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*An articulatory view of Kinyarwanda coronal harmony**

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Coronal harmony in Kinyarwanda causes alveolar fricatives to become postalveolar preceding a postalveolar fricative within a stem. Alveolar and postalveolar stops, affricates and palatals block coronal harmony, but the flap and non-coronal consonants are reported to be transparent. Kinematic data on consonant production in Kinyarwanda were collected using electromagnetic articulography. The mean angle for the line defined by receivers placed on the tongue tip and blade was calculated over the consonant intervals. Mean angle reliably distinguished alveolar and postalveolar fricatives, with alveolars showing a lower tip relative to blade. Mean angle during transparent non-coronal consonants showed a higher tip relative to blade than in contexts without harmony, and the mean angle during transparent [m] was not significantly different than during postalveolar fricatives. This is consistent with a model where Kinyarwanda coronal harmony extends a continuous tip-blade gesture, causing it to be present during 'transparent' segments, but without perceptible effect.

1 Introduction

'Coronal harmonies' are phonological patterns in which certain coronal consonants in a morphological domain are required to match along some dimension, such as the posture of the tongue tip-blade or place of constriction (dental *vs.* alveolar *vs.* postalveolar). Cross-linguistic surveys of coronal harmony are found in Shaw (1991), Gafos (1996), Hansson (2001)

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and Rose & Walker (2004). Kinyarwanda (Bantu; Rwanda) displays an example of coronal harmony. In Kinyarwanda, restrictions are enforced over combinations of sibilant fricatives in a stem. If a postalveolar (retroflex) fricative is preceded by another coronal sibilant fricative, the preceding fricative must also be postalveolar. Thus, a stem like [-ʂiːʐe] 'level off (PERF)' is acceptable, whereas one like [-siːʐe] does not occur. When sibilant fricatives are in non-adjacent syllables, harmony is optional. In this context, intervening non-coronal consonants do not interfere, as in [-aʂamuʐe] 'open one's mouth wide (PERF)'. Coronal harmonies are long-distance in the sense that the matching requirement is enforced not only over coronal consonants in clusters (if such clusters exist in the language) but also over coronals separated by an intervening segment. In some languages, Kinyarwanda included, harmony operates even among coronals separated by multiple syllables. These contexts where consonants intervene form the pivot of our focus.

The long-distance nature of coronal harmony has given rise to a debate that spans phonology and phonetics. Some researchers have claimed or speculated that the tongue tip-blade gesture or feature for which harmony is enforced can occur continuously through segments that intervene between harmonising coronals (Flemming 1995, Steriade 1995, Gafos 1996, Ní Chiosáin & Padgett 1997, Wiltshire & Goldstein 1997, Hamann 2003). This scenario, which we refer to as the Gesture Extension model, grew out of the observation that tip-blade gestures are largely independent of the articulators involved in non-coronal consonants (e.g. lips for labials, tongue dorsum for velars) and of tongue postures for vowels (involving the tongue body). This model posits that the tip-blade gesture involved in the harmony is present during intervening segments but without significant perceptible effect, with the result that intervening segments are seemingly transparent, i.e. they have no perceived coronal quality. For example, in the case of Kinyarwanda coronal harmony, the tip-blade gesture characterising postalveolar fricatives would persist during segments that intervene between harmonising sibilants, but without having sufficient acoustic consequences to be noticed as such by listeners. However, an alternative scenario has been posited for (certain) coronal harmonies, namely one in which the relevant tip-blade gesture is genuinely interrupted by intervening segments, resulting in separate instances of the tip-blade gesture in the harmonising consonants (Clements 2001, Hansson 2001, Rose & Walker 2004, McCarthy 2007).[1] We call this the Repeated Gesture model. An observation cited in support of this model is that coronal harmonies typically do not show blocking effects, i.e. they are not obstructed by the occurrence of certain intervening segments (cf. Hansson 2007).[2]

[1] See Steriade (1986) for a different perspective, which involves spreading of the [coronal] node in the feature geometry across intervening transparent segments.

