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

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1. Introduction

The classic generative view of phonology includes the important claim that phonological representations are discrete, typically implemented with binary features (Chomsky & Halle 1968; Halle 1959; Hale *et al.* 2007; Kenstowicz 1994; Kenstowicz & Kisseberth 1977, 1979). The representational claims, particularly those 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, some researchers have argued that discrete representations are insufficient, and phonological representations need to include gradience to capture observed patterns. One key area of debate has centered around the phenomenon of *incomplete neutralization,* wherein a putative phonological process neutralizing the distinction between two categories results in surface representations that are phonetically distinct from each category. For example, prosodic word-final devoicing in German has been observed to result in a derived voiceless category that is subtly distinct phonetically from the realization 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 (Goldrick & Cole 2023; Port & Leary 2005; Roettger *et al*. 2014), others have argued that the small differences reported stem from performance factors (Du & Durvasula 2023, 2024; Fourakis & Iverson 1984; Manaster Ramer 1996; Warner *et al*. 2004). As we point out below, the import of observed incomplete neutralization on phonological representations is often quite indirect since 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 much recent work. This research has sought to establish the phonological relevance of incomplete neutralization by demonstrating phonological interactions involving the incomplete neutralization process (Braver & Kawahara 2013; Braver 2019; McCollum 2019a, b; Du & Durvasula 2024). 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. In a theory with binary [back], the output of harmony in (1) is either [ɑ] or [æ] depending on the backness of the initial vowel. However, McCollum reports that results from a production study support the case 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 [1back] and non-initial back vowels are produced with decreasing backness values between 0 and 1, e.g., [0.8back]. In essence, the pattern is iterative incomplete neutralization – each incompletely assimilated vowel triggers further incomplete assimilation in the following syllable, generating the subphonemic fronting pattern reported.

(1)		UR	Traditional SR	McCollum's SR	Gloss
	a.	/pɑltæ-m-dæ/	[pɑltɑ-m-dɑ]	[pɑltɑ-m-dɑ]	axe-POSS.1S-LOC
			[+bk][+bk][+bk]	[1bk][0.8bk][0.6bk]	
	b.	/sællæ-m-dæ/	[sællæ-m-dæ]	[sællæ-m-dæ]	turban-POSS.1S-LOC
			[-bk][-bk][-bk]	[0bk][0bk][0bk]	

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 (2024) argue that demonstrating a pattern is phonetically gradient and interacts with some phonological process is not sufficient reason to introduce gradience into the phonology. They find that incompletely neutralized tonal alternations in Huai'an Mandarin interact with tone 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 the gradience non-phonological. While Du & Durvasula's (2024) findings center around a post-lexical pattern, and many previously discussed patterns of incomplete neutralization are arguably post-cyclic or post-lexical, McCollum's (2019a, b) findings are distinct since 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 paper we further probe the Uyghur backness harmony pattern via two production studies, attempting to derive the incomplete neutralization of [back] from other factors, specifically phrasal interpolation and local consonant-vowel coarticulation. To preview our results, our findings support the case that the observed gradience is derivable from phonetic centralization without any need for gradient representations in the phonology.

2. Background

2.1 Incomplete neutralization

In this section we look more closely at a specific case of incomplete neutralization, namely, final devoicing, in order to discuss the issues relevant to any discussion of the general phenomenon of incomplete neutralization. Final devoicing has been observed in a variety of languages, including Catalan (Dinnsen & Charles-Luce 1984), Dutch (Ernestus & Baayen 2006; Warner *et al.* 2004), German (Port & O'Dell 1985; Roettger *et al.* 2014), Malay (Abu Bakar *et al.* 2007), Pennsylvania Deutchified English (Anderson 2001, 2011; Anderson & Davis 2013), Russian (Dmitrieva 2005; Kharlamov 2012; Matsui 2015), among others. Though the general pattern is similar, the exact phonological domain of application differs across languages. For that reason, in what follows 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 it can be descriptively stated in a rule-based framework as in (2). Note, though usually presented as a structure-changing process that introduces [-voice], we follow Iverson & Salmons (1995; 2003) and Beckman *et al.* (2013) in analyzing it as a rule inserting [+spread glottis] on prosodic word-final obstruents.

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

While the process is described as a case of phonological neutralization, it has been known since the 1980s that devoiced word-final voiceless obstruents in German are not phonetically identical to word-final voiceless obstruents that are underlyingly voiceless (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, e.g., differences in preceding vowel duration and consonant closure duration.

Despite continued observation of similar incomplete voicing neutralizations in many experiments, the source of the incomplete neutralization has not been resolved. Some have argued that the observation falsifies models of generative phonology with categorical representations (Goldrick & Cole 2023; Port & Leary 2005; Roettger *et al*. 2014). Other researchers, however, have resisted that claim for multiple reasons. First, some have argued that the observed incomplete neutralization effect is actually a task effect stemming from the fact that participants are made aware of the contrast during the experiment, and when the actual purpose of the experiment is hidden, there is little evidence of incomplete neutralization (Fourakis & Iverson 1984; Roettger *et al.* 2014).

Second, some have claimed that the observed incomplete neutralization is actually an orthographic effect (Fourakis & Iverson 1984; Manaster Ramer 1996; Warner *et al.* 2004) --- the contrast is typically maintained in the orthography, which may cue participants to hyperarticulate the relevant word-final obstruents in order to reflect orthographic distinctions. Stark support for this view comes from the fact that Warner *et al*. (2004) found evidence of incomplete neutralization for pairs of words distinguished only in the orthography, even when they had the same pattern in the actual phonology.

Third, some have pointed out that one could reject the claim that the devoicing process is truly phonological, in which case the argument is moot. For example, one could argue that what has so far been thought of as a phonological process could simply be phonetic in nature (Dunbar 2013). In fact, Braver (2019), Braver & Kawahara (2014), and Du & Durvasula (2023, 2024) notice this weak link in typical discussions of incomplete neutralization, arguing that the processes they investigated are truly phonological. In their investigations of monomoraic morpheme lengthening in Japanese, Braver (2019) and Braver & Kawahara (2014) contend that lengthening must be phonological since there exists a general bimoraic word-minimality requirement in the language. Similarly, Du & Durvasula (2023, 2024) support their argument that the tone sandhi process in Huai'an Mandarin is phonological by noting that it feeds another tone sandhi process. These efforts reflect the need for researchers to first establish that the relevant process is phonological before interpreting the incomplete phonetic neutralization as having any import for our understanding of phonological representations.

Fourth, one could argue that while the process of final devoicing may be phonological, there is no phonological neutralization. For example, if the process inserts [+spread glottis] on prosodic word-final "voiced" obstruents, but voiceless obstruents have some other phonological feature, say [-slack], then phonetic neutralization is not expected since the outputs of the process and underlyingly voiceless obstruents will not have identical featural specifications. While this avenue has not been typically pursued in the literature, it is logically possible and consistent with many modern phonological theories. Of course, if one makes more assumptions about the nature of contrastive features, such an analysis becomes difficult to sustain. We highlight it here to show that the representational argument from incomplete neutralization often depends on other, often unstated phonological assumptions that deserve evaluation.

Finally, and somewhat related to the previous issue, some have argued against the basic premise behind incomplete neutralization claims. These authors dispute the relevance of incomplete phonetic neutralization for phonological theories with categorical representations (Chomsky & Halle 1968; Du & Durvasula 2023, 2024; Hammarberg 1976, 1982; Kahn 1976; Lyons 1974; Mohanan 1986). As discussed extensively in Du & Durvasula (2023), claims from classical generative phonology are ultimately *ceteris paribus* claims and therefore the expectation of phonetic neutralization is only true *if all other factors are held constant*. The ceteris paribus clause is by definition not satisfied in the case of phonological neutralization, where the underlying representations are different, and so one can imagine a variety of performance mechanisms that might be affected by this difference. Consequently, incomplete neutralization doesn't by itself falsify any representational claims without additional assumptions concerning other (performance) factors. In fact, we mention this last point to highlight the fact that no phonetic data is directly interpretable without a full set of additional auxiliary assumptions. As discussed in Du & Durvasula (2023), the auxiliary assumptions being used to argue against categorical representations are in fact inconsistent with the foundational claims in generative phonology. Careful consideration of performance factors and biases introduced into the experiment through experimental protocols is necessary before concluding that the relevant phonetic data deserve a representational solution. We follow up on this issue below, showing that the evidence of incomplete (asymmetrical) neutralization that McCollum (2019a, b) observed in Uyghur, while replicable, ultimately stems from inadequate control; i.e., from a violation of the *ceteris paribus* clause discussed above.

