A Theory of Subfeatural Representations: The Case of Rounding Harmony in Laal *

Florian Lionnet, *Princeton University*

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Abstract

This paper introduces SUBFEATURAL REPRESENTATIONS to capture subphonemic distinctions below the featural level, on the basis of partial effects found in a type of multiple-trigger process: "phonological teamwork". The unusual case of Laal is presented, in which rounding harmony requires two triggers: a round vowel, and a labial consonant. The coarticulatory effect of the labial consonant is shown, on the basis of instrumental evidence, to incur a distinctive, but non-contrastive, intermediate level of rounding on the target vowel, which is analyzed as being featurally [–round], but subfeaturally ⟦x round⟧ ($0 < x < 1$). ⟦x round⟧ vowels are shown to form a separate natural class that can be independently targeted by phonological processes. Subfeatural representations are argued to constitute an advantageous reification of phonetic knowledge, forming a more solid basis for phonetically driven models of phonology. This proposal builds on the insights of previous literature that perceptual representations are needed in phonology, while eschewing the need for direct reference to phonetics.

The history of phonology is in fact a long series of struggles with marginal phenomena.
Labov et al. (1991: 34)

1 Introduction

Categorical phonological processes (e.g. assimilation) that are driven by gradient, subphonemic effects traditionally considered to fall within the domain of phonetics (e.g. coarticulation), constitute a challenge for phonological theory. Such data raise the question of the nature of phonology and its relation with phonetic substance, which has given rise to a long debate in linguistic theory, opposing SUBSTANCE-FREE approaches to phonological theory, which hold that phonetic substance is not relevant to phonological theory, to PHONETICALLY GROUNDED approaches, for which (at least some) phonological phenomena are rooted in natural phonetic processes.[1]

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[1]See Blaho (2008) for a recent survey of substance-free approaches. For various phonetically grounded approaches, see Stampe (1973), Donegan and Stampe (1979), Archangeli and Pulleyblank (1994), Boersma

In this paper, I present novel data that bear on this debate: “subphonemic teamwork,” a particular kind of cumulative effect which obtains when two segments aspiring to trigger the same phonological process, but too weak to trigger it on their own, may “join forces” and together pass the threshold necessary for that process to occur (cf. Lionnet 2016). A case of teamwork is found in Woleaian (Sohn 1971, 1975, Flemming 1997, Suzuki 1997), where /a/ is raised to [e] when flanked by two syllables with a [+high] nucleus, illustrated in (1a) below. Raising does not apply if only one of the flanking syllables has a high vowel (1b).

(1)	a.	/ʉwal-i/	→	üwel-i̥	‘neck of’
		/ita-i/	→	ite-i	‘my name’
	b.	/mafili/	→	[mafili̥]	‘to listen’
		/nʉ-tage/	→	[nʉtage̥]	‘to sail with the sail narrowed’

Flemming (2002: 77) points out the difficulty in accounting for multiple-trigger processes using standard autosegmental representations: “spreading a feature from two sources onto a target achieves the same as spreading the feature from one source, so the role of the second source is unexplained.” Classic Optimality Theory (OT, Prince and Smolensky 1993), based on strict ranking, also faces a challenge, since it cannot model cumulative effects: a structure is either marked and needs to be repaired through a phonological process (M[arkedness] $\gg$ F[aithfulness]), or it is unmarked and no repair is needed (F $\gg$ M); but it cannot be weakly marked, triggering a repair strategy only if a certain threshold of markedness is reached, since no amount of violations of M will ever make up for a violation of F if F $\gg$ M, and vice-versa.

A possible solution to the latter problem is to allow two or more weak constraints, each militating for a categorical change, to gang up in order to overcome strong faithfulness. This can be done through Local Constraint Conjunction (Smolensky 1993, 1995) as in Suzuki’s (1997) account of the Woleaian data above, or in Harmonic Grammar (Legendre et al. 1990, Smolensky and Legendre 2006), as in Lionnet (2015). Such entirely grammar-driven analyses, compatible with a substance-free approach to phonology, are easy to model, but do not generalise to the full range of teamwork effects, as exemplified by the main case study of this paper. Indeed, the constraint gang-up effects that they model are categorical: the full phonological process occurs only if both weak constraints are violated at once. If it isn’t the case, nothing happens. In particular, if only one of the weak constraints is violated, no partial effect is predicted (cf. Lionnet 2016: 167–176).

A different (and not OT-specific) approach is to ground teamwork phonetically, by enriching phonology with scalar phonetic representations. In such an approach, teamwork is analysed as resulting from cumulative coarticulatory effects (cf. Flemming 1997, 2002).

The main difference between the grammar-driven and phonetically grounded approaches lies in the prediction they make in cases where one of the two (or more) triggers necessary for teamwork to occur is present: the grammar-driven approach predicts no effect, whereas the phonetically grounded account predicts that there should be a partial effect.

In this paper, I show that subphonemic teamwork is driven by partial effects, which constitutes a serious argument in favour of phonetic grounding. Instead of granting phonology

(1998), Pierrehumbert (2000), Flemming (2001, 2002), Steriade (1999, 2001, 2009), and papers in Hayes, Kirchner, et al. (2004), a.o.

direct access to the full range of phonetic information, however, I claim that coarticulatory effects that are relevant to phonological processes are encoded in stable, abstract SUBFEATURAL representations, which are a reification of PHONETIC KNOWLEDGE, a major building block of phonetically grounded approaches to phonology. Subfeatures capture perceptually distinct but featurally identical categories that are visible to the phonological grammar.

This proposal is based on the description and analysis of a particularly revealing case of teamwork: the doubly triggered rounding harmony of Laal, an endangered isolate spoken by *ca.* 800 people in Chad. [2] Though motivated in this paper by Laal data, this account also extends to more familiar cases like Woleaian *a*-raising (see Lionnet (2016: 58–162)).

The organisation of the paper is as follows. I first describe the doubly triggered rounding harmony of Laal in § 2. In § 3, I develop a theory of subfeatural representations, and then provide instrumental evidence in support of theses representations in § 4. Finally, I compare the subfeatural approach to two other alternative accounts based entirely on binary features in § 5, and argue that the former fares better than the latter on both grammatical simplicity and explanatory power.

2 The Laal doubly triggered rounding harmony

2.1 Basic pattern

Laal is characterised by a complex anticipatory rounding harmony, which applies under very restrictive conditions. First, it is parasitic: the trigger and target vowels need to be of equal height (‘αHeight’ condition) and frontness (‘βFront’ condition). Second, it is particularly unusual in requiring two triggers: a round vowel can round a preceding vowel only with the help of a labial consonant. Interestingly, the round vowel and the labial consonants — the two co-triggers— may be on either side of the target as in (2a), or both on the same side as in (2b-c). This harmony is restricted to certain specific morphological contexts, which will be discussed in § 2.4.

(2) V2[rd], Lab, αHeight, βFront $\rightarrow$ rounding

a.	/ɓɨ̀r-ú/	$\rightarrow$	ɓùrú	‘hooks’
b.	/tə̀b-ó/	$\rightarrow$	tòbó	‘fishes sp.’
c.	/dɨ̀lm-ú/	$\rightarrow$	dùlmú	‘types of houses’
d.	/pə́b-ó/	$\rightarrow$	póbó	‘cobras’
e.	/mə̂lm-ó/	$\rightarrow$	môlmó	‘Koranic school teachers’

As can be seen in (3a), Laal has twelve phonemic vowels, characterized by three degrees of aperture and an opposition between [+front] and [–front] vowels, coupled with a rounding contrast among both [+front] and [–front] vowels.[3]

[2] All the data presented here come from my own fieldwork (twelve months between 2010 and 2015). For more on Laal, see Boyeldieu (1977, 1982, 1987)

[3] The backness contrasts are captured by the feature [±front] (rather tha [±back], or [+front,–back] vs. [–front,–back] vs. [–front,+back]), based on the effects of the simple rounding harmony process that will be discussed in § 2.5: front vowels are rounded into front rounded vowels, and central vowels into back rounded vowels, i.e. central and back vowels form a natural class. Note, additionally, that the four vowels /ia ua yo ya/ are analyzed as monomoraic diphthongized vowels: they behave phonologically like the monophthongs /ɛ ɔ ø

(3) Laal vowel and consonant inventories

a.

[+front]		[–front]	
i	y	ɨ	u
e	yo	ə	o
ia	ya	a	ua
[–round]	[+round]	[–round]	[+round]

b.

	C_1 (*stem-initial*)					*elsewhere*			
Plosives	p	t	c	k	(ʔ)				
	b	d	ɟ	g		p∼b	t∼d	c∼ɟ	k∼g
	mb	nd	nɟ	ŋg					
	ɓ	ɗ	'j						
Non-plosives	m	n	ɲ			m	n	ɲ	ŋ
		l					l		
		r					r		
	w		j			w		j	
		s					s		

The examples in (4) show that all four conditions (the two triggers V_2[rd] and LabC, and the two additional conditions αHeight and βFront) must be met in order for rounding to occur. If any one of the four conditions is missing, as in (4a), the harmony fails to apply. The examples in (b, c) show that, as expected, the harmony does not apply either when more than one condition is missing.

(4) Non-application of the harmony

				V_2 [rd]	**LabC**	**αHeight**	**βFront**
a.	Only three conditions are met						
	/kə̀ə̀m-ə́/	kə̀ə̀mə́	'tree sp.-PL'	*	✓	✓	✓
	/gɨ́n-ù/ /sə̀g-ó/	gɨ́nù sə̀gó	'net-PL' 'tree sp.-PL'	✓	*	✓	✓
	/mə̀ə̀g-ú/ /ɓə̀rú/	mə̀ə̀gú ɓə̀rú	'tree sp.-PL' 'plant sp.-PL'	✓	✓	*	✓
	/pílù/ /bìrú/	pílù bìrú	'mat-PL' 'burn'	✓	✓	✓	*
b.	Only two conditions are met						
	/mèn-ú/ /mèèg-ú/	mènú mèègú	'road-PL' 'kaolin-PL'	✓	✓	*	*
	/də́n-ú/ /ɟə̀g-ù/	də́nú ɟə̀gù	'tree sp.-PL' 'knife sp.-PL'	✓	*	*	✓
	/ɟíŋ-ù/	ɟíŋ-ù	'harpoon-PL'	✓	*	✓	*

œ/ respectively, but are always realized as diphthongs: /ia/ = [e̯a∼ja], /ua/ [o̯a∼wa], /yo/ = [ɥø∼ɥo], /ya/ = [œ̯a∼ɥa].

	/tíl-ù/	tílù	'sand-PL'				
c.	Only one condition is met						
	/nèn-ù/	nèn-ù	'pus-PL'	✓	*	*	*
	/tèèr-ú/	tèèr-ú	'grass sp.-PL'				

Additionally, the teamwork effect is necessarily driven by the association of a labial consonant and a round vowel. Two labial consonants may not team up to co-trigger rounding, as shown in (5) below.[4]

(5)	/bə̀brə̀/	bə̀brə̀	*bòbrə̀	'lizard sp.'
	/pɨ́rmɨ́n/	pɨ́rmɨ́n	*púrmɨ́n	'dust'

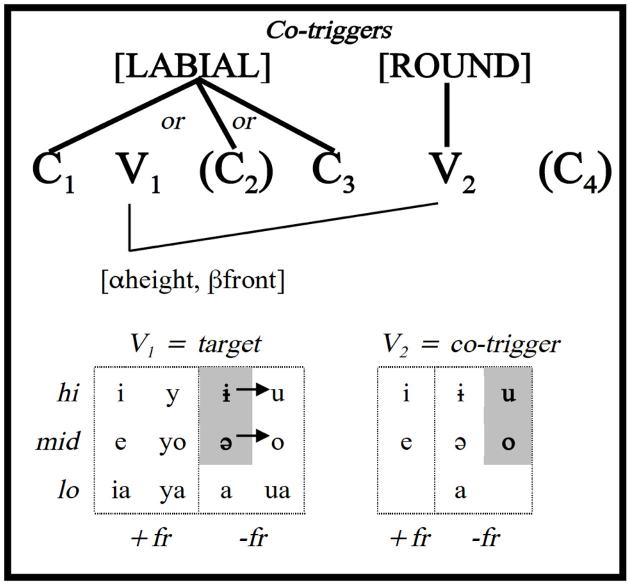
General phonotactic restrictions limit the number of potential triggers and targets of the harmony. First, since words in Laal are maximally disyllabic[5], it is impossible to derive forms that would show harmony across more than one syllable. The harmony thus involves only one target: the stem-initial vowel V_1 (there are no prefixes in Laal). The trigger is always V_2, and may be part of a disyllabic stem, or of a suffix as in the examples in (2).

Furthermore, the full vowel inventory in (3a) above is only attested in the stem-initial syllable (V_1). In V_2 position, only seven of these twelve vowels are attested: the three front rounded vowels /y yo ya/ and the two low peripheral vowels /ia ua/ are indeed never found there.[6] The only triggers of the harmony are thus /u/ and /o/ —the only two [+round] vowels attested in V_2— each of which, by virtue of the αHeight and βFront conditions, can only target one vowel: V_2 /u/ rounds V_1 /ɨ/ into [u], while V_2 /o/ rounds V_1 /ə/ into [o]. The properties of the doubly triggered rounding harmony are summarized in (6).

[4] The laryngeal and prenasalisation contrasts among plosives are neutralized in non-stem-initial position. Word-internal plosives are always voiced, word-final ones voiceless. [ʔ] is the default epenthetic consonant inserted to avoid vowel-initial words.

[5] With only a few exceptions, mostly ideophones, frozen compounds, reduplicative forms and/or loanwords, ignored here.

[6] The length contrast, which characterizes all vowels in V_1, is also neutralized in V_2, where all vowels are short, with only a handful of exceptions.

(6) 

2.2 A note on vowel harmony

The underlying forms in the examples seen so far were given after application of all other phonological processes, in particular vowel raising or lowering incurred by other vowel harmonies. A brief note on these harmonies is in order at this point, to make the data presented in the remainder of this section easier to read. No less than four harmony processes are attested in Laal. Additionally to the doubly triggered rounding harmony, a simpler rounding harmony also exists (cf. § 2.5), as well as two height harmonies: perseverative [+high] harmony and anticipatory [±low] harmony, illustrated in (7a) and (7b).

(7) a. [+high] harmony: $V_{mid} \rightarrow V_{high}$ / V_{high}—

mīīw	'liver'	mììwɨ̀r	'my liver'	/-ə̀r/ 'my' → -ɨ̀r
mɨ̄lā	'eye'	mɨ̀lɨ̀l	'my eye'	
mbūl	'navel'	mbùlɨ̀l'	'my navel'	

b. Low harmony: [–high] → [αlow] / _[αlow]

i. [–low, +high] *medio-passive* /-ɨ́ɲ/ : low → mid

ia → e	ʔiáár	'choose'	→	ʔéérɨ́ɲ	'be chosen'
a → ə	màŋà	'gather'	→	mə̀ŋɨ́ɲ	'be gathered'
ua → o	ɟuāŋ	'buy, sell'	→	ɟòŋɨ́ɲ	'buy from one another'

ii. [–low, –high] /-ə̀r/ 'my': low → mid

ia → e	piáár	'shin'	→	péérə̀r	'my shin'
a → ə	māl	'tongue'	→	mə̀lə̀l	'my tongue'
ua → o	buàg	'chin'	→	bògə̀r	'my chin'

iii. [+low] /-àr∼-àn/ 'it' (OBJ)': mid → low

e → ia	léérí	'roll'	→	liáár-àn	'roll it'
ə → a	cə̄r	'want'	→	càr-àr	'want it'
o → ua	sór	'find'	→	suár-àr	'find it'

Henceforth, the underived form of each example will be given alongside the intermediate and final derived forms.

2.3 The blocking effect of intervening /w/

The only nine (regular) exceptions to the doubly triggered rounding harmony are listed in (8a-b) below, and illustrate another intriguing property of the doubly triggered rounding harmony: the blocking effect of /w/ when it intervenes between V_1 and V_2.

