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PHONOLOGY

ARTICLE

O gradience, where art thou? Examining backness harmony in Uyghur

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Abstract

Discreteness of representations is a core commitment of classical generative phonology. However, one of the biggest arguments levelled against discreteness has come from the phenomenon of incomplete neutralisation – where the output of some phonological process on a feature [F] is phonetically distinct from underived [±F]. A sizeable body of work has contended that incomplete neutralisation crucially undermines the sufficiency of discrete representations, arguing instead for the inclusion of gradient representations. In this article, we investigate backness harmony in Uyghur, evaluating recent claims of incomplete neutralisation. Results from two production studies replicate findings from previous work on the language, but we show that, with proper experimental controls, the pattern is derivable without recourse to gradient phonological representations. We then discuss the conceptual and theoretical challenges for gradient representations along with criteria for true phonologically relevant gradience.

Contents

1. Introduction **2**
2. Background **3**
2.1. Incomplete neutralisation . . . 3
2.2. Uyghur . . . 4
3. Experiment 1: interpolation **7**
3.1. Methods . . . 9
3.2. Results . . . 11
4. Experiment 2: centralisation, coarticulation and morphotactics **14**
4.1. Methods . . . 16
4.2. Results . . . 18
5. Discussion **21**
5.1. Backness harmony in Uyghur . . . 21
5.2. Representational issues . . . 23
5.3. What constitutes a case of phonological incomplete neutralisation? . . . 25
6. Conclusion **25**
References **25**

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1. Introduction

The classic generative view of phonology includes the important claim that phonological representations are discrete, which is typically implemented with binary features (Halle 1959; Chomsky & Halle 1968; Kenstowicz & Kisseberth 1977, 1979; Kenstowicz 1994; Hale *et al.* 2007). The representational claims of generative research, particularly evident in *The Sound Pattern of English* (Chomsky & Halle 1968), led to rich discussion of the nature of phonological representations throughout the next two decades. More recently though, researchers have argued that phonological representations need to include gradience to capture observed patterns. One central area of debate has centered around the phenomenon of INCOMPLETE NEUTRALISATION, wherein a phonological process putatively neutralising the distinction between two categories results in surface representations in which the categories are still distinct phonetically. For example, prosodic word-final devoicing in German has been observed to result in a derived voiceless category that is subtly phonetically distinct from the realisation of the underlying voiceless category (Port & O'Dell 1985; Roettger *et al.* 2014). While some have argued that such results suggest a need for gradience in representations (Port & Leary 2005; Goldrick & Cole 2023), others have argued that the small differences reported stem from performance factors (Fourakis & Iverson 1984; Manaster Ramer 1996; Warner *et al.* 2004; Du & Durvasula 2022, 2025). As we point out below, the import of observed incomplete neutralisation on phonological representations is often quite indirect, given that it depends on many other tacit assumptions made by researchers, including the assumption that the relevant process is indeed phonological.

In fact, probing the phonological status of the patterns under investigation has been the explicit goal of some recent work. This research has sought to establish the phonological relevance of incomplete neutralisation by demonstrating phonological interactions involving the incomplete neutralisation process (Braver & Kawahara 2014; Braver 2019; McCollum 2019a,b; Du & Durvasula 2022). A particularly interesting and nuanced case within this line of argumentation comes from McCollum's (2019a,b) work on Uyghur vowel harmony. In (1), non-initial vowels alternate according to the backness of the initial-syllable vowel.[1] In a theory with binary [±back], the output of harmony in (1) is categorically either [ɑ] or [æ] depending on the backness of the initial vowel. However, McCollum reports that results from a production study support the proposition that non-initial back vowels are incrementally fronted, while front vowels exhibit no comparable positional differences. To account for this, he contends that [back] is continuously valued between 0 and 1. Initial-syllable back vowels are produced as [1 back] and non-initial back vowels are produced with backness values between 0 and 1, such as [0.8 back]. In essence, the pattern is iterative incomplete neutralisation – each incompletely assimilated vowel triggers further incomplete assimilation in the following syllable, generating the reported sub-phonemic fronting pattern.

(1)	*UR*	*Traditional SR*	*McCollum's SR*	*Gloss*
a.	/pɑltA-m-DA/	[pɑltɑmdɑ]	[pɑltɑmdɑ]	'axe-POSS.1SG-LOC'
		[+bk] [+bk] [+bk]	[1 bk] [0.8 bk] [0.6 bk]	
b.	/sællA-m-DA/	[sællæmdæ]	[sællæmdæ]	'turban-POSS.1SG-LOC'
		[−bk] [−bk] [−bk]	[0 bk] [0 bk] [0 bk]	

McCollum uses harmony's interaction with a structure-preserving consonantal alternation to support his argument that harmony is both phonological and gradient. However, Du & Durvasula (2022) argue that demonstrating that a pattern is phonetically gradient and interacts with some phonological process is not a sufficient reason to introduce gradience into the phonology. They find that phonetically incompletely neutralised tonal contrasts in Huai'an Mandarin interact with tone sandhi patterns in a manner that suggests the incompleteness of the tonal alternation is irrelevant for the phonology. They claim that gradient tone height in Huai'an Mandarin derives from performance factors, rendering

[1] We use archiphonemic representations in the underlying representations for alternating suffixes, in line with much previous work on Turkic, and also to avoid committing to one particular allomorph as underlying, since that is not central to the paper.

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the gradience non-phonological. While Du & Durvasula's (2022) findings centre on a postlexical pattern, and many previously discussed patterns of incomplete neutralisation are arguably post-cyclic or postlexical, McCollum's (2019a,b) findings are distinct in that they emerge from the lexical phonology of the language. In the words of Cohn (2006: 36), this claim, if true, 'would strike at the core of our understanding of the phonology'.

In this article, we further probe the Uyghur backness harmony pattern with two production studies to attempt to derive the incomplete neutralisation of [back] from other factors, specifically phrasal interpolation, centralisation and local consonant–vowel coarticulation. To preview our results, our findings support the case that the observed gradience is derivable from the interaction of coarticulation and centralisation, but not from interpolation. In turn, our results suggest there is no need for gradient representations in the phonology of the language.

2. Background

2.1. Incomplete neutralisation

In this section, we look more closely at a specific case of incomplete neutralisation, namely final devoicing, in order to examine the issues relevant to any discussion of the general phenomenon of incomplete neutralisation. Final devoicing has been observed in a variety of languages, including Catalan (Dinnsen & Charles-Luce 1984), Dutch (Warner *et al.* 2004; Ernestus & Baayen 2006), German (Port & O'Dell 1985; Roettger *et al.* 2014), Malay (Abu Bakar *et al.* 2007), Pennsylvania Dutchified English (Anderson & Davis 2013) and Russian (Dmitrieva 2005; Kharlamov 2012; Matsui 2015), among others. Though the general pattern is similar, the exact phonological domain of application differs across languages. Here, we look specifically at the pattern in German, both to be concrete and because there is a substantial amount of work on it. The final devoicing pattern in German is best described as prosodic word-final devoicing (Wagner 2002), and can be descriptively stated in a rule-based framework as in (2). Note that though devoicing is usually presented as a structure-changing process that introduces [−voice], we follow Iverson & Salmons (1995, 2003) and Beckman *et al.* (2013) in analysing it as a rule inserting [+spread glottis] on prosodic word-final obstruents.

(2) [+obstruent] → [+spread glottis] / ___]$_{\text{Prosodic Word}}$

While the process is described as a case of phonological neutralisation, it has been known since the 1980s that in German, devoiced prosodic word-final voiceless obstruents are not phonetically identical to underlyingly voiceless prosodic word-final obstruents (Port & O'Dell 1985; Roettger *et al.* 2014, among others). In fact, a variety of small differences have been noticed along dimensions that typically distinguish voiced and voiceless obstruents – for example, differences in preceding vowel duration and consonant closure duration.

Despite continued observation of incomplete voicing neutralisation in German across many experiments, the source of the incomplete neutralisation has not been resolved. Some have argued that the observation falsifies models of generative phonology with categorical representations (Port & Leary 2005; Goldrick & Cole 2023). However, others have rejected this interpretation, contending that the observed incomplete neutralisation effect is actually a task effect (Fourakis & Iverson 1984; see Winter & Roettger 2011 and Roettger *et al.* 2014 for discussion). Others have argued that the observed incomplete neutralisation is actually an orthographic effect (Manaster Ramer 1996; Warner *et al.* 2004), though in some other cases orthography is not responsible for the observed phonetic differences (Braver 2013). Alternatively, some have pointed out that one could reject the claim that the devoicing process is truly phonological, in which case the argument is moot (Dunbar 2013; Braver & Kawahara 2014; Braver 2019). Taking a markedly different approach, van Oostendorp (2008) contends that generative phonological theories can account for such patterns without recourse to gradient information if given access to representations beyond just inputs and outputs, specifically turbid representations (Goldrick 2000).

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Table 1. *Uyghur vowel inventory.*

	[−back]		[+back]	
	[−round]	[+round]	[−round]	[+round]
[+high]	i	y		u
[−high, −low]	e	ø		o
[+low]	æ		ɑ	

Finally, and somewhat related to the previous issue, some have argued against the basic premise behind incomplete neutralisation claims. These authors dispute the relevance of incomplete phonetic neutralisation for phonological theories with categorical representations (Chomsky & Halle 1968; Lyons 1974; Hammarberg 1976, 1982; Kahn 1976; Mohanan 1986; Du & Durvasula 2022, 2025). As discussed extensively in Du & Durvasula (2025), claims from classical generative phonology are ultimately *ceteris paribus* claims: the expectation of phonetic neutralisation is only true *if all other factors are held constant.* We follow up on this issue below, showing that the evidence of incomplete (asymmetrical) neutralisation that McCollum (2019a,b) observed, while replicable, ultimately stems from inadequate control – that is, from a violation of the *ceteris paribus* clause.

To be clear, while our findings suggest that previous reports of iterative incomplete neutralisation in Uyghur are spurious, they do not invalidate all reported or other potential cases of incomplete neutralisation. Furthermore, incomplete neutralisation is only a challenge to the sort of classical generative grammatical architecture assumed herein, which involves distinct phonological and phonetic modules, with limited access to phonetic information in the phonology. Incomplete neutralisation does not challenge grammatical architectures that merge the phonology and phonetics, since these allow access to gradient information throughout (e.g., Browman & Goldstein 1989; Flemming 2001).

2.2. Uyghur

Uyghur (iso: uig) is a Southeastern Turkic language spoken by approximately 12 million people, primarily in the Xinjiang Uyghur Autonomous Region in northwestern China. Notable populations of Uyghur speakers live in Kazakhstan, Kyrgyzstan and Uzbekistan; a large diaspora population of Uyghurs is also present in Europe and North America (Nazarova & Niyaz 2013). There are three main dialect groups – Central, Southern and Eastern (Tenishev 1963). Roughly, 90% of Uyghur speakers speak the Central dialect (Yakup 2005), of which the variety spoken along the Ile River in southeastern Kazakhstan is a subdialect.