2.2 Uyghur

Uyghur (iso: uig) is a southeastern Turkic language spoken by approximately 12 million, 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 Ili 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-nativized loans (Hahn 1991; Mayer *et al*. 2022; Sharma to appear). Featural descriptions for each vowel in the Uyghur inventory are presented in Table 1.

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

Table 1: Uyghur vowel inventory

2.2.2 Vowel harmony

Uyghur exhibits two types of vowel harmony, backness and rounding harmony. Both harmonies are well described (Nadzhip 1971; Hahn 1991; Vaux 2000; Engesæth *et al*. 2009; 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-neutralizing alternations among the low and high rounded vowels, as seen in (3-4). In these examples /æ y/ occur after [-back] roots while /ɑ u/ occur after [+back] roots. Observe also in (3-4) 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). Non-initial /i/ varies allophonically based on preceiding vowel backness(McCollum 2019a, b; cf. Hahn 1991). Non-initial /e/ occurs only in unassimilated loans, and as a consequence does not alternate for backness.

Although the mid rounded vowels /ø o/ regularly trigger backness alternations, they do not occur in non-initial syllables in the native and nativized 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 most productive alternation of the two is /æ~ɑ/, as it occurs in a wide range of suffixes. We focus on this alternation throughout the paper. The alternation between /y/ and /u/ is far more limited, occurring in the gerundial suffix /GU/ and in suffixes that undergo rounding harmony, e.g., 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 overt case-marked nouns, yielding words from one to five syllables in length. Example forms are shown in (5). One thing is worth briefly noting from the examples below. Low vowels raise to /i/ in medial open syllables (5f,g,j,k,m-r; Nadzhip 1971; Hahn 1991; Engesæth *et al*. 2009; Mayer *et al*. 2022). This vowel raising process is widespread in the language, but it is 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).

McCollum (2019a, b) analyzes z-score normalized F_2 (Lobanov 1971) with a mixed-effects linear regression, predicting F_2 (z) 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.

(5)

2-syllable words					
a.	bɑl-lɑr	honey-PL	c.	bæl-lær	lower.back-PL
b.	bɑl-dɑ	honey-LOC	d.	bæl-dæ	lower.back-LOC
3-syllable words					
e.	bɑl-lɑr-dɑ	honey-PL-LOC	i.	bæl-lær-dæ	lower.back-PL-LOC
f.	pɑlti-dɑ	axe-LOC	j.	sælli-dæ	turban-LOC
g.	pɑlti-lɑr	axe-PL	k.	sælli-lær	turban-PL
h.	pɑltɑ-m-dɑ	axe-POSS.1S-LOC	l.	sællæ-m-dæ	turban-POSS.1S-LOC
4-syllable words					
m.	bɑl-lir-i-dɑ	honey-PL-POSS.3-LOC	o.	bæl-lir-i-dæ	lower.back-PL-POSS.3-LOC
n.	pɑlti-lɑr-dɑ	axe-PL-LOC	p.	sælli-lær-dæ	turban-PL-LOC
5-syllable words					
q.	pɑlti-lir-i-dɑ	axe-PL-POSS.3-LOC	r.	sælli-lir-i-dæ	turban-PL-POSS.3-LOC

Though McCollum does not strictly control for flanking consonant place, he attempts to account for potential coarticulatory effects of preceding and following consonants in his model. He further attempts to account for any potential differences in coarticulation based on vowel height by directly incorporating two-way interactions between preceding and following consonants and vowel height. McCollum's goal appears, quite sensibly, to rule out as many potential confounds as posisble 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.

In his analysis, the fixed effect of syllable number did not significantly affect vowel F_2 (β=0.01, $\chi^2(1)$=0.02, p=0.88). Since he coded front vowels as 0 and back vowels as 1 for vowel backness, this indicates that front vowels exhibit no systematic fronting across syllables. He found that the interaction between backness and syllable number was, however, highly significant (β=0.35, $\chi^2(1)$=32.48, p<.001). This is consistent with the descriptive statistics reported, which support the case that back vowels exhibit monotonically increasing F_2 in non-initial syllables. The vowels /ɑ u/ and the [+back] allophone of /i/, [ə], were are characterized by significant increases in F_2 by position while the front vowels /æ y/ and the [-back] allophone of /i/, [ɪ], showed no systematic changes in F_2 by position.

McCollum infers from his findings that backness harmony in Uyghur falls out from iterative incomplete neutralization of [back]. There are several key components to his analysis. First, harmony is phonological because numerous exceptions exist and harmony also interacts with a structure-preserving consonantal alternation. Back vowels must regularly co-occur with uvular consonants while front vowels co-occur with velar consonants, as evidenced by the dative and gerundial suffixes in (3-4). Critically, there is no voiced uvular stop in the Uyghur inventory, so /g/ alternates with /ʁ/ when flanked by a back vowel and a voiced consonant. This difference in both place and manner of articulation supports the necessity of backness harmony in the lexical (or early) phonology in the language, as opposed to being a post-lexical (or late) process.

Second, once the harmony pattern is seen to be phonological, it is reasonable to wonder whether the phonetic gradience reported is due to some phonetic force or if it is part of the phonological harmony. To address this, McCollum notes that the subphonemic fronting of back vowels in non-initial positions is not accompanied by any systematic backing of front vowels. In other words, the pattern is asymmetric, and as such is not amenable to an analysis hinging on phonetic centralization. In cases of phonetic centralization of non-initial material, the pattern is relatively symmetrical (Nord 1986; Vayra & Fowler 1992; Krakow *et al.* 1995; Herman *et al*. 1997; Johnson & Martin 2001). He reasons that if the output forms examined are not derivable from centralization, then they must either derive from some other, unknown phonetic pressure or they fall out from the phonological harmony system. Since he finds no cross-linguistic phonetic process of back vowel fronting deserving of merit, he pursues a phonological analysis of these facts.

Third, McCollum contends that [-back] is the underlying, unmarked feature value while [+back] is the active, marked feature value (cf. Mayer 2021). If the gradient fronting pattern is derivable from the phonology, then linking the surface asymmetry with a featural asymmetry is a straightforward analytical choice. He marshals two types of evidence to support the activity of [+back]. First, high vowels that are not underlyingly [+round] are fronted to cardinal [i] in absolute word-final position (McCollum 2019a:12-15). Underlying and raised /i/ in non-initial positions allophonically vary for backness, [ɪ]~[ə] (McCollum 2019a, 2021). However, in word-final position /i/ is always produced with an extremely fronted [i], in contrast to its less peripheral front [ɪ] and back [ə] allophones.

In addition to word-final high vowels, McCollum (2019a:146-148) describes historical patterns of loanword adaptation in Uyghur whereby borrowings 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.

If the first two claims – that harmony is phonological and gradience is not derivable from other phonetic factors – are accepted, then the incomplete neutralization of [back] deserves a phonological account, and that account must explain the asymmetrical subphonemic shifts in vowel quality across positions. If the additional claim that [-back] is active is accepted, then the gradience reported is derivable from iterative incomplete neutralization – 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). McCollum goes on to argue that his analysis fits the data better than a traditional analysis without access to continuous phonological representations.

There exist multiple alternatives to the phonological gradience account pursued in McCollum's work. One involves rejecting the claim that backness harmony in Uyghur is phonological. This, however, is highly unsatisfactory. The harmony is replete with exceptions, and given the interaction between harmony and the dorsal consonant alternation noted above, the pattern exhibits the hallmarks of being lexical and thus phonological. In the following sections we explore two more plausible alternatives. In Section 3 we discuss an analysis depending on phrase-level interpolation. Then in Section 4 we discuss an alternative account that derives the reported fronting effects from low-level consonant-vowel interactions. In both sections we focus on the low vowel alternation due to the fact that it is more widespread and avoids many of the complicating factors, e.g., rounding harmony and the phonetics of /i/, that affect the high vowels.

