

4.5.3 Testing constraint weights with a Monte Carlo simulation

Because the corpus and wug models are fit to data sets with different roots and different token counts, it is only natural that the weights should be different between the two of them. In order to determine how different the wug patterns are from those in the corpus, I employ a Monte Carlo simulation approach (Metropolis & Ulam, 1949), similar to that used in Hayes et al. (2009).

The structure of these simulations is as follows:

1. Use the weights learned from the corpus data to predict probability distributions over possible responses in the wug test task.

2. Perform 10,000 simulated wug tests: that is, sample responses from the predicted probability distributions until the number of response tokens per input matches the number of wug test

responses.

3. Fit a MaxEnt model to each of these 10,000 simulated wug tests.

4. Compare the distribution of weights fit to these simulated tests against the weights fit to the actual wug test responses.

In essence, these simulations operate under the null hypothesis that the grammars of Uyghur speakers are optimized to match the statistical patterns in the corpus, and that the observed discrepancies between corpus and wug patterns are the result of sampling noise. To test this hypothesis, we simulate 10,000 groups of 23 Uyghur speakers who provide backness harmony judgments by frequency matching the corpus patterns, and see if the sampling noise is likely to generate weights like those observed in the actual wug test.

Because the wug responses are on the whole closer to 50% back productions than the corpus data, I follow Hayes et al. (2009) in including a *temperature parameter* when predicting the probabilities of the wug responses using the grammar trained on the corpus (Ackley, Hinton, & Sejnowski, 1985, p. 150–152). The motivation behind introducing this parameter is that wug tests tend to generate less categorical responses in way that's unrelated to grammatical factors (e.g., because participants are explicitly considering the choice between two different forms). This parameter allows this affect to be separated from the effects of the grammar. This parameter will be used throughout the chapter when models trained on the corpus data are applied to the wug data.

With temperature included, the probability of a particular candidate x given an input is:

(71)

$$P(y|x) = \frac{\exp(-H(x,y)/T)}{\sum_{z \in \Omega} \exp(-H(z,y)/T)}$$

where T is the temperature parameter, $H(x,y)$ is the harmony of candidate y given input x, and Ω is the set of all candidates given the input. As T increases, the probability of a response with a back suffix moves towards 50%. T was set to 2 for these simulations. This value was chosen because it caused the predicted frequencies for simple F and B roots to closely match the observed wug test frequencies (about 3% back and 93% back respectively).

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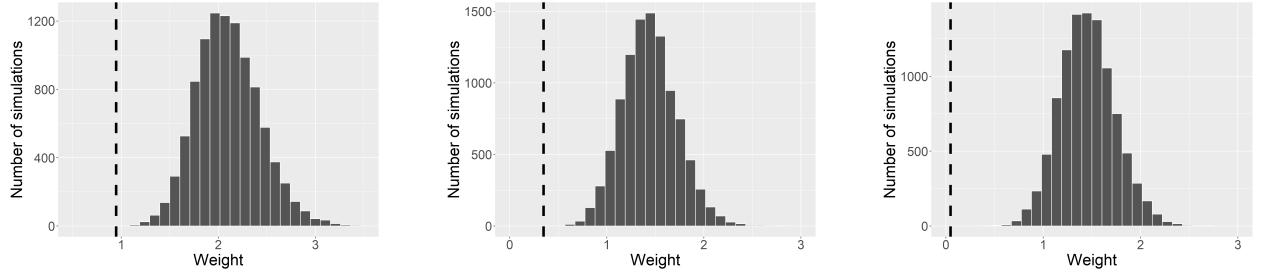
Figure 4.19: Distribution of simulation weights for VAGREEBACK-1 (left), VAGREE-BACK-2 (center), and VAGREEBACK-3 (right). Dashed lines indicate weight fit to actual wug test data.

Once we have these distributions of weights that have been fit to this simulated wug test data, we can compare the distributions against the optimal weight for the wug test, to determine how likely it is to have arisen by chance. If the weight of the constraint optimized against the wug data falls in the left tail of the distribution of weights, we can say that it is underlearned (that is, real Uyghur speakers appear to use a lower weight for this constraint than would be predicted from the simulated wug tests), while if the optimal weight falls on the right tail of the distribution, we can say that it is overlearned (that is, real Uyghur speakers appear to weight this constraint more highly than would be predicted from simulated wug tests).

Following Hayes et al. (2009), we can quantify this by looking at the where the weight fit to the actual wug test responses falls on the distribution of weights fit to the simulated wug tests. If only 5% of simulations produce a weight greater the actual wug test weight, we can say that this constraint is *overlearned* by the Uyghur speakers with an estimated *p*-value of $\hat{p} = 0.05$.

Plots of the weight distributions for each constraint are shown in Figs. 4.19 to 4.21.

Table 4.12 shows the weights fit to the corpus and wug data, and the results of the Monte Carlo simulations. Note that the increased weight of *FRONTSUFFIX in the wug test grammar, which is driven by the greater proportion of back responses for neutral roots in the wug tests, has two broad consequences for the weights of the constraints fit to the wug test data. It generally results in constraints mandating [+back] harmony to be underlearned, since their weights are proportionally less responsible for driving [+back] suffix forms, and constraints mandating [–back] harmony to be overlearned, since their weights are proportionally more responsible for driving front suffix forms.
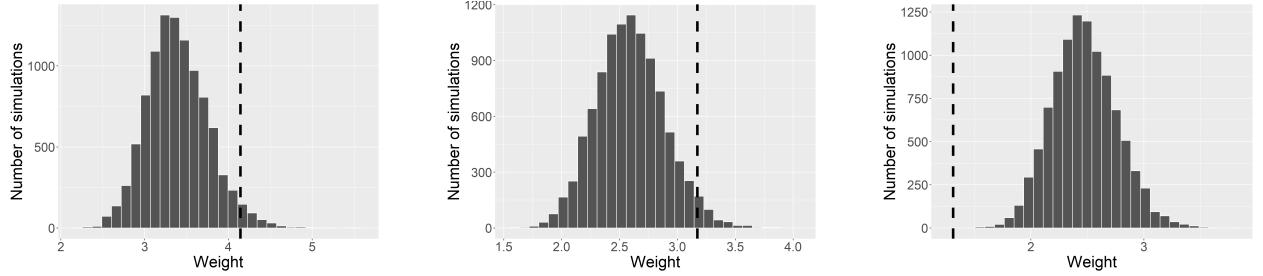
Figure 4.20: Distribution of simulation weights for VAGREEFRONT-1 (left), VA-GREEFRONT-2 (center), and VAGREEFRONT-3 (right). Dashed lines indicate weight fit to actual wug test data.
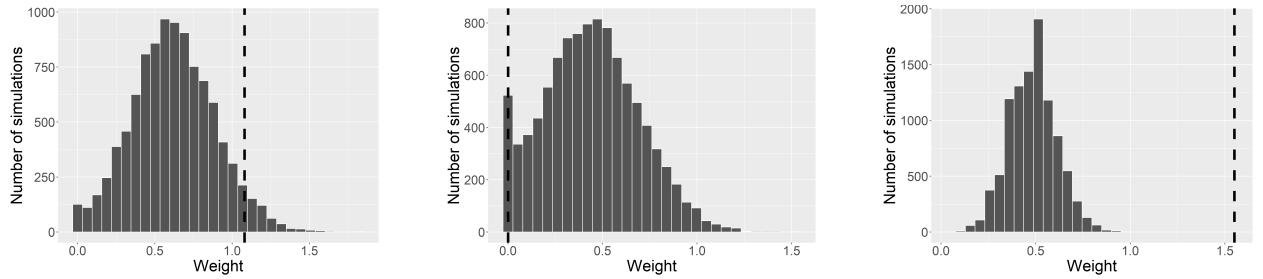
Figure 4.21: Distribution of simulation weights for CAGREEBACK (left), CA-GREEFRONT (center), and *FRONTSUFFIX (right). Dashed lines indicate weight fit to actual wug test data. The skewed distribution of CAGREEFRONT is a consequence of the requirement that constraint weights be positive.

	Corpus raw	Wug raw	Ratio	Monte Carlo Test	$\hat{p}$
VAGREEBACK-1	4.52	0.95	4.76	Underlearned	0
VAGREEBACK-2	3.12	0.35	8.91	Underlearned	0
VAGREEBACK-3	3.15	0.05	62.99	Underlearned	0
VAGREEFRONT-1	7.35	4.14	1.78	Overlearned	> 0.95
VAGREEFRONT-2	5.64	3.17	1.78	Overlearned	> 0.95
VAGREEFRONT-3	5.38	1.31	4.11	**Underlearned**	0
CAGREEBACK	1.34	1.08	1.24	**Overlearned**	> 0.95
CAGREEFRONT	0.94	0	n/a	**Non-significantly underlearned**	0.052
*FRONTSUFFIX	1.06	1.55	0.68	Overlearned	0

Table 4.12: Results of the Monte Carlo simulations. Effects that are not predicted by the overlearning of *FRONTSUFFIX are bolded.

With this in mind, there are three surprising results in Table 4.12: the weights of VAGREEFRONT-3 and CAGREEFRONT[10] are underlearned, going against the trend for FRONT constraints, and the weight for CAGREEBACK is overlearned, going against the trend for BACK constraints. Appendix I shows the results of an identical Monte Carlo simulation with the *FRONTSUFFIX constraint removed, which corroborates that these are the three constraints that are significantly different than what is predicted by the Monte Carlo simulation.

4.6 Accounting for discrepancies between corpora and wug tests

To summarize, patterns displayed by Uyghur speakers in wug tests differ from corpus patterns in three substantial ways: wug tests reveal distance-based decay in front roots, increased influence of conflicting uvulars (that is, an increased tendency for FQ roots to take back suffixes), and decreased influence of conflicting velars (that is, a decreased tendency for BK roots to take front suffixes). The apparent lack of distance-based decay in back roots is a consequence of an overall bias towards

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[10]This constraint is near-significantly underlearned ($p = 0.052$), but this method of significance testing is complicated to some degree because the constraint weight has a lower bound of 0.

back suffix forms: increased spans of transparent vowels between a back vowel and a suffix *do* decrease the vowel's influence on suffix choice (as evidenced by the VAGREEBACK weights shown in Table 4.12), but this waning influence is compensated for by the tendency to use back suffix forms as a default.

I will argue that these discrepancies can be explained by biases related to the phonetic properties of the segments that participate in backness harmony. The influence of these phonetic properties on the corpus data is obscured to some extent because of the eventual learning of harmony diacritics that specify the backness of lexical items.

4.6.1 The role of uvulars as a back trigger

The corpus results show a fallback pattern in the relationship between harmonizing vowels and dorsals: for the most part the final harmonizing vowel determines the backness of the root. Only if a root has no harmonizing elements are harmonizing dorsals considered.

This pattern holds in broad strokes in the wug test results, but an asymmetry emerges between the front dorsals /k g/ and the back dorsals /q ʁ/: a back dorsal following a front vowel skews participants to use back suffixes, while a back vowel followed by a front dorsal does not show this tendency. This is most striking in monosyllabic words with a front vowel followed by a back dorsal: in the corpus, such words *never* take back suffixes (e.g., /mæʃq/ 'exercise') while in the wug tests they take back suffixes about 1/4 of the time (e.g., /pæq/).

The asymmetry between velars and uvulars can be accounted for by considering their coarticulatory properties. Velars, while generally resistant to coarticulation on the high-low dimension, are susceptible to coarticulation on the front-back dimension: that is, velars tend to be produced backer in the presence of back vowels and fronter in the presence of front vowels (e.g., Keating & Lahiri, 1993; Recasens & Espinosa, 2009; Iskarous, McDonough, & Whalen, 2012). This leads to allophonic alternations between fronted and non-fronted /k/ in English pairs like [ki] 'key' vs. [kɔf] 'cough' respectively (e.g. Frisch & Wodzinski, 2016). Thus from a coarticulatory perspective, velars like /k g/ will tend to accommodate to the backness of surrounding vowels.

Uvulars, on the other hand, induce coarticulation on neighboring sounds. Phonetic studies of

uvulars in several languages suggest that they exert both a backing and lowering effect on nearby vowels (e.g., Alwan, 1986; Bessell, 1992; Sylak-Glassman, 2014; Gallagher, 2016; Evans, Sun, Chiu, & Liou, 2016).

Thus the asymmetry in the strength of velars and uvulars as triggers of backness harmony may be related to the asymmetry in their coarticulatory behavior on the dimension of backness: velars tend to accommodate to the backness of adjacent vowels while uvulars tend to impose their own backness on neighboring vowels. The next section describes a phonetic study that demonstrates that this asymmetry can be observed in acoustic measurements of coarticulation in Uyghur.

4.6.2 Acoustic evidence of velar-uvular asymmetries

The same set of 23 speakers who participated in the wug test study were also asked to produce a number of attested roots, shown in Table 4.13. The neutral roots are those used in the acoustic study presented in Chapter 5. Each root was produced once by each speaker in the carrier phrase below:

(72) *Mahinur _____ deydu*

"Mahinur will say _____"

Statistical analysis was performed in R (R Core Team, 2017) using the `lme4` library (Bates, Mächler, Bolker, & Walker, 2015). A linear mixed-effects model was fit to the data with F2 as the dependent variable. The independent variables were the harmonic class of the preceding consonant (back (Q), front (K), or neutral (N)); speaker gender; and the place of articulation of the consonant following the final vowel. Places of articulation assigned to each following consonant are shown in Table 4.14. A value of 'n/a' was used in these fields if vowels occurred word-initially or word-finally respectively. Random intercepts were used for each root and speaker. Because of these intercepts, speaker data was not normalized.

Additional independent variables such as place of articulation of the preceding consonant, and manner of articulation or voicing of consonants flanking the final vowel were tested, but did not improve model fit as determined by the Bayesian Information Criterion (Schwarz, 1978).

Root Type	Word	Definition	Word	Definition
Neutral	/bir/	'one'	/mis/	'copper'
	/biz/	'we'	/pil/	'elephant'
	/tʃiʃ/	'tooth'	/pir/	'master'
	/dil/	'soul'	/rim/	'Rome'
	/din/	'religion'	/sinip/	'classroom'
	/filim/	'film'	/sirt/	'outside'
	/itʃ/	'inside'	/sijir/	'milk-cow'
	/ili/	'Ili (place name)'	/siz/	'you (formal)'
	/ilim/	'knowledge'	/til/	'tongue'
	/iʃ/	'matter'	/tilsim/	'magic'
	/it/	'dog'	/tip/	'type'
	/dʒin/	'jinn'	/tiz/	'knee'
	/lim/	'joist'	/jil/	'year'
	/miŋ/	'thousand'	/zil/	'bell'
Velar	/kim/	'who'	/kit/	'whale'
	/kir/	'who'		
Uvular	/qil/	'(animal) hair'	/qiz/	'girl'
	/qiʃ/	'winter'		

Table 4.13: Roots used in the study.

Place	Consonants
Labial	p, b, m
Coronal	t, d, s, z, n, r
Palatal	ʧ, ʤ, j
Velar	ŋ
Lateral	l

Table 4.14: Place of articulation assigned to consonants in the statistical models.

The relationship between the F2 of the final root vowel and the proportion of back responses is shown in Fig. 5.1. There was a significant effect of participant gender on F2, with male speakers having lower F2 values than female speakers ($\beta = -315.81, SE = 68.98, t = -4.579, p < 0.001$).

The harmonic class of the consonant preceding the vowel also had a significant effect on F2: vowels with preceding uvulars had significantly lower F2 values than roots with preceding neutral consonants or velars. Velar consonants showed an increased F2 compared to neutral consonants, but this effect was not significant. These results are shown in Table 4.15 and Fig. 4.22.

	Estimate	Std. Error	t	p
Intercept	1900.81	70.41	27.00	< 0.001
Velar	260.27	137.48	1.89	0.07
Uvular	–426.35	141.22	–3.02	< 0.01

Table 4.15: Fixed effects for harmonic class of the preceding consonant. The reference level is neutral consonants.

The following consonant place of articulation had significant effects on F2 that are qualitatively identical to those presented in Chapter 5: tokens of /i/ with a following velar or lateral consonant had lower F2 than those with a following coronal or labial consonant, which in turn had lower F2 than those with a following palatal or no following consonant. I leave a more detailed presentation of these results for that chapter.

None of the other acoustic variables (f0, F1, F3, F4, and duration) tested under similar models were significantly predicted by the harmonizing value of the preceding consonant.

These results confirm that uvulars in Uyghur do indeed induce a backing effect on adjacent vowels. While velars induce a smaller fronting effect, this was not significant when compared to the effect of neutral consonants.
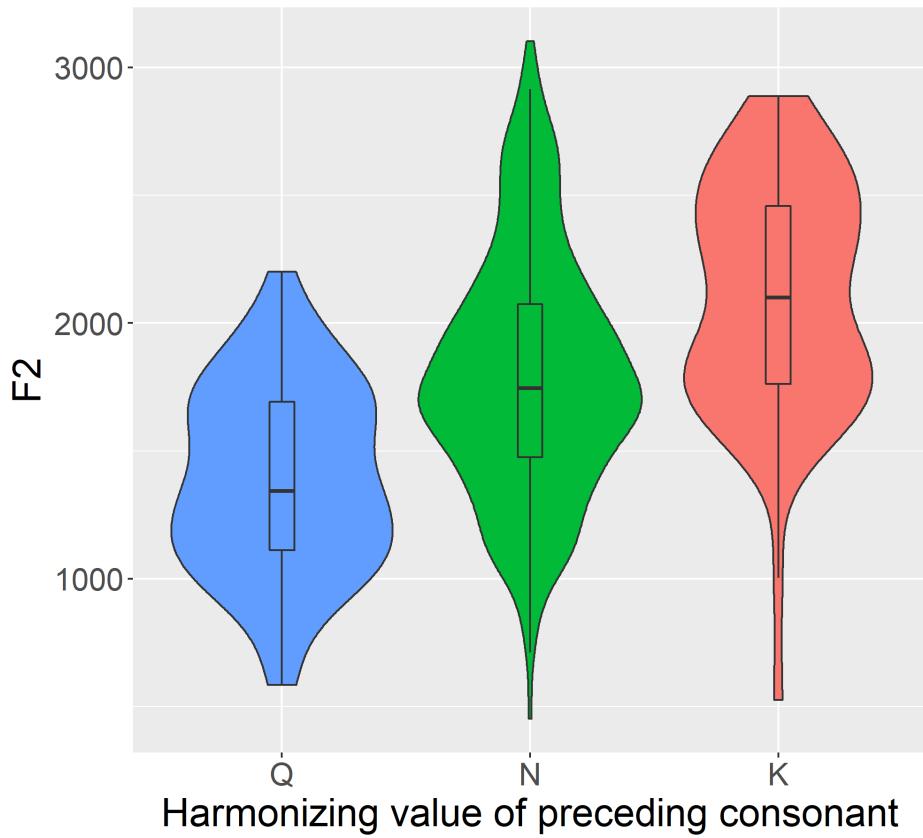
Figure 4.22: The relationship between the harmony class of the preceding consonant and vowel F2. Boxes indicate the median value and upper and lower quartiles.

4.6.3 Distance-based decay

The second discrepancy between corpus and wug patterns is the presence of distance-based decay in the wug responses. Distance-based decay is commonly observed in long-distance assimilatory and dissimilatory processes (Hayes & Londe, 2006; Hayes et al., 2009; Kimper, 2011; Zymet, 2014). The mechanisms underlying long-distance phonological processes have been suggested to be articulatory (e.g., Hansson, 2001; Walker et al., 2008), perceptual (e.g., Kaun, 2004; Gallagher, 2010), or memory-based (e.g., Gafos, 2021), and therefore we can assume the existence of distance-based decay stems from certain properties of these mechanisms. Regardless of the exact cause, the generalization is that the influence of segments participating in such processes become weaker as they become more distal from one another. Uyghur speakers display a sensitivity to distance between trigger and target on wug tests, despite this pattern not being reflected in the

corpus data. This suggests it may be a general bias in the learning of long-distance phonological processes.

4.7 Biased learning from the corpus

A natural question that emerges from the discrepancy between the corpus and wug data is how speakers come to learn patterns that are not clearly present in the corpus. In this section I will show that when certain phonetically-motivated *biases* are applied to the learning process, a model trained on the corpus data will produce similar behavior to that demonstrated in the wug tests.

4.7.1 Biases and learning in MaxEnt OT

Learning the constraint weights that best fit a data set is done by finding the weights that maximize the log likelihood of the observed data. The function to be maximized is shown in (73), where n is the number of tokens, x_i is the underlying form of the ith token, and y_i is the observed candidate of the ith token.

(73)
$$\hat{LL} = \sum_{i=1}^{n} \log P(y_i|x_i)$$

Learning optimal constraint weights can be done using standard optimization procedures (see Hayes & Wilson, 2008, for a more detailed description of the learning procedure).

A *bias term* or *regularization term* can be added to this optimization function to prevent over-fitting and to bias learned weights in particular directions. The most common type of bias is a *Gaussian prior* over weights (Goldwater & Johnson, 2003), shown in (74), where m is the number of weights, w_i is the ith weight.

(74)
$$\sum_{j=1}^{m} \frac{(w_i - \mu_i)^2}{2\sigma_i^2}$$

This constraint stipulates that our hypothesis for the weight of the ith constraint before seeing any data is normally distributed with a mean of μ_i and a standard deviation of σ. In other words,

μ_i tells us the expected value for the weight, and σ how much the weight is expected to vary from this target. As the distance between w_i and μ_i increases, the value of this term also increases.

Combining the bias term with the basic optimization function gives us the biased optimization function $\hat{LL}'$ shown in (75).

(75)

$$\hat{LL}' = \sum_{i=1}^{n} \log P(y_i|x_i) - \sum_{j=1}^{m} \frac{(w_i - \mu_i)^2}{2\sigma_i^2}$$

Note that this is just the log of the likelihood of the data under the weights (the first term) multiplied by the priors on the weights (the second term).

Optimizing this function entails maximizing the first term (the log likelihood of the observed data) while minimizing the second term (the deviation of each weight from its specified mean). If the mean for all weights is set to 0, this has the effect of preventing overfitting by discouraging large constraint weights. The choice of σ for each weight is sensitive to the number of data points: as the number of observed tokens increases, σ must decrease in order for the effect of the bias to remain constant.[11]

Goldwater and Johnson (2003) propose that, in addition to preventing overfitting, constraint biases of this sort might be used to instantiate learning biases in MaxEnt models, though they do not explicitly adopt it. This approach has been taken in several papers to model learning biases observed in artificial grammar learning experiments (e.g., Wilson, 2006; White, 2013).

4.7.2 Biases enforcing stringency relationships

A bias towards a specific constraint weight is sufficient to capture the discrepancies in velar behavior between the corpus and wug data, by specifying a bias towards a higher weight for CA-GREEBACK. It is more difficult to see how to apply it to capture distance-based decay, where we are interested not so much in the specific weights of the relevant constraints, but rather their relationship to one another: we would like the constraints mandating harmony over shorter distances to have higher weights than those over longer distances.

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[11]Specifically, $n\sigma^2$ must be held constant, where n is the number of tokens (Goldwater & Johnson, 2003).

I propose that a bias towards this kind of relationship can be imposed by considering bias terms over the *ratio* between pairs of constraint weights, rather than the weights themselves.[12] The definition of a bias term for a particular pair of weights is shown in (76).

(76)

$$\frac{(\frac{w_i}{w_j} - \mu_{ij})^2}{2\sigma_i^2}$$

As in the previous section, this is a Gaussian bias: it specifies that the learner expects the ratio of weights between two constraints w_i and w_j to be distributed normally with a mean of μ_{ij} and a standard deviation of σ_{ij}. Setting appropriate biases for the ratios between the VAGREE constraints will predispose the learner towards distance-based decay.[13]

A benefit to employing a bias like this is that it solves a well-known issue with distance-specific constraints like those used here. If the weights of distance-specific constraints are unrestricted, this allows certain typologically abhorrent[14] patterns like *anti-harmony*, where the tendency for two segments to harmonize *increases* over longer distances. Preventing such patterns from occurring is part of the motivation behind using specific decay functions to calculate constraint violations (Kimper, 2011; Zymet, 2014). An alternative solution is to put these sets of constraints into a *stringency relationship* (Prince, 1998; de Lacy, 2002), where, in this case, more proximal harmony constraints must be weighted higher than less proximal ones.[15] Bias terms mandating certain ratios between pairs of constraints have the effect of biasing the learner towards such a relationship.

4.7.3 A biased Uyghur learner

The specific biases I employ in the learner are shown in Table 4.16. All bias terms had $\sigma = 0.05$, which was chosen based on trial and error.

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[12]These biases can be implemented as differences between pairs of weights rather than ratios, but ratios are more interpretable given our knowledge of decay rates.

[13]Note that this term is not technically a prior, but should be considered a type of L2-regularization.

[14]The Latin verb *abhorrēre* can be used to mean 'to be out of harmony with', making this word particularly appropriate here.

[15]Requiring that more proximal harmony constraints also violate less proximal ones, but not vice versa, can also produce equivalent behavior given appropriate weights.

Constraint	μ
VAGREEBACK-1	0
VAGREEBACK-2	0
VAGREEBACK-3	0
VAGREEFRONT-1	0
VAGREEFRONT-2	0
VAGREEFRONT-3	0
CAGREEBACK	5
CAGREEFRONT	0
*FRONTSUFFIX	0
VAGREE-1/VAGREE-2	2.14
VAGREE-2/VAGREE-3	1.56

Table 4.16: Bias parameters used for individual constraint weights and for ratios between pairs of weights. The weight ratio biases for VAGREEBACK and VA-GREEFRONT constraints were identical.

Every constraint except CAGREEBACK had a bias term with $\mu = 0$. The value of $\mu = 5$ for CAGREEBACK was chosen to be relatively, but not outrageously, high.

The biases for the weight ratios were chosen based on the decay function presented in Zymet (2014). This function is shown in (77). x is the distance in syllables between trigger and target,[16] and k is a parameter that controls the rate of decay.

(77)

$$d(x) = \frac{1}{x^k}$$

Zymet uses this equation to calculate the violation count, which is subsequently multiplied by the corresponding constraint weight. He also suggests, based on data from a number of languages, a universal decay parameter value of $k = 1.1$, with language-specific differences in decay emerging

[16]x will never be < 1, because a trigger and target in adjacent syllables are considered to be one syllable apart.

as a function of varying constraint weights. Assuming this value of k, the violation count at a distance of one syllable is 1, at two is 0.47, and three is 0.3.

These violation counts have the effect of scaling down the constraint weight as distance increases. The values of μ for the biases on weight ratios were chosen based on the scaling factors that emerge under $k = 1.1$. Under this value of k, $\mu_{12} = \frac{d(1)}{d(2)} = \frac{1}{0.47} = 2.14$ and $\mu_{23} = \frac{d(1)}{d(2)} = \frac{0.47}{0.3} = 1.56$.

4.7.4   Biased learner results

Table 4.17 shows the results of three models: the basic model trained on the corpus data and tested on the wug data, the biased model trained on the model and tested on the wug data, and the optimal model trained and tested on the wug data. The basic model included standard regularization terms for each constraint to prevent overfitting the corpus data, but did not include the regularization terms for the ratios between VAGREE constraints, nor the bias towards a higher weight of CAGREEBACK. As with the Monte Carlo simulations, a temperature parameter was used when calculating wug probabilities under the basic and biased grammars.

The model fit directly to the wug test data did not include regularization terms or a temperature parameter: its purpose is to serve as a high-water mark indicating the best possible fit to the wug data given these constraints.

Unsurprisingly, the biased model does not fit the wug data as well as the optimal model trained on the wug data. However, it fits it substantially better than the unbiased corpus model. Plots of observed vs. expected frequencies are shown in Fig. 4.23.

Note that the root the biased model has the most difficulty predicting is FNN. This is due to the fact that the rate of distance-based decay exhibited in the wug responses differs from that proposed by Zymet (2014). The model correctly predicts that distance-based decay should occur, but underestimates the degree of decay between violations across 2 and 3 syllables. This point is returned to in Chapter 7.