[2] Sanskrit *n*-retroflexion harmony is an exception. Hansson (2001) and Rose & Walker (2004) identify Sanskrit as a particular case that shows properties which point to it involving extension of continuous retroflexion between harmonising segments.

This debate invites the instrumental investigation of coronal harmonies to examine whether the relevant tongue tip-blade gesture can be evidenced to occur in a systematic fashion during transparent segments. The present study pursues this by investigating the production of consonants in Kinyarwanda coronal harmony. The Kinyarwanda harmony system has previously been referred to as 'sibilant harmony'; however, here we leave open the question of whether other segments besides sibilants are affected by the harmony system. This research examines the production of sibilant fricatives in the language, as well as the production of certain consonants that appear to be transparent in the harmony and of ones that block harmony. Blocking in coronal harmonies is quite rare; the only other language for which it has been reported is Sanskrit (see the discussion in Hansson 2001 and Rose & Walker 2004). Kinyarwanda therefore offers a unique opportunity to explore transparency together with blocking in the coronal harmony of a contemporary language. This study reports on kinematic data collected to examine Kinyarwanda coronal harmony. The data provide a means of examining whether transparent consonants are articulatorily transparent, as claimed in the Repeated Gesture model, or whether they are merely perceived as transparent, because of the tip-blade gesture's minimal acoustic-auditory effect, as postulated in the Gesture Extension model.

1.1 Coronal harmony in Kinyarwanda

This study examines the standard dialect of Kinyarwanda, which is taught in schools and used in mass media.[3] The consonants of Kinyarwanda are given in (1).

(1) *Kinyarwanda consonant inventory*

	plosive		nasal	fricative		affricate	flap	approximant
labial	p		m		β	pf		w
labio-dental				f	v			
alveolar	t	d	n	s	z	ts		
postalveolar (retroflex)				ʂ	ʐ	tʂ	ɽ	
palatal	c	ɟ	ɲ	ç				j
velar	k	g						
glottal				h				

[3] The majority of Rwanda's population (around 7·5 million) speak Kinyarwanda as a first or second language [National Census Service (2003). *3rd general census of population and housing of Rwanda, August 2002*. Kigali: Ministry of Finance and Economic Planning, Republic of Rwanda]. Kinyarwanda is also spoken by minorities in neighbouring areas, i.e. in the south of Uganda, in the north-east of Congo-Kinshasa and the north of Burundi (Rugege 1984).

There has been debate about the articulation of certain coronal consonants. Walker & Mpiranya (2006) report preliminary acoustic and articulatory observations that are consistent with characterising the postalveolar obstruents and flap as retroflex. Kimenyi (1979: 2) labelled the postalveolar obstruents as 'alveopalatal', but did not report any instrumental analysis. Classification of the flap with the postalveolar consonants is consistent with Sibomana (1974: 5) (cf. Kimenyi 1979). We transcribe and refer to the coronals in question as retroflex here, but also investigate their articulation in our study. The following nasal–obstruent articulatory sequences occur in the language: [$^{\text{m}}$b $^{\text{ɱ}}$f $^{\text{ɱ}}$v $^{\text{n}}$s $^{\text{n}}$z $^{\text{ɳ}}$ʂ $^{\text{ɳ}}$ʐ $^{\text{ɳ}}$ɖ $^{\text{ɲ}}$c $^{\text{ɲ}}$ɟ $^{\text{ŋ}}$g].[4] The stop that we transcribe as [$^{\text{ɳ}}$ɖ] has usually been characterised as alveolar in prior descriptions (e.g. Kimenyi 1979: 3), which we presume were based on auditory perception, but Sibomana (1974: 8) characterised it as postalveolar. As we discuss in §3.1, we find articulatory evidence that this consonant is retroflex. Kinyarwanda has the following vowels /i iː e eː a aː o oː u uː/. Tones are low, high, rising and falling.