3. Experiment 1

In this section and in Section 4 we attempt to derive the results in McCollum (2019a, b) without resorting to the introduction of continuous phonological representations. In this section we focus on McCollum's (2019a, b) 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 part of the lexical phonology while gradient fronting is derivable from the phonetic module of the grammar. 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 possible to derive the fronting pattern in McCollum's data without phonological gradience.

If the phonetics operates over these windows, then it is possible to gradiently interpolate between both edges of the word. At the left edge of the word, the initial syllable is specified for [±back]. Moreover, the backness of an initial-syllable vowel is not predictable, in contrast to the backness of all other positions (for much of the native and nativized vocabulary, anyway). McCollum (2020b) shows that in the related language Kyrgyz this difference in predictability results in hyperarticulation of the initial syllable. 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.

In addition, if the right edge of the word in McCollum's data is marked by a very anterior lingual position, then gradient fronting is 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.[1] 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 toward this [-back] default articulatory setting. This is schematized 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 these two [-back] windows at each word edge would likely mitigate centralization in front vowel words, like [dæz-lær-dæ] 'crack-PL-LOC', resulting in relatively constant F_2 values throughout the word.

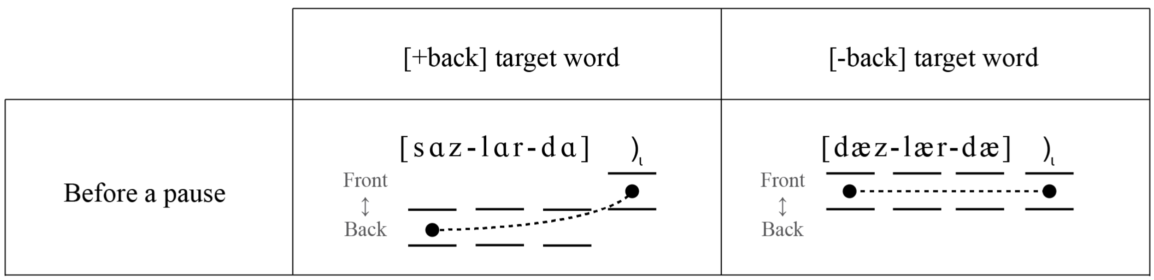

Figure 1: F_2 patterns for words uttered in isolation according to an interpolation-based account of gradient backness harmony in Uyghur.

This alternative account predicts that the F_2 trajectories within a given word, whether back or front, should depend on phrasal context, as shown in Figure 2. Specifically, back vowel words that are followed by another back vowel word should not, under this analysis, exhibit systematic fronting precisely because there is no following [-back] lingual specification. Relatedly, if the following word is [-back], F_2 of vowels in front vowel words should decrease in non-initial syllables due to 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.

[1] See Vajda (1994), Vaux (2009), and Washington (2016) for analyses of vowel harmony in Turkic as tongue root harmony.

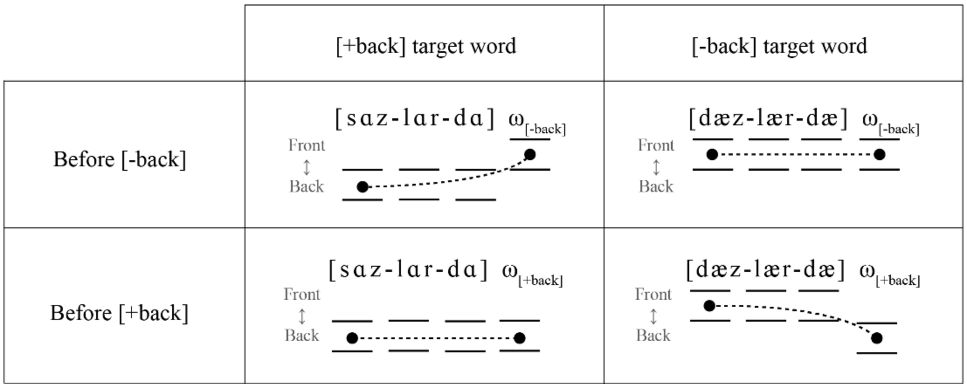

Figure 2: Predicted F_2 patterns by phrasal context if gradience is phonetic interpolation

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.

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 /-lAr/ or locative /-DA/ suffix. Trisyllabic forms were formed by concatenating both plural and locative suffixes. Roots were all CVC; all consonants were coronal or bilabial. No dorsal consonants were used due to 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 word with an initial bilabial or coronal consonant. Several sample sentences are shown in (6).

(6) Example sentences

a. bu dɑslɑrdɑ tøʃyklær bɑr

bu	dɑs-lɑr-dɑ	tøʃyk-lær	bɑr
DEM	wash.basin-PL-LOC	hole-PL	exist

"There are holes in these wash basins."

b. bu mɑllɑrdɑ tupɑ joq

bu	mɑl-lɑr-dɑ	tupɑ	joq
DEM	commodity-PL-LOC	dust	no

"There's no dust on these goods."

3.1.3 Procedure

Each participant was recorded by the first author in a quiet room. Participants wore a Shure SM-10A head-mounted microphone. All sound files were recorded to a laptop using Praat (Boersma & Weenink 2021) and a Sound Devices USBPre2 audio interface. After informed consent, participants were presented 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. Sentence lists were randomized, with the stipulation that the first five sentences for each participant were fillers. The study took approximately 15-20 minutes to complete; participants were given three brief breaks during the study.

3.1.4 Measurements

Recordings were annotated in Praat by the first two authors, such that the first three repetitions of the five total repetitions were annotated by one and the last 3 repetitions were annotated by the other. This annotation split provided the opportunity to test consistency between the two annotators using the third repetition. Note, for subsequent visual analysis and statistical modelling, we used only one of the annotations for the third repetition so as not to inflate our actual dataset. 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, excrescrent/epenthetic segment, unclear, <blank>), where <blank> stood for good word tokens that were included in the analysis. A sample annotation is provided in Figure 3.

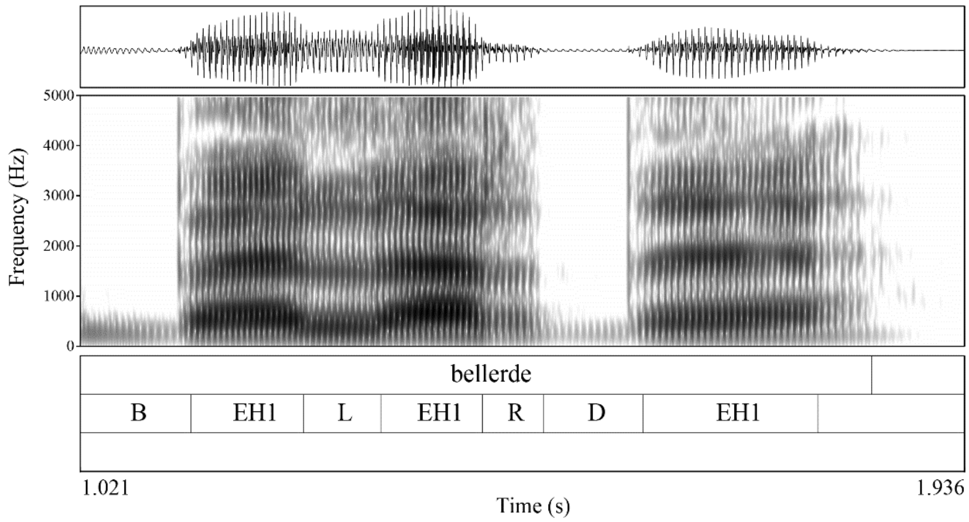

Figure 3: A sample annotation of [bæl-lær-dæ] 'lower.back-PL-LOC.' The top tier marks the test item, the middle tier marks the expected surface representation, and the bottom tier marks the quality of the pronunciation (bad, excrescrent/epenthesis, unclear, <blank>).