2.2.1. Vowel inventory

Eight vowels are contrastive in Uyghur: /i y e ø æ ɑ o u/. The vowel /e/ is marginal, occurring in initial syllables as a product of a raising process often called umlaut, as well as in non-nativised loans (Hahn 1991; Mayer *et al.* 2022; Sharma in press). Featural descriptions for each vowel in the Uyghur inventory are presented in Table 1.

2.2.2. Vowel harmony

Uyghur exhibits two types of vowel harmony, backness and rounding harmony.[2] Both harmonies are described in a number of publications (Nadzhip 1971; Hahn 1991; Vaux 2000; Engesæth *et al.* 2009;

[2]Vajda (1994), Vaux (2009) and Washington (2016) contend that backness harmony in Turkic is actually tongue root harmony.

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McCollum 2019a,b; Mayer 2021; Mayer *et al.* 2022). Of the two, backness harmony is more robust. Rounding harmony is highly restricted, applying to certain high vowels in certain environments in the standard dialect (Hahn 1991; McCollum 2019a; cf. Abdurehim 2014 on the Lopnor dialect). For this reason, rounding harmony will not be further discussed.

Backness harmony produces contrast-neutralising alternations among the low vowels and high rounded vowels, as seen in (3) and (4). In these examples [æ y] occur after [−back] roots, while [ɑ u] occur after [+back] roots. Observe also in (3) and (4) that the dorsal consonant of the dative and gerundial suffixes varies according to vowel backness: velar [k g] co-occur with front vowels, while uvular [q ʁ] co-occur with back vowels. Local voicing assimilation determines the voicing of these suffix-initial consonants.

(3) *Low vowel alternations*

a.	bæl-gæ	‘lower.back-DAT’	d.	bɑl-ʁɑ	‘honey-DAT’
b.	køl-gæ	‘lake-DAT’	e.	qol-ʁɑ	‘hand-DAT’
c.	kyl-gæ	‘ash-DAT’	f.	qul-ʁɑ	‘slave-DAT’

(4) *High round vowel alternations*

a.	bær-gy	‘give-GER’	d.	bɑr-ʁu	‘go-GER’
b.	øl-gy	‘die-GER’	e.	bol-ʁu	‘be-GER’
c.	kyl-gy	‘laugh-GER’	f.	qur-ʁu	‘build-GER’

The vowels /e i/ do not trigger backness harmony; the backness of following vowels is lexically determined (Lindblad 1990; Mayer *et al.* 2021). Furthermore, non-initial /e/ occurs only in unassimilated loans and does not alternate for backness. Hahn (1991) lists a number of allophones of /i/ and /e/ that depend on flanking consonantal context. However, McCollum (2019a,b) finds that non-initial /i/, in addition to varying by consonantal context, varies allophonically based on preceding vowel backness.

Although the mid rounded vowels /ø o/ regularly trigger backness alternations, they do not occur in non-initial syllables in the native and nativised vocabulary (cf. Abdurehim 2014 for the Lopnor dialect). This phonotactic ban on non-initial /ø o/, in conjunction with the neutrality of /e i/, limits harmony to only two consistent alternations, [æ]~[ɑ] and [y]~[u]. The more productive alternation is [æ]~[ɑ], which occurs in a wide range of suffixes. The alternation between [y] and [u] is far more limited, occurring in the gerundial suffix /-GU/ and in suffixes that undergo rounding harmony, such as the deadjectival nominalizing suffix /-lIK/.

2.2.3. McCollum (2019a,b)

McCollum (2019a,b) reports production data from a picture-naming task conducted with nine native Uyghur speakers residing in Chunja, Kazakhstan. In this task, McCollum elicited bare nouns as well as possessive, plural and overtly case-marked nouns, yielding words from one to five syllables in length. Some example forms are shown in (5). A few things are worth briefly noting from these examples. First, low vowels raise to [i] in medial open syllables, as in (5e)–(5g) and (5n) (Nadzhip 1971; Hahn 1991; Engesæth *et al.* 2009; Mayer *et al.* 2022). Second, note in (5k) that /æ/ raises to [e] before the epenthetic [i] of the first-person singular possessive suffix. This pattern, often called umlaut, affects the low back vowel as well, as in /bɑl-m/ [belim] ‘honey-POSS.1SG’ and occurs in a variety of other contexts. These two processes are common in the language, though they are not the focus of McCollum’s analysis or ours. More importantly, the data in (5) illustrate the general type of data elicited in McCollum (2019a,b).

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(5)	a.	pɑqɑ	'toad'	h.	bæl	'lower.back'
	b.	pɑqɑ-m	'toad-POSS.1SG'	i.	bel-im	'lower.back-POSS.1SG'
	c.	pɑqi-dɑ	'toad-LOC'	j.	bæl-dæ	'lower.back-LOC'
	d.	pɑqɑ-m-dɑ	'toad-POSS.1SG-LOC'	k.	bel-im-dæ	'lower.back-POSS.1SG-LOC'
	e.	pɑqi-lɑr	'toad-PL'	l.	bæl-lær	'lower.back-PL'
	f.	pɑqi-lɑr-dɑ	'toad-PL-LOC'	m.	bæl-lær-dæ	'lower.back-PL-LOC'
	g.	pɑqi-lir-i-dɑ	'toad-PL-POSS.3SG-LOC'	n.	bæl-lir-i-dæ	'lower.back-PL-POSS.3SG-LOC'

Recall that McCollum (2019a,b) reports that front vowels retain their frontness, while back vowels are incrementally fronted in non-initial syllables. Specifically, he analyses *z*-score normalised F_2 (Lobanov 1971) of target vowels with a mixed-effects linear regression, predicting F_2 based on initial-syllable backness, target vowel height, syllable number, root type (mono- or disyllabic), preceding consonant place of articulation (bilabial, coronal or dorsal) and following consonant place of articulation. McCollum's model also includes two-way interactions between preceding consonant place and vowel height, following consonant place and vowel height, initial backness and vowel height, initial backness and syllable number, initial backness and root type, and syllable number and root type. His model also incorporates a three-way interaction for initial vowel backness, syllable number and root type. In terms of random effect structure, his model includes random intercepts for speaker and target vowel, as well as by-syllable random slopes for speaker and target vowel.

Though McCollum's word list does not strictly control for flanking consonant place, he attempts to account for potential coarticulatory effects of preceding and following consonants in his statistical model. He further attempts to account for any possible differences in coarticulation based on vowel height by incorporating two-way interactions between preceding and following consonants and vowel height. McCollum's goal was to rule out many potential confounds from the elicited data to increase the relative certainty that any positional effects discovered are not due to some other factor, but are the direct result of the harmony system.

McCollum (2019a,b) discusses four possible accounts of the elicited data. The first possible account involves categorical harmony with no phonetic reduction. In essence, categorical harmony should output derived [±back] vowels that are indistinguishable from their underlying, non-derived counterparts (see, e.g., Zsiga 1997: 235). This prediction is easily falsified, as non-initial back vowels exhibit significantly higher F_2 than their initial-syllable counterparts.

The second analysis McCollum entertains involves categorical phonological harmony with phonetic centralisation. In this account, as in the first, phonological harmony operates categorically. However, phonetic reduction of non-initial syllables results in symmetric centralisation (Nord 1986; Vayra & Fowler 1992; Krakow *et al.* 1995; Herman *et al.* 1996; Johnson & Martin 2001). Crucially, the sort of incremental reduction in non-initial syllables reported in previous work (e.g., Vayra & Fowler 1992) is inconsistent with the asymmetric Uyghur pattern, where front vowels do not exhibit systematic positional shifts in F_2 comparable to their back vowel counterparts.

Third, McCollum considers the possibility that harmony is just phonetic interpolation and not phonological at all. This could produce the asymmetric shift observed, given his assumption that [−back] is default and [+back] is active (see Mayer 2021 for an analysis with [+back] as default). He marshals two types of evidence to support the activity of [+back]. First, suffixal high vowels that participate in harmony in non-final position default to [i], a [−back] vowel, when the same suffixes occur in absolute word-final position, where harmony is blocked. For instance, in non-final position, the high vowels allophonically alternate for harmony, as seen in the third-person possessive suffix: for example, [ɪ] in [dæst-ɪ-dæ] 'steppe-POSS.3-LOC' but [ə] in [ɑst-ə-dɑ] 'under-POSS.3-LOC'. Yet, when this same suffix occurs word-finally, the high vowel surfaces as [i] irrespective of the backness of the preceding vowel: [dæst-i] 'steppe-POSS.3' and [ɑst-i] 'under-POSS.3'. Second, McCollum (2019a: 146–148) describes historical patterns of loanword adaptation in Uyghur whereby borrowings

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with back vowels in the source language may be fronted in Uyghur (e.g., Arabic /ʔumr/ 'life', Uyghur /ømyr/). However, front vowels in the source language are always borrowed with front vowels.

Since McCollum elicited his data in isolation, it is possible that there is a [−back] default articulatory setting at the right edge of each word. This would be relatively consistent with articulatory studies finding default articulatory settings that resemble the lingual position of the unmarked feature value (Hudu 2010; Allen *et al.* 2013). Thus, the phonetic interpolation account would derive the incremental fronting of back vowels through gradual shifting of all vowels not phonologically specified for backness (i.e., non-initial vowels) towards the default articulatory setting, which is fully attained at the right edge of the word.

This account is, however, inconsistent with the relevant facts of Uyghur phonology. Harmony must be phonological because it is exceptionful and also interacts with a structure-preserving consonantal alternation. Back vowels regularly co-occur with uvular consonants, while front vowels co-occur with velar consonants, as evidenced by the dative and gerundial suffixes in (3) and (4). Critically, there is no voiced uvular stop in the Uyghur inventory, so /g/ alternates with /ʁ/. This difference in both place and manner of articulation supports the necessity of backness harmony in the lexical phonology in the language, as opposed to being a postlexical process.

Given the failure of these accounts, McCollum contends that harmony must be both phonological and gradient. If harmony is phonological and [+back] is active, then the gradience reported is derivable from iterative incomplete neutralisation – each syllable incompletely assimilates to the backness of the previous syllable. To model this, McCollum (2019a: ch. 6) develops a Harmonic Grammar (Legendre *et al.* 1990) analysis utilizing a gradient AGREE-like constraint that penalizes subphonemic differences in vowel backness (see Braver 2013 for a similar constraint), showing that this analysis fits the data better than a traditional analysis without access to continuous phonological representations.