Kinyarwanda displays a canonical Bantu morphological structure, in which the stem consists of the root + suffixes, with prefixes external to the stem domain. Coronal harmony is enforced within Kinyarwanda stems only. In those transcriptions below that exclude prefixes, the root is preceded by '-', according to convention.

The data in (2) show that sibilant fricatives occur in a contrastive distribution when the stem does not contain another coronal consonant.

(2)	a.	[gusuka]	'pour (INF)'
		[guʂuka]	'deceive (INF)'
	b.	[guhísa]	'make pass (INF)'[5]
		[guhíʂa]	'hide (INF)'
	c.	[$^{\text{n}}$zoːga]	'I will wash (myself)'
		[$^{\text{ɳ}}$ʐoːga]	'I scoff'
	d.	[akazuː$^{\text{ŋ}}$ga]	'vertigo (DIM)'
		[akaʐuː$^{\text{ŋ}}$ga]	'spear sp. (DIM)'

We base our description of Kinyarwanda coronal harmony on Walker & Mpiranya (2006). Previous descriptions include Kimenyi (1979) and Coupez (1980). The harmony requires that a sibilant fricative be realised as retroflex when it precedes [ʂ ʐ] in an adjacent syllable. The phonotactics of Kinyarwanda prevent clusters of sibilants; so sibilants are minimally

[4] While there is general agreement in the literature that nasal–obstruent sequences form a cluster underlyingly, controversy surrounds their syllabification and whether they are realised as single prenasalised consonants (Sibomana 1974, Kimenyi 1979, Coupez 1980, Jouannet 1983, Mpiranya 1998) or as consonant clusters (Myers 2005; see Downing 2005 for a cross-Bantu perspective). We transcribe nasal–obstruent articulatory sequences as single segments and refer to them as prenasalised consonants, but this assumption is not critical.

[5] This form is derived from /ku-hít-i-a/ → gu-hís-a → [guhísa].

separated by a vowel. As a result of the harmony, sequences in adjacent syllables such as [… s … ʐ …] are excluded (under any voicing combination in the fricatives), whereas sequences like [… ʂ … ʐ …] are permissible (again, under any voicing combination). Prenasalised fricatives also participate.

Stems illustrating the harmony are given in (3). (It may be observed in these stems that the agentive suffix /-i/ and the perfective formation /-i-e/ cause a stem-final alveolar fricative to become retroflex. In some contexts with an underlying suffix /-i-/, the perfective is expressed with the allomorph [-iʐe], which becomes [-eʐe] in (5) below, through vowel-height harmony.)

(3)	-sas-+i	→	[-ʂaʂi]	‘bed maker’
			cf. [-sasa]	‘make the bed (INF STEM)’
	-soː^{n}z-+i	→	[-ʂoː^{n}ʐi]	‘victim of famine’
			cf. [-soː^{n}za]	‘be hungry (INF STEM)’
	-sáːz-+i-e	→	[-ʂáːʐe]	‘become old (PERF)’
	n-sáːz-+i-e	→	[^{n}ʂaːʐe]	‘I am old (PERF)’
			cf. [-sáːza]	‘become old (INF STEM)’
	-úzuz-+i-e	→	[-úʐuʐe]	‘fill (PERF)’
			cf. [-úzuza]	‘fill (INF STEM)’
	βa-n-ziz-i+iʐe	→	[βaː^{n}ʐiʐiʐe]	‘they punished me (for sth) (PERF)’
			cf. [βaː^{n}ziza]	‘they punish me (for sth) (IMPERF)’

Following terminological custom, the retroflex fricative that comes later in the stem is referred to as the trigger in this harmony system and the sibilant fricative that precedes it as the target.

The harmony enforces agreement only in sibilant fricatives that precede a retroflex fricative, as evident by comparing the stem [-ʂise] ‘penetrated’ with the harmonising stems in (3). The example [-ʂise] also demonstrates that the harmony is asymmetric in the sense that alveolar fricatives do not trigger harmony in a preceding retroflex fricative.