Since we were interested in the potential effect of phrasal context on positional vowel backness, we extracted F_2 measurements for each vowel ([æ ɑ]) in target words using Praat scripts. Furthermore, we coded the context as front/back/NA depending on the backness of the first vowel in the following word, where NA stood for a pause after the test item --- in this case, we conservatively treated these items separately in the analysis since prepausal interpolation might differ from phrase-medial interpolation. Finally, we collected F_2 measurements at both the mid-point of each test vowel, and at 10% intervals of each vowel. The former allowed us to understand how the F_2 values varied generally from vowel to vowel and statistically model the changes, while the latter allowed us to see any general target interpolation during each vowel in the word.

3.2 Results

3.2.1 Mid-point analysis of F_2 measurements

In this paper, all the statistical analysis and plotting were done in R (R Core Team 2022), using the IDE Rstudio (Rstudio Team 2020). Data analysis and visualizations were done using the *tidyverse* (Wickham *et al*. 2019) suite of packages, and statistical modelling was done with the packages *lme4* (Bates *et al.* 2015) and *lmerTest* (Kuznetsova *et al.* 2017).

Overall, there were 4,438 good vowel tokens for the test vowels, constituting 96.3% of the data. Out of this, 1,482 vowels (33.4%) were in words followed by back vowels in the next word, 1,917 vowels (43.2%) were in words followed by front vowels in the next word, and 1,039 (23.4%) of the words were followed by pauses. Figure 4 shows the means and standard errors for each surface vowel in each position of disyllabic 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), as observed by the increasing F_2 values in syllables two and three was replicated. However, F_2 of [æ] decreases in non-initial syllables, in particular in the second syllable. This variation appears to exceed the smaller-scale variation reported in McCollum's data.

There is a noteworthy effect of phrasal position on vowel F_2. Crucially however, the effect of the following context applies *throughout* the test word and to both alternations vowels. Note also that the prepausal target words, both front and back, exhibited visually similar F_2 trajectories to target words before [-back] words.

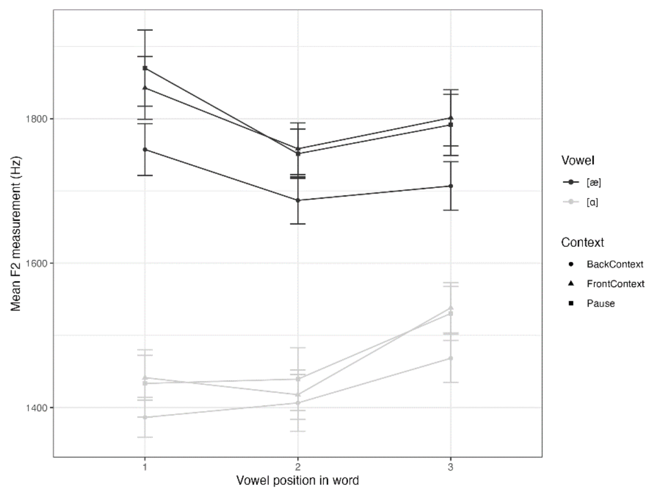

Figure 4: Mean F_2 values at vowel midpoint for [æ ɑ] based on syllable number and phrasal context. Error bars represent standard error.

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 value of each vowel. We included two independent variables and their interaction in the full model under consideration, Context (Back, Front, Pause), and the continuous variable, Vowel Position. The random effects structure included by-subject and by-item random slopes for Vowel Position. The best model was identified by Akaike Information Criterion (AIC; Akaike 1974). Note, 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). When the AIC differences between the best model and any of the other models was less than 8, we considered the relevant other model(s), too.

We ran separate mixed effects models for the two vowels [æ ɑ], as we had clear a priori expectations for each one, and would have to follow up any overall analysis with separate modelling anyway. Modelling F_2 of these vowels separately from the start avoided the challenges of interpreting three-way interactions, which would be required by a single model accounting for F_2 of both vowels.

For the vowel [æ], the best model in Table 2 was the one with fixed effect for Context and Vowel Position (model 4); however as can be seen the full model (model 5) and the model with a fixed effect for Context only (model 3) were within one AIC unit of the best model. Therefore, while we present the best fitting model here for the sake of succinctness, we also evaluated and will discuss the other two models.

Syllable	Model fixed effects	AIC
1	Intercept	32,878
2	Intercept + Vowel Position	32,877
3	Intercept + Context	32,868
4	Intercept + Context + Vowel Position	32,867
5	Intercept + Context + Vowel Position + Intercept + Context:Vowel Position	32,868

Table 2: AIC values for the different models for the vowel [æ].

The best fitting model for [æ] is presented in Table 3 below. Consistent with visual inspection, there is a clear decrease in F_2 values of [æ] in [+back] contexts compared to the prepausal condition, but there is no comparable decrement for [-back] contexts. Notably, this effect holds in the other two models, as well. Furthermore, there is a marginally significant effect of Vowel Position. However, this effect does not hold in the other two models. Consequently, the best inference based on the modelling is that there is a clear asymmetric effect of contextual backing (F_2 lowering) in the back contexts across all positions, but that there is no clear interpolation effect that incrementally changes the F_2 values of the vowel through the word.

Fixed Effect	Estimate	df	t-value	p (> |t|)
Intercept	1865	33.8	28.5	<0.0001
Vowel Position	-44.3	19.2	-1.8	0.08
Context: Front	-11.3	2195.9	-0.8	0.41
Context: Back	-56.2	1943.7	-3.7	0.0002

Table 3: The best fitting model for the vowel [æ] (baseline: Pause context)

For the vowel [ɑ], the best model was again the one with fixed effect for Context and Vowel Position (Table 4). However, three other models (model 2, model 3, and model 5) were within five AIC units of the best model. Therefore, while we once again present only the best fitting model, we also inspected and will discuss the other three models.

Syllable	Model fixed effects	AIC
1	Intercept	25,812
2	Intercept + Vowel Position	25,807
3	Intercept + Context	25,809
4	Intercept + Context + Vowel Position	25,804
5	Intercept + Context + Vowel Position + Intercept + Context:Vowel Position	25,807

Table 4: AIC values for the different models for the vowel [æ].

The best fitting model for [ɑ] is presented in Table 5. Consistent with visual inspection, there is a clear main effect of vowel position such that F_2 values increase throughout the word. Notably, this effect clearly persists in both the other models where Vowel Position is a fixed effect. The effect of Context is a bit more suspect --- while there is a positive effect of [-back] context in this model, the effect is not statistically significant in the other models which include Context as a fixed effect (the *p*-values are rather high in fact). This suggests that the effect of Context is not quite clear in our results.

Fixed Effect	Estimate	df	t-value	p (> |t|)
Intercept	1296.3	29	19.8	<0.0001
Vowel Position	75.5	20.9	2.85	0.009
Context: Front	17.9	1967.4	1.9	0.05
Context: Back	-12.4	1887.5	-1.2	0.23

Table 5: The best fitting model for the vowel [ɑ] (baseline: Pause context)

Overall, the effect of Context on F_2 values, particularly for [+back] contexts is clear for the [æ] vowel, but not for the [ɑ] vowel. Further, the fact that Context exerts an effect throughout the entire word is interesting on its own and deserves further scrutiny in subsequent work. Next, there is a clear positive effect of Vowel Position for the [ɑ] vowel, but not for the [æ] vowel. This replicates the findings of McCollum (2019a, b). Finally, the results show no evidence supporting the case that asymmetric fronting in McCollum (2019a, b) is a byproduct of phonetic interpolation. Therefore, our results are not consistent with the phonetic interpolation hypothesis.

3.2.2 F_2 contours

In this section, we show visualizations of vowel contours. While we do not perform any statistical testing of the patterns since we didn't have any explicit hypotheses about contours that we were testing, we considered it helpful to include the visualizations to assess the viability of the phonetic interpolation hypothesis.

The plot in Figure 5 suggests that the effect of context in terms of an interpolation effect is present only for the last vowel. As can be seen below, 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 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 in Figure 5. Third-syllable vowels were always word-final since they always elicited in the locative suffix /DA/, making them even more susceptible to local coarticulation with the following word. All in all, we interpret these results as evidence against any interpolation-based account of gradient harmony in Uyghur.