In the following two sections, we pursue two alternatives to McCollum's gradient phonological account. We conduct two experiments to revisit two of the phonetic alternative accounts considered and rejected by McCollum (2019a,b). Experiment 1 tests the possibility that phrasal interpolation explains gradient fronting. Experiment 2 tests the possibility that non-initial phonetic reduction, along with local consonant–vowel coarticulation, can explain the pattern found in McCollum's work. We lay out the mechanics and predictions of each account. We then test those against production data elicited with Uyghur speakers in the same location where McCollum elicited his data, Chunja, Kazakhstan.

3. Experiment 1: interpolation

In this section, we focus on McCollum's (2019a, 2019b) choice to elicit words in isolation and its potential influence on the interpretation of his results. McCollum rules out the possibility that gradient fronting in non-initial syllables could be derived from phonetics alone by noting that backness harmony interacts with a structure-preserving consonantal backness alternation. However, it is possible that harmony is phonological while gradient fronting emerges from the phonetic module of the grammar. Specifically, if the phonology–phonetics interface does not convert phonological features into explicit targets but rather to windows within which phonetics may interpolate (Keating 1988, 1990), then it is possible to derive the fronting pattern in McCollum's data.

If phonetics operates over these windows, then gradient interpolation may occur between left and right word edges. At the left edge of the word, the initial syllable is specified for [±back]. The backness of initial-syllable vowels is not phonologically predictable, in contrast to the backness of all other positions (for much of the native and nativised vocabulary, anyway). McCollum (2020) shows that in the related language Kyrgyz this difference in predictability results in hyperarticulation of the initial syllable, or alternatively hypoarticulation of non-initial syllables. If the initial syllable is the only position with unpredictable backness, and this results in increased articulatory precision, then it is reasonable to suppose that initial-syllable vowels are produced with clear phonetic targets.

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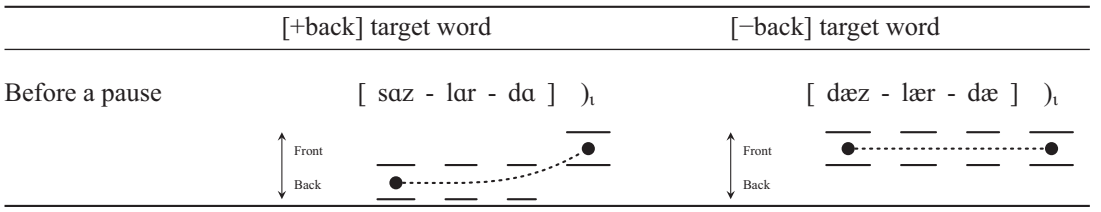


Figure 1. *F_2 patterns for words uttered in isolation according to an interpolation-based account of gradient backness harmony in Uyghur.*

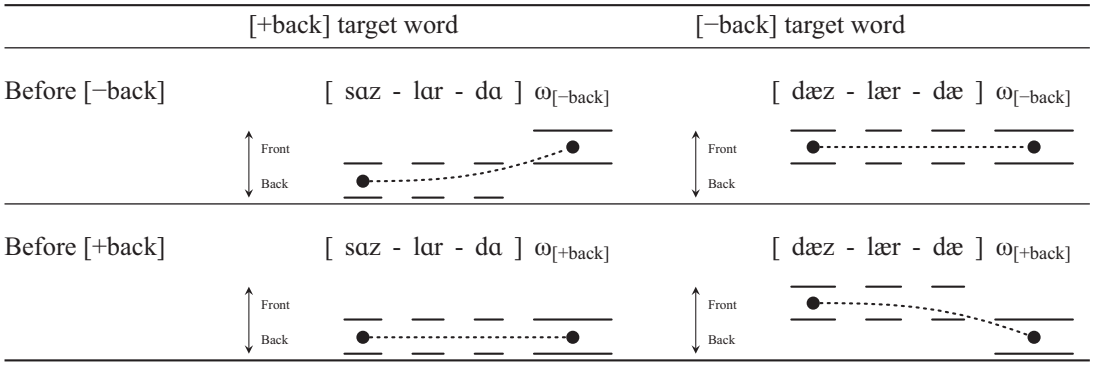


Figure 2. *Predicted F_2 patterns according to phrasal context if gradience is derivable via phonetic interpolation.*

In addition, if the right edge of the word in McCollum's data is marked by a very anterior lingual position, then gradient fronting may be derivable from interpolation between the two. Hudu (2010) and Allen *et al.* (2013) find evidence that the default articulatory settings for languages with tongue root harmony may correspond to the lingual posture of the unmarked feature value. In McCollum's analysis, [−back] is unmarked, predicting a fronted tongue body when at rest. Since words were collected in isolation, every word could have involved a transition towards this [−back] default articulatory setting. This is schematised in Figure 1. In back vowel words like [sɑz-lɑr-dɑ] 'instrument-PL-LOC', this would result in a shift from lower to higher F_2, exactly what McCollum reports. In contrast, the existence of two [−back] targets at each word edge would likely mitigate centralisation in front vowel words, like [dæz-lær-dæ] 'crack-PL-LOC', resulting in relatively constant F_2 values throughout the word.

Note that although the interpolation is visually represented with a curve in Figures 1 and 2, Keating (1990: 457) does not spell out any particular type of function that would best describe this interpolation. She writes, 'I will offer no explicit procedure for constructive paths through windows, e.g., what functions are possible, whether construction proceeds directionally, how large a span is dealt with at a time. I also leave aside the question of how timing fits into the scheme.' We use curves in our diagrams to heighten the visual distinction between shifting and non-shifting F_2 trajectories. However, in our statistical modelling we use linear functions, because they are simpler and because Keating does not explicitly spell out what sort of functions are actually necessary for her model.

The account schematised in Figure 1 is distinct from McCollum's because it invokes the phonological grammar to insert the windows present in all non-initial syllables. McCollum's discussion of interpolation assumes no non-initial windows, only an initial vowel target and a potential phrase-final default articulatory setting. While the interpolation-only account is, as McCollum (2019a,b) argues, ruled out by the presence of exceptions and structure-preserving alternations that depend on harmony, the account sketched above provides a plausible reinterpretation of his findings.

This alternative account predicts that the F_2 trajectories within a given word, be it back or front, should depend on phrasal context, as shown in Figure 2. Specifically, back-vowel words that are

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followed by another back-vowel word should not, under this analysis, exhibit systematic fronting, precisely because there is no following [−back] lingual specification. Relatedly, the F_2 of vowels in front-vowel words should decrease in non-initial syllables if the following word is [+back], because of the introduction of a [+back] specification following the target word. We can assess these predictions by evaluating the interaction of position and phrasal context for each alternating vowel. If phrasal context predicts positional changes in F_2 in a manner consistent with Figure 2, this would support the proposed phrasal interpolation account of the pattern. If, however, formant trajectories are parallel across phrasal contexts, this would critically undermine the phrasal interpolation account.

3.1. Methods

3.1.1. Participants

We recruited 16 (eight male and eight female) native speakers of Uyghur in Chunja, Kazakhstan. Participants were between 19 and 63 years of age (mean 47.1 years). All participants were born and reside in or near Chunja. Further, all speakers reported native fluency in Uyghur. Uyghurs in Kazakhstan, by necessity, are generally trilingual, speaking Uyghur, Kazakh and Russian. We chose to elicit data from speakers in Chunja because it is the seat of the Uyghur Autonomous County and Uyghur is widely spoken there, reducing the risk of recruiting speakers with limited proficiency in the language. No studies have examined the potential dialect differences between Uyghurs in Kazakhstan and those in Xinjiang or the potential effect of Kazakh and/or Russian on their phonological grammar. This, to some degree, limits comparisons with Uyghur data collected in Xinjiang. That being said, much recent work has collected data from speakers in Kazakhstan, allowing for some straightforward comparisons (McCollum 2019a,b; Mayer 2021; Mayer *et al.* 2021).

3.1.2. Stimuli

We generated 60 short Uyghur sentences. Forty sentences contained target items, which were di- and trisyllabic words composed entirely of harmonic low vowels, either /æ/ or /a/. Target items included 16 disyllabic and 24 trisyllabic words. Disyllabic words consisted of a root and either the plural suffix /-lAr/ or the locative suffix /-DA/. Trisyllabic forms were formed by concatenating these two suffixes. Roots were all CVC; all consonants were coronal or bilabial. No dorsal consonants were used, because of their participation in the harmony pattern.

All target items were the second word of the sentence and were preceded by the proximal demonstrative /bu/. Target words were followed by a bilabial or coronal consonant-initial word. Two sample sentences are shown in 6.

(6) *Example sentences*

a. bu dɑs-lɑr-dɑ tøʃyk-lær bɑr
DEM washbasin-PL-LOC hole-PL exist
'There are holes in these washbasins.'

b. bu mɑl-lɑr-dɑ topɑ joq
DEM commodity-PL-LOC dust no
'There's no dust on these goods.'

3.1.3. Procedure

Each participant was recorded in a quiet room by the first author. Participants wore a Shure SM-10A head-mounted microphone. All sound files were recorded to a laptop using Praat and a Sound Devices USBPre2 audio interface. After informed consent, participants were presented with sentences and instructed to read each sentence at a natural rate of speech. Each sentence was presented in three different scripts, Perso-Arabic, Cyrillic and Latin. Since Uyghur has been represented with all three

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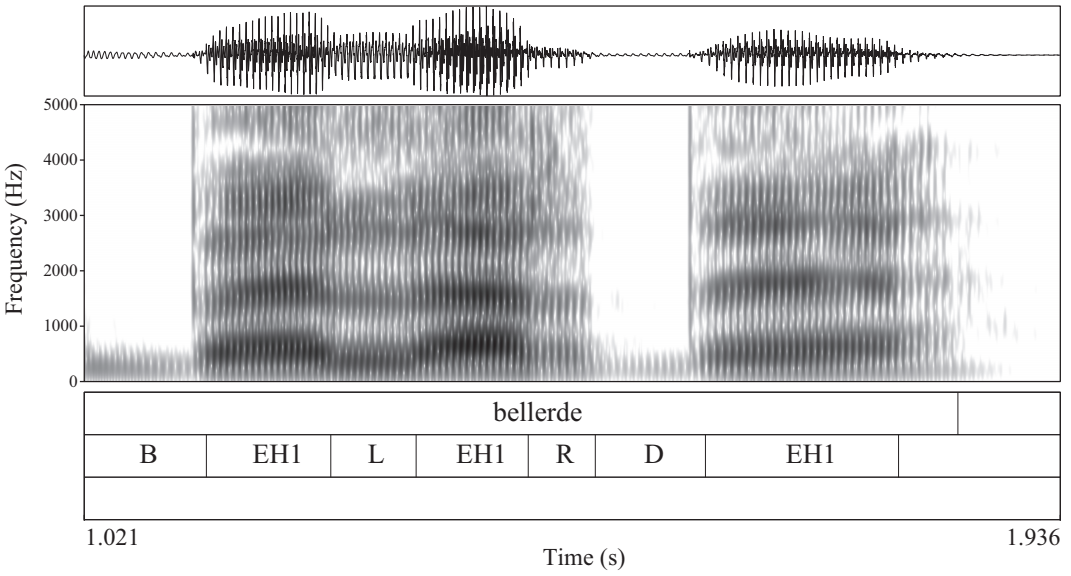


Figure 3. *A sample annotation in Praat. The top tier marks the test item, the middle tier marks the expected surface representation using ARPAbet, and the bottom tier marks the quality of the pronunciation.*

scripts, we wanted to ensure all participants could easily read the prompts. Sentence lists were randomised with the stipulation that the first five sentences for each participant were fillers. The study took approximately 15 to 20 minutes to complete; participants were given three brief breaks during the study.