(8)		*singular*		*plural suffix* /-o/ (*triggering [±low] harmony*)	
	a.	gâw	'hunter'	/gə́w-ó/	gə́wó
		gàw	'elephant trap'	/gə̄w-ō/	gə̄wō
		ɟàw	'cheetah'	/ɟə̀w-ó/	ɟə̀wó
		sàw	'fish sp.'	/sə̄w-ō/	sə̄wō
		sáw	'warthog'	/sə́w-ò/	sə́wò
		táw-ál	'shield'	/tə́w-ò/	tə́wò
		tāw-āl	'beeswax'	/tə̄w-ō/	tə̄wō
		ɟāgw-ā	'hat'	/ɟə́gw-ó/	ɟə́gwó
	b.	māw	'scorpion'	/mə́w-ó/	mə́wó
	c.	wàár	'genet'	/wə̀ə̀r-ó/	wòòró

Not only does an intervening /w/ not co-trigger the harmony (8a), it even blocks it, as clearly shown by /mə́w-ó./ in (8b), where the word-initial /m/ fails to act as a co-trigger. Word-initial /w/, on the other hand, co-triggers the harmony like any other labial consonant, as shown in (8c).[7] This blocking effect of intervening /w/ is rooted in an exceptionless phonotactic constraint that bans sequences of a round vowel followed by /w/ (with an optional intervening consonant): *U(C)w. This constraint is enforced without exception, both in the lexicon and in morphologically derived environments (cf. ex. (14) below).

2.4 Morphological conditioning

The harmony is only actively enforced between roots and number-marking suffixes (other types of suffixes and their effects will be presented in § 2.5). Laal has 29 number-marking suffixes (10 singular, 19 plural), which combine arbitrarily with a restricted set of nouns and verbs. Out of 1150 monomorphemic nouns in my corpus, 384 combine with at least one such suffix. The most frequent (/-u/) is attested with 73 nouns, while eleven of these suffixes are attested with less than five nouns each. Additionally, some of these suffixes are used to derive either the plural- or the singular subject form of 38 intransitive verbs. e.g. /ɲún/ 'go (sg subject)' vs. /ɲún-ì/ 'go (pl. subject)'.

Four number-marking suffixes contain a round vowel (henceforth "round suffixes"): the three plural suffixes /-u/ (73 occurrences), /-o/ (46), and /-or/∼/-ur/ (14), and the singular suffix /-o/ (7). The suffix /-or/∼/-ur/ varies between a mid and a high realisation, subject to [+high] harmony (cf. (7a) above). All three are used only on nouns in my corpus. The

[7] Only cases with mid vowels (i.e. ə(C)wo) are attested. The ɨ(C)w sequence is extremely rare in Laal: it is unattested in nouns, and found in only six verbs, all of which are plural forms derived from their singular counterpart through regular a → ɨ raising: Ca(a)w → Cɨ(ɨ)w, e.g. /kāw/ → /kɨ̄w/ 'eat (sg/pl)'.

doubly triggered rounding harmony is thus attested as an active process only with nouns, but that is most probably accidental.

140 out of the 1150 monomorphemic nouns in the lexicon are compatible with one of the four round suffixes above. Of these 140 nouns, only 89 have an underlying non-round V_1. 34 of these 89 nouns meet the conditions for the doubly triggered rounding harmony, i.e. their plural form has both a labial consonant (C_1, C_2, and/or C_3), and two vowels of identical height and frontness. All these nouns obey the doubly triggered rounding harmony, with only nine (regular) exceptions: the nine cases of intervening /w/, listed in (8a-b) above. This leaves 25 attested cases of active doubly triggered rounding harmony, all listed in examples (9), where V_1 an V_2 are both high and both mid respectively.[8]

(9) a.

singular		*plural* /-u, -ur/	
ɓɨ̀r-à	'fish hook'	/ɓɨ̀r-ú/	ɓùrú
cɨ́rám	'tree (sp.)	/cɨ́rm-ú/	cúrmú
dɨ̄lām	'type of house'	/dɨ̀lm-ú/	dùlmú
sɨ́b-l-ál	'lie'	/sɨ́b-ùr/	súbùr

b.

singular		*plural* /-o, -or/[9]	
bàg-à	'antelope sp.'	/bə̀g-r-ó/	bògró
báág	'ostrich'	/bə́ə́g-ó/	bóógó
málɨ̀m	'Koranic teacher'	/mə̂lm-ó/	môlmó
mə́g-əl	'mouse'	/mə́g-ór/	mógór
ɲām ɟām	'antelope sp.'	/ɲām ɟə̀m-ó/	ɲām ɟòmó
sāām	'skin'	/sə́ə́m-ó/	sóómó

c.

plural		*singular* /-o/	
ndààm-à	'Ndam people'	/ndə̀ə̀m-ó/	ndòòmó

A few nouns have more than one possible plural forms. Interestingly, two such nouns, shown in (10) below, make use of two alternate round suffixes, and contain a labial consonant. As expected, rounding harmony applies only when both vowels are of equal height before application of the harmony, i.e. with the /-o/ suffix, but not with the /-u/ suffix.

(10)

singular		*plural* /-u/			*plural* /-o/	
báág	'ostrich'	/bə́ə́g-ú/	bə́ə́gú	∼	/bə́ə́g-ó/	bóógó
tàb	'fish sp.'	/tə̀b-ú/	tə̀bú	∼	/tə̀b-ó/	tòbó

The limited productivity of the doubly triggered rounding harmony is due to the limited productivity of the number-marking suffixes, which seem to be in the process of becoming lexicalised. In this respect, it is not different from other morpho-phonological alternations that phonologists regularly choose to model. However, number marking morphology cannot be said to be entirely fossilised, since plural suffixes (including the round suffixes /-o/ and /-u/) are sometimes used on more or less recent loanwords, as shown in (11) below. Note that the first two examples illustrate the application of the doubly triggered rounding harmony to words of foreign origin (11a-b). Loanwords from Bagirmi and Arabic are most probably

[8] The full set of 25 attested cases can be found in Appendix A.

[9] The plural suffixes /-o/ and /-or/ trigger both [low] and rounding harmony.

not older than 200 to 300 years, and loanwords from French (11e) are definitely less than a century old.

(11)	*singular*		*plural*		
	málɨ̀m	'Koranic school teacher'	/mə̂lm-ó/	môlmó	< Arabic
	dɨ̄lām	'(type of) house'	/dɨ̀lm-ú/	dùlmú	< Bagirmi
	mɔ̀ɲ	'disease'	/muāɲ-ā/	muāɲā	< Bagirmi
	gâw	'hunter'	/gə́w-ó/	gə́wó	< Bagirmi
	ság	'bag'	/sə́g-ú/	sə́gú	< French

The doubly-triggered rounding harmony is also a morpheme structure constraint: there is no word in the lexicon that does not conform to its requirements. Words like [gōbə̄r] 'cloud' or [gúmlɨ́l] 'round' further show that the harmony is strictly anticipatory.

Finally, both the harmony and the *U(C)w phonotactic constraint apply only within words, and never across a word boundary, as shown below.

(12) a. mɨ̀l ɓúúrá *mùl ɓúúrá
skilled.artisans be.fearful
'The skilled artisans are fearful.'

b. mòmór wūjā *mòmə́r wūjā
'fish sp.-PL'

2.5 A phonological alternation

There is evidence that the doubly triggered rounding harmony described above is a phonological process, rather than a superficial phonetic effect. Firstly, the harmony is exceptionless: it systematically applies whenever the conditions are met. The only exceptions are entirely regular and result from an independent phonotactic restriction of the language (*U(C)w). Furthermore, it is not sensitive to speech rate: when asked to speak slowly, or even to mark a pause between the two syllables of a word where the harmony should apply, speakers never "undo" the harmony.

The most solid argument in favor of the phonological status of the harmony is its morphological conditioning: it applies as a morpheme structure constraint and between roots and number marking suffixes. With pronominal suffixes, on the other hand, anticipatory rounding harmony is systematic and unconditional, as illustrated in (13a) below, with the object suffixes /-nǔ/ 'us (EXCL)' and /-ò(n)/ 'her' (subject to [+high] harmony, cf. (7a) above). (13b) shows segmentally similar examples illustrating the doubly triggered harmony. As can be seen, the conditions for the doubly triggered harmony (LabC, αHeight and βFront) are irrelevant to the simple harmony.

(13)

				LabC	αHeight	βFront
a. Simple rounding harmony						
pɨ́r-ò	/pɨ́r-ù/	púrù	‘catch her’	✓	✓	✓
kɨ́r-òn	/kɨ́r-ùn/	kúrùn	‘place her’	*	✓	✓
dāg-òn	/də̀g-òn/	dògòn	‘drag her’	*	✓	✓
dāg-nǔ	/də̀g-nǔ/	dògnǔ	‘drag us’	*	*	✓
léér-nǔ	/léér-nǔ/	lyóórnǔ	‘wrap us’	*	*	*
b. Doubly triggered rounding harmony (cf. (2)-(4))						
ɓɨ̀r-ù	/ɓɨ̀r-ú/	ɓùrú	‘fish hook-PL’	✓	✓	✓
gɨ́n-ù	/gɨ́n-ù/	gɨ́nù	‘net-PL	*	✓	✓
sàg-ó	/sə̀g-ó/	sə̀gó	‘tree sp.-PL’	*	✓	✓
dán-ú	/də́n-ú/	də́nú	‘tree sp.-PL’	*	*	✓
tèèr-ú	/tèèr-ú/	tèèrú	‘grass sp.-PL’	*	*	*

Simple rounding harmony also fails to apply in contexts where it would violate *U(C)w, as seen in (14).

(14) a. /káw-ò/ kə́w-ò *kówò ‘be insufficient for her’
b. /káw-nǔ/ kə́w-nǔ *kównǔ ‘be insufficient for us (EXCL)’

The two rounding harmonies are thus specific to two exclusive sets of morphological environments. Given the requirement that words be maximally disyllabic in Laal, the segmental domain of application of both harmonies is exactly the same. For all of the above reasons we can safely conclude that the doubly triggered rounding harmony is a phonological process, and whatever drives it should consequently be accounted for in phonology.

In conclusion, the doubly triggered rounding harmony of Laal is a phonological process that knows no irregular exception: it systematically applies whenever the conditions summarized in (15) below are met.

(15) *Conditions on doubly-triggered rounding harmony: a summary*
a. V_2 is round (i.e. /u o/)
b. The root contains a labial consonant
c. V_1 and V_2 are of same height and frontness (i.e. /ɨ ə/)
d. C_2, $C_3 \neq$ /w/ (general phonotactic constraint*U(C)w)
e. Morphological conditioning: only as MSC and between roots and singular/plural suffixes

3 Subfeatural distinctions in phonology

On the basis of acoustic measurements presented in § 4, I argue that the coarticulatory effect of labial consonants on [ɨ ə] in Laal is such that labialised [ɨ^{B} ə^{B}] constitute a separate category, perceptually distinct, but identical to [ɨ ə] in terms of contrastive features. (The abbreviations and codes used throughout the paper are given in Table 1.[10]) I also argue

[10]Labialisation is indicated by [^{B}] rather than IPA [^{w}], to avoid any confusion. Indeed, since I ignore the coarticulatory effect of [w] (for reasons detailed in § 4), all the labialised vowels referred to here ar labialised by any labial consonant but [w].

ɨ ə	[ɨ ə] not (near-)adjacent to a labial, not followed by a round V_2
$ɨ^B$ $ə^B$	labialised [ɨ ə] , i.e. (near-)adjacent to at least one labial C
B	Labial consonant (except [w])
ɨ-word	Word whose V_1 is [ɨ]/
ə-word	Word whose V_1 is [ə]
C	Non-labial, non-palatal consonant (i.e. velar and dental-alveolar)
U	Round V_2, i.e. [u o]
B-condition	V_1 [ɨ ə] (near-)adjacent to a labial, not followed by a round V_2
U-condition	V_1 [ɨ ə] followed by a round V_2, but not (near-)adjacent to a B

Table 1: Abbreviations and codes used in the paper.

that this perceptual distinction allows [$ɨ^B$ $ə^B$] to form a natural class, targeted by the doubly triggered rounding harmony to the exclusion of [ɨ ə]. I propose a new type of phonological representations to represent the perceptual distinction between these two categories: SUBFEATURES.

3.1 Subfeatural representations: the basics

The featural system I propose is a two-tiered system: contrastive featural categories are subdivided into non-contrastive, perceptually distinct subfeatural categories arising from coarticulatory effects. This proposal is in keeping with the idea, supported by a growing body of evidence, that contrastiveness, i.e. unpredictable phonological distribution, and perceptual distinctiveness are independent criteria (Kiparsky 2013, Hall 2013 and references therein).

The subfeatural level of representation, scalar in nature, captures differences in perceptual distinctiveness resulting from coarticulation. The featural [±round] contrast may thus coexist with a multi-level subfeatural rounding scale, both being separate (but substantively related) representations of the lip-rounding continuum.[11]

By convention, contrastive categories correspond to full subfeatural values, i.e. [–F] and [+F] entail ⟦0 F⟧ and ⟦1 F⟧ respectively, unless coarticulation applies (subfeatures are represented with double square brackets). On the subfeatural scale, coarticulatorily driven subphonemic distinctions may be encoded whenever relevant, with intermediate subfeatural values x ($0<x<1$). For example in Laal, the perceptual rounding scale, corresponding at the contrastive level to the binary feature [+round] vs. [–round], can be represented as a continuum between ⟦0 round⟧ and ⟦1 round⟧. [+round] vowels are ⟦1 round⟧, [–round] vowels are ⟦0 round⟧, unless they are labialised, in which chase they are ⟦x round⟧. The [–round] category is thus subdivided into two subfeatural categories: ⟦0 round⟧ [i e ia ɨ ə a], not rounded at all, and ⟦x round⟧ [$ɨ^B$ $ə^B$], which have some proportion x of the phonetic properties that characterize fully round vowels. In other words, labial coarticulation

[11]The idea of a scalar representation of vowel rounding is already proposed by **pasquereau2016** (**pasquereau2016**), whose multi-valued [labial$x$] feature represents different degrees of rounding (form least round /o/ to most round /u/) corresponding to different degrees of phonological activity. However, [labial$x$], contrary to subfeatures, does not represent the subphonemic distinctions attested in the Laal harmony pattern. For more on scalar or multivalued features, see Ladefoged (1971: 43-44, 91-111), Johnson (1972), Lindau (1978), Clements (1991), Gnanadesikan (1997) and references therein.

increases ⟦0 round⟧ to ⟦x round⟧. The subfeatural value ⟦x round⟧ represents the consequences of labial coarticulation on the realization and perception of the feature [–round]. Subfeatures are thus determined on the basis of both phonetic factors and phonological representations.

Crucially, labialised [ɨ^{B}] and [ə^{B}] are featurally [–round], but subfeaturally ⟦x round⟧. This explains why they behave like their non-labialised counterparts with respect to the simple rounding harmony, which refers to binary features only, and how they can also be seen as a distinct category by the doubly triggered rounding harmony, which is sensitive to subfeatural distinctions, as illustrated in Figure 1.

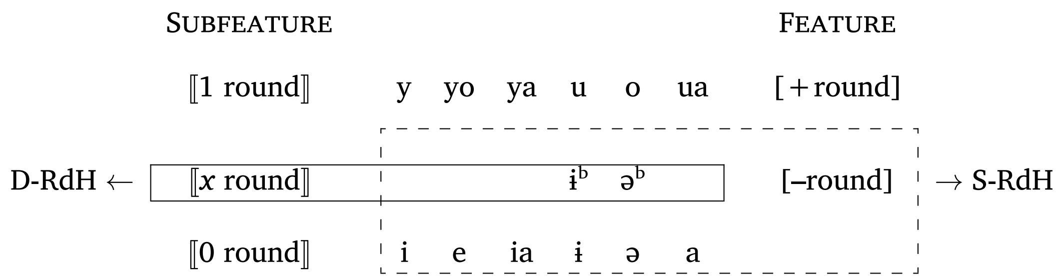


Figure 1: Targets of the doubly triggered (D-RdH) and simple (S-RdH) rounding harmonies

3.2 Calculating subfeatural values: the Coarticulation function

Coarticulatory triggers have the property of assigning to their target a proportion of increase (or decrease) in the value of the affected subfeature ⟦F⟧ incurred by the coarticulatory effect of the trigger onto the target. I will call this proportion a COARTICULATORY COEFFICIENT, and represent it as $p_{Trigger \rightarrow Target, [\![F]\!]}$, or simply p. The resulting intermediate subfeatural value x of the target segment is obtained through the application of the C(oarticulation) function defined in (16) and schematized in (18) below.