4. Experiment 2

Since results from Experiment 1 indicate that the gradience in Uyghur is not the byproduct of phrasal interpolation, we conducted a second experiment to investigate another potential explanation, low-level phonetic coarticulatory effects. If harmony is truly gradient and asymmetric, then the pattern should persist even after stricter controls for flanking segmental context are introduced. If, however, the observed phonetic pattern is derivable from these local interactions, positional F_2 distinctions in non-initial syllables should either be nullified or symmetrical once context is sufficiently controlled. Positional F_2 differences should be nullified if the phonology completely assimilates non-initial vowels with no post-phonological reduction. If, however, symmetrical changes in non-initial F_2 are found, this would support categorical phonological harmony in tandem with phonetic centralization.

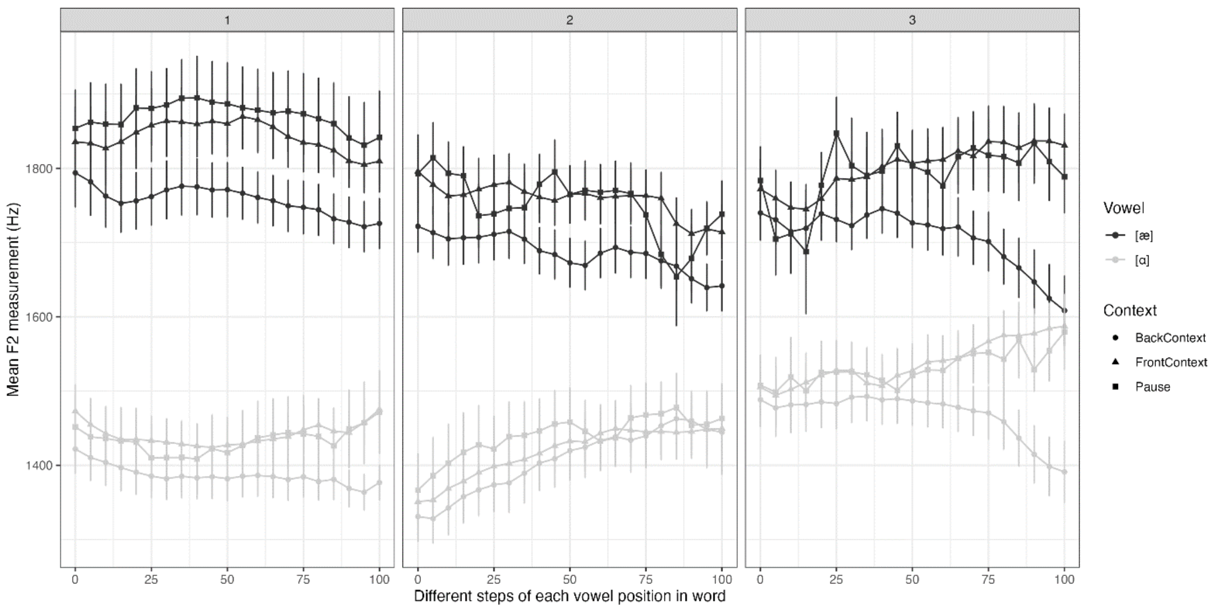

Figure 5: Mean F_2 contours for [ɑ æ] based on syllable number and phrasal context Error bars represent standard error.

While McCollum (2019a, b) used fixed effects of preceding and consonant place of articulation to reduce the possibility of local consonant-vowel interactions clouding the interpretation of the data, there is still a great deal of potential variability left unexplained by his modeling choices. He coded three levels of each contextual variable: bilabial, coronal, and dorsal, also coding the lateral as coronal in front vowel contexts but dorsal in back vowel contexts to account for the backness alternation in the lateral (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] following the bilabial stop in /bilæk/ [bɨlæk] 'wrist.' As another example, /ø/ is produced as a front vowel before velar obstruents, e.g., /køk/ [køk] 'blue', but is produced as a central vowel before the velar nasal, e.g., /køŋl-m/ [kɵŋlym] 'heart-POSS.1S.' Coarticulatory differences within a given featural natural class are reported from 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.

To more strictly control for flanking consonants, we chose to analyze the realization of the low vowels within a given morpheme across a variety of positions. By keeping the morpheme constant in our analysis, we are able to control the phonetic coarticulatory effects on vowel F_2. 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 due to 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 wordlist contained 14 disyllabic, 23 trisyllabic, 20 quadrisyllabic and 19 pentasyllabic words. The only vowels present in target words were /æ ɑ/. In addition to the target items, the wordlist 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 stems were from one to three syllables in length. Verbal stems were one or two syllables in length. Sample words from nominal and verbal stems are shown in (7-8).

(7) Sample forms from nominal stems

2-syllable words

a.	tær-dæ	'sweat-LOC'
b.	tɑr-dɑ	'string-LOC'

3-syllable words

c.	dæz-lær-dæ	'crack-PL-LOC'
d.	sɑz-lɑr-dɑ	'musical.instrument-PL-LOC'

4-syllable words

e.	sæpær-lær-dæ	'journey-PL-LOC'
f.	tɑtɑr-lɑr-dɑ	'Tatar-PL-LOC'

5-syllable words

g.	sæltænæt-lær-dæ	'dominion-PL-LOC'
h.	rɑmɑzɑn-lɑr-dɑ	'Ramadan-PL-LOC'

(8) Sample forms from verbal stems

3-syllable words

a. tæp-kæn-dæ ‘spill-NMLZR-LOC’

b. tɑp-qɑn-dɑ ‘find-NMLZR-LOC’

4-syllable words

c. tær-læ-t-kæn-dæ ‘sweat-VBZ-CAUS-NMLZR-LOC’

d. tɑrɑ-t-qɑn-dɑ ‘spread-CAUS-NMLZR-LOC’

5-syllable words

e. sæpær-læ-ʃ-kæn-dæ ‘journey-VBZ-RECIP-NMLZR-LOC’

f. nɑʧɑr-lɑ-ʃ-qɑn-dɑ ‘bad-VBZ-RECIP-NMLZR-LOC’

4.1.3 Procedure

Each participant was recorded by the first author in a quiet room. 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 words in isolation and instructed to read each at a natural rate of speech. Each word was presented in the Cyrillic script because all participants in the first experiment indicated greater familiarity with Cyrillic than Perso-Arabic and Latin scripts. The wordlist was randomized; each speaker read through the list twice, each time with a different randomization. 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 mid-point 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, <blank>), where <blank> stood for the good word tokens; 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 datasets that we created based on the 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 10% intervals of the same vowel, since F_2 contours were not pertinent to the question at hand.

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 can compare our results to McCollum's, providing a baseline with which to compare the by-morpheme analysis in the next subsection. Overall, there were 2,666 good word tokens for the test vowels, constituting 99.3% of the data. Positional vowel F_2 is shown in Figure 6.

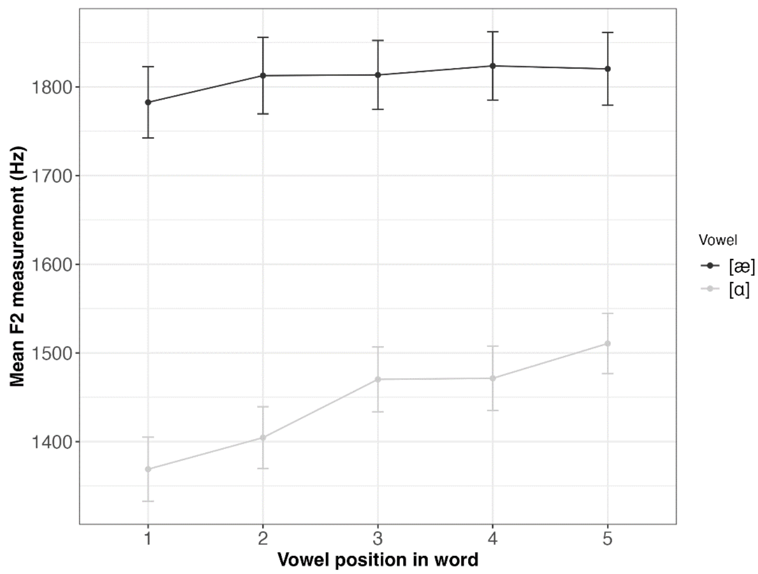

Figure 6: Mean F_2 values for the two vowels [ɑ æ] in different positions of the word. Error bars represent standard errors.