Coronal harmony is optional when the trigger and target are in non-adjacent syllables, as shown in (4).[6] Segments that intervene between harmonising sibilants are characterised as transparent, because they are not perceived as noticeably different from their counterparts in non-harmony contexts. Transparent consonants are non-coronals and [ɾ]. Comparison with infinitive or imperfective forms that lack a harmony trigger demonstrates that optional retroflex fricatives arise from coronal harmony.

[6] Harmony triggered by the fricative in the long causative suffix [-iːʂ-(i)-] affects sibilant fricatives in preceding adjacent syllables only and optionally affects ones in root-initial position (Mpiranya & Walker 2005).

(4)	[-ásamuʐe] or [-áʂamuʐe]	‘open one’s mouth wide (PERF)’
	cf. [-ásamuza]	(INF STEM)
	[-sakaːʐe] or [-ʂakaːʐe]	‘cover (the roof) with (PERF)’
	cf. [-sakaːza]	(INF STEM)
	[-zímagiʐe] or [-ʐímagiʐe]	‘mislead (PERF)’
	cf. [-zímagiza]	(INF STEM)
	[-seɽuʐe] or [-ʂeɽuʐe]	‘provoke, irritate (PERF)’
	cf. [-seɽuza]	(INF STEM)
	[^{n}suː^{m}biʐe] or [^{ɳ}ʂuː^{m}biʐe]	‘I surpass (someone with regard to something) (PERF)’
	cf. [^{n}suː^{m}bja]	(IMPERF)

A notable property of the harmony system is that it involves blocking by alveolar and retroflex stops (5a, b), palatal consonants (5c) and the alveolar affricate, which also does not undergo harmony (5d).

(5)	a.	[-síːtaːʐe]	‘make stub (PERF)’
		[-sódoːkeʐe]	‘make move slowly (PERF)’
		[-súnuːkiʐe]	‘show furtively (PERF)’
	b.	[-sáː^{ɳ}ɖaːʐe]	‘make explode (PERF)’
	c.	[-zígaɲiʐe]	‘economise (PERF)’
		[-zújaːʐe]	‘become warm (liquid) (PERF)’
	d.	[setsaguʐe]	‘cause to carve up (PERF)’

Unlike the data in (4), an alternative form where the first sibilant is retroflex is not available in (5). Yet there is no general distributional restriction that would prevent a retroflex fricative from occurring in a syllable preceding the consonants in question, as shown by examples like [guʂiːtura] ‘to scrape off’, [umuʐiɲá] ‘anger’, [imiʂáːjaːjo] ‘slow dance (sp.)’, [guʂáː^{ɳ}ɖika] ‘to attach’, [kuʐuː^{ɳ}ɖika] ‘to keep in mouth’.

Only retroflex sibilants trigger harmony. That [^{ɳ}ɖ] does not trigger retroflex harmony is seen in (5b). In the absence of a sibilant trigger for harmony, retroflex and alveolar fricatives display a contrastive distribution before [ɽ], as seen in (6a) *vs.* (b). As [ʈʂ] is rare in post-initial position in the stem, there are no examples with which to test whether it would trigger harmony.

(6)	a.	[-ziɽa]	‘be forbidden (taboo)’
	b.	[-ʂíɽa]	‘finish (INTR)’
		[-ʐuːɽa]	‘thief’

In summary, Kinyarwanda coronal harmony requires that a sibilant fricative preceding a retroflex fricative be realised as retroflex. Intervening segments are not perceptibly affected. The harmony is obligatory in adjacent syllables and optional in non-adjacent syllables. As for the other coronals, [ɽ] is transparent, but retroflex stops, palatal consonants, and alveolar stops and affricates block harmony.

1.2 Research questions for this study

Our research questions concern the characterisation of various consonants' articulations and their roles within Kinyarwanda coronal harmony. In what follows, contexts are schematised with 'V' symbolising a vowel and the embedded square brackets indicating the consonant whose articulation is being measured.