	Corpus Fit – Basic	Corpus Fit – Biased	Wug Fit
VAGREEBACK-1	3.89	3.91	0.95
VAGREEBACK-2	2.15	2.07	0.35
VAGREEBACK-3	1.05	1.19	0.05
VAGREEFRONT-1	5.35	5.74	4.14
VAGREEFRONT-2	3.72	3.69	3.17
VAGREEFRONT-3	1.96	2.04	1.31
CAGREEBACK	0	2.40	1.08
CAGREEFRONT	0	0	0
*FRONTSUFFIX	1.00	1.00	1.55
Corpus *LL*	–130,126	–134,930	n/a
Corpus *r*	0.97	0.93	n/a
Wug *LL*	–691	–655	–610
Wug *r*	0.88	0.94	0.99

Table 4.17: Results from the three models.
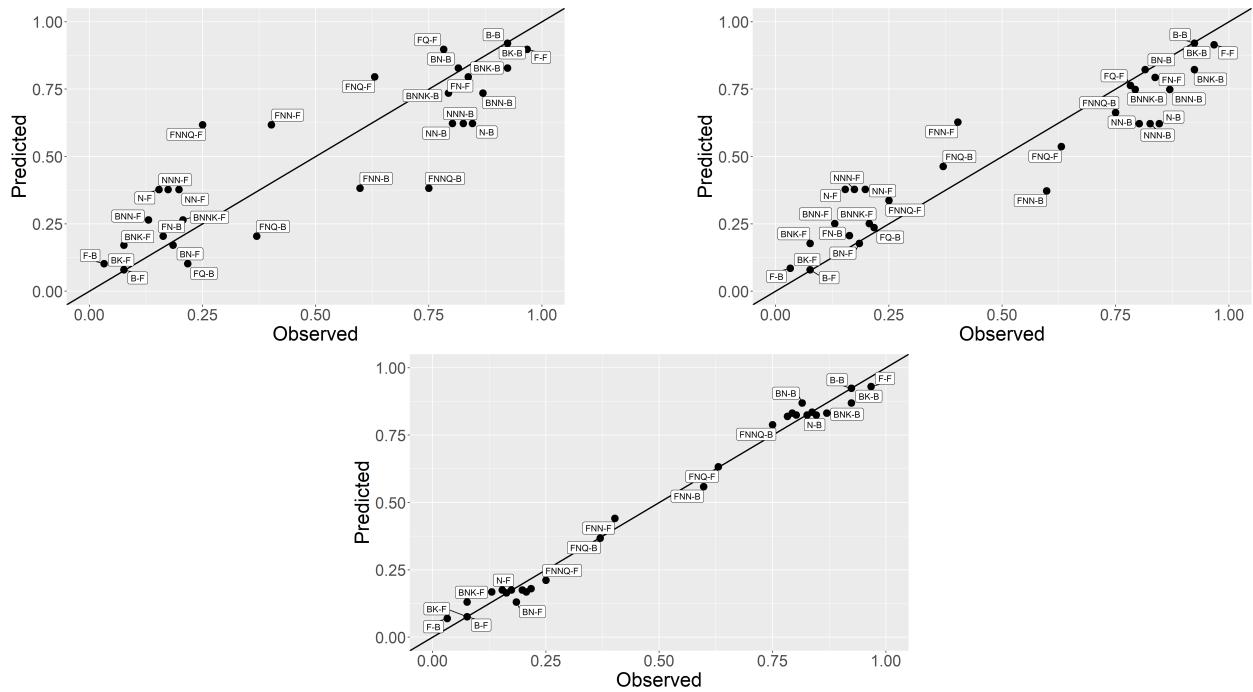
Figure 4.23: Plots of observed response frequencies against predicted response frequencies for the basic model (top left), the biased model (top right), and the optimal model (bottom). Diagonal lines represent a model whose predicts perfectly match observed frequencies. Points that deviate more from these lines are less accurately predicted by the model.

4.8 A phonetically-based model of backness harmony

The previous section demonstrated that appropriately defined phonetically-based biases can be used to generalize from corpus data to wug data in a way that is consistent with speakers' behavior. A question that is left unresolved, however, is whether backness harmony in Uyghur should be analyzed as spreading or correspondence. The analysis presented so far using AGREE constraints aligns most closely with a correspondence analysis, but this is atypical of backness harmony systems cross-linguistically.

This section takes a different approach to this problem by proposing a simple, local model of backness harmony that instantiates these biases as fixed parameters of the model based on the phonetic properties of participating segments, rather than biases that guide parameter learning.

This model shows the same ability to effectively generalize from the corpus data to the wug data, and avoids the typologically unusual claim discussed in 4.2.10 by representing backness harmony in Uyghur as a type of gradient, local spreading.

This model hinges around a constraint *ΔBACK which penalizes suffixing behavior on the basis of articulatory difficulty based on the position of the tongue at the end of the root and the goal position of the suffix. This degree of difficulty is quantified on the basis of a gradient [back] feature.[17]

4.8.1   Calculating gradient backness

Rather than categorical [back] feature that can only take on +, –, or 0 values, a gradient [back] feature may take on real values in the range $[-1, 1]$, where 1 is maximally back and -1 is maximally front. The claim that there is a gradient [back] feature at work in Uyghur backness harmony as also been made by McCollum (2019), though on the basis of phonetic data rather than response frequencies. I consider this gradience to be phonological and therefore abstract, in the sense that it stochastically drives a categorical alternation in suffix backness. However, this abstract value may be considered as reflecting articulatory (e.g., tongue backness) or acoustic/perceptual (e.g., F2 values) properties.

I employ the following model for calculating the backness value of a root to which suffixes are sensitive. Each class of segments relevant to the harmony system has an underlying [back] value, as well as a *blending value* between 0 and 1. These are shown in Table 4.18. The concept of a blending value comes from Articulatory Phonology (Browman & Goldstein, 1992; Smith, 2018), and represents the degree to which that segment resists coarticulation. In this case, these values refer to coarticulation along the front–back dimension: higher values indicate greater resistance to coarticulation, and hence a higher degree of imposition of that segment's own [back] value.

[back] values were chosen a priori to be consistent with the details of the analysis so far. Blending values were chosen to characterize the phonetic properties of the sounds in question. It will

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[17]Note that this model is intended to capture pressures that determine the quality of the first suffix attached to a root. Once the backness of the first suffix is chosen, subsequent harmonizing suffixes invariably keep the same backness only to the backness of *roots*. See the discussion at the end of Chapter 3 for more detail.

Segment	[back] value	Blending value
Front vowel (F)	−1	1
Back vowel (B)	1	1
Neutral vowel (N)	0	0.5
Neutral consonant (C)	0	0
Front dorsal (K)	−1	0.1
Back dorsal (Q)	1	0.2
Front suffixes (S_f)	−1	n/a
Back suffixes (S_b)	1	n/a

Table 4.18: Backness and blending values for the segmental classes involved in backness harmony.

be an important area for future research to investigate these parameters on the basis of specific phonetic measurements.

Let *backness*(r) refer to the overall backness of a root r, and *back_val*(s) and *blend*(s) refer to the [back] and blending values of a segment s. The backness of a root $r = s_1 \ldots s_n$ is calculated recursively as shown in 78:

(78)

$$backness(s_1) = back\_val(s_n)$$

$$backness(s_1 \ldots s_n) = (1 - blend(s_n)) \cdot backness(s_1 \ldots s_{n-1}) + blend(s_n) \cdot back\_val(s_n))$$

The backness of a root is calculated by considering each of its segments from left to right (the direction of backness harmony in Uyghur) and, for each segment, updating the root backness using a weighted combination of the backness of the root so far and the backness of the current segment. The blending value associated with each segment determines how these values are combined. Broadly speaking, this calculation is an instantiation of the *recursive neural network abstraction* (Goldberg, 2017): a backness 'state' is passed forward through the root and updated according to the backness and blending value of each subsequent segment.[18] Fig. 4.24 shows this

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[18]This is also similar to the *fold* operation used in functional programming languages.

schematically.
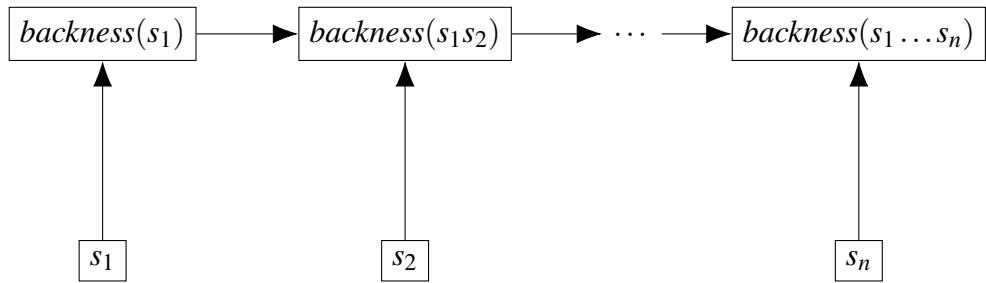
Figure 4.24: A schematic representation of the calculation of backness for a root $s_1 \ldots s_n$.

Consider a root of the form CFCNQ (e.g., /tæstiq/ 'sanction'), and assume the backness values shown in the table above. The backness of this root is -0.2, and is calculated as follows, where '|' indicates the current position of the *backness* function:

1. C|FCNQ: $backness(C) = 0$

2. CF|CNQ: $(1 - blend(F)) \cdot backness(C) + blend(F) \cdot back\_val(F) = 0 \cdot 0 + 1 \cdot -1 = -1$

3. CFC|NQ: $(1 - blend(C)) \cdot backness(CF) + blend(C) \cdot back\_val(C) = 0.9 \cdot -1 + 0 \cdot 0 = -1$

4. CFCN|Q: $(1 - blend(N)) \cdot backness(CFC) + blend(N) \cdot back\_val(N) = 0.5 \cdot -1 + 0.5 \cdot 0 = -0.5$

5. CFCNQ|: $(1 - blend(Q)) \cdot backness(CFCN) + blend(Q) \cdot back\_val(Q) = 0.8 \cdot -0.5 + 0.2 \cdot 1 = -0.2$

Here we can see that the neutral vowels attenuate the backness of preceding items without imposing their own backness values, while the uvulars attenuate the preceding backness to a lesser degree than neutral vowels, but simultaneously impose their own backness.

One may interpret the gradient [back] value as roughly corresponding to the position of the tongue in the mouth along a front-back continuum at any point in the word. The overall backness of a root reflects the tongue position root-finally. The following section defines a constraint *ΔBACK, which penalizes suffixed forms proportionally to the deviation between the [back] value of the root and that of the suffix.

4.8.2 *ΔBACK

In this section I will propose a constraint *ΔBACK which penalizes suffixes that differ in backness from the root they attach to. The backness of a root is calculated as a function of the segments in the root and the order in which they occur. The penalty has its basis in articulatory ease: greater differences in backness between root and suffix equate to greater tongue movement on the horizontal dimension. Articulatory ease has been proposed as a driving force behind the structure of phonological inventories and patterns (e.g., Lindblom & Maddieson, 1988; Lindblom, 1990; Kirchner, 1998; Kohler, 2001; Kirchner, 2004; Shariatmadari, 2006).

*ΔBACK is defined as follows:

(79)   *ΔBACK: For a root r and suffix S, the violation count of this constraint is $|backness(w) - back\_val(S)|$ where $back\_val(S_f) = -1$ and $back\_val(S_b) = 1$.

The violation count of *ΔBACK is calculated as the absolute value of the difference between the backness of the root and the backness of the suffix. This value will range from 0 (perfectly harmonious) to 2 (maximally disharmonic).[19]

The suffixed form CFCNQ-S_b will accrue a violation of 1.2, since $backness(CFCNQ) = -0.2$ and $back\_val(S_b) = 1$.

4.8.3 Model results

A simple model with two constraints was trained on the corpus data. These constraints were *ΔBACK and *FRONTSUFFIX. The [back] and blending values were identical to the previous section. The trained model was then applied to the wug data. The results are shown in Table 4.19, alongside the previous models, and the plot of observed vs. expected frequencies is shown in Fig. 4.25.

Both the biased and phonetic models produce improved fits to the wug data compared to the

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[19]When defining functions that penalize forms due to differences between desired and actual configurations, previous work has squared the differences rather than taking the absolute value (e.g., Flemming, 2001; Braver, 2019; McCollum, 2021) . This makes little difference in practice here, so I use the absolute value.

	Corpus Fit – Basic	Corpus Fit – Biased	Wug Fit	Corpus Fit – Phonetic
VAGREEBACK-1	3.89	3.91	0.95	n/a
VAGREEBACK-2	2.15	2.07	0.35	n/a
VAGREEBACK-3	1.05	1.19	0.05	n/a
VAGREEFRONT-1	5.35	5.74	4.14	n/a
VAGREEFRONT-2	3.72	3.69	3.17	n/a
VAGREEFRONT-3	1.96	2.04	1.31	n/a
CAGREEBACK	0	2.40	1.08	n/a
CAGREEFRONT	0	0	0	n/a
*FRONTSUFFIX	1.00	1.00	1.55	3.27
*ΔBACK	n/a	n/a	n/a	0.90
Corpus LL	–130,126	–134,930	n/a	–119,688
Corpus r	0.97	0.93	n/a	0.97
Wug LL	–691	–655	–610	–663
Wug r	0.88	0.94	0.99	0.93

Table 4.19: Results from the four models. Note that the substantially higher log likelihood of the phonetic model evaluated against the corpus data is due to the smaller number of regularization terms because of the smaller number of parameters.

basic model. Although the biased model fits the wug data slightly better than the phonetic model, this difference is fairly small. The most significant difference between predicted and observed frequencies for the phonetic model is, as with the biased model, for roots of the form FNN. The biased model also includes general parameters that bias constraint weights towards 0, which results in less extreme probabilities and matches wug test responses more closely.

Thus while both the biased and phonetic models constitute significant improvements over the basic model when applied to the wug test data, the difference between the two is relatively small. This may be considered a point in favor of the phonetic model: while both generalize from the corpus data to the wug data well, the phonetic model does so in a way that is consistent with a local spreading interpretation of Uyghur backness harmony using a gradient [back] feature, and
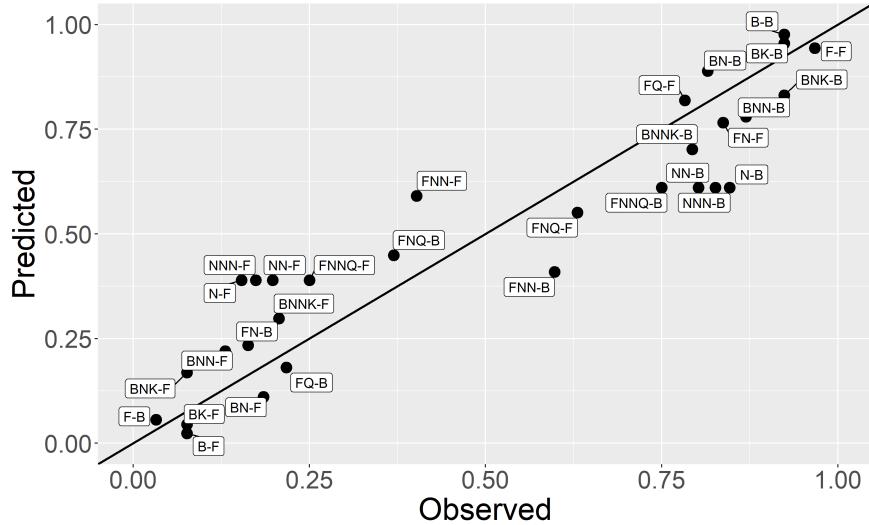
Figure 4.25: Plots of observed response frequencies against predicted response frequencies for the phonetic model. Diagonal lines represent a model whose predicts perfectly match observed frequencies. Points that deviate more from these lines are less accurately predicted by the model

using fewer free parameters. Distance-based decay emerges due to attenuation of the backness of preceding triggers by intervening material, but is masked in B and BK roots by a overarching preference for back suffixes. The tendency of uvulars to disproportionally skew responses towards back suffixes when compared to velars is captured by the difference in their respective blending strength.

4.9 Discussion

This chapter has substantiated standard descriptions of the patterns of Uyghur backness harmony based on corpus data, focusing specifically on properties of roots that govern suffix backness. Next, we looked at the results of a wug test study that showed that the patterns demonstrated by Uyghur speakers differ from the corpus in several ways: in particular, they show evidence of distance-based decay and increased influence on suffix choice from uvular sounds. The remainder of the chapter demonstrates how particular models and learning strategies can train on the corpus data and generalize to wug data in a way that's consistent with speakers' generalizations: the first

model using biases towards particular constraint weights or ratios between constraint weights, and the second by using a model based on the phonetic properties of sounds that participate in the harmony process.

The remainder of the chapter will discuss how Uyghur's harmony system came to display its distinct properties, what these results imply for previous analyses of Uyghur backness harmony, and what they imply for phonological learning in general.

4.9.1 Diachronic origins of Uyghur backness harmony

Scholars generally agree that Old Turkic and Chagatay (the direct ancestor of Uyghur and Uzbek) had a phonemic contrast between /i/ and /ɯ/ in initial syllables (Lindblad, 1990; R. F. Hahn, 1991a, 1991b; Bodrogligeti, 2001; Erdal, 2004).[20] At some point in its history, Uyghur lost the distinction between /i/ and /ɯ/ (R. F. Hahn, 1991a), which complicated the harmony system. Lindblad (1990) shows that the most frequent roots that previously had /i/ continued to take front suffixes (e.g., [biz] 'we', [ilim] 'knowledge', [itʃ-] 'drink'), the roots that previously had /ɯ/ continued to take back suffixes, and many less frequent roots that were underlyingly /i/ began to take the default back form of suffixes. Uyghur appears to be typologically unique in that the default harmony value is [+back], despite the transparent vowels being phonetically [–back]. In languages such as Mongolian and Finnish, which have similar transparent vowels, transparent roots generally behave as [–back] (Lindblad, 1990).[21]

This history explains to some extent the generally categorical nature of harmony in attested words: in earlier stages of the language when there was a clearer phonemic contrast between /i/ and /ɯ/, the choice of suffix was categorically determined by the final vowel in the root in all instances, and thus distance-based decay was not a meaningful factor.[22]

The apparent participation of dorsal segments in the harmony process may also have emerged

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[20]Though see e.g., Johanson (1998) for a critical perspective.

[21]Though some might argue whether the characterization of the transparent vowels as phonetically [–back] in Uyghur is justified: in practice they range from central to front. See Chapter 2.

[22]Though note that neutral roots exhibited within-root variation in harmonizing behavior in Old Turkic (Erdal, 2004).

from the loss of the /i/-/ɯ/ contrast: the correlation of velars with front suffixes and uvulars with back suffixes was due to co-occurrence restrictions (or root-internal harmony) that generally required front dorsals in the presence of front vowels and back dorsals in the presence of back vowels, except in certain loanwords. Thus dorsals were never actually triggers of harmony, but simply undergoers. When the phonemic contrast between /i/-/ɯ/ was lost, the dorsals took on the role of harmony triggers in roots without other harmonizing elements.[23]

4.9.2 Implications for previous analyses of Uyghur backness harmony

There have been several previous phonological analyses proposed for Uyghur backness harmony that suggest that speakers' grammars basically mirror these historical changes. The rule-based analyses of Lindblad (1990) and R. F. Hahn (1991b) account for the transparency of /i/ and /e/ by suggesting that there are covert contrasts underlyingly and at intermediate stages in derivations that are neutralized post-lexically. These contrasts account for both apparent long-distance harmony across transparent vowels, and the behavior of roots with no harmonizing elements. More recent work like Pattillo (2013) essentially maintain this approach.

According to these analyses, Uyghur has two additional vowel phonemes to those shown in Table 4.1: /ɯ/ and /ɤ/, the back counterparts of /i/ and /e/ respectively. These phonemes are found in roots: for example, the word [universitet] "university", which takes back suffixes, is claimed to underlyingly be /unɯvɤrsɯtɤt/. In addition, this analysis suggests that the apparent tendency of the dorsals /k g q ʁ/ to participate in vowel harmony is in fact an illusion: the determiner of the quality of the suffix is strictly the vowels in the root. The fact that velar and uvular consonants in roots with only transparent vowels seem to correlate with front and back suffix choice, respectively, is the product of a co-occurrence restriction on vowels and dorsals with different backness values:

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[23]It is worth noting that many Turkologists locate [back] at the level of the syllable rather than the segment, with harmonizing segments signaling the backness of their host syllable (e.g., Johanson, 1991; Éva Ágnes Csató, 2000). This makes it difficult to designate a specific segment as a trigger for harmony. A syllable-oriented approach to harmony must still grapple with questions raised in this chapter: what happens when a syllable contains conflicting signals as to harmony, such as /rɑk/ 'cancer' or /hæq/ 'payment'? Why do roots with harmonically disparate syllables like /ʃæjtɑn/ 'devil' (front syllable followed by back syllable) reliably take suffixes that harmonize with their final syllable, while others like /mæntiq/ (also front syllable followed by back syllable) reliably take suffixes with harmonize with the initial syllable?

i.e., forms like [kiʃi] "person" and [qiz] "girl" are underlyingly /kiʃi/ and /quɯz/. This restriction is violable in loanwords.

The vowels in most suffixes containing transparent vowels, such as [-imiz] "1Pl.POS", are claimed to be underlyingly unspecified for backness: i.e., /-ImIz/. Vowels that are unspecified for backness receive their backness values via an iterative spreading rule from the vowels in the root (which are always specified). Finally, a post-lexical rule converts /ɯ/ and /ɤ/ to their front counterparts /i/ and /e/. An example derivation of the form [jolimizda] "on our road" is shown in Table 4.20 (Lindblad, 1990).[24]

UR	jol-ImIz-dA	–
1	jol-ɯmIz-dA	backness spreading
2	jol-ɯmɯz-dA	"
3	jol-ɯmɯz-da	"
SR	jolimizda	fronting

Table 4.20: Derivation of [jolimizda] "on our road" according to Lindblad's analysis of Uyghur backness harmony. Voicing assimilation in the suffix /-DA/ is not illustrated.

Lindblad puts forth two motivations for assuming this covert contrast: the first is that it allows harmony to be treated as a local process across the vowel tier. The second is that it explains forms where the dorsal appears to take precedence over the harmonizing vowel in the root. Because the vowels are fully specified in roots, these apparently problematic forms can be dealt with by assuming underlying representations that produce the correct output, such as /æquɯl-lIK/ → [æqil-liq].[25]

The results in this chapter call this account into question in several ways. First, it appears that speakers are inclined to treat uvular sounds as active harmony triggers. The evidence for this comes from the fact that the presence of a uvular following a front vowel skews responses towards back,

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[24]R. F. Hahn (1991b) claims that the first vowel in *-imiz* undergoes rounding harmony as well, but Lindblad doesn't indicate this here.

[25]/æqil/ is an interesting root because in most other Turkic languages the cognate word is something like /ɑquɯl/, with a back vowel. McCollum (p.c.) speculates that this may be a case of lexicalized umlaut (see Appendix D) whose output is /æ/ rather than /e/.

even where there is no doubt to the underlying harmony of the vowels in the root. For example, the increased proportion of back responses in forms like CFCNQ or CFCNCNQ could be accounted for by suggesting that some speakers take the presence of the uvular to indicate underlying [+back] values to one or both or the neutral vowels. The increased proportion of back responses in CFQ forms, however, cannot be explained in this way, and suggests that speakers do treat uvulars as back triggers.

Second, the presence of distance-based decay is also not predicted by this analysis. If the harmonic value of suffixes is always determined by reference to the underlying [back] value of the final vowel in the root, as proposed by Lindblad (1990) and R. F. Hahn (1991b), there should be no distance effects. One might argue that this variability comes from uncertainty about the underlying [back] values of neutral vowels. A wug root like [næniʤ] could in principle correspond to underlying /næniʤ/ or /nænɯʤ/, which make opposite predictions about the harmonizing behavior of the root. The corpus results, however, suggest a nearly exceptionless co-occurrence restriction: surface /i/ is essentially always identical in backness with the nearest preceding harmonizing vowel. Given that the underlying [back] values of neutral vowels is claimed to be independent from their phonetic properties, it is unclear how the phonetic biases discussed in this chapter could be used to account for this discrepancy in the more abstract task of identifying underlying [back] values.

4.9.3 Unmarked values in backness harmony

The analysis in this chapter hinges crucially on the idea that [+back] is unmarked in Uyghur, while [–back] is marked. This pressure explains three separate phenomena: the tendency for harmonically neutral roots to take back suffixes, the tendency for recent loanwords with only harmonizing velars, such as /gips/ 'plaster', to take back suffixes (with this pressure towards the unmarked value overwhelming the weak trigger strength of the velar), and the lack of distance-based decay in B roots in the wug tests. Additional evidence that [+back] is the unmarked value comes from historical sources: Erdal (2002) suggests that the back forms of suffixes were the default category in Old Uyghur as well. Among the evidence he presents is the observation that many foreign loans into Old Uyghur took back suffixes even if their final harmonizing vowel was front (see also Zieme,

1969), though these forms seem to have mostly disappeared or been repaired in the contemporary language.

Additional evidence comes from frequency. A common assumption is that unmarked values should be observed more frequently than marked ones (e.g., Hockett, 1955; Greenberg, 1966). Excluding the transparent vowels /i/ and /e/, the vocabulary lists in a pair of Uyghur textbooks (Nazarova & Niyaz, 2013, 2016) contain 2,546 tokens of back vowels (/ɑ/: 1,595, /o/: 341, /u/: 610) but only 1,416 tokens of front vowels (/æ/: 1079, /ø/: 196, /y/: 141), and 790 tokens of back consonants (/q/: 641, /ʁ/: 149), but only 589 tokens of front consonants (/k/: 482, /g/: 107). This supports the claim that [+back] is the unmarked value.

Finally, it is perhaps telling to compare Uyghur with the closely related Uzbek: Standard Uzbek has lost vowel harmony almost completely, and formerly harmonizing suffixes have ossified to their back forms across the board, again suggesting [+back] as a default.

This claim contradicts McCollum (2019), who claims based on phonetic measurements that [–back] is the unmarked value. Specifically, McCollum notes that long sequences of harmonizing front vowels display relatively consistent frontness, as measured by F2, while similar sequences of harmonizing back vowels gradually become fronter throughout the sequence (p. 135). This is taken as drift towards a default front articulatory setting, which has been claimed to correspond to the unmarked value (e.g., Hudu, 2010; Allen, Pulleyblank, & Ọládiípọ̀ Ajíbóyè, 2013).

How can these competing claims be reconciled? One possibility, suggested by McCollum (p.c.), is based on the claims by Hockett (1955) and Greenberg (1966) that phonologically un-marked values permit greater amounts of non-distinctive variation than marked values, or, put differently, marked values have more precise perceptual targets than unmarked values. Thus se-quences of unmarked back vowels in harmonizing suffixes gradually drift towards a default, fronter articulatory setting, while sequences of marked front vowels are under greater pressure to maintain more precise phonetic targets.

4.9.4 Implications for phonological learning

The results in this chapter present evidence for the influence of phonetic biases on the learning of backness harmony in Uyghur: statistical generalizations that are robustly present in the corpus data are not attended to when backness harmony is generalized to novel words. The specific nature of this deviation between corpus and wug results suggests the contribution of phonetic biases that lead to distance-based decay and sensitivity to uvulars as back triggers.

Uyghur backness harmony is in many ways an ideal context to explore these discrepancies between lexical and wug patterns. What was at one point a relatively exceptionless harmony system with a clear phonetic basis has become complicated over time by sound change that conflated harmonic categories and, to a lesser extent, an influx of disharmonic loanwords an (R. F. Hahn, 1991a). Despite these changes, Uyghur speakers still display a sensitivity to the detailed phonetic properties of backness harmony, even though these influence of these properties is not evident in the patterns in the corpus data. More generally, this study is consistent with other results in the literature (e.g., Hayes et al., 2009; Becker et al., 2011; Zhang & Lai, 2010) that suggest that phonetic substance exerts an important influence of phonological learning. Phonological research must continue to identify the source and nature of these biases and integrate them into our models of phonological learning.

CHAPTER 5

Are neutral roots in Uyghur really neutral? Experimental evidence

5.1 Introduction

This chapter presents an experimental study that bears on how neutral roots should be integrated into Uyghur's backness harmony system: specifically, whether the arbitrary harmonizing behavior of these should be characterized as a phonological process driven by an underlying backness contrast in the vowels of such roots, or a lexical one driven by lexically-indexed harmony constraints.[1]

5.2 Background

5.2.1 Transparent vowels

As described in previous chapters, the vowels /i e/ in Uyghur are *transparent* to harmony: when preceded by harmonizing vowels they allow the backness of these vowels to pass through them, as shown in Examples (80) and (81).

(80) *Front roots with transparent vowels*
      mæstʃit-**tæ**/*-tɑ   'mosque-LOC'
      ymid-**læ**r/*-lɑr   'hope-PL'
      mømin-**gæ**/*-ʁɑ   'believer-DAT'

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(81)   *Back roots with transparent vowels*

st**u**dent-lɑr/*-lær   'student-PL'

uniwersitet-tɑ/*-tæ   'university-LOC'

amil-ʁɑ/*-gæ   'element-DAT'

Roots with only transparent vowels and no harmonizing consonants vary in whether they take front suffixes or back suffixes. The majority of such roots take back suffixes (Example 82), but a small number take front (Example 83).