We followed up on visual inspection with mixed effects modelling, as before. Again, the dependent variable was F_2 of each vowel, and the crucial (and only) independent variable was the continuous variable Vowel Position. The random effects structure was the same as before and included by-subject and by-item random slopes for Vowel Position. Note, in this case, since there was only a single independent variable, there was no need for any model comparison, and we directly present the relevant model. 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.

For the vowel [æ], the model is shown in Table 6. Consistent with Figure 6, there is no clear change in F_2 of [æ] by position in the word.

Fixed Effect	Estimate	df.	t-value	p (> |t|)
Intercept	1791	27.2	30.9	<0.0001
Vowel Position	8.1	24.8	0.79	0.44

Table 6: Summary of baseline model output for the vowel [æ].

For the vowel [ɑ], the model is shown in Table 7. In contrast to the [æ] vowel, there is a clear and large effect of vowel position on F_2 of [ɑ]. As with the previous experiment, this observation replicates the major finding in McCollum (2019a, b) that there appears to be an asymmetric effect of F_2 fronting that affects only the vowel [ɑ] in the aggregated data.

Fixed Effect	Estimate	df.	t-value	p (> |t|)
Intercept	1333.7	42.6	26.2	<0.0001
Vowel Position	47.1	55.7	4.4	<0.0001

Table 7: Summary of baseline model output for the vowel [ɑ].

4.2.2 Analysis of F_2 measurements while adjusting for morphemes

For this analysis, we only looked at four morphemic contexts in different positions. Therefore, we excluded the root morpheme. In this way, we were able to control for the effect of morphemic and immediate segmental context on vowel F_2. The analysis included 2,312 tokens of the morpheme /dA~tA/, 872 tokens of /lAr/, 288 tokens of /lA-ʃ/ and 940 tokens of /qɑn~kæn/.[2]

Figure 7 shows the by-morpheme plots for the relationship between F_2 and Vowel Position. In contrast to the aggregated analysis, visual inspection suggests there is no asymmetric fronting. Instead, there appears to be a symmetric centering of F_2 for both vowels. The figure also includes 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 at vowel midpoint, and the crucial (and only) independent variable was the continuous variable Vowel Position. However, 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 Position.

[2] Note, the total here does not add up to the total of 2,666 good word tokens mentioned earlier in section 4.2.1. This is because the words containing the different morphemes are not mutually exclusive, i.e., the same word token can have multiple morphemes being considered.

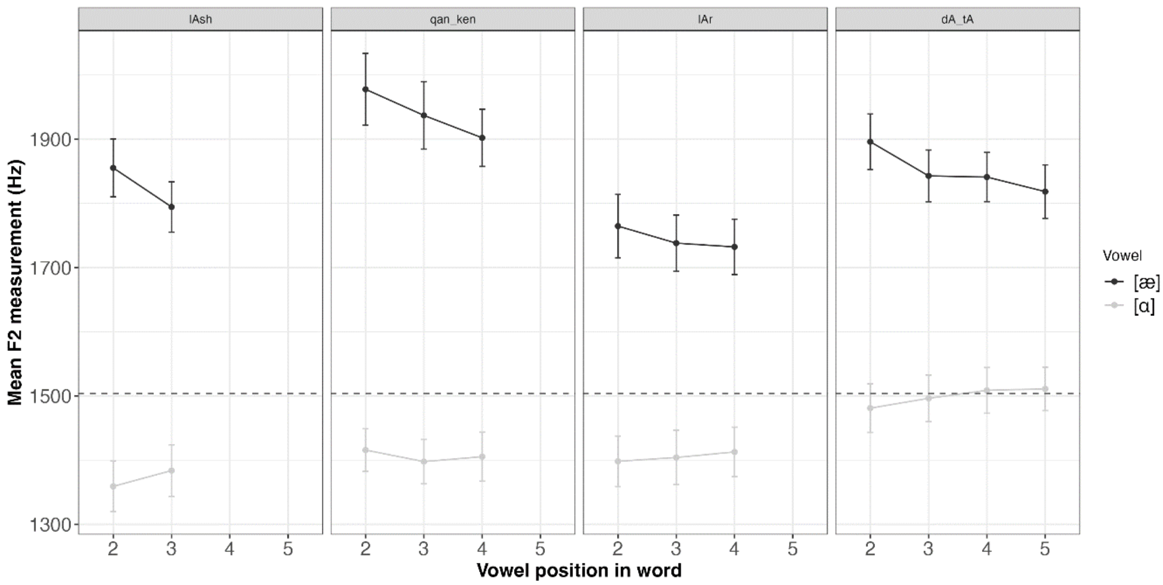

Figure 7: Mean F_2 values for [ɑ æ] in different positions of the word separated by the morpheme of the vowel. The horizontal dashed line represents the mean F_2 value for [ɨ] in filler items. Error bars represent standard error.

The model for [æ] is show in Table 8. As in Figure 7, there is a clear negative effect of vowel position on F_2. Therefore, there is evidence that the vowel is progressively backed throughout the word. The model for [ɑ] is shown in Table 9. In contrast to the [æ] vowel, there is a relatively smaller but clear positive effect of vowel position on F_2 of [ɑ]. Therefore, there is evidence that the vowel is progressively fronted throughout the word.

Fixed Effect	Estimate	df.	t-value	p (> |t|)
Intercept	1910.2	10.2	25.6	<0.0001
Vowel Position	-23.5	10.6	-3.2	0.009

Table 8: Summary of by-morpheme model output for the vowel [æ].

Fixed Effect	Estimate	df.	t-value	p (> |t|)
Intercept	1400.5	14.1	29.5	<0.0001
Vowel Position	11.8	14.1	3.8	0.002

Table 9: Summary of by-morpheme model output for the vowel [ɑ].

Once we control for morphological and segmental context, visual and statistical modelling results suggest that there is no asymmetric fronting of the [ɑ] vowel. To further probe this effect of morphology and segmental context, we compared each of the above models with the corresponding models that do not include the by-morpheme random slope of Vowel Position.

For the [æ] vowel, the AIC values for the model with and without a by-morpheme random slope of Vowel Position are shown in Table 10. The AIC difference between the two models was rather large, 127 in favor of the model with the by-morpheme random slope. This strongly suggests that that morphological (and consequently segmental) contextual information is significant for vowel F_2. Further, this finding supports the case that differences in morphemic and segmental context underlie the lack of effect of Vowel Position on F_2 of [æ] reported in the overall analysis in section 4.2.1.

S. No.	Full model	AIC
1	F_2~Position+ (Position|Sub) + (Position|Item)	26,543
2	F_2~Position+ (Position|Sub) + (Position|Item) + (Position|Morpheme)	26,416

Table 10: Comparison of models predicting for the F_2 of [æ] with and without a by-morpheme random slope for position.

For the [ɑ] vowel, the AIC values for the model with and without a by-morpheme random slope of Vowel Position are shown in Table 11. The AIC difference between the two models was rather large, 130, again in favor of the model with the by-morpheme random slope. This again suggests that there is clear and strong evidence that morphological (and consequently segmental) contextual information is important for predicting vowel F_2.

S. No.	Full model	AIC
1	F_2~Position+ (Position|Sub) + (Position|Item)	28,446
2	F_2~Position+ (Position|Sub) + (Position|Item) + (Position|Morpheme)	28,316

Table 11: Comparison of models predicting for the F_2 of [ɑ] with and without a by-morpheme random slope for position.

One last aspect of the results that we would like to mention is the fact that the estimated slope for the [æ] vowel (-23.5) is roughly twice that of the slope for [ɑ] (11.8). This is consistent with Figure 4, which shows a steeper decline in F_2 of second-syllable [æ] than second-syllable [ɑ]. If, in fact, the vowels are simply centralizing, then this is unsurprising. As can be seen in Figure 6, the back vowel [ɑ] is far closer to the average F_2 value of the central vowel [ɨ] (dashed line) than is the front vowel [æ]. Similarly, McCollum's (2019a) data, which includes z-score transformed F_2 values of all the vowels in his experiment, suggest that the front vowel [æ] is roughly twice the distance from the center of the vowel space as the back vowel [ɑ] is. Therefore, there is simply less distance (about half, in fact) between the back vowels and the center of the F_2 vowel space.