3.1.4. Measurements

The recordings were annotated in two stages using Praat (Boersma & Weenink 2021). In the first stage, the first two authors transcribed the test sentences using ARPAbet. These transcriptions, along with recorded audio, were fed to the Montreal Forced Aligner (McAuliffe *et al.* 2017), which created an initial segmentation of target sentences. The first two authors then manually adjusted the segmentations generated by the forced aligner. Specifically, each of the first two authors manually corrected half of each speaker's data, discussing and comparing these adjustments to minimise by-annotator variation. The annotation consisted of a top tier for the test item, a middle tier for the expected surface representation and a bottom tier to mark the quality of the word pronunciation (bad, excrescent/epenthetic segment, unclear), with the absence of an annotation indicating good word tokens that were analysed further. A sample annotation is provided in Figure 3.

Since we were interested in observing the potential effect of phrasal context on the fronting and backing of vowels through the span of a harmonic word, we extracted F_2 measurements for each vowel ([æ ɑ]) in target words using Praat scripts. We planned to code context as front/back, depending on the backness of the first syllable of the following word. However, during data collection many tokens were produced with pauses between the target items and the following context. Rather than throwing these tokens out, we decided to introduce a third context, pause, into our statistical modelling.

Separating pre-pausal items from fluent productions not only allowed us to preserve more of the elicited data, but also allows for a more direct comparison with McCollum's (2019a; 2019b) data, which was elicited in isolation. McCollum suggests that pre-pausal tokens may behave like items before front-vowel words; this allows us to examine that claim.

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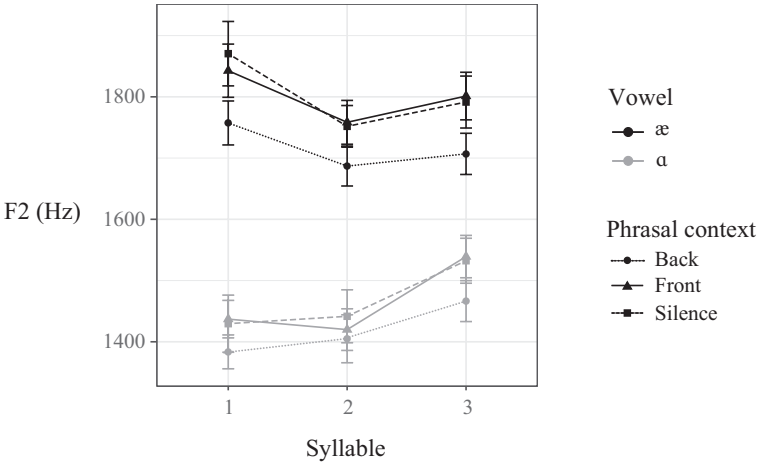


Figure 4. *Mean F_2 values at vowel midpoint for [æ a] by syllable number and phrasal context. Error bars represent standard errors.*

Finally, we collected F_2 measurements both at the midpoint of each test vowel and at 5% intervals of each vowel. Midpoint measurements allowed us to investigate how F_2 values varied generally from vowel to vowel. The more granular measurements allowed us to inspect the degree of target interpolation within each syllable.

3.2. Results

3.2.1. Midpoint analysis of F_2 measurements

All our statistical analysis and plotting were done in the programming language R (R Core Team 2022), using the IDE Rstudio (RStudio Team 2020). The data were analysed and visualised using the `tidyverse` suite of packages (Wickham *et al.* 2019), and statistical modelling was done with the packages `lme4` (Bates *et al.* 2015) and `lmerTest` (Kuznetsova *et al.* 2017). Throughout, we assume linear relationships between the factors manipulated in the experiments.[3]

Overall, there were 4,361 good vowel tokens for the test vowels, constituting 96.3% of the data. Out of this, 1,507 vowels (34.6%) were in words followed by back vowels in the next word; 1,820 vowels (41.7%) were in words followed by front vowels in the next word; and 1,034 (23.7%) of the words were followed by pauses. Figure 4 shows the means and standard errors for each surface vowel in each position of di- and trisyllabic words conditioned by the backness context of the first vowel in the next word.

As can be seen in Figure 4, the fronting of [ɑ] observed in McCollum (2019a,b) is replicated, as reflected in the increasing F_2 values. However, F_2 of [æ] decreases in second syllables. This variation appears to exceed the smaller-scale variation reported in McCollum's data.

There appears to be an effect of phrasal position on vowel F_2. Crucially, however, the potential effect of the following context applies *throughout* the test word, and to both vowels. Note also that prepausal target words, both front and back, exhibited the same qualitative F_2 trajectories as target words before [−back] words.

We followed up on visual inspection of plots with mixed-effects modelling in R using the packages `lme4` and `lmerTest`. The dependent variable was F_2 of each vowel at midpoint. We included three

[3] A reviewer suggests the possibility of using a polynomial function to fit the data from Experiment 1, observing its potential relevance for a theory of interpolation that fits curves rather than lines. We have chosen to implement our analysis with a linear model for the sake of simplicity, leaving the development of a more articulated theory of Keating's window model to future work.

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Table 2. *Summary of full model output.*

Fixed effect	Estimate	df	*t*-value	$p(>\|t\|)$
Intercept	1,744	25.5	43.8	<0.0001
Position	−37.7	46.1	−1.5	0.14
Context (Pause)	36.7	3,231.2	3.0	0.003
Context (Back)	−22.2	1,110.8	−1.5	0.14
Vowel (ɑ)	−280.9	36.5	−8.5	<0.0001
Position:Context (Pause)	35.5	1,507.7	2.4	0.02
Position:Context (Back)	7.0	409.0	0.4	0.71
Position:Vowel (ɑ)	123.5	43.6	3.7	0.0006
Context (Pause):Vowel (ɑ)	−54.4	3,921.3	−3.3	0.001
Context (Back):Vowel (ɑ)	−17.4	1,638.7	−0.9	0.39
Position:Context (Pause):Vowel (ɑ)	−40.8	2,803.9	−2.1	0.04
Position:Context (Back):Vowel (ɑ)	−21.5	948.9	−0.8	0.41

independent variables and their interaction in the full model under consideration; these were Vowel ([æ] or [ɑ]), Context (back, front, pause), and the continuous variable Position, which was centred. Other predictor variables were treatment/dummy coded. The vowel [æ] and front-vowel phrasal context served as reference levels for Vowel and Context, respectively. The random effects structure included by-subject and by-item random slopes for Vowel and Position, and by-subject and by-item random intercepts. The results are summarised in Table 2.

In this model, there are two significant two-way interactions, Vowel × Position and Vowel × Context, as well as a significant three-way interaction, Vowel × Position × Context, indicating that the effects of position and context depend on the vowel. We found the interpretation of the regression coefficients in this relatively large model challenging, as is always the case in complex models. In addition, the methodological practice of including the largest justified random effects structure (Barr *et al.* 2013), combined with the complexity of this model, results in a model that is potentially under-powered (Bates *et al.* 2018). When power is a potential issue, it is difficult to interpret the sign or magnitude of a significant effect. Further, in such cases it is also difficult to interpret any non-significant results (Gelman & Carlin 2014). Additionally, we cannot know whether a study is truly under-powered without having a clear expectation of the effect size, which is not currently possible for our research program. Therefore, we think it is useful and important to check the crucial comparisons with models assessing subsets of the data to avoid the potential over-specification, and consequent under-powering, of the model.

In this case, we ran separate models for each vowel, which reduced the complexity of both the fixed and random effects structure by removing an effect (Vowel) as well as its inclusion in multiple interaction terms. Therefore, the random effects structure included by-subject and by-item random slopes for Position, and by-subject and by-item random intercepts. These subset models also allow us to check if the manifestation of harmony for each vowel has a slope that is different from zero – a crucial question for our research program.

The model for [æ] is presented in Table 3. Observe that the only significant effect in this model is Context (pause). Crucially, there is no significant effect of Position ($p = 0.10$) when Context is front, and no significant interactions involving Position and Context ($p = 0.10$ for pause *vs.* front; $p = 0.92$ for back *vs.* front). In other words, F_2 of the front vowel [æ] does not change significantly by position, regardless of the following phrasal context.

The model for [ɑ] is presented in Table 4. Consistent with visual inspection, there is a clear effect of Position: F_2 values increase over the course of the word. The vowel [ɑ] in all positions of the word is influenced by following context. The effect of phrasal context deserves further scrutiny in subsequent

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Table 3. *Summary of model output for the [æ] model (baseline: front context).*

Fixed effect	Estimate	df	*t*-value	$p(>\|t\|)$
Intercept	1,752.0	22.7	47.8	<0.0001
Position	−26.2	17.8	−1.7	0.10
Context (Pause)	31.5	1,414.6	2.14	0.03
Context (Back)	−29.4	321.8	−1.7	0.09
Position:Context (Pause)	27.4	347.2	1.6	0.10
Position:Context (Back)	−1.9	65.8	−0.1	0.92

Table 4. *Summary of model output for the [ɑ] model (baseline: front context).*

Fixed effect	Estimate	df	*t*-value	$p(>\|t\|)$
Intercept	1,465.9	22.8	41.3	<0.0001
Position	90.3	22.0	3.2	0.004
Context (Pause)	−17.0	2,319.6	−2.2	0.03
Context (Back)	−41.5	1,653.9	−4.3	<0.0001
Position:Context (Pause)	−1.1	1,955.8	−0.1	0.91
Position:Context (Back)	−17.6	1,953.4	−1.4	0.17

work. The key finding from Table 4 is that the realisation of F_2 of [ɑ] does not depend on any interaction of Position and Context ($p = 0.91$ for pause *vs.* front; $p = 0.17$ for back *vs.* front). In other words, the positional variation for the back vowel does not significantly depend on phrasal context.

In sum, there is a clear increase in F_2 for [ɑ] in non-initial positions, but no comparable effect for [æ]. This replicates the findings of McCollum (2019a,b). In addition, our results show no evidence supporting the case that the asymmetric fronting reported by McCollum is a by-product of phrasal phonetic interpolation, since the interactions between Position and Context were not significant. Therefore, our results fail to reject the null hypothesis in favour of the phonetic interpolation hypothesis.