(82)   *Neutral stems that take back suffixes*

sir-lɑr/-*lær   'secret-PL'

din-**ʁɑ**/*-gæ   'religion-DAT'

hejt-tɑ/*-tæ   'festival-LOC'

peʔil-lɑr/*-lær   'verb-PL'

tip-**qɑ**/*-kæ   'type-DAT'

(83)   *Neutral roots that take front suffixes*

biz-**gæ**/*-ʁɑ   'us-DAT'

bilim-**gæ**/*-ʁɑ   'knowledge-DAT'

welisipit-**lær**/*-lɑr 'bicycle-PL'

5.2.2   The diachronic origins of transparent vowels

Scholars generally agree that Old Turkic and Chagatay (the direct ancestor of Uyghur and Uzbek) had a phonemic contrast between /i/ and /ɯ/ in initial syllables (Lindblad, 1990; R. F. Hahn, 1991a, 1991b; Bodrogligeti, 2001; Erdal, 2004).[2] This contrast appears to have had a low functional load: the number of true minimal pairs differing only in this vowel contrast is small, with most of the pairs of roots differing in this vowel contrast also containing dorsals that differed in quality (Erdal, 2004).[3]

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[2]Though see e.g., Johanson (1998) for a critical perspective.

[3]Because /e/ occurs almost exclusively in loanwords or as the output of umlaut (see Appendix C), it is unlikely to have had a diachronic back correspondent.

Thus no roots were harmonically neutral as is the case now, and front and back dorsals co-occurred with front and back vowels respectively. At some point in its history, Uyghur lost this distinction between /i/ and /ɯ/, which complicated the harmony system, introducing both transparent vowels, neutral roots, and consonants as harmony triggers (see also Binnick, 1991, for discussion of the inherent instability of harmony systems, and how this results primarily from language-internal factors, rather than loanwords). Lindblad (1990) shows that the most frequent roots that previously had /i/ continued to take front suffixes (e.g., /biz/ 'we', /ilim/ 'science', /itʃ-/ 'drink'), the roots that previously had /ɯ/ continued to take back suffixes, and many less frequent roots that were underlyingly /i/ began to take the default back form of suffixes. Uyghur appears to be typologically unusual in that the default harmony value is [+back], despite the transparent vowels being phonetically [−back]. In languages such as Mongolian and Finnish, which have similar transparent vowels, transparent roots generally behave as [−back] (Lindblad, 1990).[4]

Finally, it is worth noting that neutral roots have exhibited some degree of variation in their suffixing behavior for a long time. (Erdal, 2004) notes that roots such as /tiz/ 'knee' surface with both front and back suffixes in Old Turkic.

5.2.3 Previous analyses of transparent vowels

The analyses of Uyghur backness harmony in Lindblad (1990) and R. F. Hahn (1991a, 1991b) essentially recapitulate the historical development of the transparent vowels in Uyghur. These analyses suggest that there are phonemic back counterparts of /i e/, /ɯ ɤ/, which are neutralized on the surface by a post-lexical fronting rule that maps /ɯ/ → [i] and /ɤ/ → [e]. R. F. Hahn (1991b) writes that these underlying front and back counterparts "share the same set of allophones and are orthographically represented alike" (p. 34).

An example pair of derivations under this analysis involving neutral roots that differ in the backness of suffixes they take are shown in Examples (84) and (85).

(84) *Derivation of /sɯr-lAr/ 'secret-PL'*

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[4]Though some might argue whether the characterization of the transparent vowels as phonetically [−back] in Uyghur is justified: in practice they range from central to front. See Chapter 2.

1. **Underlying form**   /sɯr-lAr/

2. **Harmony**   sɯ̱r-lɑr

3. **Fronting**   si̱r-lɑr

4. **Surface form**   [sirlɑr]

(85) *Derivation of /biz-DA/ 'us-LOC'*

   Underlying form   /biz-DA/

   Harmony   bi̱z-dæ̱

   Fronting   –

   Surface form   bizdæ

Under this analysis, backness harmony in Uyghur is exclusively driven by vowels. Velars and uvulars undergo harmony when they occur in suffixes like the dative, which has the front allomorphs [-kæ]/[-gæ] and the back allomorphs [-qɑ]/[-ʁɑ], but do not serve as triggers. The apparent behavior of dorsals as harmony triggers stems from co-occurrence restrictions between the underlying neutral vowels and the dorsals: that is, we see back suffixes in forms like [qiz-lɑr] 'girl-PL' not because of the /q/, but because the vowel is underlying /ɯ/. This underlying vowel quality determines both the backness of the dorsal in the root, as well as the backness of the suffix.

McCollum (2021) looks for acoustic evidence of allophonic and phonemic contrasts between /i/ and /ɯ/. He demonstrates on the basis of phonetic measurements that there are differences in the phonetic quality of transparent vowels in suffix forms following front and back vowels respectively: these vowels tend to backer in the presence of a preceding back vowel, and fronter in the presence of a preceding front vowels, suggesting that harmony spreads locally through transparent vowels, at least at the phonetic level. Evidence for a phonemic distinction between /i/ and /ɯ/ was less compelling: McCollum found that while several speakers displayed a correlation between the F2 of transparent vowels in roots and whether they attached back or front suffixes to the root, most speakers did not show a clear relationship between the two.

The study in McCollum (2021) investigates only six roots elicited from nine speakers: /ʧiʧ/ 'tooth', /ilim/ 'knowledge', /jil/ 'year', /qiʃ/ 'winter', /pil/ 'elephant', and /ʃilim/ 'glue'. The goal of this chapter is to investigate the acoustic properties of transparent vowels in roots using a larger number of roots and speakers.

5.3 A priori arguments against a phonemic distinction between /i/ and /ɯ/

Before turning to the experimental study, I will present an argument against a phonemic distinction between /i/ and /ɯ/ on the basis of phonological contrast. Although proving a phonemic relationship between segments is often complicated, one of the basic criteria is minimal word pairs that differ only in the replacement of one segment by another. For example, the pair /ɑt/ 'horse' and /ot/ 'fire' demonstrate that /ɑ/ and /o/ are phonemically contrastive in Uyghur.

Assuming the post-lexical fronting analysis described in the previous section, we might expect there to be homophones consisting only of neutral vowels that differ in the backness of suffixes they take: for example, a hypothetical pair of words like /sip/ and /sɯp/ which surface as [sip-lær] and [sip-lɑr] respectively when the plural suffix is added and post-lexical fronting is applied.

Uyghur appears to have no such homophones. The closest thing to this is a small set of noun/verb pairs that are semantically related, but differ in backness. The verb forms in this example include the derivational suffix /-lA/, which derives verbs from noun roots, the gerund /-ʃ/, and /-mAQ/, an infinitive marker. The alternations between /-lA/ and /-li/ are caused by phonological vowel reduction (see Chapters 2 and 3).

(86)   *Verb/noun pairs with differing harmony*

      /iʃ-lAr/   → [iʃ-lɑr]   'work-PL'

      /iʃ-lA-mAK/   → [iʃ-li-**mæk**]   'work-VERBALIZER-INF' (to work)

      /iʃ-lA-ʃ/   → [iʃ-læ-ʃ]   'work-VERBALIZER-GER' (working)

      /tʃiʃ-lAr/   → [tʃiʃ-lɑr]   'tooth-PL'

      /tʃiʃ-lA-mAK/ → [tʃiʃ-li-**mæk**] 'tooth-VERBALIZER-INF' (to bite)

      /tʃiʃ-lA-ʃ/   → [tʃiʃ-læ-ʃ]   'tooth-VERBALIZER-GER' (biting)

      /iz-lAr/   → [iz-lɑr]   'trace-PL'

      /iz-lA-mAK/   → [iz-li-**mæk**]   'trace-VERBALIZER-INF' (to search)

      /iz-lA-ʃ/   → [iz-læ-ʃ]   'trace-VERBALIZER-GER' (searching)

Comparison with related languages that have no transparent vowels, such as Turkish and Tatar,

suggests that these roots may have uniformly taken front suffixes at an earlier stage before /i/ and /ɯ/ merged in Uyghur (cf. Turkish /iʃ/ 'work', /tʃiʃ/ 'tooth', /iz/ 'trace' and Kazan Tatar /eʃ/ 'work', /teʃ/ 'tooth', /ez/ 'trace'). Reconstructions of Proto-Turkic also corroborate this view (Clauson, 1972).[5]

The fact that the harmony of the verb stems is clearly indicated in many forms by the /-lA/ suffix suggests that the noun forms, with no obvious harmonic elements, may have participated in the general shift of neutral roots to take back suffixes over time (Lindblad, 1990), while the verb forms did not change in this way. That is to say, the roots plus the explicitly harmonizing verbalizer morpheme have become roots in their own right that have maintained their earlier harmonic values, while the bare transparent roots have participated in the general drift of neutral roots towards back suffixes.

The absence of minimal pairs between /i/ and /ɯ/ is not necessarily a conclusive argument against a phonemic contrast, although it is suggestive of its absence. We can see this by considering the *functional load* of this purported contrast. Metrics of functional load seek to quantify the informativeness of a contrast between two phonological units, with a higher functional load indicating a more informative contrast (e.g., Hockett, 1955; Kučera, 1963). Functional load has been calculated based on the number of minimal pairs over a particular contrast (e.g., Todd, 2012; Wedel, Kaplan, & Jackson, 2013), or by comparing the change in the entropy (Shannon & Weaver, 1949) of a corpus after the contrast has been neutralized (e.g., Surendran & Niyogi, 2006). Assuming that this entropy is calculated at the word level, both methods will produce a functional load of 0 for the /i/-/ɯ/ contrast: there are no minimal pairs between these vowels, and thus neutralizing the contrast between them does not lead to an increase in entropy.

It is not always the case that a phonemic contrast will have a non-zero functional load: the contrast between English /ŋ/ and /h/ similarly has a functional load of 0 (e.g., Surendran & Niyogi, 2006; Lin, 2019), as does the contrast between /ŋ/ and /ʒ/ (e.g., Surendran & Niyogi, 2006), but these are generally not considered to be allophones of one another. Note, however, that there are complicating factors at play with these cases. First, /h/ and /ŋ/ have non-overlapping distributions

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[5]Though Erdal (2004) suggests that the root /iz/ at its earliest stages was /ɯz/, before changing to /iz/.

in English, with the former occurring only in syllable onsets and the latter only in syllable codas, making minimal pairs unlikely. Second, some degree of phonetic similarity is usually assumed to be a prerequisite of an allophonic alternation (e.g., Peperkamp, Calvez, Nadal, & Dupoux, 2006). The pairs above have little in common from this perspective. Third, overall phoneme frequency has been shown to correlate with minimal pair counts (Wedel et al., 2013): the English phoneme /ʒ/, in addition to having a relatively restricted distribution, also has relatively low frequency, and thus a small number of minimal pairs and an accordingly low average functional load (e.g., Surendran & Niyogi, 2006; Lin, 2019).

The purported contrast in Uyghur does not have any of these confounds: the licit environments for /i/ and /ɯ/ are identical (at least in the neutral roots considered in this chapter), they are phonetically quite similar (indeed, identical on the surface according to past analyses), and quite frequent (approximately 50% of roots in the corpus contain /i/). Although to my knowledge there has been no proposed metric of expected minimal pairs and/or functional load given a phonemic contrast, the complete lack of minimal pairs would be surprising in this case. On the other hand, this is not unexpected if the harmonizing behavior of neutral roots is driven by lexical, rather than phonemic factors.[6]

5.4 Acoustic properties of neutral roots: An experimental study

Although the previous section provided synchronic structural evidence against a covert contrast analysis of neutral roots in Uyghur, this does not rule it out as a possibility. Indeed, an analysis positing a covert contrast between /i/ and /ɯ/ is descriptively sufficient, in that it allows us to capture the patterning of backness in suffixes attached to neutral roots in a principled way. Additional evidence is required, however, to determine whether this contrast is truly part of the competence of Uyghur speakers (e.g., Sapir, 1933/1949; Ohala, 1974). The question that this section will address is whether additional behavioral evidence can be furnished to support a covert contrast analysis, as proposed by Lindblad (1990) and R. F. Hahn (1991b).

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[6]Note, as mentioned earlier, that even in the ancestor languages of Uyghur where a phonetic distinction between /i/ and /ɯ/ was thought to apply, this contrast had a low functional load, perhaps accounting for its eventual disappearance.

Morphological diacritics that determine the phonologizing behavior of roots are commonly employed in phonological analyses to account for morphological behavior that is not predictable from phonological properties, and for representing exceptions to general phonological patterns. Such an analysis applied to neutral roots suggests that speakers assign roots with no phonological clues to their harmonizing behavior to one of two lexical classes: those that take front suffixes and those that take back. These classes are represented in the grammar by indexed constraints (e.g. Kraska-Szlenk, 1997, 1999; Fukazawa, 1999; Ito & Mester, 1999; Pater, 2010; Moore-Cantwell & Pater, 2016, a.o.). See Chapter 3 for an argument that an indexed constraint analysis is also appropriate for patterns of opacity in the harmony system, and Chapter 4 for an argument that the discrepancy between corpus harmony patterns and patterns in wug tests is the result of indexed constraints.

A comparison of the representations of the word 'secret' is shown under Lindblad and Hahn's covert contrast analysis in (87), and under a lexical diacritic analysis in (88).

(87)   *Underlying representation of 'secret' in a covert contrast analysis*
       /suɯr/

(88)   *Underlying representation of 'secret' in a lexical diacritic analysis*
       /sir/$_{+back}$

An additional source of evidence for evaluating between these hypotheses may be found in the phonetic details of these vowels. Benus and Gafos (2007), for example, claimed that neutral roots in Hungarian, which has a similar set of transparent vowels to Uyghur, in fact have systematic and significant differences in tongue position that correlate with their preferred suffix backness: that is, the transparent vowels in harmonically neutral roots that take back suffixes are produced somewhat backer than those same vowels in neutral roots that take front suffixes, even in unsuffixed contexts where this difference cannot be accounted for by vowel-to-vowel coarticulation (though see Blaho & Szeredi, 2013, for a critical discussion of these results).

Subtle differences might, in principle, stem from two different sources. One is that they re-

flect a covert contrast in line with the proposals like Lindblad (1990) and R. F. Hahn (1991b).[7] Sub-phonemic distinctions such as this have been shown to emerge following the collapse of two phonemically-distinct segments, either diachronically (e.g., Yu, 2007) or synchronically (e.g., Port & O'Dell, 1985). Under this interpretation, these distinctions would serve as both a phonetic correlate to an underlying distinction between /i/ and /ɯ/ in Uyghur, and a possible source of information that would guide learners towards a grammar with this underlying distinction rather than treating neutral roots as lexically specified for backness.

The second possibility is that these systematic differences do not reflect a covert phonemic contrast, but rather are the consequence of coarticulation in suffixed forms being generalized to unsuffixed forms under an exemplar-based model of lexical storage (e.g., Pierrehumbert, 2001). Under such models, speakers build an 'exemplar cloud' of root tokens they have perceived, and set their acoustic production targets based on an average across or random sampling of the acoustic properties of these tokens. Because neutral roots are frequently produced with harmonizing suffixes and these suffixes can induce front/back coarticulation on root vowels (e.g., Öhman, 1966), the exemplar clouds of neutral roots that take back suffixes will, overall, contain backer vowels than the clouds of neutral roots that take front vowels, resulting in backer productions even in unsuffixed contexts. For more discussion of this idea, see Benus and Gafos (2007).

Thus although the presence of a subtle acoustic distinction between vowels in Uyghur neutral roots that take front suffixes and those that take back suffixes does not provide conclusive evidence for a phonological grammar that contains a covert contrast between /i/ and /ɯ/, its absence may suggest that a lexically-driven account is more appropriate. The experiment in this section is designed to look for this kind of subtle acoustic variance in neutral roots.

5.4.1 Factoring out coarticulation

A challenge in looking for subtle phonetic differences of this kind is dealing with coarticulation. As described in the previous section, the backness of vowels in neutral roots with harmonizing suffixes attached (e.g., tokens like [sir-lɑr] 'secret-PL' or [welisipet-lær] 'bicycle-PL') or in roots

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[7]What I call covert contrast here is also referred to as as near-merger or near-neutralization in the literature.

with a mix of harmonizing and neutral vowels (e.g., /tɑksi/ 'taxi', /mæstʃit/ 'mosque') may be influenced by those harmonizing vowels. This kind of coarticulatory influence does not amount to a phonemic contrast (though it may lead to the development of one; see, e.g., Hyman, 1976; Ohala, 1981). The tendency of neighboring vowels to exert a phonetic influence on one another is strong, particularly if doing so does not eliminate a phonemic contrast (e.g., Öhman, 1966; Alfonso & Baer, 1982; Choi & Keating, 1990; Benus & Gafos, 2007; Cole, Linebaugh, Munson, & McMurray, 2010). Uvulars are also known to exert a backing effect on vowels (see Chapter 4).

Thus phonetic evidence of a covert phonemic contrast of this nature must come primarily from unsuffixed forms of completely neutral roots. The experiment described below focuses on the phonetic properties of such roots, and how these properties correlate with suffix choice, though it also looks at the degree of coarticulation present when such roots occur with suffixes.

5.4.2 Methodology

The 28 target roots used in this study are shown in Table 5.1. These roots were selected because they contain no harmonizing elements and are relatively common.

The target words were elicited in both unsuffixed and suffixed forms in the following carrier phrase:

(89) *Mahinur _____ deydu*
       "Mahinur will say _____"

An accompanying phrase in parentheses after the target (*orun kélish*) indicated that the target word should be produced with the locative suffix /-DA/. Stimuli were presented to each participant in one of two random orders.

Data was collected from 21 native speakers of Uyghur living in Almaty, Kazakhstan (16 F, 5 M, ages 19–62). The stimuli were presented in Cyrillic orthography. Recordings of participants' responses were made using a Zoom H4n Pro Handy Recorder.[8]

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[8]Note that these recordings were made in person; the Zoom H4n Pro Handy Recorder has no relationship to the popular video conferencing platform.

Word	Definition	Expected Harmony	Word	Definition	Expected Harmony
/bir/	'one'	F	/mis/	'copper'	F/B
/biz/	'we'	F	/pil/	'elephant'	B
/tʃiʃ/	'tooth'	B	/pir/	'master'	B
/dil/	'soul'	B	/rim/	'Rome'	B
/din/	'religion'	B	/sinip/	'classroom'	B
/filim/	'film'	F/B	/sirt/	'outside'	B
/itʃ/	'inside'	F	/sijir/	'milk-cow'	B
/ili/	'Ili (place name)'	B	/siz/	'you (formal)'	F
/ilim/	'knowledge'	F	/til/	'tongue'	B
/iʃ/	'matter'	B	/tilsim/	'magic'	B
/it/	'dog'	B	/tip/	'type'	B
/dʒin/	'jinn'	B	/tiz/	'knee'	B
/lim/	'joist'	B	/jil/	'year'	B
/miŋ/	'thousand'	B	/zil/	'bell'	F

Table 5.1: Neutral roots used in the study. The 'Expected Harmony' column indicates the predicted harmonic value given frequencies from the corpus used in Chapters 3 and 4.

5.4.3 Analysis

Vowels in both unsuffixed and suffixed target words were segmented by hand in Praat. An automated script was used to extract the following acoustic measurements at vowel midpoints: f0, F1, F2, F3, F4, and duration. F2 was predicted to be the most likely measure to reflect a covert contrast, since it is an acoustic correlate of tongue backness, but the other measures were tested as well. Uyghur has an optional, but pervasive, process of vowel devoicing that occurs before voiceless sounds in coda positions. Tokens where devoicing made formant measurements impossible were omitted. Suffixed forms of roots were coded for whether the speaker attached a front or back suffix. Eight tokens had F2 values that were identified as outliers using the interquartile range test, and were excluded.

Statistical analysis was performed in R (R Core Team, 2017) using the `lme4` library (Bates et al., 2015). A linear mixed-effects model was fit to the data with F2 as the dependent variable. The independent variables were suffix backness, speaker gender, and the place of articulation of the consonant following the final vowel. The coding for place of articulation is shown in Table 5.2. A value of 'n/a' was used in these fields if vowels occurred word-finally. Random intercepts were used for each root and speaker. Because of these intercepts, speaker data was not normalized.

Place	Consonants
Labial	p, b, m
Coronal	t, d, s, z, n, r
Palatal	ʧ, ʤ, j
Velar	ŋ
Lateral	l

Table 5.2: Place of articulation assigned to consonants in the statistical models.

Additional independent variables such as place of articulation of the preceding consonant, and manner of articulation or voicing of consonants flanking the final vowel were tested, but did not improve model fit as determined by the Bayesian Information Criterion (Schwarz, 1978).

5.4.4 Unsuffixed root results

The relationship between the F2 of the final root vowel and the proportion of back responses is shown in Fig. 5.1. There was, unsurprisingly, a significant effect of participant gender on F2: male speakers had lower F2 values than female speakers ($\beta = -326.65$, $SE = 74.47$, $t = -4.386$, $p < 0.001$). There was no significant effect of suffix choice on the F2 of the unsuffixed form: vowels in neutral roots that took back suffixes were slightly backer than those that took front suffixes, but this difference was not significant ($\beta = -2.38$, $SE = 47.82$, $t = -0.05$, $p = 0.96$).

The following consonant place of articulation had a significant effect on F2. Broadly speaking, tokens of /i/ with a following velar or lateral consonant had lower F2 than those with a following coronal or labial consonant, which in turn had lower F2 than those with a following palatal or no

following consonant. These results are shown graphically in Fig. 5.2. The fixed effects relating to consonant place are shown in Table 5.3.

None of the other acoustic variables (f0, F1, F3, F4, and duration) tested under similar models were significantly predicted by suffix backness.
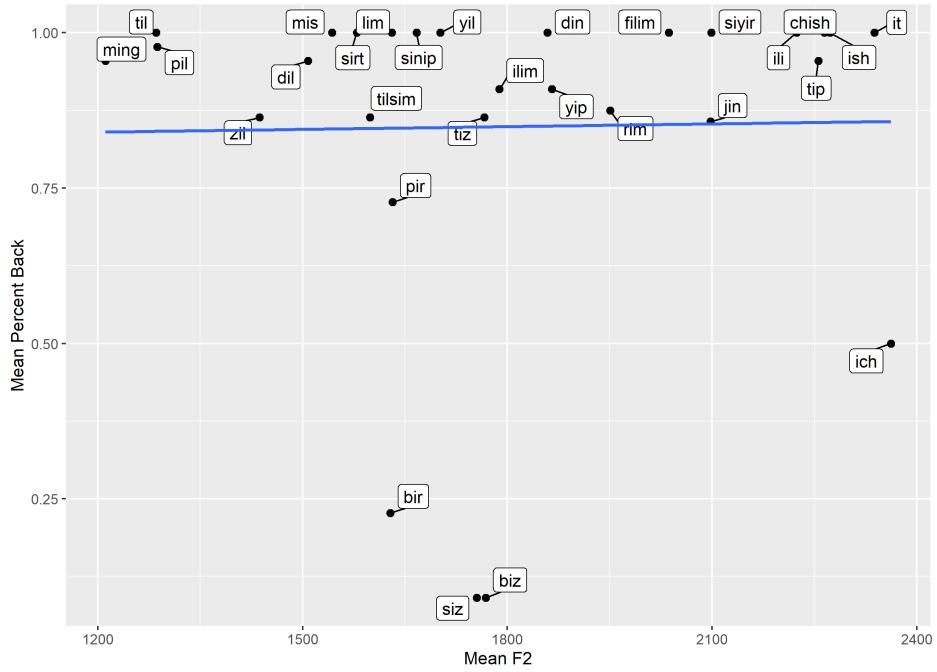
Figure 5.1: The relationship between phonetic vowel backness and proportion of responses with back suffixes.

	Estimate	Std. Error	t	p
Intercept	1892.69	80.81	23.42	< 0.001
Velar	−595.37	226.79	−2.63	< 0.05
Lateral	−378.65	117.89	−3.21	< 0.005
Labial	29.79	101.53	0.29	0.96
n/a	419.60	228.70	1.84	0.08
Palatal	443.60	142.67	3.11	< 0.005

Table 5.3: Fixed effects for following consonant place in unsuffixed root tokens. The reference level is coronal.
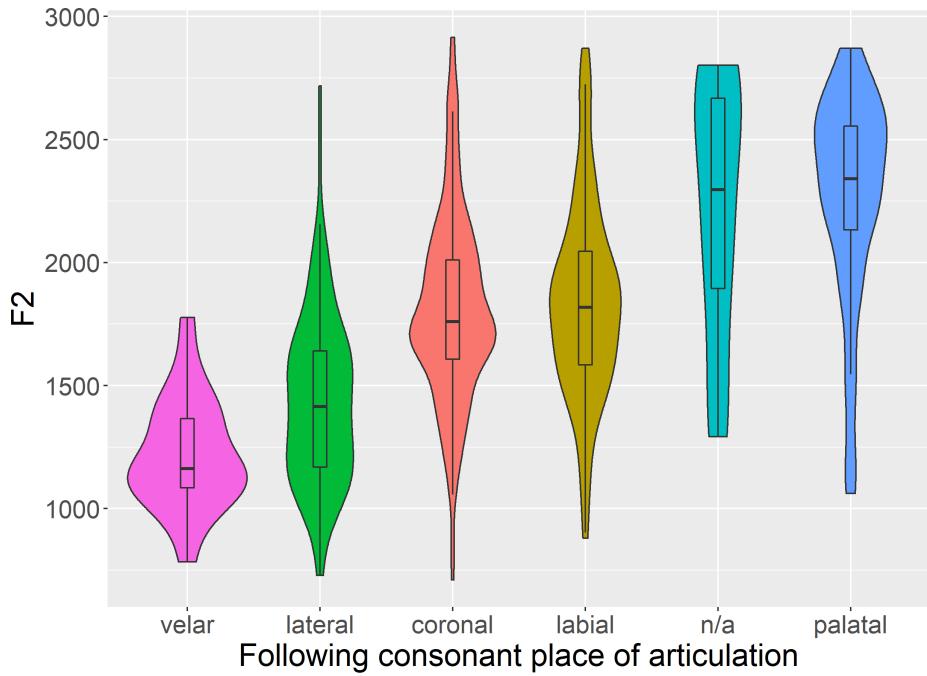
Figure 5.2: The relationship between phonetic vowel backness and proportion of responses with back suffixes. Boxes indicate the median value and upper and lower quartiles.

Fig. 5.3 shows a plot of the estimated random effects with 95% confidence intervals calculated using the `REsim` function from the `merTools` package in R. The left half of the plot shows that the random intercepts assigned to most speakers do not differ significantly from zero, though three speakers had significantly negative intercepts and three had significantly positive ones. The right half of the plot shows that four of the roots had significant negative intercepts while four had significant positive intercepts. This indicates that the F2 value of the final vowel in these roots show systematic differences from other roots, but none that are predictable from the independent variables in the model here.