Overall, our results in this sub-section suggest that once the effects of morphological and segmental information are controlled for, there is no asymmetric fronting of the [ɑ] vowel in non-initial syllables. Instead, we find a symmetric centralization of the two vowels [ɑ æ]. We interpret this to mean the Uyghur pattern cannot be seen as evidence supporting the introduction of any gradience into phonological representations. We further discuss this in the next section.

5. Discussion

5.1 Backness harmony in Uyghur

Results from these two studies support the view that there is no gradience in Uyghur backness harmony, and as a result, that the claims in McCollum (2019a, b) are unsupported. 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 centralized in non-initial syllables? The answer is quite straightforward – 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 12 and Figure 8.

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

Table 12: Morpheme counts by syllable number in Experiment 2

Given the morphotactics of the language, as well as the sample forms in (5), based on McCollum (2019a:105-107; 2019b:3) we conclude that McCollum's data exhibit the same morphological skew as our own. Recall that the language's morphotactics require PL to occur closer to the root than case-marking morphemes. Based on the sample forms from McCollum's work in (5) the following distribution of morphemes with low vowels. In syllable two, roughly 40% of experimental tokens should derive from roots, 40% from PL, and 20% from LOC. In syllable three, roughly 75% of elicited tokens should derive from LOC, and only 25% from PL. Finally, in syllables four and five, the elicited data come from LOC only, with no instances of PL in these positions. Interestingly, there is no visual difference between F_2 of /ɑ/ in syllables four and five in McCollum (2019a, b). In other words, when morpheme is held constant, no obvious by-position difference is found in McCollum's data. Given our findings, one might expect further increase in F_2 of [ɑ] due to centralization, but Figure 7 suggests that a fully centralized [ɑ] is attained by syllable four, so no further fronting would be expected in syllable five.

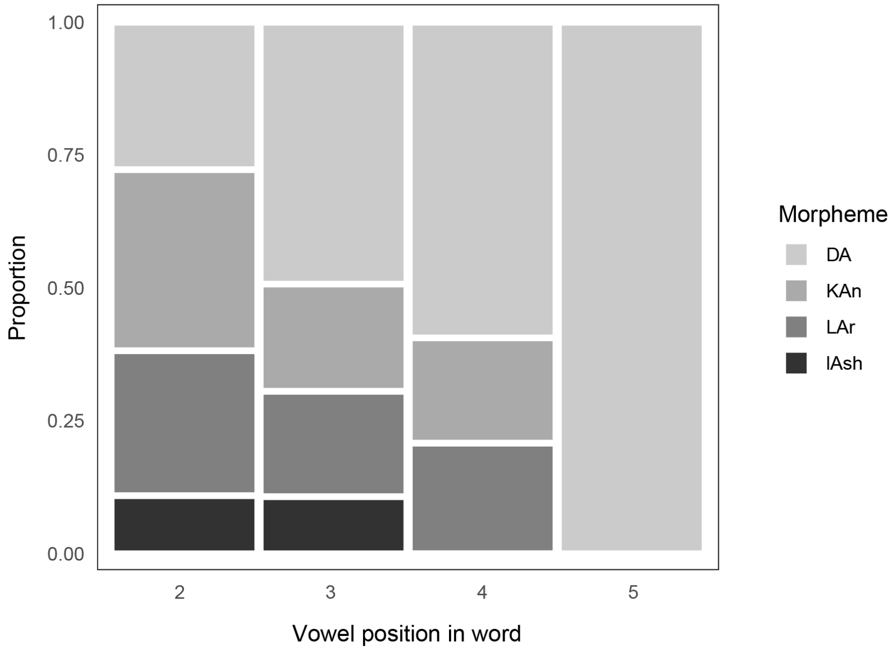

Figure 8: Plot of morphemes elicited by position in Experiment 2

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 centralization 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. As noted in previous research, the lateral is velarized in [+back] contexts, which we conclude exerts a backing effect on the onset of the following vowel relative to the coronal stop in /DA/. Since /DA/ is always word-final in these data, then the default [-back] articulatory setting should result in increased F_2 at vowel offset. The combination of these two forces, higher F_2 at both vowel onset and offset in /DA/, results in increased F_2 at vowel midpoint, as seen in Figure 4 and Figure 7.

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 value in [læʃ] and [dæ~tæ]. In earlier syllables, Table 2 and Figure 8 show a balance of these morphemes, resulting in an intermediate average F_2. In later syllables, the most frequently elicited morphemes happen to have intermediate values for F_2. In other words, the stability of F_2 of [æ] across positions in Figure 7 is just as much an accidental byproduct 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 byproduct of local contextual effects. Our results undermine claims of gradience in Uyghur, but more generally, they do not exclude the potential for incomplete neutralization 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 describe the potential costs and benefits of these representations, as well as to delineate the components of phonologically gradient incomplete neutralization.

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. Previous work in the generative program relied on featurized string-based representations, with notable success. Yet, the autosegmental representations birthed by work like Leben (1973) and Goldsmith (1976), and explored in so much subsequent work (e.g., McCarthy 1979; Pulleyblank 1983; see also Hyman 2014) introduced new ways to understand and theorize about sound patterns that have significantly shaped the field. Autosegmental representations allow a compactified encoding of transformations, replacing more complicated string-based encoding with simpler, tier-based local rules and constraints. Autosegmental principles have proven useful for metrical and hierarchical prosodic representations (Liberman 1975; Pierrehumbert 1980), feature geometric representations (Sagey 1986), alignment constraints (Kirchner 1993; Akinlabi 1996), spans (McCarthy 2004) among many others, also figuring into recent work on the computational properties of phonological patterns (Jardine 2016, 2017, 2019).

Alongside these benefits, the introduction of non-linear representations increased the expressive capacity of the phonological. 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 beyond eight. For instance, a word like [ballarda] 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 as (i) the multiple association of a single [+back] autosegment, (ii) the multiple association of two distinct [+back] autosegments (two forms that do not involve crossing lines exist), and (iii) the single association of three distinct [+back] autosegments. This predicts a potential contrast between singly- versus multiply-linked representations, which, according to Hayes (1986) is exactly what distinguishes between true and false geminates in Palestinian Arabic in Hayes (see also Hyman 1987; Kenstowicz & Kidda 1987 for similar analyses). Thus, despite an increase in representational possibilities there is evidence supporting the type of contrast introduced by this representational system. Moreover, given the set of well-formedness constraints on the representations espoused in Goldsmith (1976) and developed by later research, there is sufficient reason to believe that the representational space is not unduly expanded by the categories provided by the theory. This is due in part to the typical tradeoffs between representational and transformational complexity – as representations are enhanced, the rules operating over them can be refined. The types of local operations available to non-phonological modules of the grammar typically rely on this sort of representational expressivity.

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 via 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. As to the first possibility, we know of no independently motivated grammatical mechanism for this. Concerning the second, a later stage of phonological computation that is capable of introducing gradience is exactly the post-lexical component of Lexical Phonology (Kiparsky 1982, 1985; Mohanan 1986). Yet, the scenario laid out just above is markedly different than the post-lexical processes discussed in Lexical Phonology. In the present case, gradience emerges from some post-lexical assignment of continuous values for [back], a feature that is crucially specified by an earlier, lexical rule of harmony. In other words, this introduction of gradient backness is simply a transduction of a categorical backness value into a real-valued set of fined grained specifications for [back]. This implementational backness would be difficult to distinguish from phonetics.