Before moving on to examine F_2 contours within each vowel, let us briefly revisit the choice to introduce pause as a third phrasal context. First, pause durations were typically substantial. Consider the data in Table 5. Both median and mean pause durations were relatively long. In fact, of the 1,039 words followed by pauses, only around ten exhibited pauses of less than 30 ms. Thus, the vast majority of pauses coded reflect substantial breaks in the flow of speech. Second, our choice to code pause as a third phrasal context more effectively described the data than using the intended phrasal context. A reviewer asks if the intended phrasal context could pass through the pause to exert an effect on the F_2 values of target words. If pauses do not affect phrasal context, we would expect our tripartite coding scheme to adversely affect model fit. In short, the regression model would more poorly fit the data because of the introduction of a spurious level within the fixed effect of Context, obscuring the true phrasal context. To evaluate this possibility, we compared the fit of a model incorporating pause against a model with only two levels of context, back and front, based on the constructed stimuli. The best model was identified by the Akaike information criterion (AIC; Akaike 1974). AIC is a dimensionless unit that measures model fit while adjusting for model complexity, where a lower AIC value represents a better model. An AIC differential of 8 or more is considered a very large difference in model fit (Burnham & Anderson 2004; Burnham *et al.* 2011). The model with pause fitted the data significantly better than the model with only the intended following context (front/back), with a difference in AIC of 14.8.

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Table 5. *Median and mean pause duration (ms).*

Vowel	Median pause duration	Mean pause duration	Pause duration SD
æ	210	294	410
ɑ	199	248	220

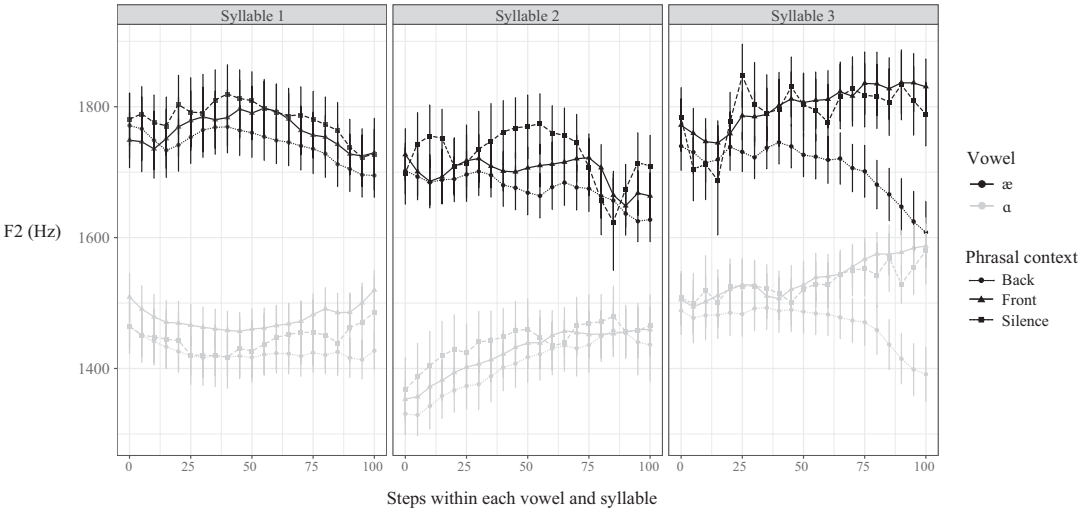


Figure 5. *Mean F_2 contours for [æ] and [a] based on syllable number and phrasal context. Error bars represent standard errors.*

3.2.2. F_2 contours

In this subsection, we show visualisations of the contours for the vowels. While we did not perform any statistical testing of the patterns, since we didn't have any explicit hypotheses about contours to test, we considered it helpful to the reader to include the visualisations to assess the viability of the phonetic interpolation hypothesis.

The plot in Figure 5 suggests that any interpolation is limited to the final vowel. Though the contours exhibit no obvious differences by context in syllables one and two, the formant trajectories bifurcate during the last half of the final vowel. Before [+back] words, both front and back vowels exhibit decreasing F_2 during the final half of the word-final vowel. Likewise, before pauses and [−back] words, F_2 of both [æ] and [ɑ] increases throughout the final vowel. In sum, the only evidence for phrasal interpolation in Experiment 1 is seen during the final half of the word-final vowel. Third-syllable vowels were always word-final, since they were always elicited in the locative suffix /-DA/, making them even more susceptible to local coarticulation with the following word or phrase boundary. All in all, we interpret these results as evidence against an interpolation-based account of gradient harmony in Uyghur.

4. Experiment 2: centralisation, coarticulation and morphotactics

Since results from Experiment 1 indicate that the gradience in Uyghur is not a by-product of phrasal interpolation, we conducted a second experiment to investigate another potential explanation, centralisation. Specifically, this second alternative derives the asymmetric fronting pattern from the interaction of symmetrical centralisation and low-level phonetic coarticulatory effects mediated by the morphotactics of the language. Previous work has found patterns of articulatory declension in a range of

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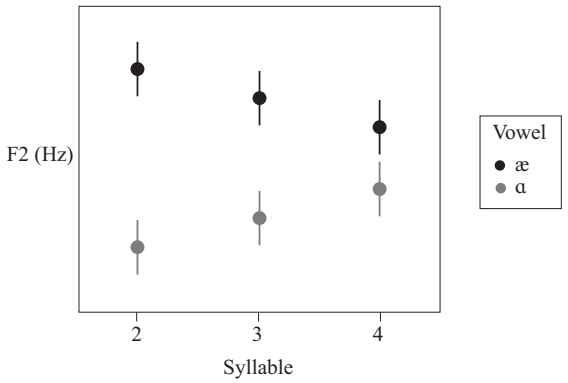


Figure 6. *Predicted F_2 of non-initial [æ] and [ɑ] under a centralisation account.*

languages (Vayra & Fowler 1992; Krakow *et al.* 1995; Tabain 2003). In these cases, vowels produced later in an utterance are increasingly hypoarticulated, yielding increased centralisation. If non-initial vowel quality is predictable based on incremental phonetic centralisation, we might expect incremental reduction of the acoustic distinctions of [±back] vowels, as schematised in Figure 6.

It is clear from McCollum (2019a,b) that the positional differences in F_2 are not symmetrical, which is why he rules out a centralisation account. However, McCollum assumes that the local coarticulatory effects from flanking consonants are sufficiently adjusted for in his model. He incorporated fixed effects of preceding and following consonant place of articulation to reduce the possibility of local consonant–vowel interactions clouding the interpretation of the data. He coded three levels of each contextual variable: bilabial, coronal and dorsal. He also coded the lateral as coronal in front-vowel contexts but dorsal in back-vowel contexts, since the lateral alternates for backness (McCollum 2021).

Choosing to use only three levels of this predictor assumes that contextual effects within a natural class defined by some place feature should be comparable. However, Hahn (1986, 1991) reports extensive variation in vowel production conditioned by flanking consonants with the same phonological place of articulation. For instance, Hahn (1991: 36–37) notes that /i/ is produced as [e] after labiodental fricatives, as in /filim/ [felim] 'film' (from Russian). However, he reports that /i/ is produced as [ɨ] preceding the lateral in /bilæk/ [bɨlæk] 'wrist', without any lowering due to the preceding bilabial stop. As another example, /ø/ is produced as a front vowel before velar obstruents, as in /køk/ [køk] 'blue', but is central before the velar nasal, as in /køŋl-m/ [køŋlym] 'heart-POSS.1SG'. Coarticulatory differences within a given featural natural class are reported in a variety of other languages (Recasens 1984a,b, 1985, 1989; Recasens *et al.* 1993; Fowler & Brancazio 2000). Thus, Hahn's reports are not surprising, and a more controlled study to evaluate the potential confounding effect of flanking consonants is necessary.

Further, we can only assume centralisation will result in symmetrical reduction on the surface if local consonantal coarticulatory effects are negligible. However, if there exist significant differences in vowel quality conditioned by flanking consonants in the language, and if the distribution of consonants that occur in target syllables is skewed to obscure the positional effects, then these local differences could affect the positional trends observed in the aggregate. In addition to the symmetrical predictions in Figure 6, asymmetric shifts become plausible once these interactions are taken into account.

Consider the following scenario. Vowel F_2 in syllables 2–4 is measured. Further, all elicited data come from two suffixes, Suffix_x and Suffix_y. Suffix_x occurs in syllables 2 and 3, while Suffix_y occurs in syllables 3 and 4, as in Figure 7a. In addition, F_2 of both [æ] and [ɑ] is markedly higher in Suffix_y than in Suffix_y. Observe that both suffixes exhibit symmetrical centralisation in Figure 7a. F_2 of [æ ɑ] in Suffix_x shifts towards more intermediate values in syllable 3, and F_2 of [æ ɑ] in Suffix_y shifts towards more intermediate values in syllable 4. Crucially, centralisation is masked in the aggregate data, as shown in

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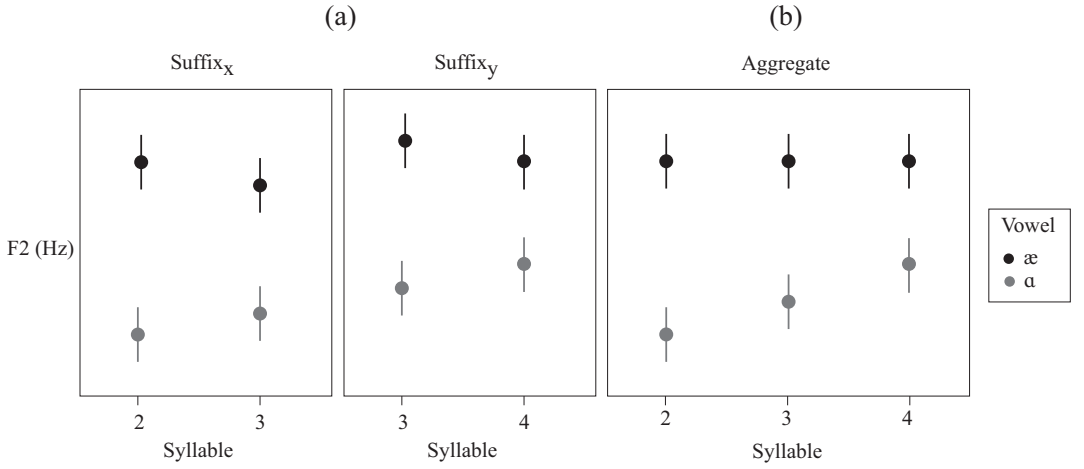


Figure 7. *Asymmetric fronting as a by-product of centralisation, coarticulation and morphotactics. Panel (a) shows by-syllable plots for each suffix. Panel (b) shows data in the aggregate.*

Figure 7b. The higher F_2 of Suffix$_y$ obscures the backing of [æ] while simultaneously exaggerating the fronting of [ɑ]. Centralisation is evident only once morphemic/segmental context is controlled.