(16) $C_p(x_{init}) = x_{init} + p(x_{end} – x_{init})$

a. p is the coarticulatory coefficient ($0 < p < 1$);

b. x_{init} is the (expected) initial ⟦F⟧ value of the target vowel before application of the coarticulatory function;

c. x_{end} is the value of the endpoint of the ⟦0...1 F⟧ subfeatural scale towards which the function tends: either 0 or 1, depending on whether the expected pre-coarticulation subfeatural value of the target is ⟦1 F⟧ or ⟦0 F⟧;

d. Cases of multiple triggers targeting the same segment are accounted for by function composition, e.g. $C_{p_1}(C_{p_2}(x_{init}))$, where composition order is immaterial (see (34) for an illustration).

Note that the C_p function can be either additive or subtractive, depending on which endpoint of the ⟦0...1 F⟧ scale the function starts from, and which one it tends toward. If, as in Laal, the pre-coarticulation subfeatural value of the target corresponds to the lower endpoint ⟦0 F⟧, the function is additive: the amount of increase incurred by the target (assuming that there is only one trigger) is $+ p(x_{end} – x_{init}) = +p(1 – 0) = + p$. The ⟦0 F⟧

value of the target segment is thus increased to ⟦p F⟧. If, on the other hand, x_{init} corresponds to the full value ⟦1 F⟧, the function is subtractive: the amount of decrease is $+\ p(x_{end}–x_{init})$ $=\ +p(0 - 1) = -p$, i.e. the target segment's initial ⟦1 F⟧ value is lowered to ⟦$(1-p)$ F⟧.[12]

The value of the binary feature that a given intermediate subfeatural value x is associated with thus depends on the initial subfeatural value of the target and the "direction" of the coarticulation function. If the function is additive (i.e. property-increasing), ⟦x F⟧ corresponds to [–F], like ⟦0 F⟧ from which it derives; if the function is subtractive (i.e. property-decreasing), ⟦x F⟧ corresponds to [+F], like the value ⟦1 F⟧ it is derived from. The only two subfeatural values that are always associated with the same featural value are ⟦0 F⟧, which systematically corresponds to [–F], and ⟦1 F⟧, which can only correspond to [+F]. Conversely, [+F] and [–F] can in theory correspond to any subfeatural value between 0 and 1 except 1 and 0 respectively ([–F] $\leftrightarrow$ ⟦x F⟧ with $0 \leq x < 1$; [+F] $\leftrightarrow$ ⟦x F⟧, with $0 < x \leq 1$). This is schematized in (17).

(17) Additive and subtractive coarticulatory functions

Additive C_p		Subtractive C_p	
⟦1 F⟧	[+F]	⟦1 F⟧	[+F]
⟦x F⟧		⟦x F⟧	
⟦0 F⟧	[–F]	⟦0 F⟧	[–F]

Doubly triggered rounding harmony targets vowels whose increased subfeatural ⟦x round⟧ value is the result of the application of the additive coarticulatory function $C_{p_{B\rightarrow ə/ɨ,[\![rd]\!]}}$, schematised in (18) below.[13]

(18) Application of C_p in Laal ($p\ =\ p_{B\rightarrow ə/ɨ,[\![rd]\!]}$):

$C_p(x_{init})$ (i.e. $+p(x_{end}–x_{init})$)

x_{init}	x	x_{end}
[ɨ ə]	[ɨ^B ə^B]	[u o]
⟦0 round⟧	⟦x round⟧	⟦1 round⟧

The value of p depends on the properties of each one of the segments involved and the perceptual correlate of their coarticulation. Additionally, the C_p function needs to be relativized to context, e.g., inter-speaker differences, distance between the target and the trigger, relative position of trigger and target, etc. (cf. Lionnet 2016). Each trigger-target

[12]This is how the inverse of the Laal pattern (subphonemically driven unrounding) would be analysed, if it were attested.

[13][u o] and [ɨ ə] differ phonetically both in rounding and in backness. Backness, however, need not be represented here, since the [±back] feature is not contrastive in Laal: /ɨ ə/ and /u o/ are both [–front] and only contrast in [±round]. ⟦x round⟧ does not refer to any articulatory gesture, only to the perceptual correlate of the binary feature [±round]. Among [–front] vowels, this perceptual correlate is mostly a certain amount of F_2 lowering, as we will see in § 4. Whatever the articulatory basis of this effect is (lip rounding and/or tongue retraction) is irrelevant to the choice of subfeature: the fact that only the feature [±round] is affected means that only the subfeature ⟦round⟧ need be represented.

interaction in each of the relevant contexts is likely to yield a different subfeatural value (e.g. [ɨ^{B}]/B__ $\neq$ [ɨ^{B}]/__B $\neq$ [ə^{B}]/B__ etc.). In the interest of a clear presentation of the theory, I tentatively consider that [ɨ^{B}] and [ə^{B}] are both $[\![x$ round$]\!]$, for all speakers, irrespective of the specific environment. This simplified analysis will be refined in § 4.4.3, after the presentation of the phonetic data in §§ 4.1 to 4.3.

3.3 Illustrative analysis: the Laal doubly triggered rounding harmony

With the analysis sketched in § 3.1 above, the doubly triggered rounding harmony can be reduced to a case of rounding harmony parasitic on height and backness, targeting only vowels that are at least $[\![x$ round$]\!]$. Any theory of parasitic vowel harmony would presumably account for the Laal harmony if it can refer to subfeatures, whether it utilizes feature spreading (e.g. Padgett 1997; Jurgec 2011, 2013), feature alignment (Smolensky 1993; Kirchner 1993; Kaun 1995), feature agreement or no-disagreement constraints (Bakovic 2000; Pulleyblank 2002), Agreement by Correspondence (Hansson 2001, 2010; Rose and Walker 2004), or Wayment's (2009) Attraction Framework.

The goal of this section is not to argue in favour of one specific theory of vowel harmony, but simply to illustrate how one such theory may easily account for the Laal harmony by simply including subfeatural representations. The illustrative analysis I propose uses Hansson's (2014) Agreement by Projection (ABP) theory, a revision of Agreement by Correspondence (ABC), couched in Optimality Theory (Prince and Smolensky 1993, 2004).[14]

First, independently of the harmony pattern, I propose that subfeatural distinctions be enforced by the phonological grammar, through high-ranked markedness constraints. The default $[\![0$ round$]\!] \leftrightarrow$ [–round] and $[\![1$ round$]\!] \leftrightarrow$ [+round] associations are enforced through the constraints defined in (19a) and (19b), while labial coarticulation is enforced by the constraint in (19c).

(19) a. $*[\![>0$ rd$]\!]/[-$rd$]$

Let X be a vowel; X may not be higher than $[\![0$ rd$]\!]$ on the subfeatural scale if it is specified as [–round].

b. $*[\![<1$ rd$]\!]/[+$rd$]$

Let X be a vowel; X may not be lower than $[\![1$ rd$]\!]$ on the subfeatural scale if it is specified as [+round].

c. $*\neg Cp_{B\rightarrow ə/ɨ}$

For each (near-)adjacent B-ə/ɨ pair, ə/ɨ must be assigned a specific value of $[\![x$ rd$]\!]$ determined from the coarticulatory context, following the $Cp_{B\rightarrow ə/ɨ}$ function (i.e. B needs to coarticulate with the vowel). Assign one violation per non-coarticulated B-ə/ɨ pair.

Constraints like (19c) penalizing the non-application of the coarticulatory function must be ranked higher than the two constraints in (19a) and (19b) if coarticulation-driven subfeat-

[14] I use classic OT (with asterisks for penalties and strict constraint domination) rather than Harmonic Grammar (HG, Legendre et al. 1990) for convenience. The same analysis could be couched in HG. However, the gang effects allowed by HG, which constitute one of the main advantages of HG over classic OT, are not motivated in the Laal data, as shown in Lionnet (2016: 170–176).

ural values are to be assigned, as shown in the tableaux in (20). In this specific case, the coarticulation function being additive, $*\neg C_{p_{B\to ə/i}}$ need only be ranked higher than $*[\![>0\ \text{rd}]\!]/[-\text{rd}]$, which is the only one that is violated if $C_{p_{B\to ə/ɨ}}$ applies.

(20)

		$*\neg C_{p_{B\to ə/ɨ}}$	$*[\![>0\ \text{rd}]\!]/[-\text{rd}]$	$*[\![<1\ \text{rd}]\!]/[+\text{rd}]$
a. /ɨ/	☞i. ɨ ⟦0 round⟧			
	ii. ɨ ⟦x round⟧		*!	
	iii. ɨ ⟦y round⟧		*!	
	iv. ɨ ⟦1 round⟧		*!	
b. /u/	i. u ⟦0 round⟧			*!
	ii. u ⟦x round⟧			*!
	iii. u ⟦y round⟧			*!
	☞iv. u ⟦1 round⟧			
c. /Bɨ/	i. Bɨ ⟦0 round⟧	*!		
	☞ii. Bɨ ⟦x round⟧		*	
	iii. Bɨ ⟦y ounrd⟧	*!	*	
	iv. Bɨ ⟦1 round⟧	*!	*	

As seen in (20), the constraints pick only one of all the possible subfeatural values comprised between 0 and 1 for each input: default 0 or 1 when there is no coarticulation (20a-b), x (and not $y \neq x$, or any other intermediate value) when B-ɨ/e coarticulation is involved (20c). To keep tableaux simple and legible, these three constraints will from now on be conflated into the placeholder constraint SUBF.

I now turn to the analysis of the harmony pattern, using Hansson's (2014) revision of Agreement by Correspondence (ABC). ABC is a theory of similarity-based segmental interaction that was initially developed for long-distance consonant agreement (Walker 1998, 2000b, 2001; Hansson 2001, 2010; Rose and Walker 2004). It has since been extended to vowel harmony (Sasa 2009; Walker 2009; Rhodes 2012), long-distance consonant dissimilation (Bennett 2013, 2015), and local effects of assimilation and dissimilation (Inkelas and Shih 2014; Shih and Inkelas 2014; Shih 2013; Sylak-Glassman 2014).

What makes ABC particularly suited to parasitic vowel harmony is its central insight that (dis)harmony is driven by similarity threshold effects. Harmony between segments is viewed as agreement between segments in a correspondence relationship based on phonological similarity. This surface correspondence is unstable (Inkelas and Shih 2014): two (or more) segments are sufficiently similar to interact (they are in correspondence), but are too uncomfortably similar to co-exist within a certain distance. Two repairs are possible: harmony (more similarity) and disharmony (less similarity).

The basic mechanics of ABC theory involve two types of Output-Output correspondence constraints: CORR-XX establishes surface correspondence between segments X similar in a particular (set of) feature(s), while IDENT-XX[F] enforces agreement in the feature [F] between segments in the correspondence set defined by CORR-XX. Both types of constraints are ranked higher than the constraints enforcing faithfulness to the assimilating feature.

Based on a diagnosis of pathological properties of the division of labor between IDENT-XX[F] and CORR-XX, Hansson (2014) proposes to conflate the work of both constraints into a single "projection-based" markedness constraint, defined as follows:

(21) $*[\alpha F][\beta rd]/[\gamma G, \delta H]$:
Let X and Y be segments; X and Y may not disagree in the feature [F] (≈IDENT-XX[F]) if they are adjacent in the projection (i.e. the ordered set of output segments) specified as $[\gamma G, \delta H]$ (≈ CORR-XX$[\gamma G, \delta H]$).

I adopt Hansson's (2014) projection-based constraints here, simply allowing them to refer to subfeatures as well as binary features.The constraint that drives the doubly triggered rounding harmony is given in (22). In order to account for the threshold effect at work, I propose that projection-based constraints refer to ranges of subfeatural values rather than single values.

(22) $*[[\![\geq x \text{ rd}]\!] - \text{rd}][[\![1\text{rd}]\!] + \text{rd}]/[+\text{syll}, \alpha\text{height}, \beta\text{front}]$:
A [–round] segment whose subfeatural ⟦round⟧ value equals or exceeds x may not directly precede a [+round] segment whose subfeatural value is ⟦1 round⟧ in the ordered set of output segments that are [+syllabic] and share the same [height] and [front] specifications. Assign one violation for each pair of neighbouring segments that meet the criteria.

The constraint in (22) (henceforth $*[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]/[+\text{syll}, \alpha\text{height}, \beta\text{front}]$) drives the harmony by establishing the threshold of subphonemic rounding beyond which a labialised [$ə^B$] or [$ɨ^B$] is targeted by the harmony at ⟦x rd⟧. This constraint stands in a markedness hierarchy that mirrors the featural similarity scale in Table 2 below, where the similarity levels are ordered based on how much they restrict the number of potential targets: the highest level of similarity is the most restrictive.[15]

similarity between trigger and target	targeted by [u]	targeted by [o]
[+syll, αheight, βfront]	[ɨ] (incl. [$ɨ^B$])	[ə] (incl. [$ə^B$])
[+syll, αheight]	[i ɨ] (incl. [$ɨ^B$])	[e ə] (incl. [$ə^B$])
[+syll, βfront]	[i ɨ e ə] (incl. [$ɨ^B$ $ə^B$])	
[+syll]	[i ɨ e ə ia a] (incl. [$ɨ^B$ $ə^B$])	

Table 2: Similarity between round and non-round vowels in Laal: tentative scale

Each level of similarity in the scale could in theory be the threshold at work in a rounding harmony process. Consequently, the similarity scale translates into a markedness-constraint hierarchy, shown in (23), in which the constraint defined in (22) is ranked highest.[16]

[15]While the ordering of the highest and lowest levels is unproblematic, there is no evidence in Laal for any ordering of the intermediate levels.

[16]The ranking of the lowest constraint $*[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]$ below all the other constraints in the hierarchy is motivated by the hypothesis that less restrictive constraints are necessarily ranked lower than more restrictive ones. Since it cannot be motivated with Laal data, this ranking will not be reported in tableaux.

(23)

$$*[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]/[+\text{syll}, \alpha\text{height}, \beta\text{front}]$$

$$|$$

$$\textsc{Ident}[\text{rd}]$$

$$*[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]/[+\text{syll}, \alpha\text{height}] \qquad *[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]/[+\text{syll}, \beta\text{front}]$$

$$*[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]/[+\text{syll}]$$

In the doubly-triggered rounding harmony, the similarity threshold at work is the highest level in the scale; IDENT[round] must thus be ranked right below the highest markedness constraint $*[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]$ $/[+\text{syll}, \alpha\text{height}, \beta\text{front}]$, but crucially higher than all the other constraints in the hierarchy, as shown in the tableaux in (24) and (25).

(24)

		SUBF	$*[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]$ $/[+\text{syll}, \alpha\text{ht}, \beta\text{fr}]$	IDENT[rd]	$*[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]$ $/[+\text{syll}, \alpha\text{height}]$	$*[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]$ $/[+\text{syll}, \beta\text{front}]$	$*[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]$ $/[+\text{syll}]$
a. /ɓɨ̀r-ú/	i. ɓɨ̀rú	*!					
	ii. ɓɨ̀^{B}rú		*!		*	*	*
	☞iii. ɓùrú			*			
b. /ɓə̀r-ú/	i. ɓə̀rú	*!					
	☞ii. ɓə̀^{B}rú					*	*
	iii. ɓòrú		*!				

Undominated SUBF ensures that (24a) /ɓɨ̀r-ú/ and (24b) /ɓə̀r-ú/ does not surface with a V_1 that is not at least $[\![x \text{ round}]\!]$, since in both forms, V_1 is adjacent to a labial consonant: candidates (24a-i) and (24b-i) are thus always suboptimal. Candidate (24a-ii) [ɓɨ̀^{B}rú] violates $*[\![\geq x \text{ rd}]\!][\![1\text{rd}]\!]/[+\text{syll}, \alpha\text{height}, \beta\text{front}]$. The fact that this constraint is ranked higher than IDENT[rd] favors candidate (24a-iii) [ɓùrú], in which rounding harmony has applied, repairing the marked structure. On the other hand, candidate (24b-ii) [ɓə̀^{B}rú] does not violate this constraint: it only violates constraints that are lower on the markedness hierarchy, and crucially ranked lower than IDENT[rd], which makes it the optimal output.