More concretely, it is necessary to ask what analytical advances have gradient representations offered. To date, work within Gradient Symbolic Representations has variously employed gradient representations (Smolensky *et al*. 2014; Smolensky & Goldrick 2016; Rosen 2016; Zimmermann 2018, 2021 among others). As noted by Hsu (2022), these real-valued representations have been used in two distinct ways. First, differing degrees of featural activation have been leveraged to account for exceptionality, specifically drawing on the prediction that featural differences, e.g., [0.2 voice] versus [0.5 voice] predict clustering of exceptional elements. Further, using gradient values to represent exceptionality also predicts implicational relations between gradiently-represented elements and scalar positional constraints (Hsu 2019; Revithiadou & Markopoulos 2021). Second, gradient values have been used to create blended representations, cases where a given element is realized when the combined value from multiple distinct sources exceeds some threshold. This is the essence of Smolensky & Goldrick's (2016) analysis of French liaison and Rosen's (2016) account of Japanese rendaku. To be clear, these are areas where gradient representations have been useful. However, the sorts of analyses proposed above are lines of research, and not clearly superior to multiple possible alternative analyses. There are many other ways to account for exceptionality and putative blended representations, including indexation (Pater 2000), cophonologies (Inkelas & Zoll 2007), or other means like Storme's (to appear) paradigm uniformity account of French liaison. In sum, it is not clear at present whether this line of work in Gradient Symbolic Representations is preferable to the other possibles avenues for generating exceptional and circumambient patterns.

Critically, in the above 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 insists output gradience is necessarily manifest in the phonetics. While input gradience may be a useful tool for analyzing exceptionality, we see no clear advantage derived from output gradience. Output gradience is deemed necessary for model fitting purposes, specifically fitting a phonological model to the phonetic outputs in a particular language. We know of no other potential advantages offered by output gradience.

Conversely, there exist a number of significant challenges that emerge when grammars encode featural gradience. One, if inputs may be gradient but not outputs, and 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, partially or entirely disjoint – this increases the featural hypothesis space of the grammar. This relates directly to long-standing claims of concerning (strict) modularity in the grammar (Chomsky 1965, 1980; Fodor 1983; see Scheer 2011 and Newell & Sailor to appear for contemporary reviews) and more particularly to the abstractness debate in the late 60s and early 70s (Kiparsky 1968/1982; Kenstowicz & Kisseberth 1977: ch. 1, 1979: ch. 6). To contextualize the issue to Uyghur, if an OT grammar with McCollum's (2019a) eleven-step featural gradient from [+back] to [-back] is adopted, 11^3 = 1,331 possible contrasts for a single feature in trisyllabic word can be generated, in contrast to the far smaller $2^3 = 8$ representations produced by 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 6-syllable word has $2^6 = 64$ representational possibilities for [back] in the standard feature theory but requires 11^6 = 1,771,561 possible backness representations under McCollum's analysis (see Du & Durvasula 2023§1.3 for similar argumentation). This considers only a single vowel feature; if a full set of features were 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 contrastive vowels in Uyghur, [back], [round], [high], and [low]. Consider Table 13 below to see the exponential increase in the representational space when finer grained representations are employed. McCollum's 11-step feature system is compared to a standard set of four binary features. Additionally, a simpler set of gradient representations is also included, distinguishing only four values along a given featural continuum.

	1σ word	2σ word	3σ word	4σ word
Standard feature theory	16	256	4,096	65,536
McCollum's 11-step features	14,641	$2.14*10^8$	$3.14*10^{12}$	$4.59*10^{16}$
Simpler 4-step set of gradient features	256	65,536	$1.67*10^7$	$4.29*10^9$

Table 13: Representing a four-feature system (e.g., Uyghur vowels) using three different granularities of representations

While the 4-step continuum in Table 13 results in a smaller increase in the feature space than McCollum's representational system, 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).

While gradient representations have been used to account for apparent under-neutralization of a contrast, there is nothing a priori to prevent over-neutralization in a theory with gradient representations. McCollum stipulates the ends of the backness continuum, [0back] and [1back]. However, given the extreme fronting of /i/ in absolute word-final position, fronting that results in a vowel with far higher F_2 than the less peripheral realizations of /i/ elsewhere in the word, it seems plausible to represent fronted word-final /i/ with a backness value outside the stipulated range of zero and one. Some phonological contrasts, like length or moraicity, illustrate that the need for values outside [0,1]. McCollum (2020a) notes lengthening to satisfy a weight-to-stress requirement in Uyghur. He also notes compensatory lengthening of vowels adjacent to deleted coda consonants, which results in extra-long vowels. If long vowels are represented as [1 long] then compensatory lengthening presumably increases the numerical value of [long] above one. More plausibly, if length is encoded with moras, then the representations must already encode values larger than one. In sum, there is no obvious way to delimit the space of continuous phonological variables between zero and one. Moreover, it is likely that over-neutralization is a necessary prediction of models with representational gradience, a prediction that is not borne out to date (Du & Durvasula 2024).

In the case of autosegments, the representational increase of adopting these representations 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 analyzing exceptions or circumambient patterns in a formalism like Harmonic Grammar 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 neutralization has consistently proposed access to gradient representations to improve model fit. In actuality, the range of possible patterns explodes with minimal, if any, evidence to support that increase. No radical revisions to our theory fall out from these representations. No keen insight into some unnoticed or unaccounted sound pattern have emerged. Perhaps they soon will but until that time there is, in our estimation, insufficient reason to accept these fine-grained representations without clearer arguments demonstrating how they advance our understanding of the phonological grammar.

5.3 What constitutes a case a phonological incomplete neuralization?

It is worthwhile at this point to lay out some basic criteria for any potential cases of incomplete neutralization. Crucially and almost tautologically, phonological incomplete neutralization 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 nothing more than phonetic centralization. Similarly, initial reports of incomplete neutralization in German have been shown to fall out from task effects, with more controlled studies drastically reducing the magnitude of the effects reported. By our judgment, such results should be excluded from consideration since they appear to be artefacts of the experimental procedures employed.

Second, phonological incomplete neutralization 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 most importantly, purported cases of incomplete neutralization would be unequivocally phonological if they, in addition to criteria one and two above, interact meaningfully with other patterns in the grammar. For instance, Du & Durvasula (2024) report phonetically incomplete neutralization of tone 3 sandhi in Huai'an Mandarin that is not derivable from phonetics or task effects. Further, the effect is large enough to be perceived by humans. However, they find that the incompletely neutralized tone behaves exactly like a fully neutralized tone, feeding another tonal alternation in the language. If incompletely neutralized sounds behave exactly like their fully phonetically neutralized counterparts, this is not evidence for gradient phonology. Instead, this would only suggest a key distinction between the phonological computation and detailed phonetic properties of the speech stream. Similarly, if incompletely neutralized sounds behave exactly like completely unassimilated sounds, this too is insufficient to demonstrate the necessity of gradience in the grammar. Stated differently, categorical feature systems can represent binary differences – effectively, change or no change. To hold up under scrutiny, any case of incomplete neutralization requiring reference to gradient representations must interact with other sound patterns in a manner distinct from both neutralized and non-neutralized sounds. In Uyghur, velar stops typically co-occur with front vowels while uvular obstruents typically co-occur with back vowels. If a partially back vowel were to result in a class of adjacent consonants distinct from these two, that would be good evidence for the phonological reality of that intermediate backness category.

One possibility that deserves mention is gradience-induced gradience. Returning to the dorsal alternations in Uyghur, if a back vowel co-occurs with a dorsal [q] and a front vowel co-occurs with velar [k], one could imagine a partially back vowel co-occurring with a stop of intermediate quality [k̠] or perhaps [q̟]. However, if the intermediacy of the consonantal category is the only evidence for the intermediacy of the vowel contrast, the argument cannot stand up. For if [k̠]/[q̟] behaves exactly like [k] or [q], then we cannot establish its meaningfulness for the phonology. And if we cannot distinguish the behavior of these intermediate sounds from their categorical counterparts, then we cannot justify the phonological significance of the causal vowel alternation.

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 neutralization of some phonological contrast. In this paper we addressed a unique pattern of purported iterative incomplete neutralization, backness harmony in Uyghur. We 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 harmony with post-phonological centralization, critically undermining the claim made in previous work that the attested gradience is not due to phonetic forces. We have also discussed the larger ramifications of a theory of gradient representations for phonology, both the expansion of the representational space and the current lack of analytical insight beyond model fitting to justify the adoption of continuous representations. Further, we have laid out a number of necessary criteria for establishing gradient phonology.

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