The scenario sketched above is one way that centralisation plus other forces in the language may yield an apparently asymmetric pattern by position. The reverse scenario, with incremental backing of [æ] in later syllables, is just as easily derivable if the coarticulatory effects or morphemic distributions are reversed. In addition, it is eminently plausible for the particular coarticulatory effects across syllables to obliterate any positional generalisations. For this reason, centralisation is truly observable only once flanking segmental context is strictly controlled. To do this, we chose to analyse the realisation of the low vowels within a given morpheme across multiple positions. By keeping the morpheme constant in our analysis, we were able to isolate the phonetic effect of harmony from local coarticulatory effects. If harmony is truly gradient, then by-morpheme analysis should exhibit the same asymmetric fronting trend found in McCollum's aggregated data.

4.1. Methods

4.1.1. Participants

We recruited 17 (seven male and ten female) native speakers of Uyghur in Chunja, Kazakhstan. One male participant's data were excluded because of repeated disfluencies. Participants were between 19 and 63 years of age (mean 33.6 years). All participants were born and reside in or near Chunja.

4.1.2. Stimuli

Stimuli consisted of 76 words varying in length from two to five syllables. The word list contained 14 disyllabic, 23 trisyllabic, 20 quadrisyllabic and 19 pentasyllabic words. The only vowels present in target words were /æ/ and /ɑ/. In addition to the target items, the word list included a large number of filler items, which contained either a high vowel or a non-alternating suffix. Target stimuli included both nouns and verbs. Nominal roots were from one to three syllables in length. Verb roots were one or two syllables in length. Sample words from nominal and verbal stems are shown in (7) and (8).

(7) *Sample forms from nominal stems*

a. *Two-syllable words*

i. tær-dæ ‘sweat-LOC’

ii. tɑr-dɑ ‘string-LOC’

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b. *Three-syllable words*

i. dæz-lær-dæ ‘crack-PL-LOC’

ii. sɑz-lɑr-dɑ ‘musical.instrument-PL-LOC’

c. *Four-syllable words*

i. sæpær-lær-dæ ‘journey-PL-LOC’

ii. tɑtɑr-lɑr-dɑ ‘Tatar-PL-LOC’

d. *Five-syllable words*

i. sæltænæt-lær-dæ ‘dominion-PL-LOC’

ii. rɑmɑzɑn-lɑr-dɑ ‘Ramadan-PL-LOC’

(8) *Sample words from verb stems*

a. *Three-syllable words*

i. tæp-kæn-dæ ‘kick-NMLZ-LOC’

ii. tɑp-qɑn-dɑ ‘find-NMLZ-LOC’

b. *Four-syllable words*

i. tær-læ-t-kæn-dæ ‘sweat-VBLZ-CAUS-NMLZ-LOC’

ii. tɑrɑ-t-qɑn-dɑ ‘spread-CAUS-NMLZ-LOC’

c. *Five-syllable words*

i. sæpær-læ-ʃ-kæn-dæ ‘journey-VBLZ-RECP-NMLZ-LOC’

ii. nɑʧɑr-lɑ-ʃ-qɑn-dɑ ‘bad-VBLZ-RECP-NMLZ-LOC’

4.1.3. Procedure

Each participant was recorded in a quiet room by the first author. Participants wore a Shure SM-10A head-mounted microphone. All sound files were recorded to a laptop using Praat and a Sound Devices USBPre2 audio interface. After informed consent, participants were presented with words in isolation and instructed to read each at a natural rate of speech. Each word was presented in the Cyrillic script only, because all participants in the first experiment indicated greater familiarity with Cyrillic. The word list was randomised; each speaker read through the list twice, each time with a different randomisation. Participants were given three brief breaks during the study. Most participants completed the study in less than 20 minutes.

4.1.4. Measurements

The measurements were largely the same as with the previous experiment – the recordings were annotated in Praat, and F_2 measurements were extracted at the midpoint of each test vowel ([æ ɑ]) using Praat scripts. The annotation scheme was again roughly the same, but we used a slightly different set of categories for the words (bad, epenthetic/excrescent vowel, unclear, notes), where the absence of an annotation indicated a good word token; all others were excluded from analysis. We don’t include a sample annotation, given the similarity to the previous scheme.

Compared to the previous experiment, there were two differences in the data sets created from our recordings. First, each word was uttered in isolation without any knowledge of upcoming stimuli, removing any potential phrasal context. Given that Experiment 1 found no significant effect of phrasal context, we were instead interested in the effect of morphemic and segmental context in this experiment. Second, we did not measure F_2 values at 5% intervals within each vowel, since F_2 contours were not as relevant to the question at hand.

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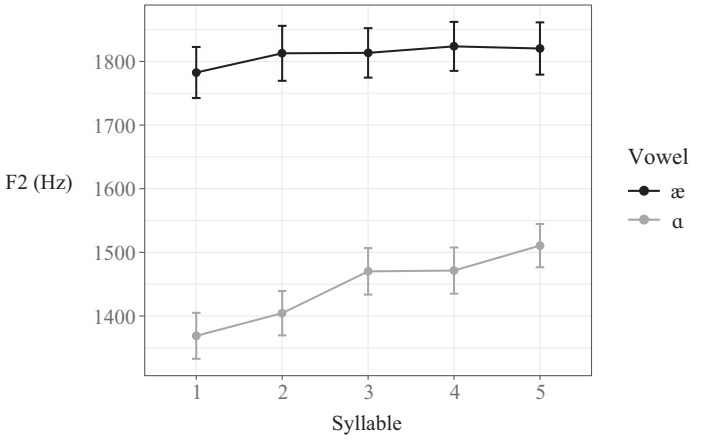


Figure 8. *Mean F_2 values for the vowels [æ] and [ɑ] in different positions of the word. Error bars represent standard errors.*

Table 6. *Summary of baseline model output.*

Fixed effect	Estimate	df	*t*-value	$p(>\|t\|)$
Intercept	1,825.8	18.8	39.6	<0.0001
Position	2.2	43.1	0.3	0.80
Vowel (ɑ)	−423.2	50.4	−15.6	<0.0001
Position:Vowel (ɑ)	68.7	44.5	5.8	<0.0001

4.2. Results

4.2.1. Overall analysis of F_2 measurements

In this section, we report results from all non-initial vowels regardless of morphemic and segmental context. By aggregating over all the data, we are able to compare our results to McCollum's and to provide a baseline with which to compare the by-morpheme analysis in the next subsection. Overall, there were 2,371 good word tokens for the test vowels, constituting 99.2% of the data. These are shown in Figure 8.

We followed up on visual inspection with mixed-effects modelling as before. Again, the dependent variable was F_2, with two fixed effects, Vowel ([æ] or [ɑ]) and the continuous predictor Position, which was centred. As in Experiment 1, [æ] was set as the reference level for Vowel. The random effects structure was the same as for the complex model in Experiment 1 – it included by-subject and by-item random slopes for Vowel and Position, and by-subject and by-item random intercepts. Finally, we removed the initial-syllable vowel from the statistical modelling to ensure that this general model is maximally comparable to the one in the next section that includes a predictor of morphemic and immediate segmental context.

Results shown in Table 6 are broadly similar to those of the previous experiment, replicating the major finding in McCollum (2019a,b). Specifically, observe that there is a non-significant effect of Position with an unstandardised effect size very close to zero, indicating that F_2 of [æ] does not systematically vary by position. In contrast, there is a highly significant interaction between Position and Vowel, indicating that F_2 of [ɑ] increases incrementally in non-initial syllables.

Although we have replicated McCollum's finding once again, our primary goal here is to investigate whether or not the immediate segmental and morphemic context is the source of the fronting pattern

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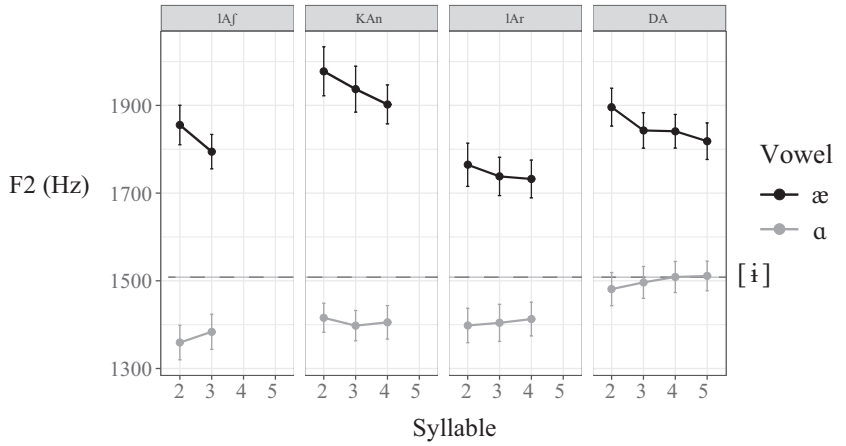


Figure 9. *By-morpheme mean F_2 values for [æ] and [ɑ] in different positions. The horizontal dashed line represents the mean F_2 value for [ɨ] in our filler items. Error bars represent standard errors.*

reported in previous work. In the next subsection, we augment our statistical model to account for consonantal and morphemic context.

4.2.2. Analysis of F_2 measurements while adjusting for morphemes

For this analysis, we controlled for morpheme, allowing us to examine the realisation of each suffix in different positions while ruling out local coarticulatory effects. Therefore, as in the previous subsection, we excluded the root morpheme from analysis. The analysis included 2,312 word tokens of the morpheme /-DA/, 872 word tokens of /-lAr/, 288 word tokens of /-lA-ʃ/ and 940 tokens of /-KAn/.[4]

Figure 9 shows the by-morpheme plots for the relation between F_2 and Position. In contrast to the overall analysis, visual inspection suggests that there is no asymmetric fronting. Instead, there appears to be a relatively symmetric centring of both [æ] and [ɑ]. The figure also includes a dashed line, which reflects the average F_2 value for the central vowel [ɨ]; we will return to this later in the section.

As before, after visual inspection we conducted mixed-effects modelling. The dependent variable was F_2, with independent variables for Position and Vowel, as well as their interaction. In this model, the random effects structure was more elaborate, incorporating the fact that the vowels were produced in different morphemes; the random effects structure included by-subject, by-item and by-morpheme random slopes for Vowel and Position, along with by-subject, by-item and by-morpheme random intercepts. As before, Position was centred. Concerning the coding for morphemic context, we coded for each contrast-neutralising alternation. Thus, [-qɑn] and [-kæn] were coded separately, as were the voiced and voiceless allomorphs of the locative suffix /-DA/ ([-dæ] and [-dɑ] were coded as 'dA', and [-tæ] and [-tɑ] were coded as 'tA'), while the allomorphs of the plural /-lAr/ and verbaliser-reciprocal suffixes /-lA-ʃ/ were coded the same.