Finally, given the inputs /mèn-ú/ and gɨ́n-ù/ in (25), SUBF strikes candidates (25a-ii) [mè^{B}n-ú] and (25b-ii) [gɨ́^{B}nù], where labial coarticulation has over-applied ([e] is not a coarticulatory target, and [g, n] are not labialisation triggers), leaving only (25a-i) [mènú] and (25b-i) [gɨ́nù] as the optimal outputs. Indeed, the violation of IDENT[rd] incurred by rounding V_1 in candidates (25a-iii) [myònú] and (25b-iii) [gúnù] is not compensated by the satisfaction of a higher constraint: there is no marked structure to repair.

(25)

		SUBF	*⟦≥ x rd⟧⟦1rd⟧ /[+syll, αht, βfr]	IDENT[rd]	*⟦≥ x rd⟧⟦1rd⟧ /[+syll, αheight]	*⟦≥ x rd⟧⟦1rd⟧ /[+syll, βfront]	*⟦≥ x rd⟧⟦1rd⟧ /[+syll]
a. /mèn-ú/	☞i. mènú						
	ii. mè^{B}nú	*!					*
	iii. myònú			*!			
b. /gɨ́n-ù/	☞i. gɨ́nù						
	ii. gɨ́^{B}nù	*!	*		*	*	*
	iii. gúnù			*!			

To complete the analysis, two undominated constraints need to be added. The first one is a positional faithfulness constraint (Beckman 1999) IDENT$_{\sigma 2}$[rd], which accounts for the fact that unrounding of V_2 is not a possible repair, as shown by candidate (26d). Note that the directionality of the harmony is accounted for by the combination of this positional faithfulness constraint and the markedness constraint penalizing ⟦≥$x$round⟧⟦1round⟧/... (which can only correspond to a [–round][+round] and not [+round][–round] sequence): if the [+round] feature of V_2 cannot be changed, then only anticipatory rounding will fix the marked ⟦≥$x$round⟧⟦1round⟧ sequence.

(26)

/ɓɨ̀r-ú/	SUBF	IDENT$_{\sigma 2}$[RD]	*⟦≥ x rd⟧⟦1rd⟧ /[+syll, αht, βfr]	IDENT[rd]
a. ɓɨ̀rú	*!			
b. ɓɨ̀^{B}rú			*!	
☞ c. ɓùrú				*
d. ɓɨ̀^{B}rɨ́		*!		*

Additionally, one needs a projection-based markedness constraint accounting for the opacity of intervening /w/, defined in (27).

(27) *[+syll](C)[–syll]/[–cons, +rd]

Let X be a syllabic vocoid and Y a non-syllabic one; X and Y may not co-occur in a sequence (optionally interrupted by a consonant) in this order if they agree in the features [consonantal] and [round] (i.e. if they are both round vocoids). Assign one violation per pair of (near-)adjacent segments meeting the criteria.

This is illustrated in (28).

(28)

/mə́w-ó/	SUBF	*[+syll](C)[–syll] /[–cons, +rd]	IDENT$_{\sigma 2}$[RD]	*⟦≥ x rd⟧⟦1rd⟧ /[+syll, αht, βfr]	IDENT[rd]
a. mə́wó	*!				
☞ b. mə́^{B}wó				*	
c. mówó		*!			*
d. mə́^{B}wə́			*!		*

Finally, the simple rounding harmony, which belongs to a separate, morphologically specific sub-grammar, is driven by a projection-based constraint referring only to binary features: *[–rd][+rd]/[+syll], defined in (29).

(29) *[–rd][+rd]/[+syll]

A [–round] segment may not directly precede a [+round] segment in the ordered set of output segments specified as [+syllabic] (i.e. a non-round vowel may not precede a round vowel). Assign one violation for each pair of neighbouring segments that meet the criteria but fail to agree.

This constraint also stands in a markedness hierarchy, mirroring the similarity scale in Table 2. In this case, however, IDENT[rd] is ranked below the lowest constraint of the hierarchy, i.e. the threshold for rounding is at the lowest possible point, as shown in (30).[17]

(30)

*[-rd][+rd]/[+syll, αheight, βfront]

*[–rd][+rd]/[+syll, αheight]　　　*[–rd][+rd]/[+syll, βfront]

*[–rd][+rd]/[+syll]

|

IDENT[round]

This is illustrated in (31).

[17] See note 16 regarding the rankings within the markedness constraint hierarchy.

(31)

		SubF	*[+syll](C)[−syll] /[−cons, +rd]	Ident$_{\sigma2}$[rd]	*[−rd][+rd] /[+syll, αht, βfr]	*[−rd][+rd] /[+syll, αheight]	*[−rd][+rd] /[+syll, βfront]	*[−rd][+rd] /[+syll	Ident[rd]
a. /léér-nǔ/	i. léérnǔ							*!	
	☞ii. lyóórnǔ								*
	iii. léérnɨ̌			*!					*
b. /kə́w-ò/	i. kə́wò	*!							
	☞ii. kə́^{B}wò							*	
	iii. kówò		*!						*
	iv. kə́^{B}wə̀			*!					*

The analysis presented above is one of many possible analyses, and illustrates one of the advantages of the subfeatural representations proposed in this paper: extend the domain of application of existing theories of vowel harmony (and more generally assimilation) to complex multiple-trigger cases involving subphonemic teamwork.

3.4 The nature of subfeatures

3.4.1 A representation of phonetic knowledge

The theory proposed here crucially rests on the assumption that phonology has access to language-specific PHONETIC KNOWLEDGE (Kingston and Diehl 1994), i.e. "the speaker's partial understanding of the physical conditions under which speech is produced and perceived" (Hayes and Steriade 2004: 1). This is true of most phonetically grounded approaches to phonology, notably Steriade's (2009) P-map and similar licensing-by-cue approaches. Subfeatures are actually a reification of this knowledge: ⟦*x* round⟧ represents the knowledge that Laal speakers have of the labial coarticulation affecting [ɨ] and [ə] and its perceptual correlate.

Importantly, phonetic knowledge is abstract, and subfeatures accordingly represent abstract categories. They are discretized, scalar representations of phonologized coarticulation, not representations of actual acoustic/perceptual information. Like tone, they are contextually determined, and capture relative levels rather than absolute values: ⟦*x* round⟧ is not an absolute F_2 value, but an indication that labialised [ə^{B}] and [ɨ^{B}] have *x*% of the phonetic property or properties that distinguish [o] and [u] from [ə] and [ɨ] respectively.

Evidence of the abstract nature of subfeatures comes from the fact that a word like /ɓɨ̀r-ú/ 'fish hooks' is always realised [ɓùrú], never [ɓɨ̀^{B}rú]. This is a problem if one is to derive the optimal output [ɓùrú] through phonotactic repair of the marked structure [ɓɨ̀^{B}rú], which is what I propose to do. Indeed, where is the form [ɓɨ̀^{B}rú] to be found if it is neither in the underlying representation, nor in the uttered/perceived surface form? The answer is that the form [ɓɨ̀^{B}rú] is the predicted realisation of /ɓɨ̀r-ú/, a prediction based on the speakers' knowledge of the coarticulatory effect of labial consonants on a neighbouring [ɨ]. Indeed, ⟦*x* round⟧ [$ɨ^B$] does exist in articulation and perception, e.g. in words like /ɓɨ̀rà/ 'fish hook' or /pɨ́r/ 'catch', where the initial vowel is always realised and perceived as ⟦*x* round⟧ [$ɨ^B$], as we will see in § 4. Based on this phonetic experience, Laal speakers are able to determine that labial consonants increase the ⟦round⟧ subfeatural value of a neighbouring non-low central vowel by the coarticulatory coefficient *p*, and can therefore predict that, if the sequence [$ɨ^B$...u] were not unlawful, /ɓɨ̀r-ú/ would be realised with a ⟦*x* round⟧ [$ɨ^B$], like in [ɓɨ̀^{B}rà] and [pɨ́^{B}r]. It is this purely abstract, predicted phonetic realisation [ɓɨ̀^{B}rú] that contains the marked structure ⟦*x* round⟧…⟦1 round⟧ that the language strives to avoid, and that it "repairs" by "rounding up" the initial vowel.[18]

This concept of a predicted (but never realised) phonetic realisation of the input, or "inferred input", was first proposed by Steriade (1997), and later developed by Jun (2002), as well as Gallagher (2007) and Flemming (2008) under the label "realised input." The major difference with subfeatural representations is that only inputs are subject to this pre-phonological phonetic interpretation in Flemming's system. It is this realised input that is then fed to the phonotactic constraint grammar. The necessity to include phonetic information in the input comes from the fact that in Flemming's approach (inspired by Steriade's (2001, 2009) licensing-by-cue), phonetically grounded processes are driven by the degree of faithfulness of the output to this phonetic information. No such mechanism is needed in the theory I propose here, which is crucially driven by markedness constraints rather than faithfulness: the input is pre-phonetic, and the predicted phonetic realisation is enforced by high-ranked coarticulatory constraints belonging to phonetic knowledge.[19]

3.4.2 Subfeatures as emergent categories

Another assumption underlying the theory is that subfeatural representations are, like contrastive features, emergent (Boersma 1998, Mielke 2008), i.e. they are generalizations that emerge from sound patterns. This assumption answers two major questions posed by subfeatural representations: the origin of subfeatures, and the limits on their values. If subfeatures are emergent, one expects to see them used in phonology only to distinguish categories that are perceptually distinct. In other words, the limits on human articulation and perception act as a stringent limiter on the possible types and number of subfeatures, as well as the values they may have.

3.5 Enforcing and manipulating subfeatures in a constraint-grammar

A crucial property of subfeatures illustrated by the analysis proposed above is that, in an OT grammar, they are not protected by faithfulness. Indeed, a faithfulness constraint referring to a subfeature, if ranked sufficiently high, would make this subfeature contrastive, contrary to the key intuition that subfeatures encode non-contrastive categories. The nature of subfeatures thus makes them invisible to faithfulness. I assume here that this is because subfeatures are not present in the input.

[18] Hansson and Moore (2011: 16) sketch a very similar hypothesis regarding Kaska back harmony, involving a purely abstract hypothesized phonetic realization of the vowel targeted by the harmony.

[19] For a more detailed comparison of subfeatures with Steriade's P-map and Flemming's Realized Input Approaches, see Lionnet 2016: 187–191).

Additionally, it is necessary to rank the markedness constraints responsible for assigning subfeatures very high in order for subfeatural distinctions to play a role in the phonological grammar. If coarticulatory effects can be seen by phonology, the markedness constraints responsible for enforcing coarticulation-driven subfeatural distinctions cannot be ranked below other constraints whose effects would undo coarticulation. An interesting consequence of the high ranking of such constraints is that they constitute the only part of the constraint grammar that can manipulate subfeatures, i.e. be satisfied by a subfeature being added to or removed from the input. All other constraints referring to subfeatures (e.g. *⟦≥ x rd⟧⟦1rd⟧/[αheight,βfront] in (22) above) can in theory be satisfied by manipulating either subfeatures or binary features, but only the latter will ever be optimal, since any subfeatural change will be filtered out by the high ranked constraints enforcing coarticulation. Subfeatural values can thus only be modified indirectly by changing the (substantively related) featural content of the input, e.g. changing [–round] into [+round] necessarily entails a change from ⟦0 round⟧ or ⟦x round⟧ to ⟦1 round⟧. In other words, the undesirable effects of coarticulation can only be undone by modifying the phonological environment responsible for it, not by simply modifying the subfeatural values that are a representation of those effects. In that sense, subfeatures are subordinate to classic binary features.[20]

3.6 The architecture of the phonological grammar

Subfeatures constitute a representation of segments in context, i.e. a representation of the phonetic knowledge of how segments interact when put together. This abstract knowledge exists alongside phonology, and is what phonology uses to predict the realisation of specific inputs. In cases where this predicted realisation violates a phonotactic constraint, a phonological operation must apply to change the coarticulatory context in order to ensure that the realisation of the output conforms to the phonotactics. The phonological grammar is thus organized in a feedback/feed forward loop (cf. Boersma 1998) that constitutes a fluid and dynamic model of the phonetics/phonology interface, where phonology and phonetic knowledge are not ordered, but parallel and interactive.

The next section presents instrumental evidence in support of subfeatural categories.

4 The phonetic underpinnings of the harmony

While the doubly triggered rounding harmony described above is, as far as I know, unique, its phonetic basis is unsurprising: labiality, rounding, height, and backness are all factors that are known to contribute to the rounding of a vowel (Terbeek 1977; Linker 1982; Kaun 1995, 2004). In this section, I present instrumental evidence showing that a labial consonant

[20] As noted by a reviewer, one could aternatively build a "phonetic filter" in GEN, which allows only output candidates that do not violate language-specific phonetic patterns to be generated. GEN would not refer directly to language-specific restrictions of course. It would refer instead to phonetic knowledge, a separate component where language-specific phonetic patterns are to be found. In that alternative —which, contrary to the one developed above, violates Richness of the Base— the constraint grammar does not enforce subfeatural distinctions: subfeatures belong exclusively to phonetic knowledge, and are enforced by the Phonetic Filter. They cannot be manipulated by either GEN or EVAL. They can only be referred to in identifying contexts. Note that such a filter would work well in parallel OT, but would be problematic in derivational approaches such as Harmonic Serialism or Stratal OT that posit levels at which representations lack non-contrastive phonetic detail.

greatly affects the non-low central vowels [ɨ ə], by significantly lowering their F2. This supports the analysis of labialised [ɨ^{B}, ə^{B}] as a separate category in Laal.

To test this, acoustic measurements were extracted from recordings made in Gori (one of the two Laal-speaking villages), Chad, in March 2014 and January 2015. Two native Laal speakers, both male, were recorded: Kalem Dakour (KD), in his late fifties, and his 27-year old son Adoum Kalem (AK). Both are also fluent in Lua, Ba, and Chadian Arabic. KD also speaks intermediate French, while AK's command of that language is limited. The recorded sessions consisted mainly in wordlists, elicited in French.

The recordings were made using a Zoom H4n recorder set at a sample rate of 44.1 kHz and 16-bit sample size, and a mono Røde NTG2 condenser shotgun microphone. Vowel formants were extracted in Praat (Boersma and Weenink 2014): the first three formants of the stem-initial vowel were automatically extracted from 546 tokens at the midpoint of the total vowel interval (defined manually), i.e. as far as possible from formant transitions. To better describe auditory frequency resolution, formant frequency values in Hertz were converted into Equivalent Rectangular Bandwidth (ERB), using Moore and Glasberg's (1983) equation. Both Hz and ERB values are provided, but the statistics and vowel plots are all based on the latter.

Since the recording sessions could only take place in a relatively noisy environment, some recordings had to be excluded from the sample due to excessive background noise. This explains why the words and number of tokens per word considered for each speaker are not always identical. The number of words and tokens are however sufficiently overlapping to make the data presented here representative.

In the figures which follow, ellipses on vowel plots indicate two standard deviations. Statistical significance is assessed using a Welch two-sample two-sided *t*-test at the 5% significance level ($p < 0.05$). (See Table 1 above for the abbreviations and codes used in this section.)

Note that words where [ɨ ə] are adjacent to a palatal consonant (e.g. [cɨ əj], etc.) were excluded from the sample because the contrast between front and back vowels is partially neutralised in this environment.

In the interest of space, I have excluded some of the acoustic measurements made for this study. First, I focus exclusively on short vowels. Additionally, the coarticulatory effect of [w] is ignored here, because the impossibility of clearly discriminating between the vowel and glide portions in /wV/ or /Vw/ sequences makes them likely to be less accurate. I also exclude all cases of multiple conditions except ə/B__B. see Lionnet (2016) for more detail on these measurements.

4.1 Effects of the B condition

Acoustic measurements clearly show that a labial consonant has a very significant F2 lowering effect on (near-)adjacent [ə] and [ɨ].