General articulation. We investigate the geometry of the tongue tip and blade in the following consonants: [ʂ ʐ] (*vs.* [s z] respectively), [ⁿɖ] (*vs.* [t]) and [ɽ] (*vs.* [t]).[7]

Simple harmony. We investigate whether retroflex fricatives in a target context for coronal harmony (harmony context [...[ʂ]Vʂ...]) are produced with a tongue tip-blade geometry that is not distinct from their counterparts in a non-harmony context ([...[ʂ]Vt...]).

Blocking: (i) *Blocking consonants*. Cross-linguistically, blocking consonants may differ in whether they are affected by or exhibit the harmonising gesture. With this in mind, we investigate whether there is a difference in the geometry of the tongue tip-blade during [t] and [ⁿɖ] in a blocking context ([...sV[t]Vʐ..., ...sV[ⁿɖ]Vʐ...]) *vs.* a non-harmony context ([...sV[t]Vz..., ...sV[ⁿɖ]Vz...]).

(ii) *Potential targets that precede blockers*. We investigate whether consonants that are reported to block harmony genuinely block it. We examine whether there is a difference in the geometry of the tongue tip-blade during an alveolar fricative in a blocking context ([...[s]VtVʐ..., ...[s]VⁿɖVʐ...]) *vs.* a non-harmony context ([...[s]VtVz..., ...[s]VⁿɖVz...]). If [t] and [ⁿɖ] block coronal harmony, the fricatives under comparison should not differ significantly in their tip-blade posture, whereas if harmony affects the fricative in the blocking context, the fricatives should differ significantly in this respect.

(iii) *The non-trigger status of* [ⁿɖ]. We examine whether [ⁿɖ] triggers harmony (although it is not reported to). We evaluate whether there is a difference in the geometry of the tongue tip-blade during an alveolar fricative in an [ⁿɖ] context ([...[s]Vⁿɖ...]) *vs.* during a retroflex fricative (pooling across the contexts of non-harmony [...[ʂ]Vt...] and harmony [...[ʂ]Vʂ...]). If [ⁿɖ] triggers harmony, one could expect the alveolar and retroflex fricatives under comparison not to differ significantly in tip-blade posture; otherwise they should differ significantly in this regard.

'*Transparent' non-coronal consonants*. To empirically assess the Gesture Extension *vs.* Repeated Gesture models for Kinyarwanda coronal harmony, we investigate whether retroflexion is present in harmony contexts during non-coronal consonants that are perceived as transparent. We ask

7 [t] was chosen to compare with [ɽ] and [ⁿɖ] rather than [d], because the occurrence of [d] in Kinyarwanda is quite limited.

whether there is a difference in the geometry of the tongue tip-blade during [m] and [k] in a harmony context ([…ʂV[m]Vʐ…, …ʂV[k]Vʐ…]) *vs*. a failed harmony context ([…sV[m]Vʐ…, …sV[k]Vʐ…]) *vs*. a non-harmony context ([…sV[m]Vz…, …sV[k]Vz…]). 'Failed harmony' refers to the pronunciation option in which coronal harmony fails to occur in non-adjacent syllables. A finding of no significant difference for the tip-blade posture during [m] and [k] across these contexts would be consistent with the Repeated Gesture model. If the tip-blade posture during [m] and [k] in the harmony context was like that of the retroflex fricatives, and significant differences were only found between the harmony context *vs*. each of the others, then the Gesture Extension model would be supported for Kinyarwanda.

The status of [ɽ] *in harmony*: (i) *The non-trigger status of* [ɽ]. We examine whether there is a difference in the geometry of the tongue tip-blade during an alveolar fricative in an [ɽ] context ([…[s]Vɽ…]) *vs*. a non-harmony context ([…[s]Vz…]). If no significant difference was found in the two contexts, that would be consistent with [ɽ] not triggering harmony. If a difference was found in the two contexts, then it would be necessary to examine the difference further to assess its implications.