The model output in Table 7 suggests a markedly different picture of positional vowel shifts. The significant effect of Position, −27.1 Hz, suggests incremental backing of [æ], a trend not apparent in Table 6. Additionally, the significant interaction of Position and Vowel, 35 Hz, suggests a slight fronting of 7.9 Hz per syllable for [ɑ] (−27.1 (Position) + 35.0 (Position:Vowel(ɑ)) = 7.9). Given the simpler model reported in Table 6 and the apparent asymmetric fronting in Figure 8, the question now is which model best describes the actual data. We compared model fit as before, using AIC. The more complex

[4] The total here does not add up to the total of 2,666 good word tokens mentioned in §4.2.1. This is because the words containing the different morphemes are not mutually exclusive; that is, the same word token can have multiple morphemes being considered. Consequently, the total count over the number of word tokens for each individual morpheme is greater than the total number of good word tokens.

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Table 7. *Summary of by-morpheme model output.*

Fixed effect	Estimate	df	*t*-value	$p(>\|t\|)$
Intercept	1,848.0	14.6	32.4	<0.0001
Position	−27.1	11.7	−4.4	0.0008
Vowel (ɑ)	−405.9	4.5	−13.2	<0.0001
Position:Vowel (ɑ)	35.0	76.4	6.0	<0.0001

Table 8. *Comparison of the simpler and by-morpheme models.*

S. No.	Full model	AIC
1	F_2~Vowel + Position + Vowel:Position + (Position|Sub) + (Position|Item)	55,398
2	F_2~Vowel + Position + Vowel:Position + (Position|Sub) + (Position|Item) + (Position|Morpheme)	55,113

Table 9. *Summary of by-morpheme model output for the [æ] model.*

Fixed effect	Estimate	df	*t*-value	$p(>\|t\|)$
Intercept	1,910.3	10.2	25.6	<0.0001
Position	−23.5	10.6	−3.2	0.01

Table 10. *Summary of by-morpheme model output for the [a] model.*

Fixed effect	Estimate	df	*t*-value	$p(>\|t\|)$
Intercept	1,400.5	14.1	29.5	<0.0001
Position	11.8	14.1	3.8	0.002

model, which controlled for morphemic and segmental context, exhibited significantly lower AIC than the simpler model, as seen in Table 8. In fact, the difference in AIC, 285, indicates that relative to the model incorporating morphemic and segmental context, the simpler model receives no support from the data.

As with Experiment 1, we looked at each vowel separately with the accordingly smaller random effects structure. Specifically, each smaller model included by-subject and by-item random slopes for Position, along with by-subject and by-item random intercepts. The model for [æ] is shown in Table 9. Consistent with visual inspection of Figure 9, there is a clear negative effect of Position on F_2. Therefore, there is more evidence that the vowel [æ] is progressively backed throughout the word.

The model for [ɑ] is shown in Table 10. In contrast to the [æ] model, there is a smaller but clearly positive effect of Position on F_2 of [ɑ]. Therefore, there is evidence that the vowel is progressively fronted throughout the word, albeit to a smaller degree than the backing of [æ] seen in Table 9.

These visual and statistical modelling results suggest that there is no asymmetric fronting of [ɑ] once we control for morphological and segmental context. To further probe this effect of morphology and segmental context, we compared each of the two vowel-specific models with the corresponding models that do not include the by-morpheme random intercept and random slope of Position. For [æ], the AIC values of the simpler model and by-morpheme were 26,543 and 26,416, respectively. The difference between the two was rather large, 127, in favour of the model controlling for morphemic and segmental context. For [ɑ], the AIC values of the simpler model and by-morpheme were 28,446 and 28,316,

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Table 11. *Morpheme counts by syllable number in Experiment 2.*

Morpheme		Syllable 2	Syllable 3	Syllable 4	Syllable 5	Total
LOC	/-DA/	312	757	741	502	2,312
PFV	/-KAn/	383	310	247		940
PL	/-lAr/	307	305	260		872
VBLZ-RECP	/-lA-ʃ/	123	165			288

respectively. The AIC difference between the two models was once again rather large, approximately 130, again in favour of the model controlling for morphemic and segmental context. This again suggests that there is clear and strong evidence that morphological – and consequently segmental – contextual information is important for explaining the quality of the low vowels.

One last aspect of the results that we would like to mention is the difference in the estimated slopes of [æ] and [ɑ] across positions. In both, the larger and the smaller models, the estimated slopes for the [æ] vowel, −27.6 and −23.5 Hz, are much steeper than the slopes for [ɑ], 7.9 and 11.8 Hz. This is consistent with the first- and second-syllable vowels in Figure 4, which shows a steeper decline in F_2 for second-syllable [æ] than for second-syllable [ɑ]. As can be seen in Figure 9, the F_2 of the back vowel [ɑ] is much closer to the average F_2 value of the central vowel [ɨ] (dashed line) than the front vowel [æ]. Similarly, McCollum's (2019a) data, which includes *z*-score transformed F_2 values of all the vowels in his experiment, suggests that the front vowel [æ] is roughly twice the distance from the centre of the vowel space as the back vowel [ɑ]. Therefore, there is simply less distance (about half, in fact) for the back vowels to traverse to centralise than the front vowels. The smaller positional effects for [ɑ] may plausibly derive from this fact.

Overall, our results in this subsection suggest that once the effects of morphological and segmental information are adjusted for, there is no asymmetric fronting of [ɑ] in non-initial syllables. Instead, what we see is more consistent with a symmetric centralisation account. Consequently, analysing the Uyghur pattern does not require the inclusion of gradient phonological representations. We discuss our interpretation of these results further in the next section.

5. Discussion

5.1. Backness harmony in Uyghur

Results from these two studies indicate that there is no gradience in Uyghur backness harmony. As a consequence, we conclude that the claims in McCollum (2019a,b) are unsupported. Before discussing the larger implications of our findings, it is important to note some of the limitations of our study, particularly as they relate to McCollum (2019a,b). First, we investigated the realisation of only one harmonic pairing, /æ/–/ɑ/, while McCollum examined all harmonic pairings. Second, we investigated only a small number of suffixes, whereas McCollum elicited data from a larger set of suffixes. In both respects, the present study was more targeted than McCollum's. While the more focussed nature of the present study to some degree limits the amount of extrapolation merited by our findings, on the other hand, the more controlled nature of our study also unveiled confounding forces not controlled for in McCollum's study. Therefore, a fuller study of all harmonic pairings and a larger set of target morphemes would be extremely useful.

A key question that emerges from our study is why do aggregated results continually show what appears to be asymmetric fronting when in fact vowel quality is phonetically centralised in non-initial syllables? The answer is quite straightforward, and was foreshadowed earlier – aggregated results do not show the skewed distribution of morphemes elicited in each syllable. Consider the by-syllable counts of morphemes elicited in Experiment 2, shown in Table 11 and Figure 10.

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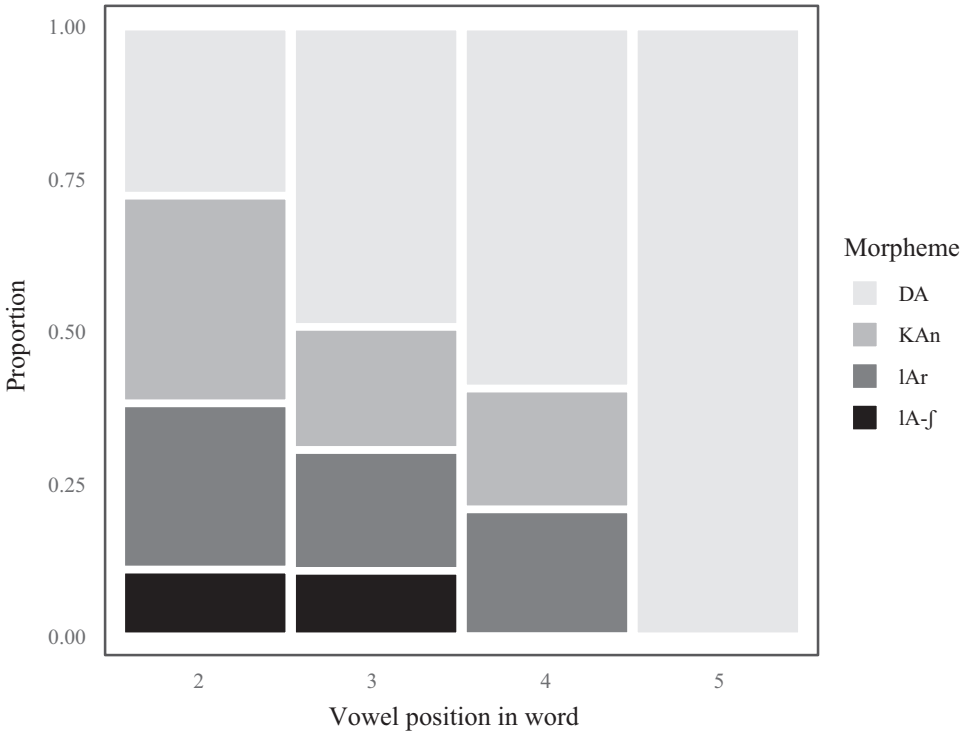


Figure 10. *Plot of morphemes elicited by position in Experiment 2.*

Given the morphotactics of the language, as well as the sample forms in (5), which are based on McCollum's (2019a: 105–107; 2019b: 3), we conclude that McCollum's data exhibit the same morphological skew as our own. Concerning the only two low vowel suffixes elicited by McCollum, /-DA/ and /-lAr/, the locative /-DA/ obligatorily occurs further from the root than the plural /-lAr/. Thus, the counts of /-lAr/ in syllables two and three of McCollum's data should be higher than those of /-DA/. In syllables four and five, though, McCollum's data are drawn entirely from /-DA/.

This morpheme count skew does not, in and of itself, explain why in three phonetic studies of Uyghur backness harmony, aggregated data display asymmetric fronting despite non-initial centralisation of backness. The skewed distribution of morphemes required by the language's morphotactics introduces different segmental contexts that are responsible for the apparent fronting pattern.