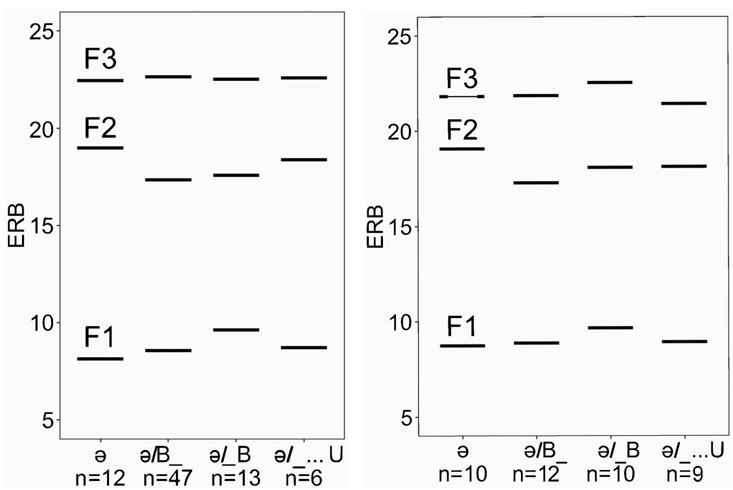
4.1.1 Effect of the B condition on [ə]

The [ə]-words included in the sample for both speakers are summarised in Table 3 (the full list can be found in Table 6 in Appendix B). The total number of tokens within each condition includes repetitions, e.g. three separate productions of the word [pə́d] 'pass' and one production of the word [mə́l] 'be straight' constitute a total of four [Bə] tokens.

	AK		KD		
condition	#w	#t	#w	#t	example
ə	5	12	4	10	gə̄rī
B	23	60	7	22	
Bə	18	47	4	12	pə́d
əB	5	13	3	10	kə́m
BəB	1	3	1	3	mə̀mlə̀l
U	2	6	2	9	də́nú

Table 3: ə-words sample, B and U conditions (both speakers)

Figure 2 shows the mean F1, F2 and F3 values of stem-initial [ə] in each of the B and U conditions, for both speakers. As can be seen, the two B conditions appear to have a strong lowering effect on F2. The U condition also seems to lower F2 somewhat, but to a lesser extent. F1 and F3 appear to be unaffected.[21] In the remainder of this section, I will concentrate on the F2 lowering effect of the B and U conditions.

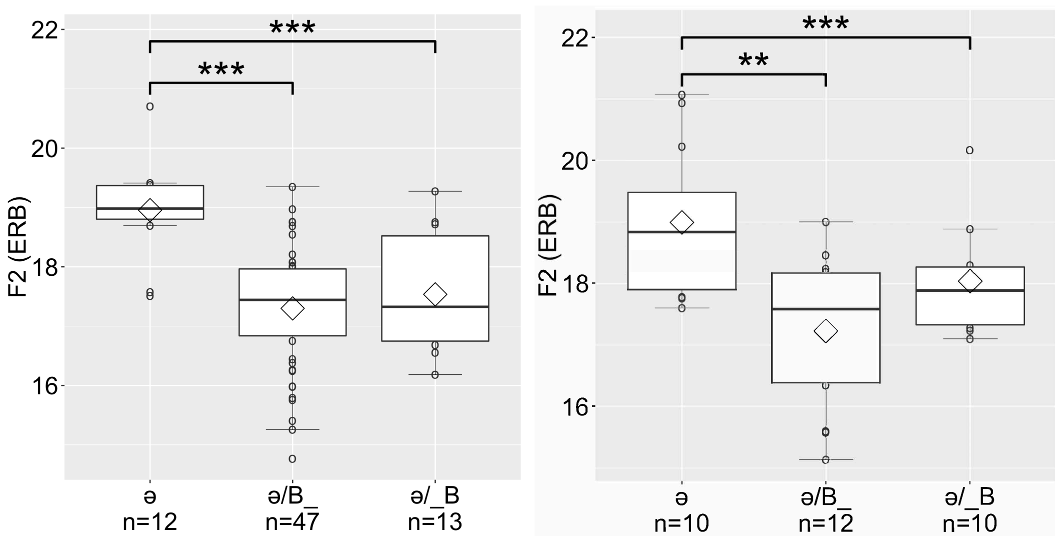


(a) (b)

Figure 2: Effect of B and U conditions on [ə]: (a) speaker AK; (b) speaker KD.

Figure 3a shows the distribution of the F2 values of non-labialised [ə] vs. [ə]/B_ and [ə]/_B in AK's speech. As can be seen from these figures and from Tables 8 and 9 in Appendix C, a neighbouring labial consonant has a strong, consistent, and highly statistically significant F2 lowering effect on [ə]: [ə]/B_ is on average 1.66 ERB (288 Hz) lower in F2 than [ə] ($t(20) = -5.6$, $p = 9.96e^{-6}$), while [ə]/_B is 1.42 ERB (250 Hz) lower ($t(22.8) = 3.9$, $p = 7.79e^{-4}$). Since the lowering of F2 incurred by the B_ and _B conditions is of similar magnitude, both can be collapsed into one single category: [$ə^B$], which in this case is on

[21] The observed F3 variations in KD's speech are never statistically significant.



(a) (b)

Figure 3: Effect of /B__ and /__B conditions on F2 of [ə]: (a) speaker AK; (b) speaker KD.

average 1.61 ERB (279 Hz) lower in F2 than [ə] ($t(18) = 5.9$, $p = 1.54e^{-5}$). The overall F2 lowering effect is of a similar magnitude in KD's speech, as shown in Figure 3b: the effect of a preceding B being stronger ($\Delta F2 = -1.76$ ERB (–311 Hz), $t(24.5) = -3.7$, $p = 0.001$) than that of a following B ($\Delta F2 = -0.95$ ERB (–181 Hz), $t(19.9) = 2.1$, $p = 0.049$). [$ə^{B}$] is on average 1.43 ERB (256 Hz) lower in F2 than [ə] ($t(21.5) = 3.4$, $p = 0.003$).

The vowel plots in Figure 4 very clearly show that the distribution of [Bə] and [əB] mostly overlap, and that they are distinct from both [ə] and [o]: both Bə and əB (= $ə^{B}$) are exactly between [ə] and [o] in terms of F2.[22]

4.1.2 Effect of the B condition on [ɨ]

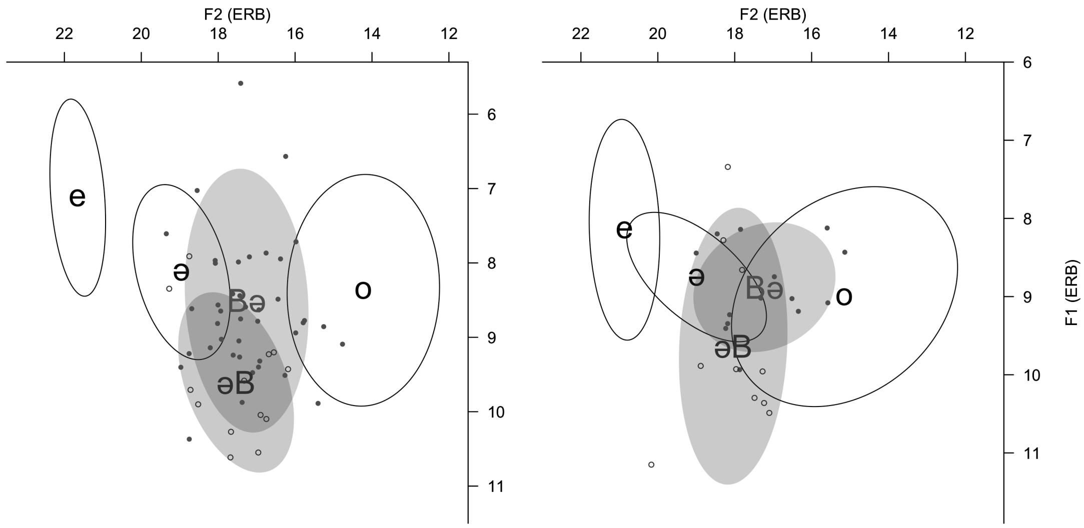
The coarticulatory effects on [ɨ] are congruent with, and stronger than the effects on [ə], for both speakers, and across the two conditions B and U. The list of ɨ-words included in the sample are listed in Table 7 in Appendix B, and summarized in Table 4.[23]

Note that two of the above conditions (U in *gɨ́nù* 'nets', and ɨCB in *lɨ̀gmà* 'horses') are attested in only one word each. Each one was recorded only once, from one speaker only (AK and KD respectively). I will return to these two words below.

Figure 5 presents the mean F1, F2 and F3 values of stem-initial [ɨ] in both B_ and _B conditions environments, for both speakers. As for Figure 2 for [ə], only F2 seems to be affected by a preceding or following labial consonant, and it is strongly affected, for both speakers.

[22]Box plots and vowel plots for the collapsed [$ə^{B}$] and [$ɨ^{B}$] categories for both speakers can be found in Figures 11 to 14 in Appendix D in the supplementary materials.

[23]There are 220 ɨ-words in the lexicon, including 199 in which V_1 /ɨ/ is neither preceded nor followed by a palatal consonant.

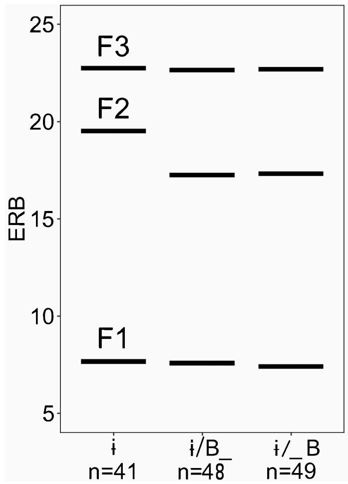


(a) (b)

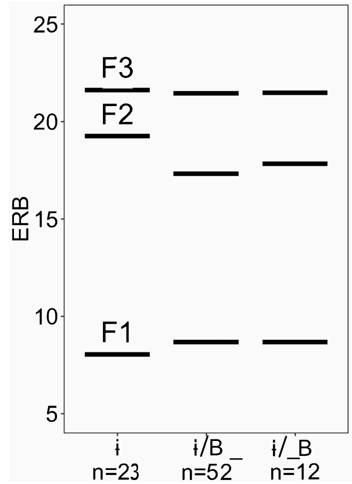
Figure 4: [ə]/B_ and [ə]/_B plotted against [e], [ə] and [o]: (a) speaker AK; (b) speaker KD.

	AK		KD		
condition	#w	#t	#w	#t	example
ɨ	24	41	9	23	dɨ̄gā
B	36	97	36	65	
Bɨ	19	48	29	52	ɓɨ̀rà
ɨB	17	49	6	12	lɨ̀bár
ɨCB	0	0	1	1	lɨ̀gmà
U	1	1	0	0	gɨ́nù

Table 4: ə-words sample, B and U conditions (both speakers)



(a)



(b)

Figure 5: Effect of B conditions on [ɨ]: (a) speaker AK; (b) speaker KD.

As shown in Figure 6, the F2 lowering effect of the B condition on [ɨ] is drastic and very highly significant for both speakers. In AK's speech, F2 is on average 2.25 ERB (407 Hz) lower in [ɨ]/B_ than [ɨ] ($t(79.7) = -14.6$, $p = 2.20e^{-16}$), 2.20 ERB (396 Hz) lower in [ɨ]/_B ($t(87.7) = 12.5$, $p = 2.20e^{-16}$), and overall 2.22 ERB (402 Hz) lower for labialised [$ɨ^B$] than for [ɨ] ($t(75) = 15.4$, $p = 2.20e^{-16}$). For KD, the findings are extremely similar: 1.96 ERB (343 Hz) lower in [ɨ]/B_ ($t(59.9) = -8.6$, $p = 5.40e^{-12}$), 1.42 (257 Hz) lower in [ɨ]/_B ($t(18.1) = 4.1$, $p = 6.67e^{-4}$), and 1.87 ERB (328 Hz) lower overall ($t(56) = 8.5$, $p = 1.10e^{-11}$).

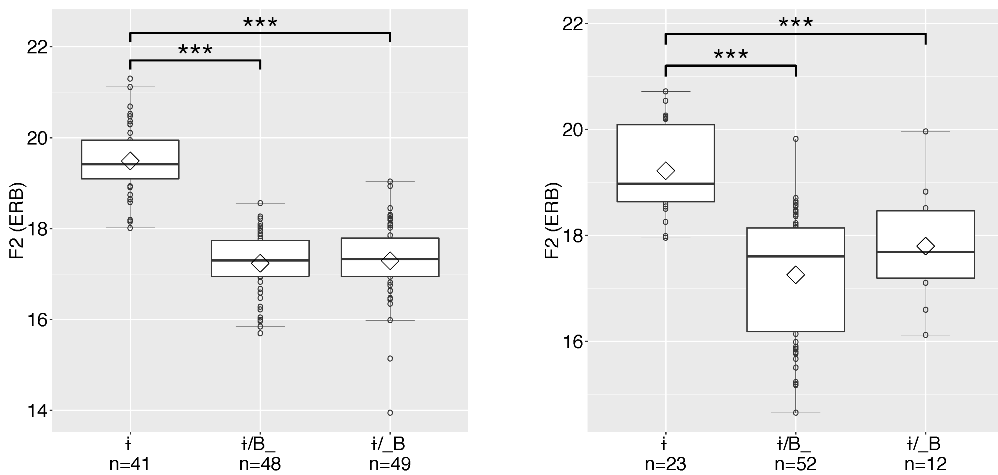
The vowel plots in Figure 7 show that the B_ and _B environments have virtually the same effect on a neighbouring [ɨ]. The distribution of labialised [ɨ]/B_ and [ɨ]/_B (= [$ɨ^B$]) with respect to [ɨ] and [u] is similar to that of [ə]/B_ and [ə]/_B (= [$ə^B$]) with respect to [ə] and [o]: [ɨ] and [$ɨ^B$] have virtually non-overlapping distributions, and [$ɨ^B$] seems to be exactly between [ɨ] and [u], for both speakers.

As mentioned earlier, only one token illustrating the ɨCB condition could be included in the sample: the plural noun [lɨ̀gmà] 'horses' (KD). With only one token, it is impossible to draw any generalisations. However, it is noteworthy that the mean F2 of [ɨ] in [lɨ̀gmà] 18.02 ERB (1407 Hz) is much closer to that of KD's [ɨ]/_B (17.80 ERB / 1378 Hz) than to that of non-labialised [ɨ] (19.22 ERB / 1635 Hz), and the mean F2 difference between the [ɨ] in [lɨ̀gmà] and KD's non-labialised [ɨ] ($\Delta F2 = 1.20$ ERB (227 Hz)) is very close to that between KD's [ɨ] and [ɨ]/_B ($\Delta F2 = -1.42$ (–257 Hz)). This suggests that the intervening non-labial consonant does not prevent labialisation of the preceding [ɨ].

4.2 Effect of the U condition

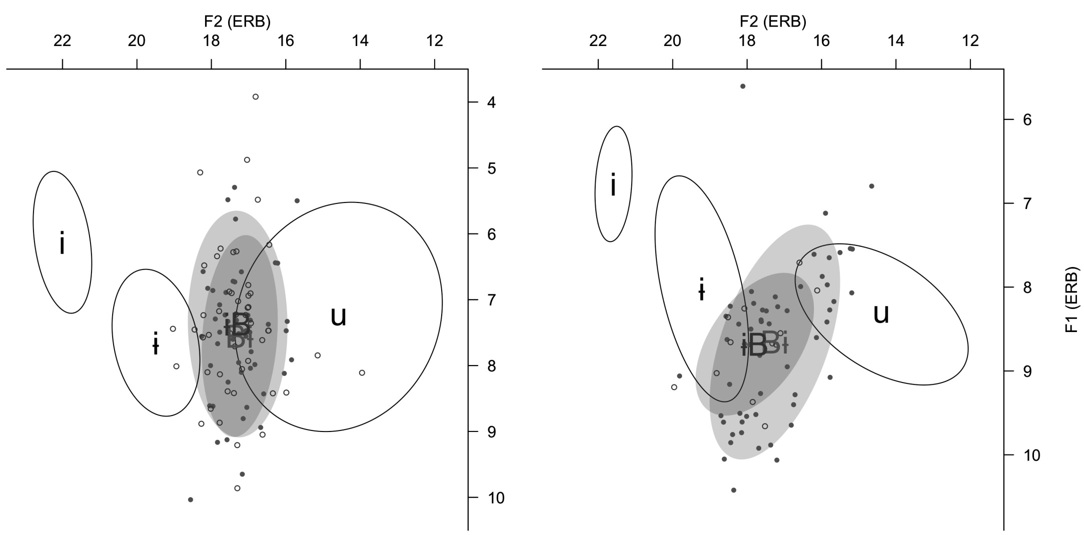
4.2.1 Effect of the U condition on [ə]

As previously noted, the charts in Figure 2 show a lowering of the mean F2 [ə] in the presence of a following round vowel for both speakers, although this lowering effect is less strong than that caused by either of the two B environments. [ə]/_U is on average 0.57 ERB (110 Hz) lower than [ə] for AK, (Figure 8a), 0.89 ERB (172 Hz) lower for KD



(a) (b)

Figure 6: Effect of /B_ and /_B conditions on F2 of [ɨ]: (a) speaker AK; (b) speaker KD.