5.4.5 Suffixed root results

In addition to unsuffixed roots, the acoustic properties of the final vowel in suffixed tokens of neutral roots were measured to see if suffix vowels induce a coarticulatory effect on the final vowel in the root. A similar model was fit to the data, with participant gender, suffix backness, and place
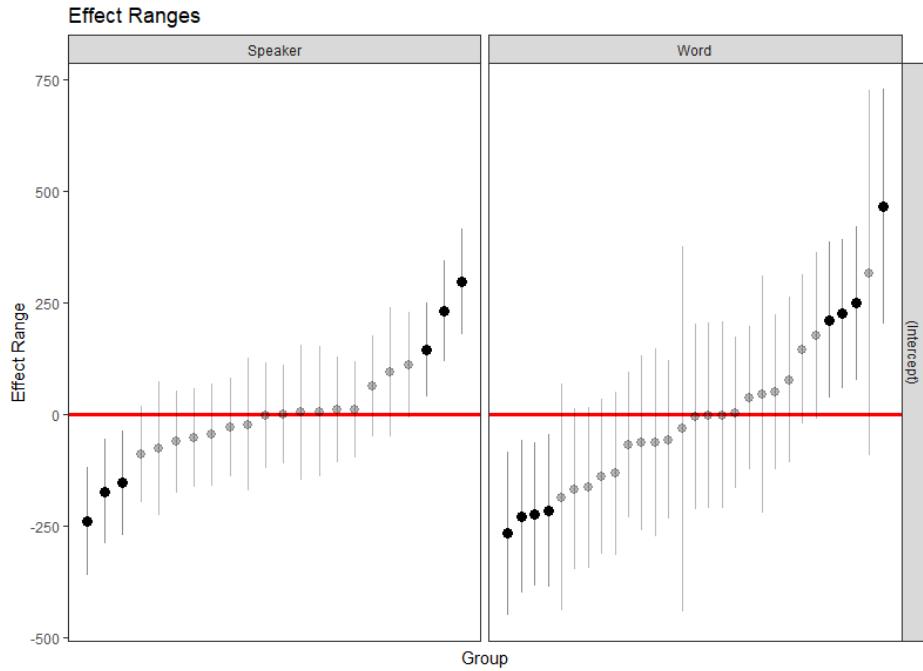
Figure 5.3: Estimated random intercepts with 95% confidence intervals. Speaker or word intercepts in gray do not differ significantly from zero.

of articulation of the consonant following the final root vowel as the independent variables, F2 of the final root vowel as the dependent variable, and random intercepts for both speaker and word. There was again a significant effect of gender, with male speakers having lower F2s than female speakers ($\beta = -285.59$, $SE = 52.08$, $t = -5.48$, $p < 0.001$). There was no main effect of suffix backness: though front-suffixed roots tended to be produced with a slightly higher F2 than back-suffixed roots, this difference was not significant ($\beta = 35.12$, $SE = 54.43$, $t = 0.645$, $p = 0.52$). These results are shown in Fig. 5.4. Fixed effects related to final consonant place are shown in Table 5.4.
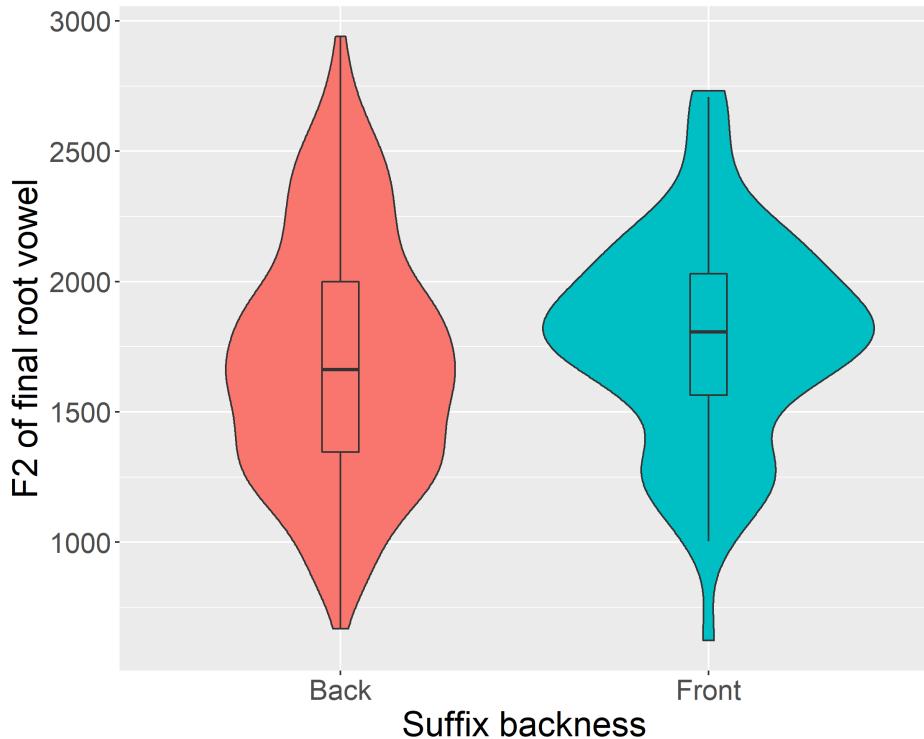
Figure 5.4: F2 of the final neutral vowel in roots with front and back suffixes attached.

	Estimate	Std. Error	*t*	*p*
Intercept	1833.92	76.49	23.98	< 0.001
Velar	−515.97	247.95	−2.08	< 0.05
Lateral	−398.830	129.07	−3.090	< 0.01
Labial	−34.24	111.21	−0.31	0.76
n/a	451.21	247.95	1.82	0.08
Palatal	473.19	166.80	2.84	< 0.001

Table 5.4: Fixed effects for following consonant place in suffixed roots. The reference level is coronal.

5.5 Discussion

These results show no systematic acoustic contrast in unsuffixed tokens between vowels in neutral roots that take front suffixes and vowels in neutral roots that take back suffixes. Even in suffixed forms, the degree of coarticulation between the suffix vowel and final neutral vowel in the root

does not reach significance, though it trends in the expected direction. This mirrors the results for Hungarian found in Blaho and Szeredi (2013), and also corroborates the results for Uyghur in McCollum (2021).

These results support one of the central claims of this dissertation, which is that the harmonizing behavior of neutral roots (among other aspects of the harmony system) is governed by lexically listed constraints, rather than a (quasi-)covert phonological contrast as posited by Lindblad (1990) and R. F. Hahn (1991b). Although the lack of a consistent phonetic difference does not definitely rule out speakers intuiting a covert contrast from learning data, it casts doubt on the parsimony of such an analysis. A covert contrast analysis requires that learners intuit the existence of a phonemic category that has no clear phonetic correlates, while an analysis using lexically indexed constraints requires only that they learn the idiosyncratic harmonizing behavior of certain roots.

It is possible that, as claimed by Benus and Gafos (2007), a covert contrast between /i/ and /ɯ/ is indistinguishable acoustically but present articulatorily. This discrepancy between tongue position and acoustic output can occur in so-called *quantal regions*, where large differences in tongue position result in comparatively small differences in acoustic output (Stevens, 1972, 1989). It is impossible to rule the possibility of such differences out based on an acoustic study alone, though the wide range of variation in F2 for the vowel /i/ shown in Fig. 5.1 suggest that this is not a case of quantality masking acoustic variation. It is also worth noting that McCollum (2021) identifies significant acoustic differences in neutral vowels in harmonizing suffixes that are conditioned by preceding harmonic vowels. These differences would be unexpected under a quantal account of the lack of variation in root vowels.

These results also indicate that there are other factors that drive variation in the acoustic realization of /i/, such as adjacent consonant identity. These factors, however, seem to be orthogonal to the harmonizing behavior of these roots.

CHAPTER 6

A challenge for tier-based strict locality from Uyghur backness harmony

Researchers in computational linguistics propose that insights from theories of computation can guide how we study linguistic systems and what predictions we make about the structures of natural language (e.g., Heinz, 2018). Hypothesizing that some aspect of language is bound by a particular computational structure has the potential to capture the wide variety of patterns seen across languages, while simultaneously constraining the types of patterns we should expect.

It is commonly accepted that phonological processes are regular: that is, they can be computed by regular grammars/automata (e.g., Johnson, 1972; Kaplan & Kay, 1994). This applies to both phonological stringsets (the properties of surface strings that may be characterized by phonotactic and markedness constraints) and phonological maps (the relationship between underlying and surface forms).

A stronger claim is that all phonological stringsets are tier-based strictly local (TSL) languages, which are subregular. That is, valid stringsets can be expressed as prohibitions on substrings, but these substrings may belong to "tiers" which contain only some subset of the segments in a language (Heinz et al., 2011). This is referred to as the *weak subregular hypothesis* (Heinz, 2018).[1]

There are several existing counterexamples against TSL as an upper bound for phonological complexity. Some suprasegmental patterns have been identified as being outside of TSL, such as culminative quantity-sensitive stress rules (Baek, 2017) and circumambient patterns like unbounded tone plateauing (Jardine, 2016). A handful of segmental patterns that cannot be generated

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[1]The *strong subregular hypothesis* claims that phonological stringsets are either strictly local (SL) or strictly piecewise (SP) languages (Heinz, 2010). Some autosegmental processes like stress have been claimed to be fully regular (e.g., Graf, 2010), though there is debate on whether alternative analyses are possible (Heinz, 2010).

by single TSL grammars are described by McMullin (2016). McMullin claims that some of these exceptions can be captured using the intersection of multiple TSL grammars. However, the more complex patterns require a more powerful system, such as using an Optimality Theory account with markedness constraints based on violations of TSL grammars. de Santo and Graf have formalized the intersection of multiple TSL languages as multi-tier strictly local (MTSL) languages, and proposed an extension of TSL, structure-sensitive TSL (SS-TSL), that allows the more problematic patterns described by McMullin to be captured (de Santo & Graf, 2017). A more complex formalism, Input-Output TSL (IO-TSL) presents a generalization of SS-TSL that appears to be necessary to describe the pattern of Sanskrit *nati* (Graf & Mayer, 2018). Graf has also defined an extension of strictly piecewise (SP) grammars, interval-based SP (IBSP) grammars, which introduces domain restrictions to SP grammars and allows the problematic suprasegmental patterns described above to be captured (Graf, 2017).

This chapter provides new data on a phonological process that is beyond the capacity of TSL grammars, providing an additional counterexample to the weak subregular hypothesis: backness harmony in Uyghur.[2] This pattern is of interest for several reasons. First, it is a *segmental* process that cannot be generated by TSL grammars. These patterns are less common than suprasegmental patterns (Jardine, 2016). Furthermore, this pattern is significantly more complex than any segmental pattern previously discussed: Uyghur backness harmony cannot be captured by *any* of the classes that have been commonly investigated in subregular phonology, with the exception of the overly powerful IO-TSL language class. This makes it a particularly difficult case for anything but the weakest versions of the subregular hypothesis.

The chapter is organized as follows. Section 6.1 will give a brief description of the properties of TSL languages. Section 6.2 will briefly describe Uyghur backness harmony, and Section 6.3 will show that this pattern cannot be generated by grammars in any of the commonly employed subregular classes. We briefly sketch an enhancement similar to SS-TSL that is able to capture this pattern. This enhancement is described more completely by Graf and Mayer (2018).

Given this data, it is either the case that previously considered subregular language classes are

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[2]This chapter is a collaboration with Travis Major that was previously published as Mayer and Major (2018). Slight modifications have been made to better situate it in the context of the dissertation.

insufficient to capture all phonological stringsets, or that another analysis for this phenomenon must be adopted. The remainder of the chapter outlines some possibilities for reconciling this data with the weak subregular hypothesis. This topic is taken up again in Chapter 7.

6.1   Tier-based strictly local languages

Tier-based strictly local languages fall within the subregular hierarchy, shown in Figure 6.1. Researchers have identified a variety of subregular language classes, and established their mathematical properties and the relationships between them (e.g., Schützenberger, 1965; Eilenberg, 1974; Simon, 1975; Pin, 1986). I will not go into detail here about the subregular hierarchy in general, but many excellent descriptions and applications can be found elsewhere (e.g., Rogers & Pullum, 2011; Rogers, Heinz, Fero, & Hurst, 2013; Heinz, 2018; Yli-Jyrä, 2003; Yli-Jyrä et al., 2013).

$$\text{Regular} \longrightarrow \text{Star-Free} \longrightarrow \text{LTT} \longrightarrow \text{LT} \longrightarrow \text{SL}$$
$$\longrightarrow \text{PT} \longrightarrow \text{SP}$$
$$\text{TSL}$$
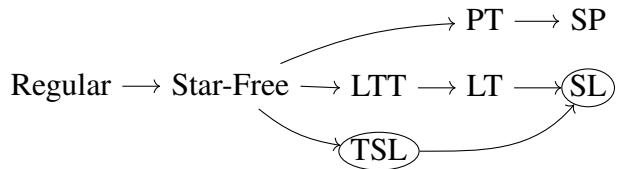
Figure 6.1: The subregular hierarchy. Classes discussed in this section are circled.

The class of TSL languages properly contains the class of strictly local (SL) languages and is properly contained within the class of star-free languages. It is incomparable with other subregular classes (Heinz et al., 2011). I first describe the properties of SL languages, and then examine how TSL languages expand on these.

Σ represents an alphabet. I will use the alphabet $\Sigma = \{a, b, c\}$ throughout the examples in this section. The symbols $\rtimes$ and $\ltimes$ are initial and final markers respectively, which are not in Σ. I will occasionally omit these for readability. The k-factors of a string $w \in \Sigma^*$ are defined as all substrings of $\rtimes^{k-1} w \ltimes^{k-1}$ that are of length k, where a^n indicates the symbol a repeated n times. A string u is a substring of a string s if $s = xuy$ for some strings $x, y \in \Sigma^*$. We can define a function $F_k(w)$ that returns the set of k-factors of w:

$$F_k(w) = \{u \mid u \text{ is a } k\text{-factor of } \rtimes^{k-1} w \ltimes^{k-1}\} \tag{6.1}$$

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For example, $F_2(ababac) = \{\rtimes a, ab, ba, ac, c\ltimes\}$.

A strictly k-local grammar consists of a finite set of k-factors taken from $(\{\rtimes, \ltimes\} \cup \Sigma)^k$, which describe illicit substrings.[3] A string $w \in \Sigma^*$ is well formed with respect to a k-SL grammar G iff $F_k(w) \cap G = \emptyset$, i.e., if it contains no illicit substrings. A language L is SL iff there is some $k \in \mathbb{N}$ such that L can be generated by a strictly k-local grammar.

For example, suppose we want to define a language that prohibits all strings in which b is immediately followed by c. We could define a strictly 2-local grammar $G = \{bc\}$, which rules out strings such as $w_1 = ababca$, because $F_2(w_1) \cap G = \{bc\}$, but permits strings such as $w_2 = abacba$, because $F_2(w_2) \cap G = \emptyset$.

TSL grammars differ from SL grammars in that they are defined over a tier $T \subseteq \Sigma$ (Heinz et al., 2011). Only the segments on this tier are considered when checking for illicit k-factors. Formally, the representation of a string on a tier is generated by means of an erasing, or projection, function E_T, which removes symbols from the string that are not in T:

$$E_T(\sigma_1 \cdots \sigma_n) = u_1 \cdots u_n \tag{6.2}$$

where $u_i = \sigma_i$ iff $\sigma_i \in T$ and $u_i = \lambda$ (the empty string) otherwise. A k-TSL grammar consists of a set of k-factors taken from $(\{\rtimes, \ltimes\} \cup T)^k$. A string $w \in \Sigma^*$ is well formed with regard to a TSL grammar G iff $F_k(E_T(w)) \cap G = \emptyset$, i.e. if it contains no illicit substrings when projected on T. A language L is TSL iff it can be generated by a strictly k-TSL grammar some $k \in \mathbb{N}$.

Suppose we want to define a language where words cannot contain both b and c. SL grammars are unable to capture this. We may define a strictly k-local grammar G that contains the k-factor $ba^{k-2}c$. This factor will rule out words like $aba^{k-2}ca$, but not words like $aba^{k-1}ca$, because the window of length k over which the k-factors operate is too small to see both the b and the c. Increasing k will not help, since it is always possible to increase the number of intervening a's. This is the result of a general property of SL languages (Rogers & Pullum, 2011):

Theorem 1 (Suffix substitution closure). *A language L is SL iff there is some $k \in \mathbb{N}$ such that if there is a string x of length $k - 1$ and strings u_1, t_1, u_2, and t_2, such that $u_1xt_1 \in L$ and $u_2xt_2 \in L$*

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[3]These can equivalently be formulated as licit substrings.

then $u_1 x t_2 \in L$.

In contrast, it is trivial for a TSL grammar to capture this by letting $T = \{b, c\}$ and $G = \{bc, cb\}$. Under this formulation, the number of intervening a's is irrelevant, because they are excluded from T.

6.1.1 Why TSL as an upper bound?

TSL grammars have been proposed as an upper bound for phonological complexity for several reasons (see Heinz, 2018, for an overview). First, they are expressive enough to capture the vast majority of phonological patterns, including long-distance harmony patterns. At the same time, they are sufficiently restrictive to rule out many of the phonologically implausible patterns that can be described using regular grammars, such as languages where words must have an even number of vowels. Thus TSL seems to strike a reasonable balance between expressiveness and restrictiveness.

In addition, TSL has been shown to have several desirable learning properties. Formally, it has been shown that both 2-TSL (Jardine & Heinz, 2016) and k-TSL grammars (Jardine & McMullin, 2017) are learnable in polynomial time from positive data. This is not true of regular languages (Gold, 1967). Experimental results in artificial grammar learning studies (Moreton & Pater, 2012) have also suggested that learners prioritize hypotheses that fall in the 2-TSL class of grammars (Lai, 2015; McMullin, 2016; McMullin & Hansson, 2019).

Because a TSL grammar is restricted to a single tier, multiple interacting long-distance patterns sometimes cannot be handled by a single TSL grammar. This problem becomes more acute if these patterns conflict. Apparent examples of such patterns are sibilant harmony in Tamashek Tuareg and Imdlan Tashlhiyt (McMullin, 2016) and Sanskrit *nati* (Graf & Mayer, 2018). I will show below that the standard description of Uyghur backness harmony also falls into this problematic class of patterns.

6.2   Uyghur backness harmony

Uyghur has a rich system of vowel and consonant harmony along several dimensions. We focus here on backness harmony, which requires suffix forms to agree in backness with vowels and certain consonants within a root.

	Front		Back	
	Unrounded	Round	Unrounded	Round
High	i	**y**		**u**
Mid	e	**ø**		**o**
Low	**æ**		**ɑ**	

Table 6.1: The Uyghur vowel system. Harmonizing vowels are in bold.

	Front	Back
Voiceless	k	q
Voiced	g	ʁ

Table 6.2: The harmonizing Uyghur dorsal consonants

The Uyghur vowels are shown in Table 1. The vowels behave as front or back as specified in the table, with the exception of /i/ and /e/, which are transparent to harmony processes (Lindblad, 1990; R. F. Hahn, 1991b).[4] We refer to /i/ and /e/ as *transparent* vowels, and the remainder of the vowels as *harmonizing* vowels. A subset of the dorsal consonants, shown in Table 2, also participate in backness harmony as both triggers and undergoers, with velars patterning with front vowels, and uvulars patterning with back vowels.[5]

Native Turkic roots tend to be harmonious with respect to backness. This is not an absolute requirement for roots, however, and disharmonious roots are especially common in loanwords (e.g. /pæmidur/ 'tomato'). Such roots play a particularly interesting role in harmony processes.

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[4]Note that these vowels are the only ones in the system that have no counterparts differing only in backness. Because /e/ only occurs in loanwords and as the result of certain phonological processes, we focus primarily on /i/ throughout the chapter.

[5]The velar sounds /χ/ and /ŋ/ do not harmonize.

The segments of a large class of Uyghur suffixes are underlyingly unspecified for backness. These suffixes take on the back feature of the roots they attach to. We will use the locative case marker /-DA/ as a representative example throughout the chapter, but similar patterns occur with many other suffixes.

Form	Gloss	Harmony type	
ɑpæt-**tæ** custom-LOC	"in the custom"	Closest front vowel	(6.3)
qojʧi-**dɑ** shepherd-LOC	"on the shepherd"	Closest back vowel	(6.4)
gezit-**tæ** newspaper-LOC	"on the newspaper"	Closest front dorsal	(6.5)
qirʁiz-**dɑ** Kyrgyz-LOC	"on the Kyrgyz"	Closest back dorsal	(6.6)
rɑk-**tɑ** cancer-LOC	"on the cancer"	Closest back vowel across front dorsal	(6.7)
mæʃq-**tæ** exercise-LOC	"on the exercise"	Closest front vowel across back dorsal	(6.8)

Table 6.3: Examples of Uyghur backness harmony. The alternating suffix is indicated in bold, and the harmony triggers are underlined.

The examples in Table 6.3 provide a representative characterization of the pattern. Each example has a corresponding description of the particular type of harmony it illustrates. We refer back

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to these examples throughout the chapter.

The voicing alternation of the initial segment in the suffix is not important, but note crucially that the vowel changes from front to back depending on the root. The general process for determining the backness value of the suffix is as follows:

1. Match the backness of the final harmonizing vowel in the root. In Example (6.3) the root is treated as a front root even though it contains both front and back vowels because the final harmonizing vowel /æ/ is front. In Example (6.4), the root is treated as a back root because the final harmonizing vowel /o/ is back, despite the intervening transparent vowel.

2. If the root has no harmonizing vowels, find the final dorsal consonant in the root and match its backness. Note that in Example 6.5, the root is treated as front even though it has only transparent vowels because the root contains /g/, while in Example 6.6 the root is treated as back because of its uvulars.

Harmonizing vowels always take precedence over harmonizing dorsals, as Examples 6.7 and 6.8 show. In these examples the harmonizing vowel determines the form of the suffix, even though a dorsal with the opposite backness intervenes. The process of only falling back on consonants to determine suffix backness when insufficient information from vowels is available is the cause of the difficulties for TSL, as we will see in the next section.

Form	Gloss	Harmony type	
it-**tɑ** dog-LOC	"on the dog"	No harmonizers, arbitrarily back	(6.9)
biz-**dæ** we-LOC	"on us"	No harmonizers, arbitrarily front	(6.10)

Table 6.4: Examples of roots with arbitrary backness specification. The alternating suffix is indicated in bold.

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Words with no harmonizing vowels or dorsals are arbitrarily specified for backness.[6] This is shown in Table 6.4. Such roots are theoretically problematic, but we will set them aside for now and return to them in Section 6.11.

6.3 Uyghur backness harmony is not TSL

In this section we focus on the pattern involving harmonizing vowels and dorsals described above. We do not attempt to model roots with no harmonizing elements, nor apparent exceptions to the pattern, like those described in Chapter 3.

Because the actual segmental content is not of crucial importance, we use a more abstract notation to simplify the specification of the grammars. V_f and V_b refer to the sets of front and back harmonizing root vowels.

$$V_f = \{\text{y, ø, æ}\} \tag{6.11}$$

$$V_b = \{\text{u, o, ɑ}\} \tag{6.12}$$

C_f and C_b refer to the sets of front and back harmonizing dorsal root consonants.

$$C_f = \{\text{k, g}\} \tag{6.13}$$

$$C_b = \{\text{q, ʁ}\} \tag{6.14}$$

We use the symbols S_f and S_b to refer to the sets of front and back suffix forms.

These symbols comprise an alphabet $\Sigma_h = \{V_f, V_b, C_f, C_b, S_f, S_b\}$. I define a homomorphic mapping function $h : \Sigma^* \mapsto \Sigma_h^*$ that converts strings from the full Uyghur alphabet (including morpheme boundaries) to the notation described above (i.e., it maps root symbols individually according to the definitions in (6.11) to (6.14), entire suffixes to S_f or S_b, and all other sounds to the empty string λ).

Uyghur backness harmony can be characterized succinctly with the following regular expression, which picks out licit strings. The class of regular languages is closed under homomorphism.

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[6]There is a statistical tendency for such roots to be treated as back.
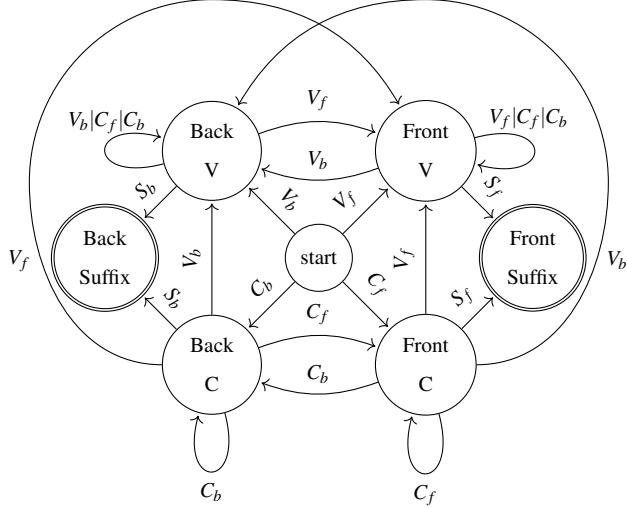
Figure 6.2: An FSA that generates Uyghur backness harmony.

The following regular expression captures licit forms under backness harmony.

$$\overline{((S_f|S_b)^*V_f\overline{(V_b|S_f|S_b)}^*S_f)|(\overline{(S_f|S_b)}^*V_b\overline{(V_f|S_f|S_b)}^*S_b)|(\overline{(V_f|V_b|S_f|S_b)}^*C_fC_f^*S_f)|(\overline{(V_f|V_b|S_f|S_b)}^*C_bC_b^*S_b)}$$
(6.15)

A finite-state automata representation of the regular expression in (6.15) is shown in Fig. 6.2.

Thus it is clear that this pattern is at most regular.

6.4 Challenges for TSL

In this section we will show that Uyghur backness harmony as described in (6.15) cannot be captured using TSL grammars, but first we must comment on the choice of notation. Although the set of regular languages is closed under relabeling, the set of SL (and hence TSL) languages is not. For example, the language $(ab)^*$ is SL, but its image under the relabeling $\{a \mapsto c, b \mapsto c\}$, $(cc)^*$, is not SL. To avoid an increase in generative capacity, we apply this relabeling to the *grammar* rather than the language. In other words, the relabeling is applied to the *k*-factors defined in the grammar, and the resulting grammar filters out candidate strings in the image of that relabeling. This provably results in no increase in generative capacity so long as the mapping is many-to-one, as it is here (Aksënova, Graf, & Moradi, 2016).

To deal with the vowel component, we can define a grammar over the tier

$$T_v = V_f \cup V_b \cup S_f \cup S_b \tag{6.16}$$

containing the following illicit 2-factors:

$$V_f S_b \tag{6.17}$$

$$V_b S_f \tag{6.18}$$

These factors rule out forms like *[ɑpæt-tɑ] and *[qojtʃi-dæ].

Harmony with dorsals can be captured by defining a grammar over the tier

$$T_c = C_f \cup C_b \cup S_f \cup S_b \tag{6.19}$$

containing the following illicit 2-factors:

$$C_f S_b \tag{6.20}$$

$$C_b S_f \tag{6.21}$$

These factors rule out forms like *[gezit-tɑ] and *[qirʁiz-dæ]. Thus 2-TSL grammars can capture the vowel and consonant patterns in isolation.

The difficulty arises when combining these two patterns into a single TSL grammar. Because harmonizing dorsal and vowel information must be considered simultaneously, we must define a grammar over a tier that contains both the relevant dorsals and vowels:

$$T = T_v \cup T_c \tag{6.22}$$

The grammar over T must be able to look to the beginning of the string to check for the presence of harmonizing vowels. We extend T to contain $\rtimes$ and use $C = C_f \cup C_b$ for the sake of brevity. Suppose we define k-factors over T for some fixed k of the following form:

$$V_b C^{k-2} S_f \tag{6.23}$$

$$V_f C^{k-2} S_b \tag{6.24}$$

$$\rtimes C^{k-3} C_b S_f \tag{6.25}$$

$$\rtimes C^{k-3} C_f S_b \tag{6.26}$$

(6.23) and (6.24) try to capture harmony with vowels, while (6.25) and (6.26) try to capture cases with only harmonizing dorsals. These cannot work for all possible forms. Consider the following word on T:

$$w = V_b C_f^{k-1} S_f \tag{6.27}$$

This word, which has a mismatch between the final vowel and suffix form, will be erroneously included because the number of post-vowel dorsal consonants is too large for the k-factors to see both the vowel and suffix form at the same time. Checking for the absence of harmonizing vowels is bounded by k under suffix substitution closure, and therefore a TSL grammar over a tier containing both harmonizing dorsals and vowels cannot capture this pattern for arbitrary values of k, placing it outside of TSL.

Form	Gloss	T_v	T_c	Harmony type	
rɑ̠k-**tɑ** cancer-LOC	"on the cancer"	$V_b S_b$	$C_f S_b$	Closest back vowel across front dorsal	(6.28)
mæ̠ʃq-**tæ** exercise-LOC	"on the exercise"	$V_f S_f$	$C_b S_f$	Closest front vowel across back dorsal	(6.29)

Table 6.5: Examples of Uyghur backness harmony over intervening, conflicting dorsals. The alternating suffix is indicated in bold, and the harmony triggers are underlined.

Another possibility for capturing this pattern is to use the intersection of the TSL languages on T_v and T_c defined in (6.16)–(6.18) and (6.19)–(6.21) respectively. The class of TSL languages is not closed under intersection, and the resulting language falls in the class of multi-tier strictly local languages (MTSL), which properly contains the class of TSL languages (de Santo & Graf, 2017). Even this more powerful formalism cannot capture this pattern. The difficulty arises from the fact that violations on T_c should be ignored unless neither V_f nor V_b appear in T_v. Consider again

examples (6.7) and (6.8), which we repeat in Table 6.5 along with their tier-based representations.

Violations on one tier cannot be overlooked given the contents of another, so this grammar rules both (6.28) and (6.29) as illicit because they are ill-formed on T_c. It would rule them ill-formed on T_v if suffixes of the opposite backness were used. Thus Uyghur backness harmony is also not MTSL.

6.5 Challenges for other subregular language classes

The previous section showed that neither TSL nor MTSL grammars can capture the pattern in (6.15). We focused on these classes because they have received the most consideration as possible subregular upper bounds for phonotactic complexity. In this section we will sketch the arguments that the other subregular classes of languages that have been applied to phonology, including more expressive extensions of TSL, do not contain this pattern. We do not provide formal definitions of these language classes here, but refer the reader to previous work.

6.5.1 Uyghur backness harmony is not SS-TSL or SS-MTSL

Structure sensitive tier-based strictly local (SS-TSL) languages generalize the tier-projection process used in TSL (de Santo & Graf, 2017). TSL uses a 1-Input Strictly Local (1-ISL) projection, meaning that the projection function considers each segment in isolation (i.e., whether that segment is a member of T; Chandlee, 2014). SS-TSL generalizes this projection to a k-ISL projection, which means the projection function can consider a window of size k around the target segment. For example, we may define a SS-TSL grammar that will project a segment a to a tier only when it is immediately followed by segment b, but not otherwise. Structure sensitive multi-tier strictly local languages (SS-MTSL) are the intersection of multiple SS-TSL languages.