When the morpheme-specific F_2 patterns in Figure 7 are considered, it is obvious that F_2 of [ɑ] in [-lɑʃ] is lowest, with F_2 of [ɑ] in [-qɑn] and [-lɑr] slightly higher, and F_2 of [ɑ] in [-dɑ]~[-tɑ] being the highest. In the first three cases, there is at least one flanking consonant that exerts a backing effect on the low vowel: the velarised lateral, the voiceless uvular stop or the trill (Klatt & Stevens 1969; Recasens 2013). The fact that F_2 of [ɑ] in [-lɑʃ] was lower than in [-lɑr] is surprising, since both the dark lateral and the trill may trigger backing of flanking vowels. Perhaps in this instance, the adjacent uvular stop that always immediately followed the sibilant, as in [nɑʃɑrlɑʃqɑndɑ], contributes to the lowering of F_2. Most significantly, the F_2 of [ɑ] in the locative suffix [-dɑ]~[-tɑ] is around 100 Hz higher than in the other suffixes elicited. We attribute this to the preceding dental stop as well as a default [−back] articulatory affecting word-final vowel quality, consistent with McCollum's description and our results from Experiment 1. The combination of these two forces, higher F_2 at vowel onset and offset in [-dɑ]~[-tɑ], results in increased values at vowel midpoint, as seen in Figure 9.

Turning now to /æ/, F_2 of this vowel differed considerably across the four morphemes elicited in Experiment 2. The second formant was highest in [-kæn], lowest in [-lær] and of intermediate values

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in [-læʃ] and [-dæ]~[-tæ]. Recasens & Pallarès (1999) and Recasens (2013) find that the trill induces backing of adjacent vowels in Catalan. We thus tentatively assume the trill exerts a similar backing effect on the low front vowel in Uyghur. In contrast, we assume the velar in the perfective suffix [-kæn] triggers coarticulatory fronting (Delattre *et al.* 1955; Öhman 1966: Figure 5), resulting in the higher F_2 of [æ] in [-kæn]. In earlier syllables, Table 11 and Figure 10 show a balance of these morphemes, resulting in an intermediate mean F_2. In later syllables, the most commonly elicited morphemes happen to have intermediate values for F_2. In other words, the stability of F_2 of [æ] across positions in Figure 9 is just as much an accidental by-product of experimental methods as the fronting of [ɑ].

These findings strongly suggest that backness harmony is not gradient in Uyghur, and that the apparent fronting reported in previous work is a by-product of local contextual effects. Our results undermine claims of gradience in Uyghur, but more generally, they do not rule out the potential for incomplete neutralisation or the inclusion of gradient representations in the phonological module of the grammar. In the next two subsections, we address these two more general topics. Our aim is to lay out the potential costs and benefits of these representations, and to delineate the components of phonologically gradient incomplete neutralisation.

5.2. Representational issues

In order to more fully understand the potential costs and benefits of introducing gradience into the phonology, it is useful to consider another representational shift in phonological theory, the advent of autosegmental representations. The autosegmental representations birthed by works such as Leben (1973) and Goldsmith (1976), and explored in so much subsequent work (e.g., McCarthy 1979; Pulleyblank 1983; see Hyman 2014 for more recent discussion) introduced new ways to understand and theorise about sound patterns that have significantly shaped the field.

Alongside these benefits, the introduction of non-linear representations increased the expressive capacity of the phonological grammar. Relevant to the discussion of Uyghur, consider the possible trisyllabic words representable with string-based [±back]. Since [±back] is binary, there are $2^3 = 8$ representations possible for such a string. Once multiple association of a single autosegment is introduced, the possibilities expand. For instance, a word like [bɑllɑrdɑ] is represented with three distinct [+back] features in a string-based representation, and crucially there is no other arrangement of [+back] that generates this form. However, this same form is representable in autosegmental phonology as the multiple association of a single [+back] autosegment; the multiple association of two separate [+back] autosegments (two such representations that do not involve crossing lines exist); or the single association of three separate [+back] autosegments.

Now we can contrast the costs and benefits of autosegmental representations with the consequences of admitting gradient representations. As noted in McCollum (2019a), gradient representations are largely incompatible with autosegments, specifically multiple linkage. If a word like [bɑllɑrdɑ] is derived by multiple linkage of a single autosegment, from what mechanism can subphonemic differences between these three /ɑ/ vowels emerge? The autosegmental analysis is most straightforwardly interpreted as assigning an identical value for [±back] to each linked vowel. Introducing gradience with autosegments requires an additional means of assigning gradience to the links, or a distinct later round of phonological computation wherein gradience is introduced.

Concretely, it is necessary to ask what analytical advances have gradient representations offered? To date, the framework of Gradient Symbolic Representations has used such representations to account for a variety of exceptional patterns (Rosen 2016; Smolensky & Goldrick 2016; Hsu 2019; Revithiadou & Markopoulos 2021). Critically, in these cases, gradient symbols are introduced in the input and manipulated during computation, but are absent from the output (Smolensky *et al.* 2014; Goldrick *et al.* 2016). As Hsu (2022) notes, output gradience is the largest unresolved question for work using gradient representations, with some work (e.g., Zimmermann 2018) allowing for output gradience that has no unique phonetic consequences, in contrast to work like McCollum (2019a,b) that

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Table 12. *Representing a four-feature system (e.g., Uyghur vowels) using three different granularities of representations.*

	One syllable	Two syllables	Three syllables	Four syllables
Standard binary features	16	256	4,096	65,536
Four-valued features	256	65,536	1.67×10^7	4.29×10^9
Eleven-valued features	14,641	2.14×10^8	3.14×10^{12}	4.59×10^{16}

insists output gradience is manifest in the phonetics. While input gradience may be a useful tool for analysing exceptionality, there is, at present, no clear advantage derived from output gradience.

Conversely, a number of significant challenges emerge when grammars encode featural gradience. First, if inputs may be gradient but not outputs, or *vice versa,* a question of representational uniformity emerges. If one set of representations, inputs or outputs, is a strict superset of the other – or, even worse, disjoint – the featural hypothesis space of the grammar is necessarily increased. To contextualise the issue to Uyghur, let us for the sake of discussion treat the infinite possible values for [back], if conceived of as gradient, as a highly multivalent set of scalar values between [+back] and [−back]. For convenience, McCollum (2019a) discretises backness to an eleven-step scale. Thus, if an OT grammar with McCollum's (2019a) eleven-step scale from [+back] to [−back] is adopted, $11^3 = 1,331$ possible [back] contrasts within a trisyllabic word can be generated, in contrast to the far smaller $2^3 = 8$ representations produced by typical string-based representations. Further, since OT demands a rich base, the set of input vowel representations must also be 11^3 for the same trisyllabic word. The issue is only exacerbated in longer words: a six-syllable word has $2^6 = 64$ representational possibilities for [±back] in standard feature theory, but requires $11^6 = 1,771,561$ possible backness representations under McCollum's analysis (see Du & Durvasula 2025 for similar argumentation). This considers only a single vowel feature; if a full set of features is similarly fine-grained, the representational space explodes even more. As an example of slightly increasing complexity, let us consider the four features necessary to uniquely identify all the vowel contrasts in Uyghur: [back], [round], [high] and [low]. Table 12 shows the exponential increase in the representational space when more fine-grained representations are employed. McCollum's eleven-step feature system is compared with a standard set of four binary features, and with a simpler multivalent set of representations that only distinguishes four values along a given featural continuum.

While the four-step scale in Table 12 results in a smaller increase in the feature space, there is nothing *a priori* that precludes adopting even more granular representations than McCollum does. To militate against some of the potential increase in the representational space derived from gradient representations, McCollum (2019a) contends that phonological representations should at minimum reflect discriminable surface contrasts. Just noticeable differences along some phonetic dimension then become the yardstick for phonological contrasts (Flanagan 1955; Huggins 1972). Problematically, language experience significantly affects an individual's ability to discriminate a set of similar sounds (Tervaniemi *et al.* 2006; Liu 2013; Jongman *et al.* 2017), which seriously undermines any attempt to generate a universal set of gradient feature values (see Mielke 2008 for an alternative approach).

In the case of autosegments, the representational increase is modest compared to fully specified strings, but the theoretical advantages are numerous. However, no comparable theoretical advantages have been demonstrated by work advancing output gradience. Gradience may be a useful tool for analysing exceptions in a formalism like HG, but work in that vein that espouses output gradience has yet to offer compelling theoretical reasons to adopt these finer-grained surface representations. Instead, research on incomplete neutralisation has consistently proposed access to gradient representations to improve model fit. No radical revisions to our theory fall out from these representations. No keen insights into some unnoticed or unaccounted-for sound pattern have emerged. Perhaps they soon will, but until that time there is, in our estimation, insufficient reason to accept these fine-grained

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representations without clearer arguments demonstrating how they advance our understanding of the phonological grammar.

5.3. What constitutes a case of phonological incomplete neutralisation?

It is worthwhile at this point to briefly lay out a few basic criteria for any potential case of incomplete neutralisation. If one assumes the classic generative grammatical architecture, crucially and almost tautologically, phonological incomplete neutralisation must not be derivable from either task effects or phonetic effects. Our modelling in the previous section illustrates this point. Once morphemic and segmental context are controlled, the apparent fronting pattern in Uyghur turns out to be phonetic centralisation.

Second, phonological incomplete neutralisation must exhibit a difference large enough to be perceived by humans. If, for instance, the magnitude of a durational effect is only one to two milliseconds and extant evidence suggests humans do not reliably perceive comparable modulations in consonant duration (e.g., Huggins 1972), then those results do not unequivocally bear on the topic at hand.

Third, and perhaps most importantly, purported cases of incomplete neutralisation would be unequivocally phonological if they uniquely interact with other patterns in the grammar. For instance, Du & Durvasula (2022) report phonetically incomplete neutralisation of tone sandhi in Huian Mandarin that is not derivable from phonetics and task effects, and is large enough to be perceived by humans. Yet, they find that incompletely neutralised tones behave exactly like fully neutralised tones, feeding another tonal pattern in the language. To hold up under scrutiny, any case of incomplete neutralisation requiring reference to gradient representations must interact with other sound patterns in a manner distinct from both neutralised and non-neutralised sounds. To quote Prince (1983: 31), 'It is a rule of thumb of practical ontology that a thing exists to the extent that other things interact with it, make use of it.' If gradient representations exist in the phonological grammar, then the best evidence for them will come from patterns wherein gradiently valued elements uniquely interact with other parts of the grammar.

6. Conclusion

The classic generative view of phonology includes a commitment to discrete representations. This view, however, has been challenged repeatedly over the last four decades, often centering around patterns of incomplete neutralisation of some phonological contrast. In this article, we addressed a unique pattern of purported iterative incomplete neutralisation, backness harmony in Uyghur. We have reported results from two experiments intended to evaluate whether gradient representations are necessary to model the pattern. Results indicate that the pattern is derivable from a categorical phonological pattern of harmony with post-phonological centralisation, critically undermining the claim made in previous work that the attested gradience is phonological and not due to phonetic forces. We have also discussed the larger ramifications of a theory of gradient representations for phonology and laid out a number of necessary criteria for establishing gradient phonology.

Competing interests. The authors declare no competing interests.

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