(a) (b)

Figure 7: ɨ]/B_ and [ɨ]/_B plotted against [i], [ɨ], and [u]: (a) speaker AK; (b) speaker KD.

(Figure 8b). However, this difference is not statistically significant, as shown in Appendix C ($t(13.7) = 1.7$, $p = 0.12$ for AK; $t(18) = 2.0$, $p = 0.059$).

This can be seen on the vowel plot in Figure 9 (short vowels only), where the centre of the [ə...U] ellipse is noticeably further right than that of the [ə] ellipse —indicating a substantial mean F2 difference— but the F2 range of [ə...U] is nearly entirely contained within that of the []]ə ellipse, contrary to that of [ə^{B}] (=[Bə] + [əB]) ellipse, which is clearly occupies an intermediate range between [ə] and [o].

4.2.2 Effect of the U condition on [ɨ]

The effect of a following round vowel on [ɨ] cannot be tested convincingly, since only one word illustrating this condition is attested in the language: [gɨ́nù] 'nets', of which only one token, produced by AK, could be included in the sample. It is however interesting to note that the F2 value of the [ɨ] in [gɨ́nù] (1696 Hz / 19.56 ERB) does not show any sign of lowering. It is actually 0.07 ERB (8 Hz) higher than the mean F2 of AK's non-labialised [ɨ] (19.49 ERB / 1688 Hz). This clearly contrasts with the extent of the effect of the B condition on [ɨ] (average F2 lowering of 2.22 ERB / 402 Hz for AK; cf. Table 9 in Appendix C), and suggests that a round V_2 has no more effect on a preceding [ɨ] than it does on a preceding [ə].

4.3 Cumulative effect

When more than one condition is met, the effect of each individual condition is cumulative. This can be illustrated with AK's short [ə] in the B__B condition only. As can be seen in Figure 10 and in Table 9 in Appendix C, the cumulative F2 lowering effect of two labial consonants (B_B) on [ə], such as in [mə̀mlə̀l] 'my grand-child', is significantly greater than that of a single labial consonant. Indeed, [ə]/B_B is 2.51 ERB (425 Hz) lower in F2 than [ə] ($t(10) = 8.4$, $p = 7.72e\text{-}6$), and 0.91 ERB (146 Hz) lower than that of short [ə^{B}] ($t(.7) = -4.1$, $p = 0.011$).

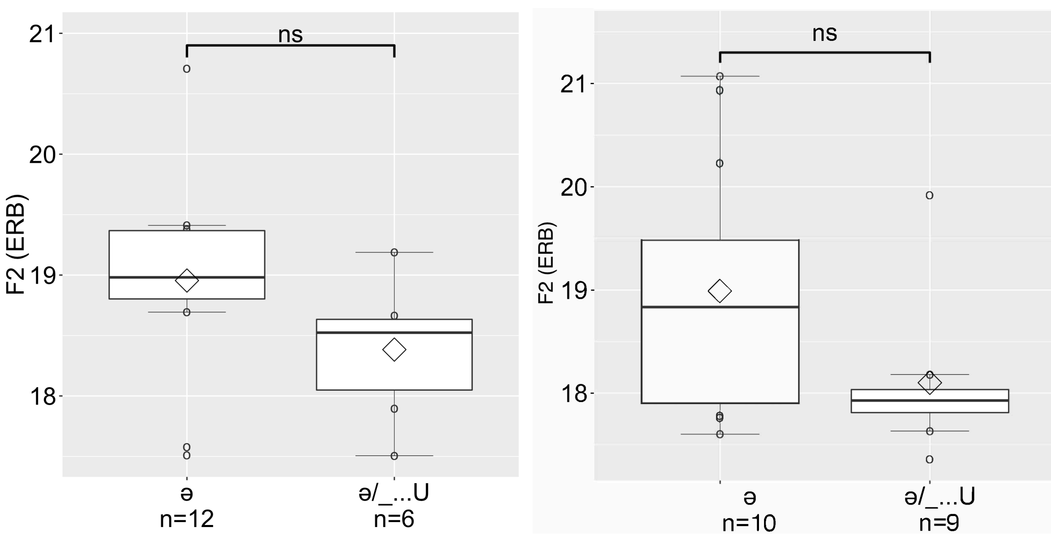
4.4 Summary and discussion

4.4.1 Coarticulatory effect from the labial consonant only

In summary, we have seen that a labial consonant has a very significant F2-lowering effect on a neighbouring non-low central vowel. The average F2 difference between non-labialised [ɨ ə] and labialised [ɨ^{B} ə^{B}] for both speakers is between 181 Hz (0.95 ERB) and 407 Hz (2.25 ERB).

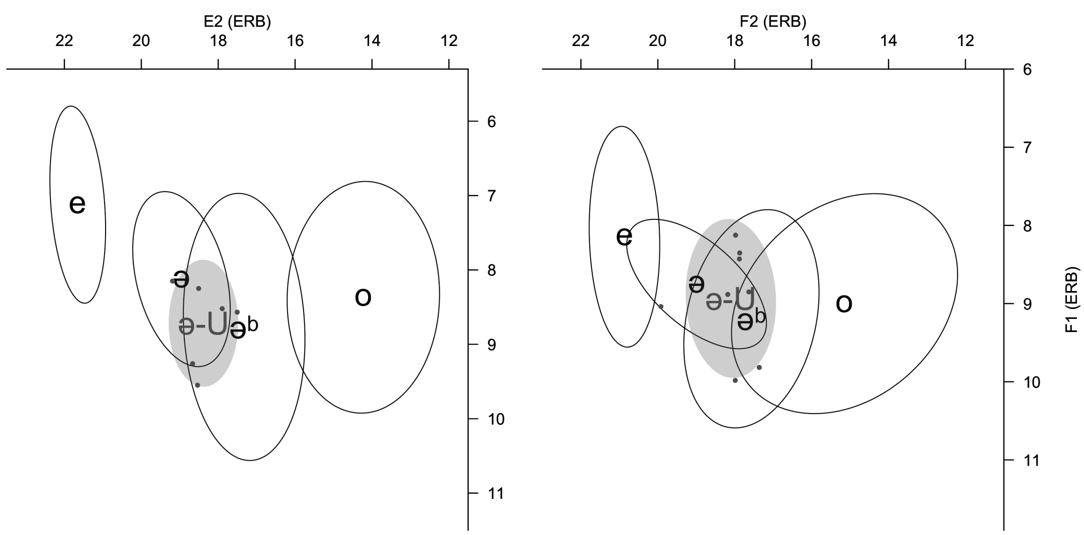
We can conclude that there is a clear phonetic distinction between non-labialised and labialised non-low central vowels. Although no perception experiment has been carried out yet to verify whether this strong acoustic difference is perceived as different by speakers, F2 differences of that magnitude are so likely to be perceptible that I feel comfortable hypothesizing that they actually are.

We have also seen that the apparent (more limited) lowering effect of a following round vowel is not statistically significant. This seems to indicate that the role of the [round] V_2 in



(a) (b)

Figure 8: Effect of U condition on F2 of [ə]: (a) speaker AK; (b) speaker KD.



(a) (b)

Figure 9: [ə]/_...U plotted against [e], [ə], [ə^B], and [o]: (a) speaker AK; (b) speaker KD.

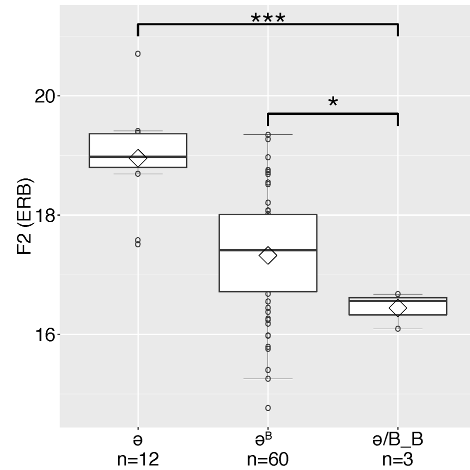


Figure 10: Effect of B_B condition on F2 of [ə] (speaker AK)

the harmony is purely phonological, and the height identity requirement between the trigger and target is likely due to a phonological similarity precondition on rounding harmony.

4.4.2 Cumulative coarticulation

Interestingly, the cumulative coarticulatory effect of B (cf. Figure 10) is irrelevant to the harmony. Whether [$ɨ^{B}$, $ə^{B}$] are subphonemically rounded by one labial or more strongly by two labials does not change anything to their status as targets: both are rounded in the presence of a following round vowel, and kept unchanged otherwise. In other words, the threshold of subphonemic rounding is such that the effect of one labial consonant is enough to reach it.[24]

4.4.3 Calculating *p* and *x* in Laal

The coarticulatory coefficient $p_{B \rightarrow ə/ɨ, [\![rd]\!]}$ involved in the labialisation of [ə ɨ] can be calculated on the basis of the F2 measurements provided above. For example, assuming that the F2 values of [ə] (18.95 ERB) and [o] (14.31 ERB) correspond to the subfeatural values ⟦0 round⟧ and ⟦1 round⟧ respectively, the proportion of increase from ⟦0 round⟧ [ə] to ⟦*x* round⟧ [$ə^{B}$] $p_{B \rightarrow ə/ɨ, [\![rd]\!]}$ in AK's speech can be calculated as the ratio between ΔF2[$ə^{B}$]–[ə] and ΔF2[o]–[ə], as shown in (32).

(32) $$p_{B \rightarrow ə/ɨ, [\![rd]\!]} = \frac{F2[ə^{B}] - F2[ə]}{F2[o] - F2[ə]} = \frac{17.35 - 18.95}{14.31 - 18.95} = 0.34$$

Table 5 provides the value of *p* for all trigger-target pairs (i.e. B→ə and B→ɨ), for both speakers.

[24] The cumulative effect is, however, crucial in a case of subphonemic teamwork like Woleaian *a*-raising, briefly illustrated in the introduction, where the threshold of subphonemic raising is reached only by the coarticulatory effect of two triggers (cf. Lionnet 2016: 105–111)

	$p_{\mathrm{B}\to ə/ɨ,⟦\mathrm{rd}⟧}$	$p_{\mathrm{B}\to ɨ,⟦\mathrm{rd}⟧}$
AK	0.34	0.47
KD	0.39	0.40

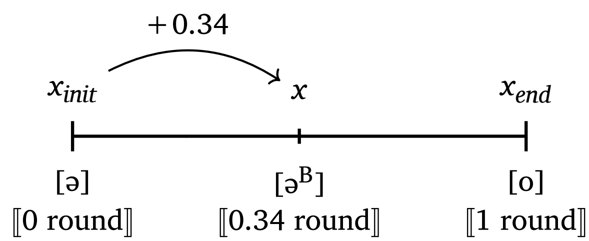
Table 5: Values for $p_{\mathrm{B}\to ə,⟦\mathrm{rd}⟧}$ and $p_{\mathrm{B}\to ɨ,⟦\mathrm{rd}⟧}$ for speakers AK and KD.

The subfeatural value of x of an ⟦x round⟧ vowel can then be determined by applying the C_p function defined in (16) above, as shown in (33).

(33) Application of C_p function in /pə́d/ ($p = p_{\mathrm{B}\to ə/ɨ,⟦\mathrm{rd}⟧}$; speakerAK):

a.
$$
\begin{aligned}
x &= C_p(x_{init}) \\
x &= x_{init} \quad + p(x_{end} - x_{init}) \\
&= 0 \quad + 0.34(1-0) \\
&= 0.34
\end{aligned}
$$

b. Illustrative schema:



In other words, in AK's speech, a labial consonant increases the subfeatural ⟦round⟧ value of a (near-)adjacent [ə] by ≈ 34%, making labialised [$ə^{\mathrm{B}}$] subfeaturally ⟦0.34 round⟧.

In a form like [məmlə̀l] 'my grand-son', where the first [ə] is surrounded by two labial consonants, the same function applies twice (i.e. is composed with itself, cf. (16d)), as illustrated in (34).[25]

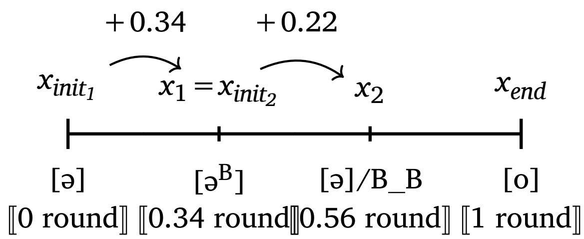
(34) Iterative application of C in /mə̀mlə̀l/: $x = C_p(C_p(x_{init}))$ ($p = p_{\mathrm{B}\to ə/ɨ,⟦\mathrm{rd}⟧}$):

a. First application:
$$
\begin{aligned}
x_1 &= C_p(x_{init_1}) \\
&= x_{init_1} \quad + p(x_{end} - x_{init_1}) \\
&= 0 \quad + 0.34(1-0) \\
&= 0.34
\end{aligned}
$$

b. Second application:
$$
\begin{aligned}
x_2 &= C_p(x_{init_2}) \\
&= C_p(x_1) && (x_{init_2} = x_1) \\
&= x_1 \quad + p(x_{end} - x_1) \\
&= 0.34 \quad + 0.34(1-0.34) \\
&= 0.34 \quad + 0.22 \\
&= 0.56
\end{aligned}
$$

[25]We saw that a preceding and a following B had virtually the same coarticulatory effect. If it were not the case, the two functions would be different.

c. Illustrative schema:



This prediction almost perfectly matches the observed F2 decrease incurred by two labial consonants on [ə] (cf. Table 9 in Appendix C). Indeed, the observed F2 value of [ə]/B_B (16.44 ERB) corresponds to 54% of that of ⟦0 round⟧ [ə] (18.95 ERB), given that ⟦1 round⟧ [o] is 14.31 ERB. Compare with the predicted 56% in (34b).

To refine the analysis developed in § 3 above, there should be as many coarticulation enforcing constraints (i.e. $*\neg C_{p_{\mathrm{B}\rightarrow ə/ɨ,⟦\mathrm{rd}⟧}}$; cf. (19c)) as there are $p_{\mathrm{Tr}\rightarrow \mathrm{Ta},⟦\mathrm{rd}⟧}$ values. For example, for AK, one needs both $*\neg C_{p_{\mathrm{B}\rightarrow ə,⟦\mathrm{rd}⟧}}$ setting the proportion of ⟦round⟧ caused by B on [ə] at 34%, and $*\neg C_{p_{\mathrm{B}\rightarrow ɨ,⟦\mathrm{rd}⟧}}$ setting the proportion of increase caused by B on [ɨ] at 47% (cf. Table 5).

The threshold at work in the doubly-triggered rounding harmony can be defined as ⟦$\geq$ 0.34⟧ for AK and ⟦$\geq$ 0.39⟧ for KD (i.e. the lowest *x* value obtained through B-ɨ/ə coarticulation). The constraint driving the doubly-triggered rounding harmony, defined in (22) above (as well as the other constraints in the markedness constraint hierarchy in (23)) can thus be redefined as shown in (35):

(35) AK: $*⟦\geq 0.34\ \textsc{rd}⟧⟦1\textsc{rd}⟧/[+\text{syll}, \alpha\text{height}, \beta\text{front}], \gg ...$
KD: $*⟦\geq 0.39\ \textsc{rd}⟧⟦1\textsc{rd}⟧/[+\text{syll}, \alpha\text{height}, \beta\text{front}], \gg ...$

As seen, every one of the constraints referring to subfeatures exists in as many variants as there are relevant coarticulatory contexts, i.e. as there are *p* and *x* values, and of course as many as there are speakers. In this way, the theory of subfeatural representations can easily accommodate for interspeaker variation.