Intuitively, one might try to capture the Uyghur pattern by projecting harmonizing dorsals only when they are not preceded by a harmonizing vowel. It is easy to show using the suffix substitution closure property discussed at the end of Section 6.1 that cannot work for all forms. Assume a 2-SS-TSL grammar that includes the illicit 2-factor $C_b S_f$. Assume also that the projection function

is k-ISL for some k, with the target segment falling into the final slot in the window (i.e., the context we consider is the target segment plus the preceding $k-1$ segments). The string $V_f C_b^k S_f$ will be excluded from this language even though it is a valid Uyghur word because the last of the k occurrences of C_b will be projected onto the tier. SS-MTSL fails for the same reason.

6.5.2 Uyghur backness harmony is not PT or SP

Piecewise testable (PT) grammars are an extension of strictly piecewise (SP) grammars. SP grammars are similar to SL grammars but prohibit *subsequences* (i.e., precedence relations between segments) rather than substrings (Simon, 1975). PT languages are the closure of SP languages under the Boolean operators $\land$ and $\neg$ (Rogers et al., 2013). Informally, these grammars extend SP with the ability to *require* some subsequence be present in a string.

Even the basic vowel harmony pattern cannot be captured by a PT language. The intuition behind this is that the backness of suffixes is determined by the immediately preceding harmonizing vowel, but PT languages cannot precisely capture the order in which vowels occur. For example, $V_f V_b S_b$ and $V_b V_f S_b$ both contain the subsequences $V_f S_b$ and $V_b S_b$, but the first is a legal word while the second is not. We can show this more formally using the following theorem (Rogers et al., 2013):

Theorem 2 (*k-Subsequence Invariance*). *A language L is Piecewise Testable iff there is some $k \in \mathbb{N}$ such that for all strings x and y, if x and y contain the same set of subsequences of length k or less, then either $x \in L$ and $y \in L$ or $x \notin L$ and $y \notin L$.*

Consider the following pair of words for some $k \in \mathbb{N}$:

$$w_1 = (V_f V_b)^k S_b \tag{6.30}$$

$$w_2 = (V_b V_f)^k S_b \tag{6.31}$$

These words contain the same subsequences of length k or less,[7] but w_1 is a valid word while

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[7]This can be shown by induction: both words contain the same subsequences when $k = 1$, and the subsequences added with each increase in k will be the k-subsequences generated by prepending V_f or V_b to all subsequences of length $k-1$.

w_2 is not. Thus even the simplest subcase of Uyghur backness harmony is not PT, and since PT properly contains SP, it is also not SP.

6.5.3   Uyghur backness harmony is not LTT or LT

Locally threshold testable (LTT) grammars are an extension of locally testable (LT) grammars. LT languages are the closure of the SL languages under the Boolean operators $\wedge$ and $\neg$ (Rogers & Pullum, 2011; Rogers et al., 2013). Informally, these grammars extend SL with the ability to *require* some element be present in a string. LTT languages are the closure of LT languages under the first order logic operators $\forall$ and $\exists$, which quantify over position indices (Rogers & Pullum, 2011; Rogers et al., 2013). Indices can be compared for equality and successorship. Informally, this extension allows LTT grammars to count the number of occurrences of each k-factor up to a certain threshold.

It is simple to show that Uyghur backness harmony as described in (6.15) is outside of LTT by appealing to the following theorem (Rogers et al., 2013):

Theorem 3 (Local Threshold Test Invariance). *A language L is Locally Threshold Testable iff there is some $k \in \mathbb{N}$ and some threshold $t \in \mathbb{N}$ such that, for all strings x and y, if for any k-factor w, x and y contain the same number of occurrences of w or have at least t occurrences, then either $x \in L$ and $y \in L$ or $x \notin L$ and $y \notin L$.*

Consider the following two words for some $k \in \mathbb{N}$:

$$w_1 = (C_f)^{k-1}V_b(C_f)^{k-1}V_f(C_f)^{k-1}S_f \tag{6.32}$$

$$w_2 = (C_f)^{k-1}V_f(C_f)^{k-1}V_b(C_f)^{k-1}S_f \tag{6.33}$$

Both have the same number of occurrences of every k-factor, but w_1 is a valid Uyghur word while w_2 is not. Therefore Uyghur backness harmony is not LTT, and since LTT properly contains LT, it is also not LT.

6.5.4 Uyghur backness harmony is not IBSP

Interval-based strictly piecewise (IBSP) grammars are an extension of SP grammars that allow *k*-subsequences to be defined over a particular interval, such as a word or a prosodic phrase (Graf, 2017). The set of IBSP languages properly contains both TSL and SP languages, and is properly contained by the star-free languages. Uyghur backness harmony is a word-level process, and an IBSP grammar that is defined over words will encounter the same issues as the PT and SP grammars described above. We can think of no interval below the word that is able to avoid these problems, and so we conjecture that Uyghur backness harmony is not IBSP.

6.6 A formal upper bound for Uyghur backness harmony

The pattern in (6.15) can be captured by the non-counting (NC) or star-free languages, which are the most expressive subregular language classes (McNaughton & Papert, 1971). NC grammars allow the use of the first order logic operators $\exists$ and $\forall$, which quantify over position indices in the string. Indices can be compared for equality, using the $\approx$ operator, and precedence, using the $<$ operator. Predicates over indices $P(x)$ are true if the symbol at index x is P. All of the language classes described above are properly contained by the class of NC languages.

The following expressions define a NC grammar that captures licit forms under Uyghur backness harmony.

$$\forall x[S_b(x) \Rightarrow \forall y[V_f(y) \Rightarrow \exists z[V_b(z) \wedge y < z < x]]] \tag{6.34}$$

$$\forall x[S_f(x) \Rightarrow \forall y[V_b(y) \Rightarrow \exists z[V_f(z) \wedge y < z < x]]] \tag{6.35}$$

$$\forall x[S_b(x) \wedge \neg \exists y[V_f(y) \vee V_b(y)] \Rightarrow \forall z[C_f(z) \Rightarrow \exists w[C_b(w) \wedge z < w < x]]] \tag{6.36}$$

$$\forall x[S_f(x) \wedge \neg \exists y[V_f(y) \vee V_b(y)] \Rightarrow \forall z[C_b(z) \Rightarrow \exists w[C_f(w) \wedge z < w < x]]] \tag{6.37}$$

The first two expressions require suffixes to match the backness of the final harmonizing root vowel. The latter two require suffixes to match the backness of the final harmonizing root dorsal if there are no harmonizing root vowels.

Although further weakening the weak subregular hypothesis to include NC languages captures

the data presented above, this is not a desirable result from the perspective of learnability. It has been shown that TSL languages are efficiently learnable in polynomial time from polynomial data (Heinz, Kasprzik, & Kötzing, 2012; Jardine & Heinz, 2016; Jardine & McMullin, 2017), while NC languages are not (Gold, 1967). This makes theories of phonological learning somewhat more problematic. Below we briefly sketch a proposal for a new subregular class that is less powerful than the NC class but still sufficient to capture this pattern.

6.7 O-TSL

A generalization of TSL called output tier-based strictly local (O-TSL), can capture Uyghur backness harmony (Graf & Mayer, 2018; Burness & McMullen, 2019). SS-TSL generalizes the projection function of TSL from a 1-ISL map to a k-ISL map. The class of 1-ISL maps is identical to the class of 1-output strictly local (1-OSL) maps, meaning the TSL projection function could be equally characterized as a 1-OSL function (Chandlee, 2014). O-TSL generalizes the projection mechanism to be k-OSL. This allows the tier projection function to consider material already on the tier when choosing whether to project a segment from the input. Burness and McMullen (2019) demonstrate that 2-OTSL languages are learnable in polynomial time from positive data.

The pattern in (6.15) requires a 2-OSL projection function that behaves as follows: V_f, V_b, S_f, and S_b are always projected, while C_f and C_b are only projected if the previous symbol is not V_f or V_b. In other words, we stop adding dorsals to the tier as soon as we encounter a harmonizing vowel. 2-factors defined over this tier would simply check for backness mismatches between the suffix and the preceding symbol.

Because IO-TSL (Graf & Mayer, 2018) is a more general case of O-TSL, it too can capture Uyghur backness harmony.

6.8 Backness harmony as a transformation

Although Uyghur backness harmony is unexpectedly complex when considered as a constraint on licit word forms, that is, a model of a stringset, it is computationally simple when considered

as a transformation from underlying to surface forms (e.g., Heinz, 2018). As a transformation, backness harmony can be captured using a fairly simple left subsequential function (e.g., Heinz & Lai, 2013; Chandlee, 2014). I will not present the corresponding subsequential transducer here, but it is similar in structure to the FSA shown in Fig. 6.2. From this perspective of transformations, the pattern in Uyghur is computationally simpler than other types of attested vowel harmony, such as dominant-recessive or stem-control systems, which are *weakly deterministic* (Heinz & Lai, 2013; Meinhardt, Mai, Baković, & McCollum, 2020), and systems like Tutrugbu ATR harmony, which is non-deterministic (McCollum, Baković, Mai, & Meinhardt, 2020). I leave the significance of this divergence in complexity between stringset and transformational representations of Uyghur backness harmony as an interesting question for future research.

6.9   Revisiting the data

Although we can define more powerful formalisms that allow Uyghur backness harmony to be modeled using formal language theory, this is not particularly desirable. An O-TSL grammar can capture Uyghur backness harmony (and is learnable in polynomial time), but the artificial grammar learning results from McMullin (2016); McMullin and Hansson (2019) suggest that this pattern may prove difficult for human learners. In addition, the relative scarcity of segmental patterns that appear to be beyond TSL should cause us to treat this data with skepticism. The next few sections aim to provide a more precise empirical description of the pattern so we can revisit the computational analysis.

6.10   An analysis without transparent vowels

The issues this pattern poses for TSL representations hinge on backness being determined first from vowels, and then from consonants if the vowels prove insufficiently informative. A possible alternative analysis that is compatible with a TSL representation is that Uyghur in fact has no transparent vowels. Rather, there are two different surface versions of /i/ and /e/ which are not reflected in the orthography or in past descriptions of the phonology, one of which is front and

one of which is back. We represent the back variants as /ɯ/ and /ɤ/ respectively, and refer to the pairs as /I/ and /E/ when backness is not important. Such an analysis makes the 2-factors defined over T_v in the previous section sufficient to capture Uyghur backness harmony: V_f now includes /i/ and /e/, and V_b includes /ɯ/ and /ɤ/, so no reference to consonants is necessary. This account is supported by historical evidence: Uyghur once had a distinction between the front and back unrounded vowels /i/-/ɯ/ as in Turkish, but these vowels have since collapsed into /i/ (Lindblad, 1990; R. F. Hahn, 1991a, see previous chapters for a more detailed description of the diachronic development of this contrast).

Under this formulation, /I/ and /E/ are underlying specified as [+/− back]. This allows us to tidily capture forms like (6.9) and (6.10), which no longer need to be arbitrarily specified as front or back, but now select their suffix based on the quality of the final vowel, as below:

ɯt-**tɑ**	"on the dog"	(6.38)
dog-LOC		

biz-**dæ**	"on us"	(6.39)
we-LOC		

The generalization that suffixes tend to match the backness of the final harmonizing vowel in the root, or, if these are lacking, the final dorsal, can be captured by co-occurrence restrictions: /I/ and /E/ must agree in backness with the nearest harmonizing vowel or dorsal, which gives the appearance of suffixes harmonizing with consonants. Thus we can reanalyze (6.4), (6.5), and (6.6) as below.

qojtʃɯ-**dɑ**	"on the shepherd"	(6.40)
shepherd-LOC		

gezit-**tæ**	"on the newspaper"	(6.41)
newspaper-LOC		

qɯrʁɯz-**dɑ**	"on the Kyrgyz"	(6.42)
Kyrgyz-LOC		

In sum, this approach allows us to determine suffix backness by looking only at the final vowel in the root, which is always specified for backness. This removes the need for a dorsal consonant tier,

and allows this pattern to be captured easily by the TSL grammar over T_v described in the previous section.

For reasons discussed earlier in this dissertation, we do not pursue this analysis further. Chapter 4 demonstrates based on wug test responses that speakers do indeed treat uvulars as back triggers, even in roots with no transparent vowels, and Chapter 5 demonstrates that there is no difference in vowel backness between neutral roots that take front suffixes and those that take back.

6.11 Uyghur backness harmony as a lexicalized process

The characterization of Uyghur backness harmony in Sections 6.2 and 6.4 is incompatible with the theory that all phonological stringsets are TSL languages. A major theme of this dissertation, however, has been that lexicalization plays an important role in the backness harmony system: it governs opaque behavior (Chapter 3), obscures phonetic learning biases that come out in wug tests (Chapter 4), and is responsible for determining the harmonic behavior of roots that do not contain harmonizing elements (Chapter 5) or harmonize idiosyncratically (Chapter 3 and Appendix A). One might reasonably ask whether this degree of lexicalization can reconcile the weak subregular hypothesis with the complexity of the pattern in Uyghur: that is, whether the productive grammar learned by Uyghur speakers is less complex than the patterns in attested words.

Under a lexicalized account of backness harmony, all roots are specified lexically as taking either front or back suffixes (or, put in a slightly different way, speakers simply memorize which roots take which suffixes). This pattern is easily captured using a TSL grammar, and is consistent with the hypothesis that morphotactic processes are also maximally TSL (Aksënova et al., 2016). Such an account does not suggest that there is no phonological component to backness harmony. As Chapter 4 demonstrates, speakers also learn the phonological properties of roots associated with each harmony class, and use these to generalize to new root forms.

Positing a lexicalized or morphological process over a phonological one is often based on the complexity of the phonological analysis required to capture the pattern, particularly regarding learnability. Such analyses often require underlying forms that differ substantially from any surface form, baroque interactions between independent processes (e.g., rules or constraints), and

Active	Passive	Gloss
ɸeɾa	ɸeɾahia	'to spread'
oma	omaki	'to run'
inu	inumia	'to drink'
eke	ekeŋia	'to climb'
tupu	tupuɾia	'to grow'
aɸi	aɸitia	'to embrace'
huna	hunaia	'to conceal'
kata	kataina	'to laugh'
ako	akona	'to teach'
heke	hekea	'to descend'

Table 6.6: Maori passives

some way to capture inconsistent generalizations and variation within or between speakers. Examples include French liaison (e.g., Bybee, 2001), Polish /o/-/u/ alternation (Sanders, 2003), irregular English past tense morphology (Albright & Hayes, 2003), and possessive prefixes in Odawa (Bowers, 2015). Such cases have two common themes, both of which are relevant to Uyghur. First, these processes typically originated as predictable and productive phonological patterns that were subsequently obscured by diachronic change. This led to a reanalysis by language learners, since insufficient evidence was available to reconstruct the original pattern. Second, in the absence of reliable structural cues, speakers tend to rely on statistical generalizations to determine the appropriate surface realization in unfamiliar cases.

We focus on Maori passives as a representative example. This was first raised as a challenge for phonological analysis by Hale (1968) and has been written on extensively since (see ʻŌiwi Parker Jones, 2008, for an excellent overview). Table 6.6 (from ʻŌiwi Parker Jones, 2008) shows a sample of Maori passive forms.

This pattern developed as the result of all word-final consonants being lost in unsuffixed forms, but maintained in medial position when the passive suffix /-ia/ is present. A phonological analysis must either make reference to properties of the roots that systematically predict particular suffix

forms (which are not obvious) or assume the presence of word-final consonants underlyingly and a process of surface deletion. Even in the latter case, bizarre assumptions are often required to support this analysis, such as Hale's suggestion that there is an underlying /p/ at the end of certain forms that is never realized in *any* surface form (Hale, 1968). There is also evidence that these passive forms have been analyzed as separate, competing allomorphs by speakers, with /-tia/ coming to be preferred as the default but substantial free variation possible within and between speakers. Statistical analysis also shows that the suffix form can be predicted reasonably well from subtle properties of the root, suggesting that speakers may be sensitive to statistical generalizations when choosing the appropriate suffix ('Ōiwi Parker Jones, 2008).

Uyghur backness harmony shares many of the properties of the Maori passive system. Disharmonic roots tend to be mostly loanwords or compounds, suggesting an increase in such roots as more foreign words entered the language. Similarly, as described earlier, historical Uyghur once had a distinction between the front and back vowels /i/-/ɯ/ that collapsed into /i/, eliminating the backness contrast that would have determined the suffix of many of the problematic forms discussed here (Lindblad, 1990; R. F. Hahn, 1991a). As demonstrated by the responses of the participants in Chapter 5, there is also inter-speaker variation on which suffixes certain forms take.

The question that remains here is whether lexicalization is also responsible for the apparent mathematical complexity of the pattern: that is, can we determine whether speakers learn a productive grammar that is computationally simpler? The next chapter will address this issue using an extension of TSL to represent the gradient responses found in the wug test data presented in Chapter 4.

6.12   Discussion and conclusion

A motivation that is commonly put forward for studying phonological processes through the lens of formal complexity is that it serves as a sort of meta-language that allows a detailed characterization of the data that is agnostic to any particular theory. This in turn provides clear requirements for the expressive and restrictive capabilities of any theory leveled at the data (e.g., Rogers & Pullum, 2011; Heinz, 2018). If generalizations about the formal complexity of phonological patterns are

taken to be indicative of a learning bias towards patterns in a particular subregular region, formal language theory may also be used to upper bounds on the complexity of patterns that can be effectively learned (e.g., Lai, 2015; McMullin, 2016; McMullin & Hansson, 2019). In this chapter we presented a pattern that is a challenge for current hypotheses about how complex phonological stringsets may be.

We first showed that the pattern of root-suffix backness harmony in Uyghur cannot be generated by a tier-based strictly local grammar, nor by *any* of the subregular language classes previously applied to phonology except the powerful IO-TSL and star-free classes. This is problematic for the weak subregular hypothesis, which claims that all phonological stringsets are maximally TSL. We then briefly touched on an alternative analysis that suggests the pattern is phonological and contained solely on the vowel tier, but rejected it for reasons given in Chapter 5. Finally, we suggested that if backness harmony is indeed a lexicalized process, this could be consistent with the idea that TSL languages provide an approximately correct upper bound on phonological learnability. To demonstrate this, we would need to show that the productive pattern of backness harmony learned by speakers is computationally simpler than the pattern demonstrated in attested forms. This question is taken up in the next chapter.

In addition to the simple presentation of this data as a challenging case for subregular phonology, we hope that we have illustrated how theories of formal complexity can serve as useful conceptual tools in addition to those traditionally employed by phonologists.

CHAPTER 7

Capturing gradience in long-distance phonology using probabilistic tier-based strictly local grammars

7.1   Introduction

Subregular phonology attempts to find proper subclasses of the finite-state languages and transductions that are sufficiently powerful to model natural language phenomena (see Heinz, 2018). These models provide a strong mathematical foundation for phonological analysis, establish tighter bounds on the range of observed cross-linguistic variation, and have implications for theories of phonological learning (e.g., Lai, 2015; McMullin, 2016; McMullin & Hansson, 2019).

The class of *tier-based strictly local languages* (TSL; Heinz et al., 2011) has proven useful for modeling long-distance phonotactic phenomena that more restricted classes like the *strictly local languages* (SL) cannot. Grammars that generate the TSL languages remove all symbols from input strings that do not belong to a specified subset of the alphabet before identifying phonotactic violations, allowing non-local dependencies to be regulated in a local manner.

Long-distance phonology frequently exhibits *gradience*, both in response frequencies and in speaker acceptability judgments (e.g., Albright & Hayes, 2003; Daland et al., 2011; Zuraw & Hayes, 2017, a.o.). This gradience often manifests as *distance-based decay*, where long-distance dependencies hold less strongly as the amount of irrelevant material between relevant segments increases. While several accounts of distance-based decay (e.g., Kimper, 2011; Zymet, 2014) have been presented in the framework of Optimality Theory (Prince & Smolensky, 1993/2004), to my knowledge none have been presented using models from subregular phonology.

Developing a formal language model that is able to represent this kind of gradience will allow

us to address a question raised in the previous chapter: do Uyghur speakers learn a productive grammar for backness harmony that is computationally simpler than the pattern displayed in attested words? If this is the case, it will provide evidence for the weak subregular hypothesis (Heinz, 2018), which suggests that all phonological markedness patterns can be captured by TSL grammars.

This chapter presents *probabilistic tier-based strictly local* (pTSL) grammars, a natural extension of TSL that probabilizes the projection function used to construct tier representations. This allows the conditional probability of any grammatical projection given an input string to be assigned in a way that permits gradience in long-distance patterns to be captured without an explicit notion of distance (see McMullin, n.d., for a similar observation) and presents a unified account of distance-based decay with other types of blocking. This method of probabilizing the projection function may also be applied with minimal modifications to other extensions of TSL, such as MTSL and SS-TSL/IO-TSL (e.g., de Santo & Graf, 2017; Graf & Mayer, 2018).

The chapter is structured as follows. Section 7.2 provides background on the SL and TSL classes. Section 7.3 defines pTSL and discusses some of its properties, including its relationship to TSL. Sections 7.4 and 7.5 apply pTSL models to vowel harmony in Hungarian and Uyghur, demonstrating that these models can effectively capture speaker judgments and production frequencies in an interpretable way, while also discussing some shortcomings of the model. Section 7.6 summarizes the chapter, proposes several natural extensions of pTSL that overcome its limitations, and explores the implications from the Uyghur data for the existence of learning biases towards computationally simpler patterns.[1]

7.2 Background

7.2.1 Strictly local languages

ε denotes the empty string and S^* the Kleene closure of the set S. S^k denotes the proper subset of S^* that only contains strings of length k, and s^k represents a string consisting of k occurrences of

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[1]Companion software to this chapter can be found at `https://github.com/connormayer/pTSL`.

the symbol s.

Let Σ be some fixed alphabet and $s \in \Sigma^*$. The set $f_k(s)$ of *k-factors* of s consists of all the length-k substrings of $\rtimes^{k-1} s \ltimes^{k-1}$, where $\rtimes, \ltimes \notin \Sigma$ and $k \geq 1$. For example, $f_2(ababac) = \{\rtimes a, ab, ba, ac, c\ltimes\}$.

Definition 1. A *strictly k-local grammar* is a set $G \subseteq (\Sigma \cup \{\rtimes, \ltimes\})^k$. A stringset $L \subseteq \Sigma^*$ is *strictly k-local* (SL-k) iff there is some strictly k-local grammar G such that $L = \{s \in \Sigma^* \mid f_k(s) \cap G = \emptyset\}$.

Intuitively, G defines a *grammar* of forbidden substrings that no well-formed string may contain. The class SL of strictly local stringsets is $\bigcup_{k \geq 1}$ SL-k.

Example 1. Consider a language with the following stress pattern: (a) words must have primary stress on the final syllable; (b) words must contain exactly one syllable with primary stress.

Assuming $\Sigma := \{\acute{\sigma}, \sigma\}$, this pattern can be generated using the SL-2 grammar $G := \{\acute{\sigma}\acute{\sigma}, \acute{\sigma}\sigma, \sigma\ltimes, \rtimes\ltimes\}$, and thus is SL-2. For example, the string $\acute{\sigma}\sigma$ is illicit because $f_2(\acute{\sigma}\sigma) \cap G = \{\acute{\sigma}\sigma, \sigma\ltimes\} \neq \emptyset$, whereas the string $\sigma\acute{\sigma}$ is licit because $f_2(\sigma\acute{\sigma}) \cap G = \emptyset$.

7.2.2 Tier-based strictly local languages

For every $T \subseteq \Sigma$, a *simple tier projection* π_T is a transduction that deletes all symbols not in T:

$$\pi_T(\varepsilon) := \varepsilon$$

$$\pi_T(\sigma u) := \begin{cases} \sigma \pi_T(u) & \text{if } \sigma \in T \\ \pi_T(u) & \text{otherwise} \end{cases}$$

where $\sigma \in \Sigma$ and $u \in \Sigma^*$.

Definition 2. A *tier-based strictly k-local* (TSL-k) grammar over an alphabet Σ is a tuple (T, G), where $T \subseteq \Sigma$ and $G \subseteq (T \cup \{\rtimes, \ltimes\})^k$. A stringset $L \subseteq \Sigma^*$ is TSL-k iff there exists a TSL-k grammar such that $L = \{s \in \Sigma^* \mid f_k(\pi_T(s)) \cap G = \emptyset\}$. It is TSL iff it is TSL-k for some k.

In other words, TSL languages are string languages that are SL once one masks out all irrelevant symbols or, alternatively, languages that are SL over a *tier* to which a subset of relevant symbols are projected (cf. Goldsmith, 1976).

Example 2. Consider a language over the alphabet $\Sigma := \{\acute{\sigma}, \sigma\}$ such that words must contain exactly one syllable with primary stress (i.e., exactly one $\acute{\sigma}$). This language cannot be characterized by any SL-k grammar: for example, for any value of k we can produce strings of the form $\acute{\sigma}\sigma^{k-1}\acute{\sigma}$, which violate the restriction on multiple primary stresses but cannot be prohibited by a SL-k grammar because the window of length k is not large enough to "see" both stresses at the same time.

We can define a TSL-2 grammar that accepts this language. Let $T := \{\acute{\sigma}\}$ and $G := \{\rtimes\ltimes, \acute{\sigma}\acute{\sigma}\}$. Any illicit string of the form $\acute{\sigma}\sigma^*\acute{\sigma}$, for instance, will first be projected to $\acute{\sigma}\acute{\sigma}$. This projection will be rejected because $f_2(\acute{\sigma}\acute{\sigma}) \cap G = \{\acute{\sigma}\acute{\sigma}\} \neq \emptyset$.

7.3 Probabilistic tier-based strictly local languages

7.3.1 Probabilistic tier projection functions

Definition 3. A discrete probabilistic function $f : X \to (Y \to [0,1])$ assigns to each $x \in X$ a conditional probability distribution over the set Y. For a particular x, $\sum_{y \in Y} f(x)(y) = 1$.

The simple tier projection function π_T discussed in the previous section can be generalized to a *probabilistic tier projection function* $\pi_P : \Sigma^* \to (\Sigma^* \to [0,1])$. This is a discrete probabilistic function that, given a string, returns a probability distribution over projections of that string to a tier. π_T can be thought of as a special case of π_P where a single output has a probability of 1 and all other outputs have a probability of 0.

The distribution over outputs given an input is calculated based on probabilities associated with projecting individual symbols. Let $P_{proj} : \Sigma \to [0,1]$ represent the probability that a symbol in Σ is projected to the tier: for example, $P_{proj}(a) := 0.5$ indicates that there is a 50% chance that each a symbol will be projected.

We may notate a sequence of symbols x as $(x_n)_{n \in I}$ where I is the *index set* of the sequence. A sequence y that is a subsequence of x can be written $(y_n)_{n \in J}$ where $J \subseteq I$. Using this notation, we can define the probability of projecting a particular string $y \in \Sigma^*$ from the input $x = (x_n)_{n \in I}$ as

follows:

$$\pi_P(x)(y) := \sum_{J \in J'} \left[\prod_{k \in J} P_{proj}(x_k) \cdot \prod_{k \in I \setminus J} \left[1 - P_{proj}(x_k) \right] \right]$$

where

$$J' := \{ J \in \mathscr{P}(I) \,|\, (x_n)_{n \in J} = y \}$$

and $\mathscr{P}(I)$ is the powerset of I. That is, we calculate the probability of projecting the output y given the input x by summing the probabilities of all subsequences of x that are equal to y. The probability of each of these subsequences is the product of the probabilities associated with projecting each symbol that is projected and with not projecting each symbol that is not projected. Any y that is not a subsequence of x will receive a probability of zero. The probabilities of all possible projections for an input string x sum to one:

$$\sum_{y \in \Sigma^*} \pi_P(x)(y) = 1$$

Example 3. Let $\Sigma := \{a, b, c\}$, and assume that π_P is defined using the following projection probabilities:

$$P_{proj}(a) := 1.0$$

$$P_{proj}(b) := 0.5$$

$$P_{proj}(c) := 1.0$$

For the input *abbc* the probability of projecting *ac*, $\pi_P(abbc)(ac)$, is

$$= P_{proj}(a)[1 - P_{proj}(b)][1 - P_{proj}(b)]P_{proj}(c)$$

$$= 1.0 \cdot 0.5 \cdot 0.5 \cdot 1.0$$

$$= 0.25$$

The complete distribution over possible projections of *abbc* is:

$$\pi_P(abbc)(abbc) = 0.25$$

$$\pi_P(abbc)(abc) = 0.5$$

$$\pi_P(abbc)(ac) = 0.25$$

All other projections have probabilities of zero.

7.3.2 Probabilistic tier-based strictly local grammars

Definition 4. A *probabilistic tier-based strictly k-local* (pTSL-k) grammar over an alphabet Σ is a tuple (π_P, G), where π_P is a probabilistic projection function with specified projection probabilities for each $s \in \Sigma$ and $G \subseteq (\Sigma \cup \{\rtimes, \ltimes\})^k$ is a set of prohibited k-factors.