5 Alternatives using only binary features

As two anonymous referees noted, one could object that concluding that the difference between coarticulated and non-coarticulated [ɨ ə] is distinctive and relevant to phonological processes does not necessarily warrant proposing an entirely new set of representations. In this section, I develop two alternative analyses of the Laal pattern using only traditional binary (or privative) features, and show their weaknesses compared to the subfeatural account.

5.1 The [labial] approach

The first possibility is to represent the coarticulatory effect of labial consonants on neighbouring central vowels with the feature [labial]: labialised [ɨ^B ə^B] are both [–round] and [labial], and the doubly-triggered rounding harmony targets only [labial] vowels: $V_{[\text{labial}]} \rightarrow [+\text{round}]$ / __C(

This supposes both that the CPlace feature [labial] and VPlace feature [round] are phonologically different (as in VPlace theory, cf. Ní Chiosáin and Padgett 1993, a.o.). This account is descriptively adequate: the feature [labial] plays exactly the same role as the ⟦*x* round⟧ subfeature advocated for above, without adding any novel representations to the phonological machinery.

However, the distinction between [labial] and [round] vowels has five main problems, that are avoided in the subfeatural approach.

First, the fact that labial consonants and round vowels pattern together in the doubly triggered rounding harmony is exactly the kind of arguments used elsewhere to argue in favor of considering labial consonants and round vowels as carrying the same contrastive feature, as opposed to two substantively separate features [labial] and [round] (cf. Unified Feature Theory: Clements 1989, Clements and Hume 1995; also Ní Chiosáin and Padgett 1993: 2).

More problematic is the fact that the [labial] account is more stipulative than the subfeatural one. Indeed, the CPlace feature [labial] seems to have properties that other binary or privative CPlace features do not have, and such properties must be stipulated. For example, one must stipulate that [labial], despite being a CPlace feature, may be borne by a vowel.[26] Additionally, In order to maintain the non-structure-preserving nature of this allophony (i.e. [ɨ ə] and [ɨ^{B} ə^{B}] do not constitute contrastive phonemes respectively), one also has to stipulate that [labial] is non-contrastive on vowels, and never part of any vowel's underlying representation: it may only be assigned to a vowel through coarticulation (or spreading) from a neighbouring consonant. No such stipulation is necessary in the subfeatural approach, where ⟦*x* round⟧ is not specific to consonants, but substantively related to the VPlace feature [±round], and is, like any other subfeature, defined as non-contrastive and never present underlyingly.

The third problem posed by the [labial] approach is that there is no natural relation between the [round]-[labial] featural difference and the acoustic differences observed between the two categories of vowels. Indeed, while it seems natural for a vowel that has only 34% of what constitutes a fully round vowel (as in the case of AK's [ə^{B}] vs. [o]) to be characterized as ⟦.34 round⟧, it is not clear why a [labial] vowel (let alone a labial consonant) should be realised with 34% of the phonetic correlate of the feature [round]. It is actually not entirely clear how a [labial] vowel should be realised.

Fourth, such a convenient split between two similar features —one vocalic, the other one consonantal— is not available in all cases of teamwork. Cases that involve only vocalic triggers and targets, such as the Woleaian alternation illustrated in § 1, could not be accounted for in the same way (cf. Lionnet 2016: 105–111).

Finally, the [labial] account seems to be mostly based on convenience, rather than explanatory adequacy, and misses an important generalization. What the acoustic measurements show in Laal is partial F2 lowering, which is not accounted for by the feature [labial] and the mostly artificial distinction between [labial] and [round].

[26]Note that this goes against the feature geometry of vowels proposed by Ní Chiosáin and Padgett (1993: 2), for whom "vowels cannot bear CPlace features (by definition)", and "consonant-vowel... interaction involves only VPlace features."

5.2 The backness approach

Another possibility is to consider that the doubly-triggered rounding harmony is actually better characterized as a [+back] harmony. Indeed, front vowels do not take part in the harmony —which we have seen involves only [–front] vowels— and rounding and backness are systematically correlated among [–front] vowels: the central vowels are always [–round], and the back ones always [+round]. There is thus a confound: the doubly-triggered harmony may be regarded equally as rounding harmony, or as [+back] harmony.

The advantage of choosing the latter option is that it leaves the feature [+round] available to account for the labial coarticulatory effect on [ɨ] and [ə]. Non-low central vowels [ɨ ə] would thus not be analyzed as partially rounded into [ɨ^{B} ə^{B}], but fully rounded into [ʉ ɵ] in the vicinity of a labial consonant. All that is left to do is restrict the possible targets of [+back] harmony to [–front, +round] vowels with the same height specification as the trigger vowel: [ʉ ɵ] $\rightarrow$ [u o] / __(CC)V[+back, αheight].

This analysis, which seems to render the use of subfeatures unnecessary, would be descriptively adequate if one focused only on the doubly triggered harmony. However, it has less explanatory power than the subfeatural account, and encounters numerous problems when the simple rounding harmony described in § 2.5 is considered, which seriously undermines its validity.

Firstly, it mischaracterises the doubly triggered rounding harmony, by failing to capture its most interesting property: the substantive relation that exists between the activity of the two triggers. Indeed, Both the alternation and the instrumental measurements indicate that the doubly triggered rounding harmony is a single process, involving only one property: rounding —not two separate properties and processes: rounding from the labial consonant, backing from the V$_2$. In that sense, ⟦*x* round⟧ [ɨ^{B} ə^{B}] is a better transcription and analysis than [+round,–back] [ʉ ɵ], since it clearly indicates the degree and provenance of the partial rounding effect. The substantive relation between the partial coarticulatory effect of the labial co-trigger and the categorical effect of the round vowel is also very well represented in the two-tiered feature+subfeature system, whereas it is not at all represented in either the [labial] vs. [round] or [–back, +round] vs. [+back, +round] accounts.

But more importantly, by making the vowel inventory more complex, it severely mischaracterises the simple rounding harmony as well, and unnecessarily complicates its analysis. As shown in (36), the recognition of a featural distinction between [ʉ ɵ] and [u o] requires a third feature to account for the now five-way horizontal distinction: [±front] and [±round] are not sufficient anymore, [±back] is also necessary (compare with the inventory in (3a) in above).

(36)	[+front]		[–front]		
	i	y	ɨ	[ʉ]	u
	e	yo	ə	[ɵ]	o
	ia	ya	a		ua
	[–round]	[+round]	[–round]	[+round]	[+round]
			[–back]		[+back]

This complicates the analysis of the simple rounding harmony. If one analyzes it as one single rounding harmony process, then [+front] vowels are rounded into [y yo ya], as expected, but [–front] vowels are changed to central rounded vowels [ʉ ɵ ɞ].[27] To get the latter to be realised as [u o ua], one would further need to change these vowels into [+back] [u o ua], either through a high ranked constraint against central rounded vowels (in parallel OT), or with a late rule ensuring that [ʉ, ɵ, ɞ] are unconditionally changed to [+back] on the surface (in a rule-based account). However, this option is actually not available, since [ʉ ɵ] (= [ɨ^{B} ə^{B}]) are attested on the surface, as shown by the phonetic measurements in § 4. They are not contrastive, but they are definitely part of the inventory, as conditioned allophones of /ɨ,ə/, which means that there cannot be a high-ranked constraint (or a late rule) banning them from surface representations.

A second option is to analyze the [ɨ ə a] → [u o ua] change as a case of [+back] harmony (similar to the one involved in the doubly triggered harmony, but without the height and frontness conditions). What appears to be a very simple case of rounding harmony is here divided into two unrelated processes, driven by two different rules or set(s) of constraints: rounding harmony among [+front] vowels, [+back] harmony among [–front] vowels, as illustrated in (37):

(37) a. [+front] target: [–round] → [+round]

/ndììl-ùn/	ndỳỳl-ùn	'pinch her'
/léér-òn/	lyóór-òn	'wrap her'
/siár-uàn/	syár-àn	'tear them (neut.) apart' [28]

b. [–front] target: [–back] → [+back][29]

/kɨ́r-ùn/	kúr-ùn	'place her'
/də̀g-òn/	dòg-òn	'drag her'
/dàg-uàn/	duàg-àn	'drag them (neut.)'

However, there is no evidence that (37a) and (37b) are distinct processes, and treating them separately goes against both the economy principle and the human instinct for pattern recognition.

In conclusion, the [labial] and [+back] accounts seem to be uninsightful and unnecessarily complicated solutions whose unique advantage is to avoid adding new representations to phonological theory. However, they only achieve this representational economy at the expense of grammatical simplicity, and more importantly explanatory power. I contend that the new subfeatural representations proposed here offer a simpler and more explanatory account of the Laal data, a criterion I think should be ranked above representational economy in designing a theory.

6 Conclusion

I have proposed in this paper to enrich phonology with subfeatural representations capturing non-contrastive but perceptually distinctive categories arising through coarticulation. Sub-

[27]It is unclear what the low vowel in this series –i.e. the rounded version of /a/– would be, since this feature combination is unattested, or at least never realised in the language

[28]Note that the round vowel /ua/ of the suffix is realised [a], because of the ban against low peripheral vowels in V_2 position (cf. § 2.1).

[29][–round] is either redundantly changed to [+round], or actively so by the rounding harmony rule described in (37a).

features are phonetically grounded, scalar representations that are substantially related to binary features, in a two-tiered featural system. I have shown how successfully subfeatural representations account for the partial, cumulative effects that drive subphonemic teamwork, on the basis of a phonological and acoustic analysis of the doubly triggered rounding harmony of Laal.

The instrumental evidence provided in § 4 shows that the Laal harmony is driven by a partial subphonemic effect originating in coarticulation. This constitutes a strong argument in favour of subfeatural representations, and against grammar-driven accounts using Local Constraint Conjunction or Harmonic Grammar, which fail to predict such partial effects. I have also shown that the subfeatural approach is superior to more traditional analyses based solely on binary features, in that it offers a simpler, more intuitive, and more explanatory account of the vowel-harmony system of Laal.

The theory of subfeatural representations proposed here is also a theory of the interface between phonetics and phonology, whereby phonology and phonetics are separate, but mediated by the phonetically grounded, abstract representations of phonetic knowledge, reified into subfeatures.

Finally, future research in phonetics and phonology may benefit from including subfeatures. Because they represent non-fine-grained, non-contrastive properties, subfeatures show promise for tackling the issue of categories that seem to be ‘intermediate between contrast and allophony’ (Hall 2013: 215), for example, quasi-phonemic contrast (Scobbie and Stuart-Smith 2008; Kiparsky 2013; Kavitskaya 2014; a.o.), covert contrast (Macken and Barton 1980; Maxwell and Weismer 1982; a.o.), incomplete neutralisation (Dinnsen and Garcia-Zamor 1971; Port et al. 1981; Slowiaczek and Dinnsen 1985; a.o.), near-mergers (Labov et al. 1991), or phonetic analogy effects (Steriade 2000), which are still a problem for phonological theory.

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Appendix A Attested cases of doubly triggered rounding harmony

a.	*singular*		*plural* /-u, -ur/	
	bɨ́nàn	‘okra’	/bɨ̂nn-ú/	bûnnú
	bɨ̀g-ál	‘bark’	/bɨ̄g-ū/	būgū
	ɓɨ̀r-à	‘fish hook’	/ɓɨ̀r-ú/	ɓùrú
	ɓɨ̄g-āl	‘tree sp.’	/ɓɨ̄g-ùr/	ɓùgùr
	cɨ́rám	‘tree (sp.)	/cɨ́rm-ú/	cúrmú
	dɨ̄lām	‘type of house’	/dɨ̀lm-ú/	dùlmú
	màl	‘skilled artisan’	/mɨ̀l/ ∼ /mɨ̀lù/	mɨ̀l ∼ mùlù
	sɨ́b-l-ál	‘lie’	/sɨ́b-ùr/	súbùr
	sɨ̀m-à	‘fishing net’	/sɨ̀m-ú/	sùmú
b.	*singular*		*plural* /-o, -or/	
	bàg-à	‘antelope sp.’	/bə̀g-r-ó/	bògró
	báág	‘ostrich’	/bə́ə́g-ó/	bóógó
	ɓàg-ál	‘head’	/ɓə̀g-ór/	ɓògór
	bǎl	‘fish sp.’	/bə̀l-ò/	bòlò
	málɨ̀m	‘Koranic teacher’	/mə̂lm-ó/	môlmó
	màm-ál	‘grand-child’	/mə̀m-ór/	mòmór
	màm-ál wūj	‘fish sp.’	/mə̀m-ór wūjā/	mòmór wūyā
	mə́g-əl	‘mouse’	/mə́g-ór/	mógór
	ɲām ɟām	‘antelope sp.’	/ɲəm ɟə̀m-ó/	ɲəm ɟòmó
	pàb	‘cobra’	/pə̀b-ó/	pòbó
	sààb	‘fabric, garment’	/sə̀ə̀b-ó/	sòòbó
	sám	‘boa’	/sə́m-ò/	sómò
	sāām	‘skin’	/sə́ə́m-ó/	sóómó
	tàb	‘fish sp.’	/tə̀b-ó/	tòbó
	wàár	‘genet’	/wə̀ə̀r-ó/	wòòró
c.	*plural*		*singular* /-o/	
	ndààm-à	‘Ndam people’	/ndə̀ə̀m-ó/	ndòòmó

Appendix B Words included in the Laal study

(a)

condition	*n*			*n*
ə	**10**	dərə́l	5	'fish sp.'
		lə̀r	2	'traps sp.'
		də̀gə́n	2	'drag me'
		gə̄rī	1	'tree sp. (PL)'
B	**22**			
Bə	12	ɓə̂n	6	'pinch'
		mə̀gə̀n	2	'my lower back'
		ɓə̀gyə̀r	2	'fish sp.'
		pə̀gyə́l	2	'quarrel'
əB	10	gə́m	6	'fish sp.'
		gə̀m	1	'fever'
		kə́m	3	'fish sp. (PL)'
BəB	**3**	mə̀mlə̀l	3	'my grandchild'
U	**9**	sə̀gú	4	'tree sp. (PL)'
		kə́rù	5	'fish sp.'

(b)

condition	*n*			*n*
ə	**12**	gə̀gíɲ	2	'disagree'
		gə̄rī	2	'tree sp. (PL)'
		nə̀rə́l	2	'my son'
		lə̀r	3	'wait'
		tə̀grə̀	3	'sieve (gerund)'
B	**60**			
Bə	47	mə̀g	1	'lower back'
		pə́grí	1	'think of me (associative)'
		pə̄nàr	1	'his nose'
		bə̄rī	2	'back'
		mə̀l	2	'be straight'
		mə̀lí	2	'tongues'
		pə́d	2	'pass'
		pə̀gyə́l	2	'quarrel'
		pə̄nà	2	'your nose'
		bə̀g	3	'mat sp.'
		ɓə̀glə̀l	3	'my head'
		ɓə̀nə̀	3	'glue (gerund)'
		mə̀lə̀l	3	'my tongue'
		pə́grə́n	3	'think of me'
		ɓə́l	4	'not yet'
		ɓə̂n	4	'glue, stick'
		pə̄nì	4	'my nose'
		ɓə̀	5	'head (genitive)'
əB	13	gə́m	1	'fish sp.'
		gə̀m	2	'fever'
		nə̀m	3	'my brother'
		tə́bí	3	'tell'
		kə́m	4	'fish sp. (PL)'
BəB	**3**	mə̀mlə̀l	3	'my grand-child'

condition	*n*			*n*
U	**6**	sə̀gó	1	'tree sp. (PL)'
		də́nù	5	'tree sp. (PL)'

Table 6: ə-words. (a) speaker KD; (b) speaker AK.