Definition 5. The function $val_{(\pi_P,G)}$ computes the probability that is assigned to a input string x by the corresponding pTSL-k grammar. $val_{(\pi_P,G)}(x)$ is defined as

$$\sum_{y:f_k(y)\cap G=\emptyset} \pi_P(x)(y)$$

In other words, the probability computed by $val_{(\pi_P,G)}(x)$ is the sum of the probabilities of all possible subsequences (or projections) of the input string x that do not contain a prohibited k-factor. Note that *val* does not constitute a probability distribution over input strings: in general $\sum_{x \in \Sigma^*} val_{(\pi_P,G)}(x) \neq 1$. Instead, *val* may be interpreted as the conditional probability of any well-formed tier projection given the input.

Example 4. Assume a pTSL-2 grammar defined over the alphabet $\Sigma := \{a, b, c\}$. Let π_P be defined as in Example 3 and $G := \{ac\}$. $val_{(\pi_P,G)}(abbc) = 0.75$, because the sum of the probabilities of all projections of *abc* that do not contain the 2-factor *ac* is $0.25 + 0.5 = 0.75$.

7.3.3 Some properties of pTSL

A stringset $L \subseteq \Sigma^*$ is pTSL-k iff there is some pTSL-k grammar (π_P, G) such that $L = \{w \in \Sigma^* | val_{(\pi_P,G)}(w) > 0\}$. Alternatively, we may say that L is *accepted* by this grammar. The set of pTSL stringsets is the union of all pTSL-k stringsets where $k > 0$.

It is straightforward to show that for every L that is TSL, it is possible to define a pTSL grammar that accepts L. This relationship does not hold in the opposite direction: given a pTSL stringset L, it is not always possible to construct a TSL grammar that accepts L, though certain subclasses of pTSL will always have corresponding TSL grammars. Thus TSL is a proper subset of pTSL. See Appendix J for additional discussion.

7.3.4 Relating pTSL probabilities to production frequencies

Studies of gradience in phonology typically use as empirical data either speaker ratings of individual forms (e.g., Albright & Hayes, 2003; Daland et al., 2011) or response frequencies of particular word forms (Hayes & Londe, 2006; Zuraw & Hayes, 2017). To model empirical data using pTSL, we must be explicit about how the conditional probabilities assigned to inputs relate to these measurements. In the case of word ratings, it seems sensible to suggest that assigned probabilities should be positively correlated with ratings. The case of response frequencies is more difficult. Consider a case where a particular word occurs in two forms: y_1 or y_2 (for example, with the front or back form of a suffix under a vowel harmony system). It will not in general be the case that $val_{(\pi_P, G)}(y_1) + val_{(\pi_P, G)}(y_2) = 1$, so the probabilities supplied by the model cannot be treated as response frequencies.

For a pTSL grammar (π_P, G), I relate probabilities assigned by $val_{(\pi_P, G)}$ to response frequencies as follows:

$$P(y_1) := \frac{val_{(\pi_P, G)}(y_1)}{val_{(\pi_P, G)}(y_1) + val_{(\pi_P, G)}(y_2)}$$

$$P(y_2) := 1 - P(y_1)$$

Note that this formula may be straightforwardly extended to a larger number of categorical outcomes. The choice of which forms to group together in this way is independent of the pTSL grammar. This choice can be thought of as analogous to the GEN function in OT which designates a similar set of surface forms by mapping a UR to collection of candidates (Prince & Smolensky, 1993/2004). The pTSL grammar scores these candidates numerically (similar to any weighted constraint-based grammar), and their predicted frequencies are calculated based on simple normalization, rather than via exponentiation in, for example, a maximum entropy grammar (Smolensky, 1986; Goldwater & Johnson, 2003).

The next two sections provide some empirical justification for this relationship between values assigned to words and predicted response frequencies, and use pTSL to analyze two cases of gradient, long-distance phonological processes.

7.4   Gradient transparency in Hungarian vowel harmony

The Hungarian vowel harmony system requires suffix vowels to match the backness of the final front (/y y: ø ø:/; Table 7.1) or back (/u u: o o: ɔ a:/; Table 7.2) vowel in the root (e.g., Hayes & Londe, 2006; Hayes et al., 2009).

<div align="center">

yʃt-nɛk/*-nɔk   'cauldron-DAT'

sɛm**ø**ltʃ-nɛk/*-nɔk   'wart-DAT'

ʃof**ø**:r-nɛk/*-nɔk   'chauffeur-DAT'

</div>

<div align="center">

Table 7.1: Simple front harmonizing forms (Hayes et al., 2009, p. 829)

</div>

<div align="center">

ɔbl**ɔ**k-nɔk/*-nɛk   'window-DAT'

bi:r**o**-nɔk/*-nɛk   'judge-DAT'

glyk**o:**z-nɔk/*-nɛk   'glucose-DAT'

</div>

<div align="center">

Table 7.2: Simple back harmonizing forms (Hayes et al., 2009, p. 829)

</div>

The front unrounded vowels /i i: e: ɛ/ are *transparent* to harmony, meaning that they do not serve as harmony triggers for suffixes, but allow the harmonic values of preceding segments to "pass through" them. Roots with only transparent vowels generally take front suffixes (Table 7.3), but a small set takes back suffixes (Table 7.4). Roots with front vowels followed by transparent vowels invariably take front suffixes (Table 7.5), while roots with back vowels followed by transparent vowels vary in whether they take front or back suffixes (Table 7.6).

<div align="center">

kɛrt-nɛk/*-nɔk   'garden-DAT'

tsi:m-nɛk/*-nɔk   'address-DAT'

rɛpɛs-nɛk/*-nɔk   'splinter-DAT'

</div>

<div align="center">

Table 7.3: Transparent forms that take front suffixes (Hayes et al., 2009, p. 830)

</div>

The variation in forms like those in Table 7.6 is sensitive to the height and count of transparent vowels: harmony from the back trigger is more likely to be blocked (and a front suffix attached) if the intervening transparent vowels are lower (i.e., /i/ and /i:/ are less likely to block than /e:/, which

<div align="center">

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</div>

hi:d-nɔk/*-nɛk   'bridge-DAT'

ʃi:p-nɔk/*-nɛk   'whistle-DAT'

dɛre:k-nɔk/*-nɛk   'waist-DAT'

Table 7.4: Transparent forms that take back suffixes (Hayes et al., 2009, p. 830)

fysɛr-nɛk/*-nɔk   'spice-DAT'

ø:rizɛt-nɛk/*-nɔk   'custody-DAT'

Table 7.5: Front harmonizing forms with transparent vowels (Hayes et al., 2009, p. 829)

dome:n-nɔk/-nɛk   'domain-DAT'

bohe:m-nɔk/-nɛk   'easy going-DAT'

honve:d-nɔk/-nɛk   'Hungarian soldier-DAT'

poe:n-nɔk/-nɛk   'punch line-DAT'

Table 7.6: Back harmonizing forms with transparent vowels (Hayes et al., 2009, p. 830)

is less likely to block than /ɛ/), and as their number increases (Hayes & Londe, 2006; Hayes et al., 2009).

As part of a broader study, Hayes et al. (2009) administered an online wug test (Berko, 1958) to 131 Hungarian speakers. Participants were presented with 13 wug words from a set of about 1600 wug words embedded in frame paragraphs and asked to choose the form of the dative suffix to attach (front [-nɛk] or back [-nɔk]). Participants were then asked to rate each form and suffix combination on a scale of 1-7, with 7 being the best. Each wug word belonged to one of the following templates: BN, BNN, and N, where each B and N were sampled from the set of back and transparent vowels respectively according to their lexical frequencies. For simplicity, I treat consonants as completely transparent, ignoring the effects of final consonant on suffix choice observed by Hayes et al. (2009).

To test whether the equation relating word ratings to response frequencies given in Section 7.3.4 holds for real data, I calculated the predicted proportion of back suffixes per root type based on speakers' ratings of front and back suffixed forms. The correlation between the proportion of back responses predicted using this method and the proportion observed was extremely high ($r = 0.99$),

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suggesting that this method is a good characterization of the link between ratings and response frequencies.

To test whether pTSL can adequately model this data, I defined a pTSL-2 grammar (π_P, G) over $\Sigma := \{B, I, \text{e:}, \text{e}, S_f, S_b\}$, where $I := \{\text{i}, \text{i:}\}$, $\text{e} = \varepsilon$ and S_f and S_b are front and back suffixes. Note that although TSL (and hence pTSL, for the same reasons discussed in de Santo & Graf, 2017) is not in general closed under relabeling, it is closed if no segment corresponds to more than one abstract symbol. This is the case here, and hence the relabelings used here and in the next section do not influence the expressiveness of the models.

The set of prohibited 2-factors G was defined to be $\{BS_f, IS_b, \text{e:}S_b, \text{e}S_b\}$. P_{proj} was fixed to 1 for $\{B, S_f, S_b\}$. Maximum likelihood optimization was used to calculate the values of P_{proj} for the remaining symbols using the `minimize` function from the Python library `scipy.optimize` (Virtanen et al., 2020). Optimization was performed 100 times with random starting probabilities. The difference in maximum log likelihood between the best and worst fits was less than 10^{-6}, and the differences between optimal projection probabilities similarly small, indicating that the search space is largely convex.

The optimal values were approximately:

$$P_{proj}(\text{I}) = 0.39$$

$$P_{proj}(\text{e:}) = 0.66$$

$$P_{proj}(\text{e}) = 0.82$$

These probabilities directly reflect the tendencies of these segments to act as harmony blockers. Fig. 7.1 shows the probability distribution over projections of the input form $Be:IS_f$, demonstrating how $val_{(\pi_P, G)}$ calculates its probabilities.

Fig. 7.2 plots the proportion of back suffix responses predicted by the model against the observed proportions in wug tests. The correlation between the two is strong ($r = 0.83$). The correlation between probabilities assigned to each word by the model and human ratings is also strong ($r = 0.88$). Note that although the predicted frequencies of the model differ somewhat from the observed responses, it captures the observed effects of height and count on responses. Direct comparison between the maximum entropy Optimality Theory models fit to wug test data in Hayes et al.
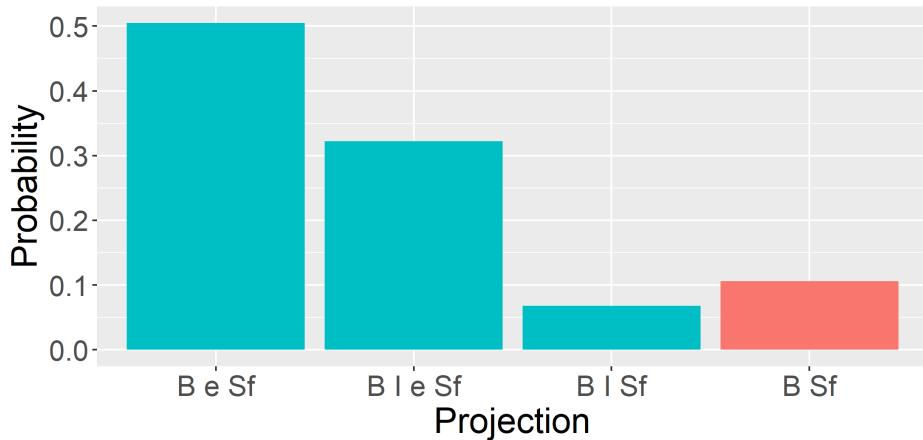
Figure 7.1: Probability distribution over projections of $BIeS_f$. Ungrammatical projections are colored red. $val_{(\pi_P, G)}(BIeS_f) = 0.895$, which is the sum of the probabilities of the grammatical projections. Note that the probability of a particular projection is independent of whether or not it is grammatical: here, ungrammatical BS_f has a higher probability of being projected than grammatical BIS_f.

(2009) and this model is difficult for several reasons: Hayes et al. fit their data to individual forms rather than averages over templates, include constraints that model root-final consonant effects on vowel harmony, and do not present predicted frequency data. I note, however, that the authors report a correlation of $r = 0.575$ between predicted and observed frequencies, which suggests this model may be more successful in capturing height and count effects on vowel harmony.

Note that the pTSL model has the least success predicting the frequency of neutral forms with back suffixes: it predicts they should be more common than they are. The final section of this chapter discusses how pTSL may be extended to capture this phenomenon.

7.5 Gradient judgments in Uyghur backness harmony

Like Hungarian, Uyghur displays backness harmony (e.g., Lindblad, 1990; R. F. Hahn, 1991a, 1991b; Abdulla et al., 2010).

The basic characterization of this process is that suffixes must agree in backness with the final front (/æ ø y/; Table 7.7) or back (/u o ɑ/; Table 7.8) harmonizing root vowel.
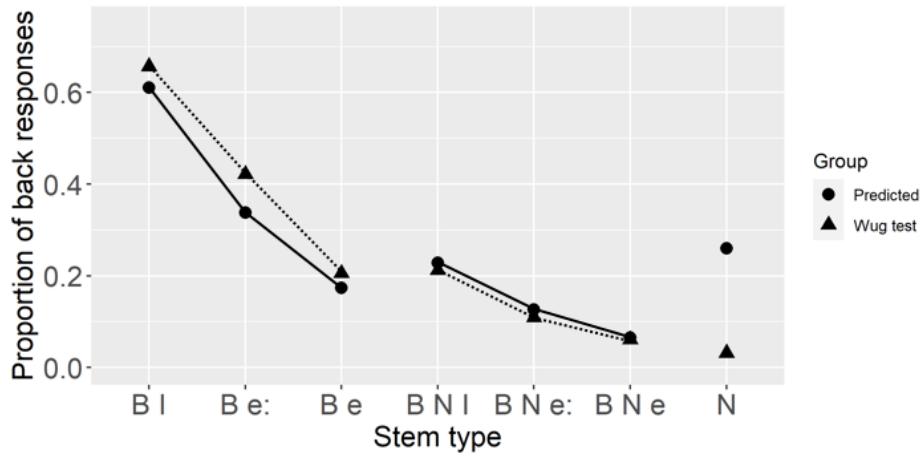
Figure 7.2: Observed against predicted proportion of back responses by root template.

t**y**r-d**æ**/*-dɑ	'type-LOC'
p**æ**n-l**æ**r/*-lɑr	'science-PL'
munb**æ**r-**gæ**/*-ʁɑ	'podium-DAT'

Table 7.7: Simple front harmonizing forms

p**u**l-**ʁɑ**/*-gæ	'money-DAT'
t**o**p-**qɑ**/*-kæ	'ball-DAT'
ætr**ɑ**p-t**ɑ**/*-tæ	'surroundings-LOC'

Table 7.8: Simple back harmonizing forms

The vowels /i e/ are *transparent* to harmony (Tables 7.9 and 7.10).

m**æ**stʃit-t**æ**/*-tɑ	'mosque-LOC'
ymid-l**æ**r/*-lɑr	'hope-PL'
m**ø**min-**gæ**/*-ʁɑ	'believer-DAT'

Table 7.9: Front roots with transparent vowels

If a root contains no harmonizing vowels, the front dorsals /k g/ (Table 7.11) and back dorsals /q ʁ/ (Table 7.12) may serve as harmony triggers.

There are a small number of roots with front dorsals that take back suffixes (Table 7.13). The opposite case (stems with only back dorsals that take front suffixes) does not appear to occur.

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student-lɑr/*-lær   'student-PL'

uniwersitet-tɑ/*-tæ   'university-LOC'

ɑmil-ʁɑ/*-gæ   'element-DAT'

Table 7.10: Back roots with transparent vowels

kishi-lær/*-lɑr   'person-PL'

negiz-gæ/*-ʁɑ   'basis-DAT'

Table 7.11: Front dorsal roots that take front suffixes

qiz-lɑr/*-lær   'girl-PL'

jiʁin-dɑ/*-dæ   'meeting-LOC'

Table 7.12: Back dorsal roots that take back suffixes

ingliz-lɑr   'English person-PL'

etnik-lɑr   'ethnic group-PL'

rentgen-ʁɑ   'x.ray-DAT'

gips-qɑ   'plaster-DAT'

Table 7.13: Front dorsal roots that take back suffixes

When a root contains a harmonizing vowel with a following dorsal that conflicts in backness, the final vowel generally takes precedence (Table 7.14), although there are a small number of roots containing front vowels with following uvulars that take back suffixes (Table 7.15).

mæntiq-qæ   'logic-DAT'

æqil-gæ   'intelligence-DAT'

rɑk-lɑr   'cancer-PL'

pɑkit-lɑr   'fact-PL'

Table 7.14: Conflicting vowels and dorsals, vowel takes precedence

The uvular consonants may thus be characterized as *gradient blockers*: they generally allow the backness of the preceding vowel to pass through to the suffix, but will occasionally impose their own, blocking harmony with the vowel. See Mayer and Major (2018) for a discussion of the

tæst**iq-qa**	'approval-DAT'
tæʃwi**q**-lɑr	'publicity-PL'
tætqi**q**-lɑr	'research-PL'

Table 7.15: Conflicting vowels and dorsals, dorsal takes precedence

challenges of modeling this pattern using TSL.

7.5.1 Wug-testing backness harmony

Chapter 4 presented results from wug tests performed on 23 speakers of Uyghur living in Kaza-khstan. These tests included nonce words of the templates shown in Table 7.16, where *C*, *K*, and *Q* are transparent, velar, and uvular consonants, and *N*, *F*, and *B* are transparent, front, and back vowels respectively.

F roots	CFC, CFCNC, CFCNCNC
B roots	CBC, CBCNC, CBCNCNC
FQ roots	CFQ, CFCNQ, CFCNCNQ
BK roots	CBK, CBCNK, CBCNCNK

Table 7.16: Root templates used in the wug task.

These templates vary the distance between final harmonizing vowel and suffix, as well as the presence or absence of a conflicting dorsal between the two. Participants produced four words from each template (48 words total) in unsuffixed and suffixed form in paragraphs designed to provide a naturalistic context. Suffixed forms were coded for whether they contained a back or a front suffix. See Chapter 4 for more detail.

The proportion of back responses is shown in Fig. 7.3. These results indicate that (a) dishar-monic suffix forms become more likely as the distance between the final harmonizing vowel and the suffix increases, and that this effect is significantly stronger for front roots, and (b) an inter-vening uvular between a front vowel and suffix skews responses towards back, but an intervening velar between a back vowel and a suffix does not.

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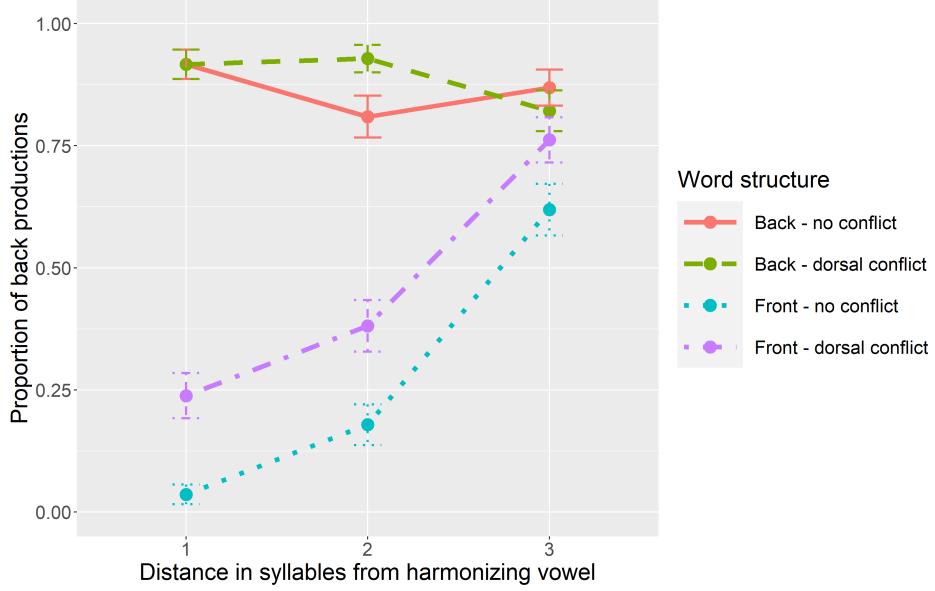
Figure 7.3: Wug word responses from Mayer et al. (2019). Error bars are +/- one standard deviation.

7.5.2 Modeling wug test data using pTSL

I defined a pTSL grammar (π_P, G) over $\Sigma := \{C, K, Q, N, F, B, S_f, S_b\}$, with $G := \{FS_b, BS_f, KS_b, QS_f, NS_f\}$. The first four k-factors prohibit backness clashes between suffixes and root vowels and consonants. The final k-factor captures the overall tendency towards back suffixes as the distance between the harmonizing vowel and suffix increases. Note that in Uyghur the neutral vowels behave as gradient triggers for back harmony, while in Hungarian they trigger front harmony.

P_{proj} was fixed to 1 for $\{F, B, S_f, S_b\}$. Maximum likelihood optimization on the remaining parameters was performed in the same manner as for the Hungarian data.

The optimal values were approximately:

$$P_{proj}(C) = 0.08$$

$$P_{proj}(K) = 0.07$$

$$P_{proj}(Q) = 0.24$$

$$P_{proj}(N) = 0.30$$

Fig. 7.4 shows the proportion of back responses predicted by the model.
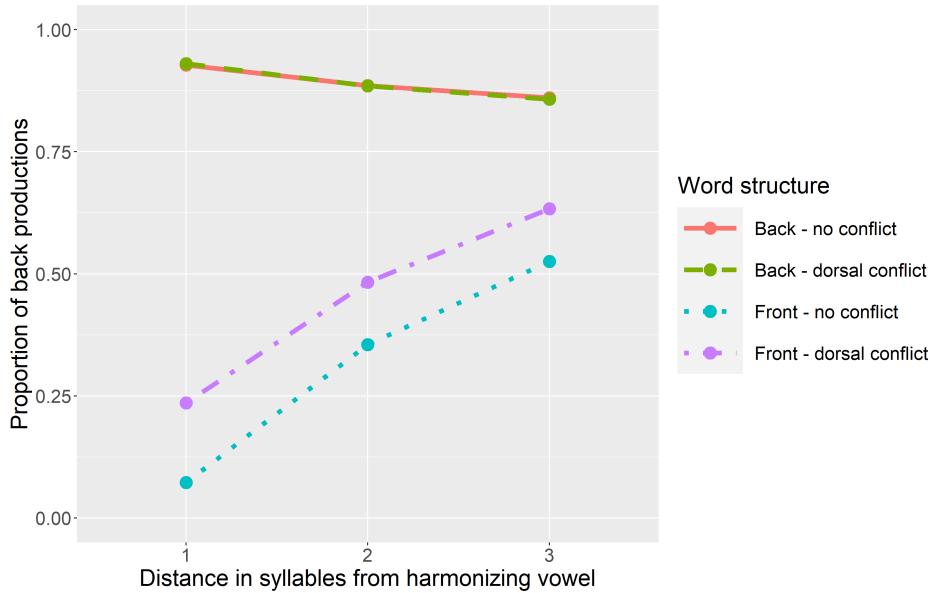
Figure 7.4: Predicted responses by the optimal pTSL model.

The model captures both the gradient blocking displayed by uvulars and the distance-based decay over transparent vowels. Although the model assigns virtually identical frequencies to back roots with and without blockers, this is perhaps not a major shortcoming, since the observed differences in the wug tests are fairly small and difficult to account for in a principled way. More worrying is that the model incorrectly predicts the rate of distance-based decay introduced by transparent vowels. The wug test responses for front roots in Fig. 7.3 show a smaller decrease in front responses between 1 and 2 syllables, followed by a larger decrease between 2 and 3 syllables. The predictions of the model shown in Fig. 7.4 display a larger decrease in front responses between 1 and 2 syllables than between 2 and 3. This is an unavoidable consequence of the mathematical properties of pTSL: as independent probabilities are multiplied together to form a joint probability, the rate of change of the joint probability slows with each multiplication (see Fig. 7.5).

The failure of the model to represent this pattern should not be seen as a significant shortcoming, however. Zymet (2014) identifies decay rates for a range of phonological patterns, and finds that all of them exhibit the kinds of exponential properties that pTSL can represent. Thus the Uyghur wug test results present an interesting exception to general rates of distance-based decay. I discuss this issue in more detail in the next section, and show how pTSL can be extended to cope

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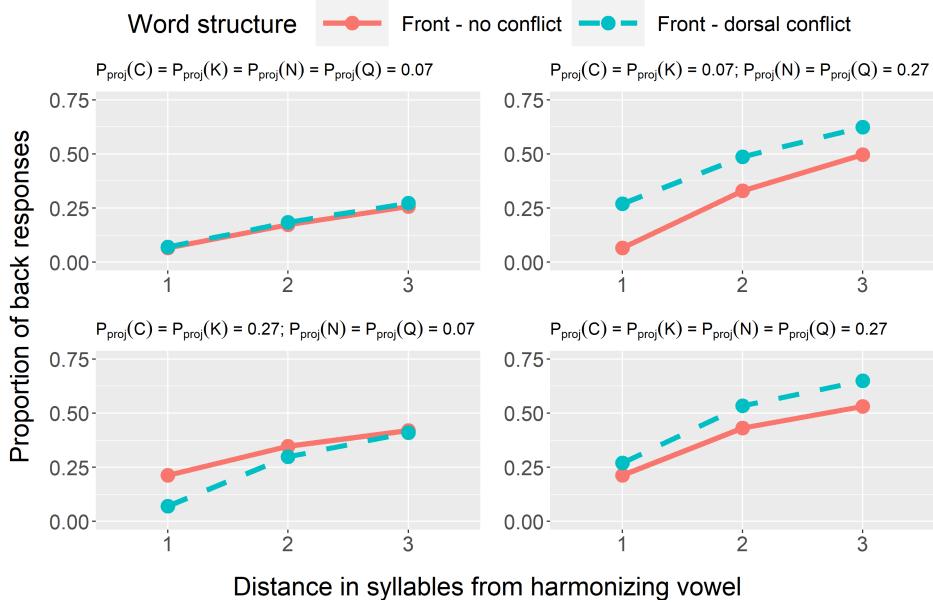
Figure 7.5: Predicted responses for front roots by models with different projection probabilities.

with it.

7.6 Discussion

pTSL grammars allow conditional probabilities to be assigned to stringsets in ways that capture gradient effects in long-distance phonological patterns. The parameters of these grammars have a simple and intuitive interpretation from the perspective of autosegmental phonology: the set of prohibited k-factors G corresponds to a set of inviolable local markedness constraints, and the probabilistic projection function π_P defines how likely each segment is to be projected to the tier on which these violations are evaluated. This allows superficially disparate effects such as distance-based decay and gradient blockers to be treated uniformly.

McMullin (n.d.) observed independently that the idea of modeling distance-based decay as a function of probabilities associated with intervening material, as pTSL does, is similar to the decay functions used in Kimper (2011) and Zymet (2014). For example, he shows that the decay function in Zymet (2014), $\frac{1}{k^x}$, where k is a constant and x is the number of transparent segments between trigger and target, can be implemented by assigning all intervening segments a probability

$\frac{1}{k}$ of serving as a blocker. A detailed comparison of these optimality theoretic models with pTSL is beyond the scope of this chapter: however, I note that the decay functions proposed in the literature treat all intervening segments alike, while pTSL allows individual projection frequencies for each segment (though this is complicated by the effects of constraint definitions and weights in the OT models). In addition, pTSL lends itself to natural extensions that overcome the limitations of both pTSL and decay functions, while extensions of OT models with decay functions are less straightforward.

7.6.1 Extending pTSL to handle contextual projection and biases

Generalizations of TSL where the projection function is sensitive to input context (e.g., de Santo & Graf, 2017), output (or tier) context (e.g., Mayer & Major, 2018), or both (e.g., Graf & Mayer, 2018) may be probabilized in a way similar to what has been presented here. This will allow projection probabilities to be conditioned on context. For example, instead of $P_{proj}(x_i)$, we may use $P_{proj}(x_i|x_{i-1})$, $P_{proj}(x_i|y_{j-1})$ (where y_{j-1} is the previously projected symbol), $P_{proj}(x_i|x_{i-1}, y_{j-1})$, etc.

This extension is useful to address two shortcomings of pTSL observed in the Hungarian and Uyghur examples above. In Hungarian, the pTSL model assigns substantially higher ratings to NS_b forms than speakers do. These ratings are simply $1 - P_{proj}(N)$: if the transparent vowel projects, the form will contain an illicit k-factor, while if it does not project, the root will be licit. A better fit for these forms could be achieved by conditioning on the preceding vowels: that is, transparent vowels are more likely to project when not preceded by a back vowel. pTSL may also be extended to capture lexically-specific phonology (e.g., Pater, 2000) such, as the differences in the effect of uvulars on suffix form between the Uyghur roots in Tables 7.14 and 7.15, by conditioning projection probabilities on word identity rather than local context.

The pTSL model of Uyghur wug test data successfully captures distance-based decay and gradient blocking effects of uvular consonants. It fails, however, to predict the correct rate of decay: specifically, the observed productions show a small increase in back responses when a single transparent vowel intervenes between a front vowel and suffix and a larger increase when an

additional transparent vowel is added. The model predicts the opposite (see also Chapter 4, where a similar result emerges from the use of decay functions). The correct rate can be achieved by conditioning the projection probability of neutral vowels on the preceding vowel: neutral vowels after a harmonizing vowel are less likely to project than those after a neutral vowel.

Finally, biases towards particular constraint weights have been employed in previous optimality theoretic models of phonology to explore how biased learning differs from simpler optimization methods like maximum likelihood estimation (e.g., Wilson, 2006). It is straightforward to incorporate similar biases into pTSL models by defining priors over projection probabilities and incorporating them into the learning process. Additionally, it may be interesting to explore pTSL modeling of feature-based representations. I leave these as interesting areas for future research.

7.6.2 Do Uyghur speakers display complexity biases?

Chapter 6 closed with an unresolved question: is it possible to reconcile the apparent mathematical complexity of Uyghur backness harmony with the weak subregular hypothesis (Heinz, 2018)? This hypothesis suggests that all segmental phonological markedness patterns in the world's languages can be characterized by tier-based strictly local grammars, and is broadly borne out by typological data. Uyghur, however, presents an exception to this generalization: the "fallback pattern" displayed between harmonizing vowels and consonants cannot be captured by any TSL Grammar.

One possibility for salvaging the weak subregular hypothesis is that the pattern observed in Uyghur is largely *lexicalized*: that is, although the fallback pattern is an accurate characterization of the attested data, it is not the representation that speakers acquire in their grammars. Evidence from wug tests that speakers in fact learn a computationally simpler grammar (i.e., a TSL grammar) would be striking evidence for a phonological learning bias that favors patterns that are TSL.

Modeling the wug test data from Chapter 4 using a pTSL model allows us to address this question directly. Although speakers display evidence for certain biases that have made their learned grammars diverge somewhat from patterns in attested words, these biases do not appear to result in simpler grammars from a computational perspective. Recall that under the pTSL grammar defined above, QS_f is an illegal subsequence, and consider the string FQ^*S_f. Assuming that $P_{proj}(Q) < 1$,

there will always be one legal projection containing no instances of Q, regardless of the number of Qs intervening between the F and S_f. This means that the pTSL grammar will always assign a non-zero probability to strings of this form. We have seen in Chapter 6 that no TSL grammar can accomplish this. Thus the pTSL grammar here has no equivalent TSL grammar, which indicates that speakers' deviations from the corpus patterns do not seem to result in a simpler grammar.

My perspective on this issue, which is admittedly speculative, is that the subregular hypothesis is an important characterization of the typological data, but does not reflect a *learning bias* towards phonological patterns of a certain complexity. Rather it tell us something about the nature of the phonetic interactions or processes that tend to become phonologized. Phonotactic restrictions may arise to avoid configurations of segments that are challenging for articulatory or perceptual reasons (Gallagher, 2010; Gafos, 2021), and phonological alternations may emerge for similar reasons, or as a consequence of coarticulation between nearby segments that becomes phonologized (Ohala, 1981). These kind of local phonetic effects give rise to phonological patterns that are, for the most part, also local in some sense, where other domains such as syntax, for example, are subject to different pressures that in turn lead to different computational properties (such as constraints on working memory, efficient information structure, and so on; see, for example, M. Hahn, Jurafsky, & Futrell, 2020; M. Hahn, Degen, & Futrell, 2021). Consequently, strictly local or tier-based strictly local models are sufficient to model the vast majority of segmental phonology.[2] The question of the source of these computational generalizations is perhaps similar to the debates on whether typological generalizations in phonology are the consequence of a learning bias towards certain types of phonetically-natural patterns, or a transmission bias that favors the development of certain types of patterns over others (Blevins, 2004).

If the pressures that govern the development and evolution of phonological patterns tend to give rise to local interactions, then Uyghur backness harmony is the exception that proves the rule. The participation of consonants in the harmony system arose from a co-occurrence restriction between vowels and dorsal consonants that was rendered opaque by the merger of /i/ and /ɯ/ and the

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[2]A corollary of this idea is that TSL patterns should generally have some plausible phonetic grounding in the choice of segments that are projected to the tier: in harmony systems, for example this might be the set of segments for which changes in tongue dorsum position along the front-back axis have appreciable perceptible differences.

disharmonic roots that give evidence of the fallback pattern entered the language via borrowing. This specific confluence of historical changes has resulted in a phonological pattern that is more complex than most segmental patterns. This is consistent with observations that 'unnatural' phonological patterns often have origins in a cascading series of 'natural' sound changes (e.g., Minkova, 1993; Labov, 1994; Lass, 1997; Hayes & White, 2015; Beguš, 2018b, 2018a). In this case, this complexity does not seem to pose any difficulties for learners.

CHAPTER 8

Conclusions

This dissertation has explored the phonetic, phonological, and computational properties of backness harmony in Uyghur. As a whole, the dissertation demonstrates that backness harmony in Uyghur consists of a productive phonological core with many lexicalized components that have emerged as a consequence of extensive borrowing and sound change. I have related data from Uyghur backness harmony to issues such as the nature of phonological opacity and exceptionality, phonetic biases on phonological learning, and the mathematical complexity of phonological patterns.

8.1 Future directions

There are a number of important areas for future work suggested by this dissertation.

The innovative claim of Chapter 3 that opacity in Uyghur backness harmony is fundamentally a type of phonological exceptionality was made on the basis of corpus data and limited elicitation. Although these are useful sources of evidence, experimentally demonstrating the connection between word frequency and rates of opacity will be an important validation of this claim. This hypothesis could be tested using wug studies probing how speakers navigate the interaction between raising and harmony in novel words. A corresponding perceptual study using eye-tracking or similar methodologies would also be valuable to probe how unexpected certain forms are (e.g., will a raised form that demonstrates surface-true rather than opaque harmony result in a greater reading disfluency if that word is high-frequency?).

It will also be important for the study of Uyghur in general to have access to more conversational written or acoustic corpora. The corpora used in this dissertation came from newspaper

writing, which is relatively formal. Memorized irregular forms tend to be preserved best in prestigious, standardized language styles. More casual speech is likely to display less influence from prescriptive language use and better represent the input to Uyghur learners, which may provide additional insights into the phonetic and phonological properties of backness harmony.

Finally, corpus and wug studies on different languages to evaluate the productivity of opaque phonological patterns and the presence or absence of learning biases will be important for the continued development of phonological theory. The nature of opacity and the phonological learner have been perennial questions of interest to the field, and methodological approaches like those employed in this dissertation can lead us to new and valuable insights in these areas. In particular, a general assumption in phonology is that we should situate as much of our analyses as possible in a productive grammar, rather than relying on lexical or morphological stipulation. This dissertation has provided evidence from a variety of sources that lexicalization plays a pervasive role in Uyghur backness harmony, which both informs us about the nature of opacity in the language, and highlights phonetic learning biases that are not detectable when looking only at attested data. I suspect that taking a similar approach to other languages may reveal many of them to behave similarly. This will have valuable implications for phonological theory, and linguistic theory more broadly.

APPENDIX A

Morpheme-specific exceptionality in backness harmony

This appendix discusses a few cases of morpheme-specific exceptionality in Uyghur backness harmony. These include suffixes that prefer to harmonize with consonants over vowels, a small set of truly idiosyncratic harmonizers, and a number of harmony blocking suffixes, which impose their own backness on following suffixes.

A.1   The suffix /-lUQ/

The derivational morpheme /-lUQ/ (surface forms [-lik], [-liq], [-lyk], [-luq]) behaves idiosyncratically, with a tendency to harmonize with uvulars in roots rather than vowels.

(90)   *Idiosyncratic harmonization of /-lUQ/*

mæntiq-q**æ**	'logic-DAT'	mænti**q**-li**q**	'logical'
æqil-**gæ**	'intelligence-DAT'	æ**q**il-li**q**	'intelligent'
hæq-q**æ**	'wage-DAT'	hæ**q**-li**q**	'paid (adj.)'

It is likely that this does not constitute a productive exception to general harmony patterns, but rather that these suffixed forms have become roots in their own right and display lexicalized harmonic idiosyncrasies. For example, it is always the case that, with the exception of the suffixes that block harmony (see Section A.3), all suffixes attached to a root will share the same harmonic value. Attested forms like [pærq-liq-lær] 'difference-LIQ-PL (different (ones))' are surprising because they appear to consist of the root /pærq/ followed by the back form of /-lUQ/ and the front form of /-lAr/. This harmonizing behavior is exactly what is predicted if the root is /pærqliq/, however, since the suffix /-lAr/ simply agrees with the last harmonizing vowel in the root.

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A.2 Idiosyncratic harmonizers

There are at least a few words or phrases where suffixes do not always agree in backness with the final harmonizing vowel.

(91) *Harmony exceptions*

sowet-lær/-lɑr 'soviet-PL'

deŋiz sɑhil-i-gæ/-ʁɑ 'ocean shore-3.POS-DAT' (cf. [sɑhil-ʁɑ] 'shore-DAT')

Such words are exceedingly rare.

A.3 Harmony blockers

There are a fair number of suffixes in Uyghur that do not harmonize, and may impose their own harmonic value on the remainder of the word. These suffixes include the progressive suffix /-wɑt/, the similitude marker /-Dæk/, the locative relativizer /-Diki/, the genitive relativizer /-niŋki/, the imperfective participle /-diʁan/, and most suffixes that mark person and number on verbs.

(92) *Examples of non-harmonizing suffixes*

/kyl-wɑt-GAn/	→ [kyl-iwɑt-qɑn]	'laugh-PROG-PERF'
cf. /kyl-GAn/	→ [kyl-gæn]	'laugh-PERF'
/rɑjon-lAr-Diki-GA/	→ [rɑjon-lɑr-diki-gæ]	'region-PL-LOC.REL-DAT'
cf. /rɑjon-lAr-GA/	→ [rɑjon-lɑr-ʁɑ]	'region-PL-DAT'
/ujʁur-lAr-niŋki-GA/	→ [ujʁur-lɑr-niŋki-gæ]	'Uyghur-PL-GEN.REL-DAT'
cf. /ujʁur-lAr-GA/	→ [ujʁur-lɑr-ʁɑ]	'Uyghur-PL-DAT'
/tɑʃ-Dæk/	→ [tɑʃ-tæk]	'stone-SIMIL (stone-like)'
/køn-i-du/	→ [køn-i-du]	'accept-NONPAST-3'
/sɑt-i-mæn/	→ [sɑt-i-mæn]	'sell-NONPAST-1.SG'

There is at least one suffix which is a partial harmonizer: the delimiting suffix /-Gitʃæ/. This suffix surfaces as either [-kitʃæ], [-gitʃæ], [-qitʃæ], [-ʁitʃæ], with the initial consonant harmonizing but the final vowel remaining front in all contexts.

(93)   *Examples of partially harmonizing suffixes*
        /ʁuldʐɑ-ʁitʃæ/   → [ʁuldʐɑ-Gitʃæ]   'Ghulja-DELIM'
        /yrymtʃi-Gitʃæ/   → [yrymtʃi-Gitʃæ]   'Ürümchi-DELIM'

It is unclear whether this suffix imposes its own harmonic value or behaves like the suffix /-tʃæ/ discussed in Chapter 3 because suffixes are not typically attached to forms ending in /-Gitʃæ/.

APPENDIX B

Exceptions to vowel reduction

There are a number of morphological exceptions to vowel reduction beyond roots that simply fail to raise (see Chapter 3). Vowels in certain suffixes do not reduce, such as the progessive suffix /-wɑt/ and the abilitative suffix /-AlA/, while others, such as the perfective suffix /-GAn/, do.[1]

(94)   *Examples of non-reducing suffixes*

jygyr-iw**ɑ**t-i-du/*jygyr-iw**i**t-i-du   'run-PROG-NONPAST-3'

bol-iw**ɑ**t-i-du/*bol-iw**i**t-i-du   'become-PROG-NONPAST-3'

jygyr-**æ**læ-j-du/*jygyr-**i**læ-j-du   'run-ABIL-NONPAST-3'

bol-**ɑ**lɑ-j-du/*bol-**i**lɑ-j-du   'become-ABIL-NONPAST-3'

(95)   *Examples of reducing suffixes*

jygyr-g**i**n-i/*jygyr-g**æ**n-i   'run-PERF-3.POS'

bol-ʁ**i**n-i/*bol-ʁ**ɑ**n-i   'become-PERF-3.POS'

The progressive suffix /-wɑt/ also does not trigger vowel reduction in vowel-final roots.

---

[1]Note that both /-wɑt/ and /-AlA/ are grammaticalized contractions of what were once multi-word phrases. /-wɑt/'s origins are described below. In Kazakh, abilitative constructions are still multi-word expressions, such as /bɑr-A ɑl-A-mIn/ → [bɑrɑ ɑlɑmɯn] 'I will be able to go' (McCollum p.c.). The failure of these two suffixes to undergo raising may be due to this historical origin.

(96) *Failure of /-(i)wɑt/ to trigger vowel reduction in vowel-final verb roots.*

/ɑŋlɑ-wɑt-i-du/	→ [ɑŋl**ɑ**-wɑt-i-du]	'listen-PROG-NONPAST-3'
/tɑllɑ-wɑt-i-du/	→ [tɑll**ɑ**-wɑt-i-du]	'choose-PROG-NONPAST-3'
/søzlæ-wɑt-i-du/	→ [søzl**æ**-wɑt-i-du]	'speak-PROG-NONPAST-3'
/ʧæklæ-wɑt-i-du/	→ [ʧækl**æ**-wɑt-i-du]	'forbid-PROG-NONPAST-3'

cf.

/ɑŋlɑ-GAn/	→ [ɑŋl**i**-ʁɑn]	'listen-PERF'
/tɑllɑ-GAn/	→ [tɑll**i**-ʁɑn]	'choose-PERF'
/søzlæ-GAn/	→ [søzl**i**-gæn]	'speak-PERF'
/ʧæklæ-GAn/	→ [ʧækl**i**-gæn]	'forbid-PERF'

This effect of /wɑt/ on the raising behavior of vowel-final verbs makes sense when its origin as a contraction of the phrase /-p jɑt-/ is considered (R. F. Hahn, 1991b). The suffix /-p/ chains related clauses, and the verb root /jɑt-/ means 'to lie' or 'to settle'. In these cases the final vowel in the root would occur in a closed syllable, and hence be ineligible for raising (e.g., the historical form [ɑŋlɑ-p jɑt-i-du] 'She is listening'). Thus the raising behavior of the historical form is maintained, despite it violating general synchronic phonotactic restrictions.

Similarly to the /-wɑt/ construction, there are two contractions that are commonly used but, unlike /-wɑt/, may be produced in uncontracted form (utterances like [ɑŋlɑp jɑtidu] are not grammatical in modern Uyghur). The first is /-p ɑl-/ → [-wɑl-], where the verb root /ɑl/ means 'to take' and which expresses a subject doing something for their own benefit (e.g., [oqup ɑldi] or [oquwɑldi] 'She studied (for her own benefit)'). The second is /-p bær-/ → [-wær-], where the verb root /bær/ means 'to give' and which expresses the subject either doing something for someone else's benefit, or doing something in spite of some difficulty (e.g., [oqup bærdi] or [oquwærdi] 'She kept studying (in spite of some difficulty)'). These contractions both have effects on vowel reduction that are somewhat, but not completely, predictable from their uncontracted forms.

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(97)   *Idiosyncratic vowel reduction in /-p ɑl-/ contractions.*

/hæjdæ-p ɑl-di/   → [hæjdæp ɑldi]   'drive-IP take-3.PAST'

                   → [hæjd**i**wɑldi]/*[hæjd**æ**wɑldi]

/ɑŋlɑ-p ɑl-di/   → [ɑŋlɑp ɑldi]   'listen-IP take-3.PAST'

                   → [ɑŋl**i**wɑldi]/*[ɑŋl**ɑ**wɑldi]

(98)   *Idiosyncratic vowel reduction in /-p bær-/ contractions.*

/hæjdæ-p bær-di/   → [hæjdæp bærdi]   'drive-IP give-3.PAST'

                    → [hæjd**æ**wærdi]/*[hæjd**i**wærdi]

/ɑŋlɑ-p bær-di/   → [ɑŋlɑp bærdi]   'listen-IP give-3.PAST'

                    → [ɑŋl**ɑ**wærdi]/*[ɑŋl**i**wærdi]

The final vowel in roots ending with /æ/ or /ɑ/ raises before [-wɑl-] but not before [-wær-] despite the similarity of surface configurations and that neither raise in the uncontracted form (since the vowel in question occurs in a closed syllable). The raising behavior here appears to be based on syllabifications of the uncontracted surface forms without word boundaries: /ɑŋlɑ-p ɑl-di/ will syllabify as [ɑŋ.lɑ.pɑl.di], placing the final vowel of the root in an open syllable, while /ɑŋlɑ-p bær-di/ will syllabify as [ɑŋ.lɑp.bær.di], which places the final vowel of the root in a closed syllable.

APPENDIX C

Umlaut

The second vowel raising process in Uyghur, aside from vowel reduction, is traditionally referred to as *umlaut* or *regressive vowel assimilation*, raises /æ ɑ/ to [e] in initial open syllables when the vowel in the following syllable is [i] (and sometimes /æ/).[1]

(99) */ɑ/ umlaut*

jɑn   'side'   jen-i   'side-3.POS'

bɑʃ   'head'   beʃ-i   'head-3.POS'

bɑr-di   'go-3.SG.PAST'   ber-iʃ   'go-GER'

jɑz-di   'write-3.SG.PAST'   jez-iʃ   'write-GER'

(100) */æ/ umlaut*

tæn   'body'   ten-i   'body-3.POS'

χæt   'letter'   χet-i   'letter-3.POS'

bær-di   'give-3.SG.PAST'   ber-iʃ   'give-GER'

kæs-ti   'cut-3.SG.PAST'   kes-iʃ   'cut-GER'

Reduced vowels do not serve as triggers for umlaut.

(101) *Failure of reduced vowels to trigger umlaut*

bɑlɑ   'child'   bɑli-ni/*beli-ni   'child-ACC'

ɑpɑ   'mom'   ɑpi-si/*epi-si   'mom-3.POS'

ætæ   'tomorrow'   æti-din/*eti-din   'morning-ABL'

ælæm   'anger'   ælim-i/*elim-i   'anger-3.POS'

---

[1]The relatively restricted distribution of /e/ makes it difficult to find examples where it could trigger umlauting, and hence it is unclear whether it is also a trigger.

The vowel [æ] may also trigger umlaut when present in suffixes (this raises the question of whether regressive assimilation is really an appropriate term for this process).

(102)   *Umlaut triggered by /æ/*

/jæ-mAK/	→ [je-mæk]/*[jæ-mæk]	'eat-INF'
/dæ-mAK/	→ [de-mæk]/*[dæ-mæk]	'say-INF'
/bær-Aj/	→ [ber-æj]/*[bær-æj]	'give-1.SG.OPT'
/bær-AlA-i-du/	→ [ber-ælæ-j-du]/*[bær-ælæ-j-du]	'give-ABIL-NONPAST-3'
/kæl-Aj/	→ [kel-æj]/*[kæl-æj]	'come-1.SG.OPT'
/kæl-AlA-i-du/	→ [kel-ælæ-j-du]/*[kæl-ælæ-j-du]	'come-ABIL-NONPAST-3'

cf.

/bɑr-Aj/	→ [bɑr-ɑj]/*[ber-ɑj]	'go-1.SG.OPT
/bɑr-AlA-i-du/	→ [bɑr-ɑlɑ-j-du]/*[ber-ɑlɑ-j-du]	'go-ABIL-NONPAST-3'
/qɑl-Aj/	→ [qɑl-ɑj]/*[qel-ɑj]	'stay-1.SG.OPT'
/qɑl-AlA-i-du/	→ [qɑl-ɑlɑ-j-du]/*[qel-ɑlɑ-j-du]	'stay-ABIL-NONPAST-3'

Like vowel reduction, umlaut does not apply exceptionlessly, with /æ/ raising more frequently than /ɑ/.[2]

(103)   *Exceptions to umlaut with /ɑ/*

sɑn	'number'	sɑn-i	'number-3.POS'
kɑr	'business'	kɑr-i	'business-3.POSS'
ʤɑj	'place'	ʤɑj-i	'place-3.POSS'

(104)   *Exceptions to umlaut with /æ/*

| pær | 'feather' | pær-i | 'feather-3.POS' |

Similarly, there are a number of morphologically conditioned exceptions or extensions to umlaut. The present/future suffix /-i/ triggers umlaut of /æ/, but not /ɑ/:

---

[2]One can imagine modeling this using *MAP constraints (Steriade, 2001; Zuraw, 2007; Steriade, 2009; Zuraw, 2013): because the phonetic distance between /ɑ/ and /e/ is greater than that between /æ/ and /e/, the latter is penalized less for rising than the former.

(105)   *Idiosyncratic behavior of the present/future suffix /-i/*

/bɑr-i-mæn/   → [bɑr-i-mæn]/*[ber-i-mæn]   'go-NONPAST-1SG'

/bær-i-mæn/   → [ber-i-mæn]/*[bær-i-mæn]   'give-NONPAST-1SG'

/tɑp-i-du/   → [tɑp-i-du]/*[tep-i-du]   'find-NONPAST-3'

/tæp-i-du/   → [tep-i-du]/*[tæp-i-du]   'kick-NONPAST-3'

Umlaut occurs in certain contractions despite these no longer constituting separate words. Recall the pair of constructions described in Appendix B: /-p ɑl-/ → [-wɑl-], which expresses a subject doing something for their own benefit, and /-p bær-/ → [-wær-], which expresses the subject either doing something for someone else's benefit, or doing something in spite of some difficulty. These contractions exhibit umlaut in the same manner as the uncontracted forms, despite forming a single word.

(106)   *Word-medial umlaut in contracted forms*

/bɑr-ip ɑl-iʃ/   → [ber-ip **e**l-iʃ]   'go-IP take-GER'

                → [ber-iw**e**l-iʃ] / *[ber-iw**i**l-iʃ], *[ber-iw**ɑ**l-iʃ]

/tæp-ip ɑl-iʃ/   → [tep-ip **e**l-iʃ]   'kick-IP take-GER'

                → [tep-iw**e**l-iʃ] / *[tep-iw**i**l-iʃ], *[tep-iw**ɑ**l-iʃ]

/bɑr-ip bær-iʃ/   → [ber-ip b**e**r-iʃ]   'go-IP give-GER'

                → [ber-iw**e**r-iʃ] / *[ber-iw**i**r-iʃ], *[ber-iw**æ**r-iʃ]

/tæp-ip bær-iʃ/   → [tep-ip b**e**r-iʃ]   'kick-IP give-GER'

                → [tep-iw**e**r-iʃ] / *[tep-iw**i**r-iʃ], *[tep-iw**æ**r-iʃ]

Note in particular that the same idiosyncratic raising behavior imposed by the present/future suffix /-i/ is observed.

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(107)   *Word-medial umlaut in contracted forms with non-past suffix*

/bɑr-ip ɑl-i-mæn/   → [ber-ip **ɑ**l-i-mæn]   'go-IP take-NONPAST-1.SG'

                       → [ber-iw**ɑ**l-i-mæn]

                       → *[ber-iw**i**l-i-mæn], *[ber-iw**e**l-i-mæn]

/tæp-ip ɑl-i-mæn/   → [tep-ip **ɑ**l-i-mæn]   'kick-IP take-NONPAST-1.SG'

                       → [tep-iw**ɑ**l-i-mæn]

                       → *[tep-iw**i**l-i-mæn], *[tep-iw**e**l-i-mæn]

/bɑr-ip bær-i-mæn/   → [ber-ip b**e**r-i-mæn]   'go-IP give-NONPAST-1.SG'

                       → [ber-iw**e**r-i-mæn]

                       → *[ber-iw**i**r-i-mæn], *[ber-iw**æ**r-i-mæn]

/tæp-ip bær-i-mæn/   → [tep-ip b**e**r-i-mæn]   'kick-IP give-NONPAST-1.SG'

                       → [tep-iw**e**r-i-mæn]

                       → *[tep-iw**i**r-i-mæn], *[tep-iw**æ**r-i-mæn]

There's an interesting discrepancy to be observed here between the behavior of umlaut on these forms and the behavior of vowel raising described in Appendix B: vowel raising treats these forms as if the word boundary had been erased, while umlaut does not.

APPENDIX D

Lexicalized opacity

Some roots have undergone "permanent" umlauting and no longer contain any harmonizing vowels in *any* surface realization (though some still contain harmonizing dorsals). These roots generally harmonize as their historical non-raised forms would have, although this is not always the case (Abdulla et al., 2010).

(108)   *Permanently raised roots with historically-consistent harmony*

Modern form	Gloss	Historical form
beliq-tɑ	'fish-LOC'	bɑliq
etiz-dɑ	'field-LOC'	ɑtiz
hekim-dæ	'governor-LOC'	hækim
ʃehit-tæ	'martyr-LOC'	ʃæhit

(109)   *Permanently raised roots with historically-divergent harmony*

Modern form	Gloss	Historical form
peqir-dɑ	'I (humble)-LOC'	pæqir
deŋiz-dɑ	'ocean-LOC'	dæŋiz
zemin-lɑr	'land-PL'	zæmin
semiz-lɑr	'fat-PL'	sæmiz

Note that the forms that differ in harmony from the original value of the raised vowel all involved the raising of /æ/. This aligns with the general tendency towards back harmonizers as the default in neutral roots.

APPENDIX E

A sketch of an analysis of vowel reduction

This appendix presents a sketch of an analysis of vowel reduction, which is introduced in Chapter 2 and factors heavily into the opacity discussed in Chapter 3. The analysis largely follows that of McCollum (2020), with additional machinery added to account for roots that resist raising. This analysis is not intended to be comprehensive, but rather to provide a sense of how vowel reduction occurs based on an interaction between the Uyghur stress system and a constraint against heavy syllables.

McCollum assumes that Uyghur words have a single primary stress that always occurs on the final syllable, and no secondary stress. This is generated by the ranking ALLFEET-R ≫ PARSE-σ, IAMB ≫ TROCHEE. McCollum also assumes that the low vowels /ɑ æ/ must be bimoraic and codas must be moraic. Non-low vowels may be either monomoraic or bimoraic, but default to being monomoraic. Finally, vowel reduction never occurs in initial syllables (see, e.g., Casali, 1997; Beckman, 1999; Gordon, 2004, a.o.) or non-derived environments (see, e.g., Łubowicz, 2002). In the analysis below I will not consider candidates that violate any of these assumptions.

The following constraints from McCollum (2020) account for raising in medial, open syllables.

- STRESS2WEIGHT: Stressed syllables must be heavy.

- *HEAVY: Syllables should not be heavy.

- DEP-μ: Don't insert a mora.

I include a broad constraint to capture faithfulness violations that include featural changes and mora deletion:

- ID: Don't change feature or mora values of input segments.

A more comprehensive analysis would need to expand this blanket constraint to account for a variety of details, such as the asymmetry of raising rates between /ɑ/ and /æ/, why these vowels raise to [i] rather than any of the other potentially monomoraic vowels, and so on. For the purposes of this analysis, this constraint simply enforces the restriction that we should be faithful to input segments unless we have good reason not to be.

The application of these constraints is shown in Tables E.1 and E.2 (I assume a simple ranked model here for presentational purposes, but it is straightforward to produce numeric weights that allow the same generalizations to be captured in a MaxEnt model).

/bɑlɑ/	S2W	*Heavy	Dep-μ	ID
☞ a. bɑ$_{\mu\mu}$.'lɑ$_{\mu\mu}$		**		
b. bɑ$_{\mu\mu}$.'li$_{\mu\mu}$		**		*!
c. bɑ$_{\mu\mu}$.'li$_{\mu}$	*!	*		*

Table E.1: Tableau for [bɑlɑ] 'child'.

/bɑlɑ-ni/	S2W	*Heavy	Dep-μ	ID
a. bɑ$_{\mu\mu}$.lɑ$_{\mu\mu}$.'ni$_{\mu\mu}$		***!	*	
☞ b. bɑ$_{\mu\mu}$ li$_{\mu}$.'ni$_{\mu\mu}$		**	*	*
c. bɑ$_{\mu\mu}$ li$_{\mu}$.'ni$_{\mu}$	*!	*		*

Table E.2: Tableau for [bɑli-ni] 'child-ACC'.

Note that an additional mora is added to the final syllable here to satisfy the Stress2Weight constraint. McCollum (2020) supports this analysis with acoustic measurements showing vowel lengthening in word-final /i/.

The failure of closed medial syllables to reduce can be captured by a high-ranked constraint preventing consonant deletion.

- Max-C: Don't delete consonants.

This constraint combined with the fact that coda consonants are always moraic means that reducing low vowels in closed syllables can never create a light syllable. Its application is shown in Table E.3.