(a)

condition	*n*			*n*
ɨ	**23**			
		dɨ̀gɲál	6	'fish sp.'
		dɨ̄gɨ̄ɲ	6	'fish sp. (PL)'
		sɨ́gál	1	'ear'
		sɨ́gí	2	'ears (PL)'
		dɨ̀gɨ̀n	2	'be heavy (PL)'
		dɨ̄gā	1	'bad'
		dɨ̀gà	2	'pickaxe'
		dɨ̄lā	2	'fish sp.'
		bɨ̀là	1	'empty'
B	**64**			
Bɨ	52	mɨ̄rā	2	'cows'
		mɨ̄n-nǎŋ	1	'our face'
		ɓɨ̀gál	1	'tree sp.'
		bɨ̀gà	1	'shell'
		bɨ̀gál	2	'pubis'
		bɨ̀glɨ̀l	3	'my pubis'
		bɨ̀gí nùrú	1	'our pubis'
		bɨ̀glàl	1	'his pubis'
		mɨ̄g	3	'pass (PL)'
		bɨ̀l	1	'trash'
		mɨ́ná	4	'thing'
		bɨ́nàn	1	'gombo, okra'
		ɓɨ̀rà	1	'fish hook'
		mɨ̀dál	1	'evening'
		mɨ̀lɨ̀l	1	'my eye'
		mɨ̀làl	1	'his eye'
		mɨ́n(í)	2	'eyes'
		mɨ̄rgā	1	'beers'
		mɨ́rííl	1	'plant sp.'
		ɓɨ̀lál	4	'speech'
		ɓɨ̀dɨ́l	1	'one'
		pɨ́rɨ́l	5	'catch me'
		pɨ́nán	2	'millet shaft'
		pɨ́r	3	'catch'
		pɨ̄lā	2	'debt'
		pɨ̄l	2	'refuse'
		ɓɨ̀l	1	'hole'
		bɨ̄rgā	1	'hurry'
		ɓɨ́lá	2	'speak'
ɨB	12	lɨ̀bár	4	'plunge, immerse'
		nɨ̀mɨ́l	1	'kin'
		nɨ̄mɨ̄n	1	'salt'
		sɨ̀mà	2	'fishing net'

condition	*n*			*n*
		tɨ̀bà	2	'tobacco'
		dɨ̀mɨ́l	2	'Bagirmi'
ɨCB	1	lɨ̀gmà	1	'horses'

(b)

condition	*n*			*n*
ɨ	**41**	dɨ̀g	3	'be bad (PL)'
		dɨ̄gā	3	'be bad'
		dɨ̄gɨ̄ɲ	2	'fish sp. (PL)'
		dɨ̀gɲál	1	'fish sp.'
		dɨ̄g	1	'draw water'
		dɨ̂gɨ̀	1	'draw water (GERUND)'
		dɨ̂lɨ̀	1	'cut (GERUND PL)'
		gɨ́g	1	'doubt'
		gɨ́ná	1	'net sp.'
		kɨ̀n	1	'arrive (PL)'
		lɨ̀gɨ̀	2	'braid (GERUND PL)'
		lɨ̀r	1	'wait'
		nɨ̀ŋɨ̀	1	'throw (GERUND PL)'
		sɨ̀g	3	'how many/much'
		sɨ̄g	3	'stand (PL)'
		sɨ̀gí	2	'ears'
		sɨ̀glà	1	'your ear'
		sɨ̀glàn	2	'its ear'
		sɨ̀glə̀l	1	'my ear'
		sɨ́ŋ	3	'stamp (PL)'
		sɨ́r	2	'drink'
		sɨ̀rɨ̀	2	'drink (GERUND)'
		tɨ̄n	1	'lie down'
		tɨ́rí	2	'beams'
B	**97**			
Bɨ	48	bɨ̀l	5	'trash'
		bɨ̀n mɨ̄n	2	'my forehead'
		bɨ́nàn	3	'okra'
		ɓɨ̀dɨ́l	3	'one'
		ɓɨ̀l	4	'hole'
		ɓɨ̀lál	3	'speech'
		ɓɨ̄lāy	1	'holes'
		mɨ̄lā	1	'eye'
		mɨ̀lɨ̀	4	'stab (GERUND PL)'
		mɨ́n nì	1	'my eyes'
		mɨ́ná	3	'thing'
		mɨ̄rā	7	'cow'
		mɨ̄rgā	1	'alcohol (PL)'
		mɨ́rɨ́íl	1	'plant sp.'
		pɨ̄l	2	'refuse (PL)'
		pɨ́r	4	'catch'
		pɨ̀rɨ̀	1	'catch (GERUND)'
		mɨ̀ɨ̀rnǎŋ	1	'curse (PL) us (incl)'
		mɨ̀ɨ̀rnɨ̀rí	1	'curse (PL) them'
ɨB	49	dɨ̄b	1	'forge'

condition	*n*			*n*
		dɨ̄m	5	‘Bagirmi people’
		dɨ̀mɨ́l	3	‘Bagirmi’
		dɨ́b	3	‘hit’
		dɨ́bàn	1	‘hit it’
		dɨ̂bɨ̀	5	‘hit (GERUND)’
		dɨ̄m	1	‘moor’
		dɨ̂mɨ̀	5	‘moor (GERUND)’
		lɨ̀mɨ̀	3	‘measure (GERUND)’
		nɨ̀bɨ̀	1	‘smoke fish (GERUND PL)’
		nɨ̄mɨ̄n	6	‘salt’
		nɨ̀mɨ́r	1	‘my sister’
		sɨ̀mà	4	‘fishing net’
		tɨ́màn	1	‘its paw’
		tɨ́már	2	‘his hand’
		tɨ́mí	2	‘hands’
		tɨ́mɨ́r	5	‘my hand’
U	**1**	gɨ́nù	1	‘net sp. (PL)’

Table 7: ɨ-words. (a) speaker KD; (b) speaker AK.

Appendix C T-test results

	Hz		ERB				
condition	F2	ΔF2	F2	ΔF2	*t*	*df*	*p*
ə	1598		18.99				
ə/B_	1287	–311	17.23	–1.76	–3.7	24.5	0.001**
ə/_B	1417	–181	18.04	–0.95	2.1	19.9	0.049*
$ə^{B}$	1342	–256	17.57	–1.43	3.4	21.5	0.003**
ə/_...U	1426	–172	18.10	–0.89	2.0	18	0.059
ɨ	1635		19.22				
ɨ/B_	1291	–343	17.25	–1.96	–8.6	59.9	$5.40e^{-12}$***
ɨ/_B	1378	–257	17.80	–1.42	4.1	18.1	$6.67e^{-4}$***
$ɨ^{B}$	1306	–328	17.35	–1.87	8.5	56.0	$1.10e^{-11}$***

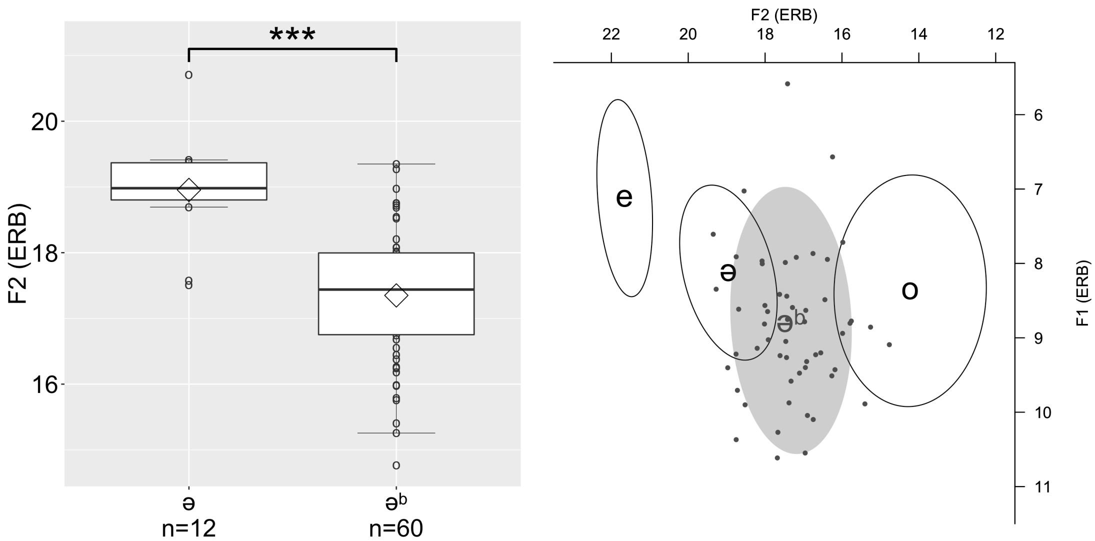
Table 8: *T*-test results for speaker KD

	Hz		ERB				
condition	F2	ΔF2	F2	ΔF2	*t*	*df*	*p*
ə	1583		18.96				
ə/B_	1295	–288	17.30	–1.66	–5.6	20.0	$9.96e^{-6}$***
ə/_B	1333	–250	17.54	–1.42	3.9	22.8	$7.79e^{-4}$***
$ə^{B}$	1304	–279	17.35	–1.61	5.9	18.0	$1.54e^{-5}$***
ə/B_B	1158	–425	16.44	–2.51	8.4	10	$7.72e^{-6}$***
ə/_...U	1473	–110	18.38	–0.57	1.7	13.7	0.12
$ə^{B}$	1304		17.35				
ə/B_B	1158	–146	16.44	–0.91	–4.1	4.7	0,011*
ɨ	1688		19.49				
ɨ/B_	1281	–407	17.24	–2.25	–14.6	79.7	$2.20e^{-16}$***
ɨ/_B	1292	–396	17.29	–2.20	12.5	87.7	$2.20e^{-16}$***
$ɨ^{B}$	1287	–402	17.27	–2.22	15.4	75.0	$2.20e^{-16}$***

Table 9: *T*-test results for speaker AK

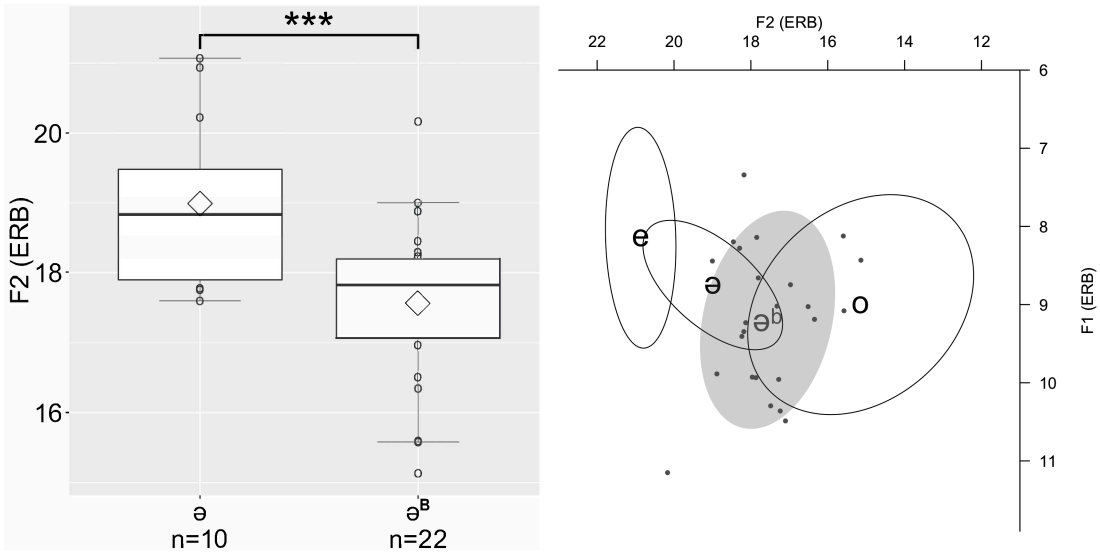
Appendix D Box plots and vowel plots

Figures 11 to 14 contain box plots and vowel plots for the collapsed [ə^{B}] and [ɨ^{B}] categories for the data in Figures 3, 4, 6 and 7 in the paper.



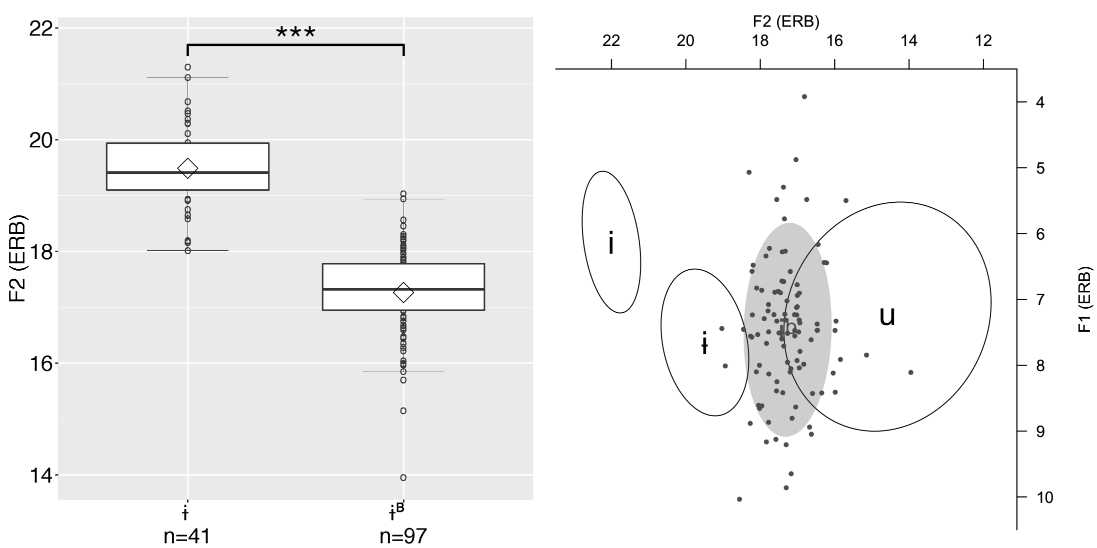
(a) (b)

Figure 11: (a) Overall effect of B condition on F2 of [ə]; (b) [ə^{B}] (= [ə]/B_ and [ə]/_B) plotted against [e], [ə], and [o] (speaker AK).



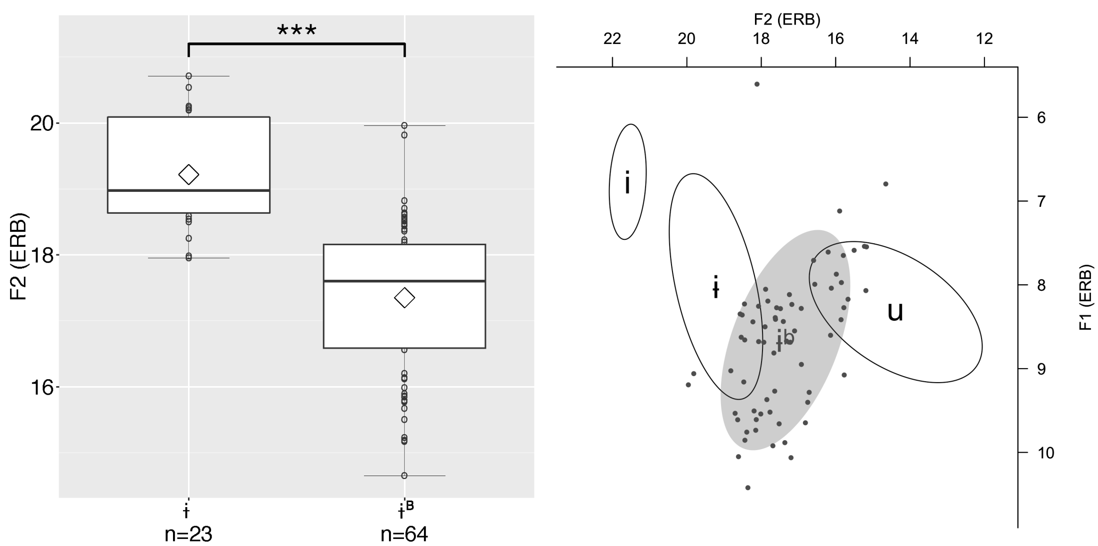
(a) (b)

Figure 12: (a) Overall effect of B condition on F2 of [ə]; (b) [ə^{B}] (= [ə]/B_ and [ə]/_B) plotted against [e], [ə], and [o] (speaker KD).



(a) (b)

Figure 13: (a) Overall effect of B condition on F2 of [ɨ]; (b) [ə^{B}] (= [ɨ]/B_ and [ɨ]/_B) plotted against [i], [ɨ], and [u] (speaker AK).



(a)

(b)

Figure 14: (a) Overall effect of B condition on F2 of [ɨ]; (b) [ə^{B}] (= [ɨ]/B_ and [ɨ]/_B) plotted against [i], [ɨ], and [u] (speaker KD).