/adæm-ni/	MAX-C	S2W	*HEAVY	DEP-μ	ID
☞ a. $\alpha_{\mu\mu}$.dæ$_{\mu\mu}$m$_\mu$.'ni$_{\mu\mu}$			***	*	
b. $\alpha_{\mu\mu}$ di$_\mu$m$_\mu$.'ni$_{\mu\mu}$			***	*	*!
c. $\alpha_{\mu\mu}$ di$_\mu$m$_\mu$.'ni$_\mu$		*!	**		*
d. $\alpha_{\mu\mu}$ di$_\mu$.'ni$_{\mu\mu}$	*!		**	*	*

Table E.3: Tableau for [adæm-ni] 'man-ACC' (cf. [adim-i] 'man-3.POS').

Finally, there is the question of how to account for roots that categorically resist raising, such as /hɑwɑ/ 'weather'. One possibility, which is broadly consistent with existing literature (e.g., Yakup, 2013; Özçelik, 2015; Major & Mayer, 2018) is to assume these forms have underlyingly specified stress/footing and a high ranked faithfulness constraint that mandates stress be maintained in this position:

- ID-STRESS: Stressed syllables in the input must be stressed in the output.

Such an analysis applied to the input /hɑwɑ-ni/ 'weather-ACC' is shown in Table E.4.

/hɑ'wɑ-ni/	ID-STRESS	S2W	ALLFEET-R	*HEAVY	DEP-μ	ID
☞ a. hɑ$_{\mu\mu}$.'wɑ$_{\mu\mu}$.ni$_\mu$			*	**		
b. hɑ$_{\mu\mu}$.wɑ$_{\mu\mu}$.'ni$_{\mu\mu}$	*!			***	*	
c. hɑ$_{\mu\mu}$.wɑ$_{\mu\mu}$.'ni$_{\mu\mu}$	*!	*!		***		
d. hɑ$_{\mu\mu}$.'wi$_\mu$.ni$_\mu$		*!	*	*		*
e. hɑ$_{\mu\mu}$.'wi$_{\mu\mu}$.ni$_\mu$			*	**		*!

Table E.4: Tableau for [hɑwɑ-ni] 'weather-ACC'.

This analysis predicts that final syllables in non-raising forms like [hɑwɑ-ni] 'weather-ACC' should be shorter than final syllables in raising forms like [bɑlɑ-ni] 'child-ACC' because the former are not stressed. Alternative possible analyses, such as indexed faithfulness constraints, do not make this prediction. I leave this as an interesting area for future research.

APPENDIX F

Rounding harmony

Uyghur also has a system of rounding harmony that applies only to high vowels. This phenomenon does not factor heavily into this dissertation, but I describe it here for completeness.

A number of suffixes display alternations between [i], [y], and [u] depending on the root. If the final harmonizing vowel in the root is a rounded front vowel (/y/ or /ø/) the suffix form will contain /y/; if the final harmonizing root vowel is a rounded back vowel (/u/ or /o/) the suffix form will contain [u]; if the final harmonizing root vowel is unrounded, or if the root contains no harmonizing vowels, the suffix will contain [i]. This process typically occurs with suffixes that trigger vowel epenthesis, such as /-m/ '1Sg.POS' or /-ʃ/ 'GER'. A high vowel is epenthesized between the stem and suffix the stem ends in a consonant.

(110)   *Examples of rounding harmony on epenthetic vowels*

      /dɑtʃɑ-m/ → [dɑtʃɑm]   'villa-1.POS'

      /tɑm-m/ → [tɑm-im]   'wall-1.POS'

      /bæt-m/ → [bæt-im]   'page-1.POS'

      /pul-m/ → [pul-um]   'money-1.POS'

      /gyl-m/ → [gyl-ym]   'flower-1.POS'

      /it-m/ → [it-im]   'dog-1.POS'

Not all epenthetic vowels display rounding harmony. For example, /kyl-wɑt-GAn/ 'laugh-PROG-PERF' generally surfaces as [kyl-iwɑt-qɑn], though [kyl-ywɑt-qɑn] is also possible.

A number of suffixes with non-epenthetic vowels also display rounding harmony, such as /-lUQ/, which forms adjectives from nouns (among other uses).

(111)   *Examples of rounding harmony on non-epenthetic vowels*

/qorɑl-lUQ/   → [qorɑl-liq]   'weapon-LIQ (armed)'

/tæm-lUQ/   → [tæm-lik]   'taste-LIQ (tasty)'

/tuz-lUQ/   → [tuz-luq]   'salt-LIQ (salty)'

/øz-lUQ/   → [øz-lyk]   'self-LIQ (reflexive)'

APPENDIX G

The Uyghur morphological transducer

This appendix describes the properties of the morphological transducer used to analyze the corpus data in Chapters 3 and 4. The transducer I use is a modified version of the *apertium-uig transducer*. This is implemented using finite-state transducers (FST): specifically, within the HFST framework (Helsinki Finite State Technology; Linden, Silfverberg, Axelson, Hardwick, & Pirinen, 2011). A FST is a finite-state automaton (FSA) that contains two tapes: in this case, one corresponding to underlying analyses and one to surface forms. Each transition or arc in the transducer has a symbol corresponding to each tape. Either tape may be designated as the input. The transducer reads the input and takes the appropriate transitions between states. The symbols on the transitions corresponding to the output tape are written to an output buffer. If the transducer reaches a valid output state after consuming the entire input, then the contents of the output buffer are returned.

Any SPE-style system that uses sequences of rewrite rules to map from underlying analyses to surface forms can be implemented as a finite-state transducer (Johnson, 1972; Kaplan & Kay, 1994). In practice, this poses several problems, the most serious of which is that although the mapping from an underlying analysis to a surface form is deterministic given a set of rules, the inverse is not true in general. In fact, it is possible for a given surface form to correspond to a large, or even infinite, number of underlying analyses under certain rule systems. This quickly becomes intractable for any practical implementation of a morphological transducer. The *two-level morphology* framework (Koskenniemi, 1983, 1984, 1986; Beesley & Karttunen, 2003), which is implemented in HFST, was designed to mitigate these issues.

Two-level morphology divides the mapping between underlying analyses and surface forms into two stages. The first stage maps between a morphological analysis and an abstract morphophonological form, which allows a minimal representation of roots and suffixes. For example,

the analysis *qiz<dat>* will map to *qiz>*{*G*}{*A*} at this level, where > represents a morpheme boundary and {*G*} and {*A*} are essentially archiphonemes. It is this stage that solves the problem of overgeneration of underlying analyses: every valid underlying root must be encoded at this level.

The output of the first level then serves as input to the next level, which maps abstract morphophonological forms to surface forms. In this case, the phonological rules specified in the transducer will map {*G*} to *gh* and {*A*} to *a*, producing the surface form *qizgha* "to a girl."

In HFST, the first stage is implemented using the LEXC formalism, while the second is implemented using the TWOLC formalism. The rules specified at these levels are compiled into FSTs, which are then compose-intersected to form a single transducer. This transducer will only accept or propose underlying roots that are specified in the lexicon. Unfortunately, this introduces a degree of brittleness, since the transducer will not recognize any forms that are not present in the lexicon, and has no means by which to 'guess' the underlying form from the surface form unless augmented with additional tools.

G.1 Modifying the transducer

The transducer was modified to detect harmony by splitting each tag or tags corresponding to a haronizing suffix into three different forms corresponding to front variants (e.g., *<dat-f>*), back variants (e.g., *<dat-b>*), and ambiguous variants (e.g., *<dat>*). These tags are mapped to more restricted, though still abstract, morphological forms in the first stages. For example, *<dat-f>* will map to {*Gf*}{*Af*}, while *<dat-b>* will map to {*Gb*}{*Ab*}.

The second stage has been modified to map the newly introduced archiphonemes at the first stage to a restricted set of surface forms with corresponding backness. For example, it maps {*Gf*} and {*Af*} to only front allophones, and {*Gb*} and {*Ab*} to only back allophones. Several other complications relating to the interaction of harmony with other processes were also accounted for.

APPENDIX H

Other wug word breakdowns

This section presents more granular breakdowns of the wug word responses presented in Chapters 4 and 7. Words are represented in Uyghur Latin orthography. The analyses generally refer to the templates shown in Fig. H.1, but breakdowns at the level of the root are presented here for completeness.
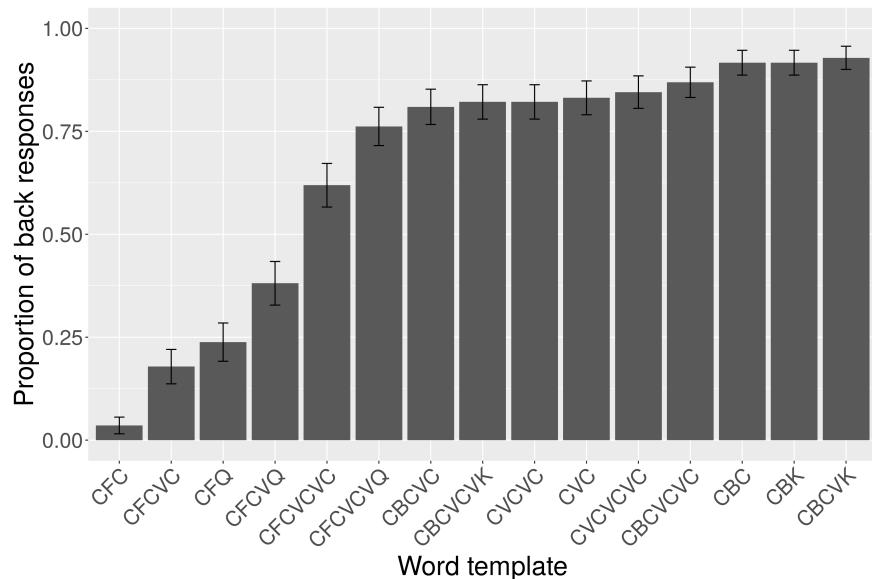
Figure H.1: Wug results by template where transparent segments are still included. Error bars are +/– one standard deviation.
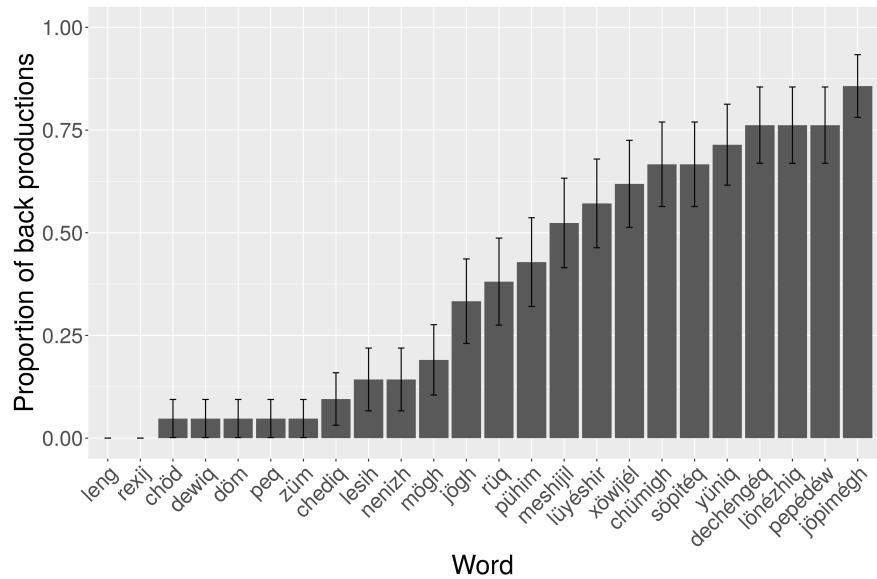
Figure H.2: Wug results by word for front triggers. Error bars are +/− one standard deviation.
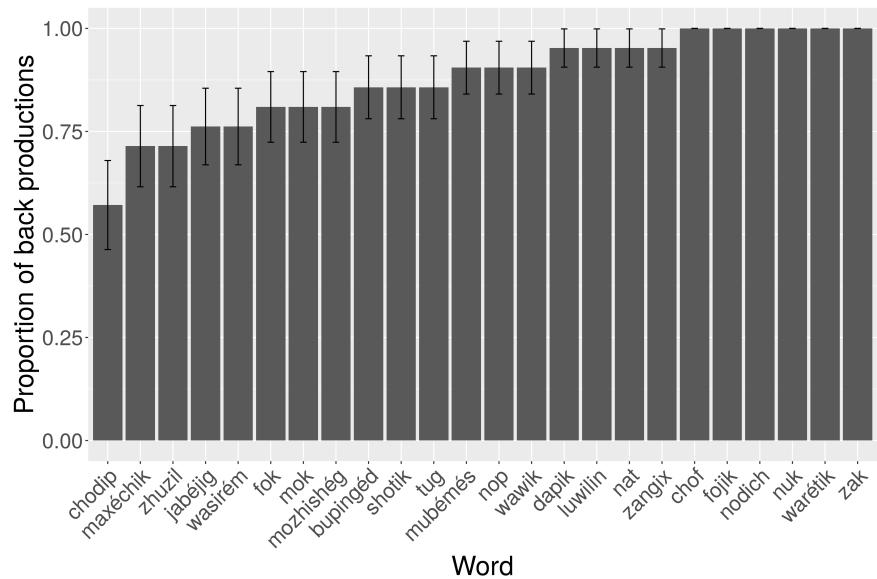
Figure H.3: Wug results by word for back triggers. Error bars are +/− one standard deviation.
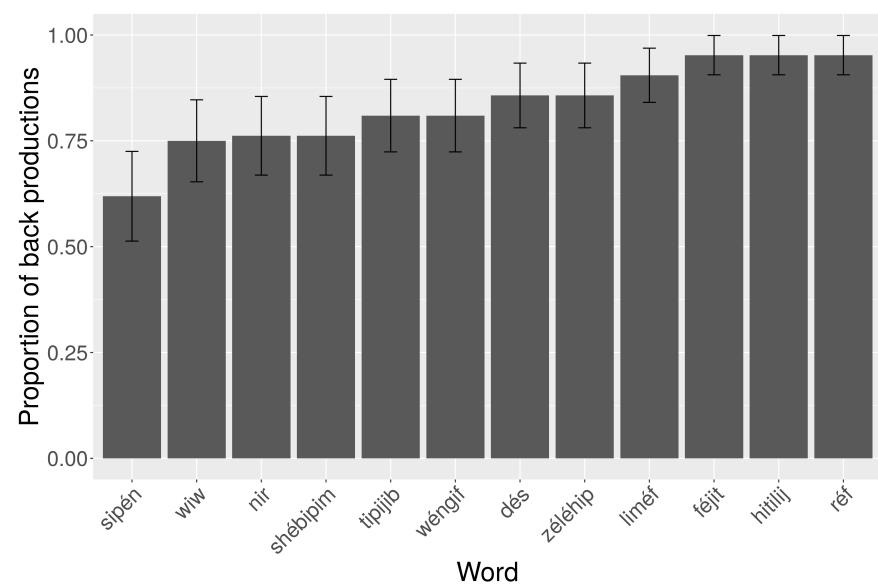
Figure H.4: Wug results by word for neutral stems. Error bars are +/− one standard deviation.

APPENDIX I

Monte Carlo simulations without *FRONTSUFFIX

This appendix presents the results of the Monte Carlo simulation from Chapter 4 run without the *FRONTSUFFIX constraint. Removing this constraint allows the constraint weights that are underlearned and overlearned by speakers to be more clearly identified, although it suggests that the lack of distance-based decay in back roots is due to the weights of the VAGREEBACK cosntraints, rather than the interaction between distance-based decay and a bias towards back suffixes.
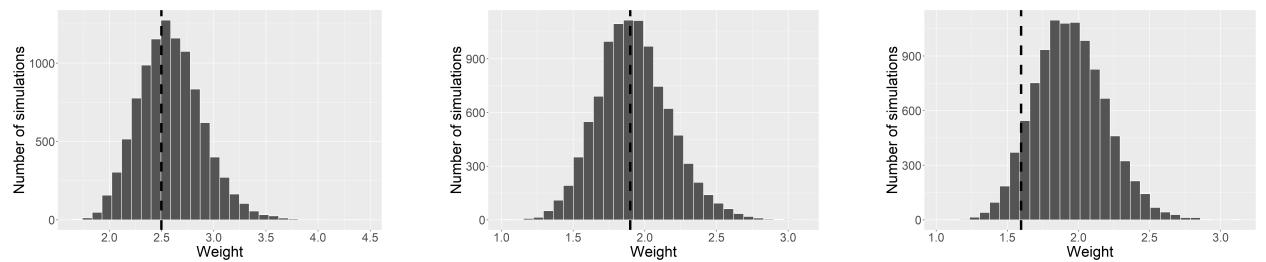
Figure I.1: Distribution of simulation weights for VAGREEBACK-1 (left), VAGREE-BACK-2 (center), and VAGREEBACK-3 (right). Dashed lines indicate weight fit to actual wug test data.
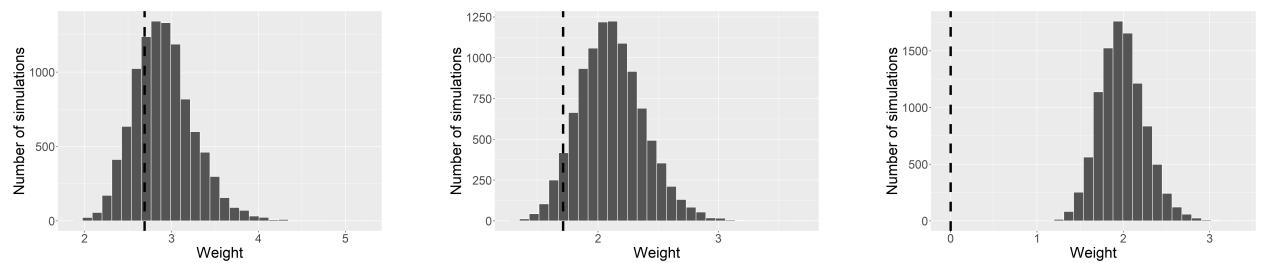
Figure I.2: Distribution of simulation weights for VAGREEFRONT-1 (left), VA-GREEFRONT-2 (center), and VAGREEFRONT-3 (right). Dashed lines indicate weight fit to actual wug test data.

Figure I.3: Distribution of simulation weights for CAGREEBACK (left) and CA-GREEFRONT (right). Dashed lines indicate weight fit to actual wug test data.

	Corpus raw	Wug raw	Ratio	Monte Carlo Test	$\hat{p}$
VAGREEBACK-1	4.52	0.95	4.76	Neither underlearned nor overlearned	0.402
VAGREEBACK-2	3.12	0.35	8.91	Neither underlearned nor overlearned	0.480
VAGREEBACK-3	3.15	0.05	62.99	Near-significantly underlearned	0.079
VAGREEFRONT-1	7.35	4.14	1.78	Neither underlearned nor overlearned	0.268
VAGREEFRONT-2	5.64	3.17	1.78	Near-significantly underlearned	0.057
VAGREEFRONT-3	5.38	1.31	4.11	Underlearned	0
CAGREEBACK	1.34	1.08	1.24	Overlearned	> 0.95
CAGREEFRONT	0.94	0	n/a	Near-significantly underlearned	0.051

Table I.1: Results of the Monte Carlo simulations with *FRONTSUFFIX.

These results are consistent with the claim in Chapter 4 that the long-distance harmony constraints are underlearned in the wug tests, resulting in distance-based decay, the constraint CA-GREEBACK is overlearned, showing increased influence of uvular triggers, and the constraint CA-GREEFRONT is underlearned, showing decreased influence of velar triggers.

APPENDIX J

Relating TSL and pTSL grammars

This appendix describes the ways in the TSL and pTSL grammars discussed in Chapter 7 are related.

Recall that a stringset $L \subseteq \Sigma^*$ is TSL if there is some TSL-k grammar (T, G) such that $L = \{s \in \Sigma^* | f_k(\pi_T(s)) \cap G = \emptyset\}$ (Section 7.2.2), and that a stringset $L' \subseteq \Sigma^*$ is pTSL if there is some pTSL-k grammar (π_P, G') such that $L' = \{w \in \Sigma^* | val_{(\pi_P, G')}(w) > 0\}$ (Section 7.3.3). This appendix demonstrates that the class of TSL stringsets is a proper subclass of the pTSL stringsets. Appendix K describes algorithms that are successful for converting certain subclasses of pTSL grammars to equivalent TSL grammars.

Theorem 4. *TSL $\subsetneq$ pTSL*

To prove this theorem, we must show that TSL $\subseteq$ pTSL and TSL $\neq$ pTSL.

First, we show that TSL $\subseteq$ pTSL. Consider an arbitrary TSL grammar (T, G) over Σ that accepts the stringset L. In order to define a pTSL grammar (π_P, G') that also accepts L, we define the projection probabilities for each $s \in \Sigma$ as follows

$$P_{proj}(s) := \begin{cases} 1 & \text{if } s \in T \\ 0 & \text{otherwise} \end{cases}$$

and set $G' := G$. Under this definition of π_P, each input will have exactly one possible projection, and this input will receive a non-zero probability only if this projection contains none of the prohibited k-factors in G'. This evaluation procedure is identical to that used by the corresponding TSL grammar.

Example 5. Consider the TSL-2 grammar (T, G) presented in Example 2. The corresponding pTSL-2 grammar (π_P, G') has $G' := G$, and defines the projection probabilities as:

$$P_{proj}(\sigma) = 0$$

$$P_{proj}(\acute{\sigma}) = 1$$

Next, we show that TSL $\neq$ pTSL. This can be demonstrated by counterexample.

Consider a pTSL-2 grammar (π_P, G) over $\Sigma := \{a, b, c\}$. Let π_P be defined such that b and c always project, a sometimes projects, and $G := \{ba, bc, cc\}$. Table J.1 shows a number of inputs, their possible projections, and whether they are accepted by the grammar.

Block	Input	Projections	Accepted?
1	b	b	✓
	c	c	✓
	bc	<u>bc</u>	✗
2	cc	<u>cc</u>	✗
	cac	<u>cc</u>, cac	✓
3	ba	b, <u>ba</u>	✓
	ac	c, ac	✓
	bac	<u>bc</u>, <u>bac</u>	✗

Table J.1: Sample inputs to the pTSL grammar. Prohibited 2-factors are underlined.

Now suppose that there is some corresponding TSL-2 grammar (T, G') that accepts the same stringset. At the very least, this grammar must assign the same acceptability judgments to the inputs in Table J.1 as those shown in the rightmost column. What remains to be worked out is which symbols such a grammar would need to (deterministically) project and which 2-factors it would need to prohibit in order to do this.

To correctly handle the inputs in Block 1 of Table J.1, this grammar must project both b and c: if b were not projected, the projections of c and bc would be identical, meaning either both would be accepted or both would be rejected. Similarly, c must be projected to differentiate between the projections of b and bc. Finally, G' must contain the prohibited 2-factor bc, since this is the only

2-factor of the projection of *bc* that is not contained in the projections of *b* or *c*.

The inputs in Block 2 of Table J.1 demonstrate two facts: first, the corresponding TSL-2 grammar must project *a*: otherwise, the projections of the inputs *cc* and *cac* will be identical. Because all symbols are projected, this effectively means the corresponding TSL-2 grammar is an SL-2 grammar. Second, G' must contain *cc*, since this is the only 2-factor of the projection of *cc* not also present in the projection of *cac*.

The inputs in Block 3 of Table J.1 dash any hopes for an equivalent TSL-2 grammar. Consider the 2-factors of the projections of each of these inputs:

$$f_2(\pi_T(bac)) = \{ \rtimes b, ba, ac, c \ltimes \}$$
$$f_2(\pi_T(bab)) = \{ \rtimes b, ba, ab, b \ltimes \}$$
$$f_2(\pi_T(ac)) = \{ \rtimes a, ac, c \ltimes \}$$

Note that every 2-factor of the projection of the ungrammatical input *bac* is present in the 2-factors of the projections of the grammatical inputs *ba* or *ac*: there is no 2-factor we can use to reject *bac* without rejecting either *ba* or *ac*, and thus our TSL-2 grammar cannot accept the same stringset as the pTSL-2 grammar defined above (this can also be demonstrated using suffix substitution closure; Rogers & Pullum, 2011).

We can also demonstrate that there is no TSL-*k* grammar for $k > 2$ that accepts the same stringset as this pTSL-2 grammar (the case of $k = 1$ is trivially true). Note that the considerations of which symbols to project exemplified by Blocks 1 and 2 in Table J.1 still apply regardless of our choice of *k*, so the question becomes whether we can define *k*-factors for $k > 2$ that produce the correct behavior.

Input	Projections	Accepted?
baa*	b, <u>ba</u>, <u>ba</u>a, …	✓
aa*c	c, ac, aac, …	✓
baa*c	<u>bc</u>, <u>ba</u>c, <u>ba</u>ac, …	✗

Table J.2: Additional sample inputs to the pTSL grammar. Prohibited 2-factors are underlined.

Consider a generalization of the input forms in Block 3 of Table J.1, shown in Table J.2. The

original pTSL-2 grammar will accept all inputs of the form baa^* and aa^*c, and will reject all inputs of the form baa^*c. For any value of $k > 2$ we might choose for an equivalent TSL-k grammar, every k-factor of the projection of the input $baa^{k-2}c$ will be present in the projections of the inputs baa^{k-2} or $aa^{k-2}c$, and so the former input cannot be rejected without also rejecting one of the latter two. Thus there is no value of k for which a TSL-k grammar will reject the set baa^*c while accepting the sets baa^* and aa^*c.

Thus no TSL grammar can be defined that accepts the same stringset as the pTSL-2 grammar described above, and so TSL $\neq$ pTSL.

APPENDIX K

Algorithms for converting subclasses of pTSL to TSL

There are at least two subclasses of pTSL for which equivalent TSL grammars can always be constructed. The first is the trivial subclass of pTSL where every prohibited k-factor contains only symbols whose projection probabilities are < 1. This means that every input will have at least one possible projection that contains none of the prohibited k-factors, and thus all inputs will be accepted. Accordingly, the equivalent TSL grammar will contain no prohibited k-factors (and so the choice of T is unimportant).

A more interesting subclass of pTSL for which equivalent TSL grammars can always be constructed consists of pTSL grammars where every prohibited k-factor contains only symbols that are always projected. In these cases, I conjecture that the following algorithm will always generate an equivalent TSL grammar, though I do not provide a formal proof here.

Consider an arbitrary pTSL grammar (π_P, G) such that all k-factors in G contain only symbols with a projection probability of 1. This can be converted to an equivalent TSL grammar (T, G') by performing two steps:

1. $G' := G$

2. $T := \left\{ s \in \Sigma \mid P_{proj}(s) > 0 \right\}$

Recall that an input will only receive a probability of 0 if all of its possible projections contain prohibited k-factors. Consider an input that does not contain a prohibited k-factor, but where one may be created if certain symbols are deleted. If any of these symbols have projection probabilities greater than 0, there will be at least one possible projection where they are not deleted, and the prohibited k-factor is not produced. Hence this input will not receive a probability of zero. Defining

T to be the set of all symbols with non-zero projection probabilities ensures that such strings will be accepted by the corresponding TSL grammar.

Example 6. Consider the pTSL-2 grammar defined in Example 4 in Chapter 7, which meets the criterion described above. The corresponding TSL-2 grammar has $G := \{ac\}$ and $T := \{a,b,c\}$. This grammar accepts all input strings over $\{a,b,c\}$ except those that contain the substring *ac*. This is exactly the set to which the original pTSL-2 grammar will assign non-zero probabilities.

Example 7. The pTSL-2 grammar used as a counterexample in Appendix J does not meet the criterion for this algorithm to be applied: the prohibited 2-factor *ba* contains the symbol *a*, which does not have a projection probability of 1. The TSL grammar generated by this algorithm will erroneously reject the class baa^*.

The trouble in Example 7 arises because always projecting *a* can both prevent a prohibited *k*-factor from being formed (as for the input *cac*) and retain a prohibited *k*-factor present in the input (as for the input *ba*). In the pTSL grammar we consider simultaneously the cases where *a* does and does not project, while in the corresponding TSL grammar we must choose one or the other. This will produce the incorrect output for one of these forms, and we have seen above that no choice of *k*-factors can mitigate this conflict without producing incorrect results for other forms.

For pTSL grammars where *k*-factors contain only symbols with projection probabilities of 1 (as in Example 6), choosing to project, in the corresponding TSL grammar, all symbols that sometimes project in the pTSL grammar can only have the effect of *preventing* the formation of prohibited *k*-factors. The projection of a given input where all sometimes-projecting symbols are projected will never contain more prohibited *k*-factors than projections where some or none of these symbols project. Thus choosing to project such symbols in the corresponding TSL grammar deterministically generates the "most grammatical" projection: if this projection contains no prohibited *k*-factors, the input will be accepted by both the original pTSL grammar and its corresponding TSL grammar, and so the two will behave equivalently.

It may be the case that there are additional subclasses of pTSL for which equivalent TSL grammars may always be constructed. I leave this as an interesting area for future research.

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