(ii) '*Transparent*' [ɽ]. We ask if there is a difference in the geometry of the tongue tip-blade during [ɽ] in a harmony context ([…ʂV[ɽ]Vʐ…]) *vs*. a failed harmony context ([…sV[ɽ]Vʐ…]) *vs*. a non-harmony context ([…sV[ɽ]Vz…]). A finding of no significant difference for [ɽ] in the harmony context *vs*. the other contexts would be consistent with harmony not affecting [ɽ]. If differences were found, further data analysis would be necessary to assess their source and theoretical implications.

2 Method

The Carstens Articulograph AG200 EMA magnetometer system was used to track horizontal and vertical movements of receivers adhered to the tongue tip and blade. In addition to two reference receivers on the bridge of the nose and on the maxillary gum, two receivers were placed on the tongue: on the tongue tip, 7 mm behind the extended tip, and on the tongue blade, 7 mm behind the receiver on the tongue tip. All receivers were placed in the midsagittal plane. The kinematic data were sampled at 200 Hz, and the resulting position function (and velocities) were low-pass filtered at 15 Hz. An audio recording, sampled at 16 kHz, was made simultaneously with the collection of articulatory data. Articulatory data were corrected for head movement and rotated to the occlusal (bite) plane, which defines the x-axis in the head-based coordinate system.

Subject. Articulatory kinematic data were acquired from one native male speaker of the standard dialect of Kinyarwanda (the third author of this paper), using the EMA magnetometer system. This subject was raised in Rwanda, where he lived until he was 28, after which he resided in France, where he continued to speak Kinyarwanda at home. At the time the data were collected, he had been residing in the United States for five months.

stimulus	transcription		no.
soma bajaata gusa	[βaʐaːta]	(nonce form)	9
soma basaandaaje gusa	[βasaːⁿɖaːʐe]	'they blew up'	7
soma basaandaaze gusa	[βasaːⁿɖaːze]	'blow them up'	6
soma basaaraaje gusa	[βasaːɽaːʐe]	(nonce form)	7
soma basakáaje gusa	[βasakáːʐe]	'who have covered (the roof) with'	7
soma basakáaze gusa	[βasakáːze]	'let them cover (the roof) with'	7
soma basamáaje gusa	[βasamáːʐe]	'who are attractive'	7
soma basamáare gusa	[βasamáːɽe]	'let them get distracted'	7
soma basamáaze gusa	[βasamáːze]	'let them be attractive'	8
soma basaraje gusa	[βasaɽaʐe]	'they made someone lose voice'	8
soma basaraze gusa	[βasaɽaze]	'make them lose voice'	7
soma basaré gusa	[βasaɽé]	'let them get foolish'	7
soma basataje gusa	[βasataʐe]	(nonce form)	6
soma basataze gusa	[βasataze]	(nonce form)	7
soma basazé gusa	[βasazé]	'who just became foolish'	7
soma bashakáaje gusa	[βaʂakáːʐe]	'who have covered (the roof) with'	7
soma bashamáaje gusa	[βaʂamáːʐe]	'who are attractive'	6
soma basharáaje gusa	[βaʂaɽáːʐe]	(nonce form)	7
soma basharaje gusa	[βaʂaɽaʐe]	'they made someone lose voice'	8
soma bashashé gusa	[βaʂaʂé]	'who have made the bed'	7
soma bashata gusa	[βaʂata]	(nonce form)	7
soma batarata gusa	[βataɽatá]	'who do not fail (an exam)' (loan)	6
soma bazaata gusa	[βazaːta]	'they will throw'	5

Table I

The collected data. The first column gives the stimuli as presented to the subject to speak aloud. The second column gives the transcription of the target word; its English gloss is given in the third column. The final column gives the number of viable tokens recorded for each target word.

In addition to Kinyarwanda, which is his first language, the subject is fluent in Swahili, French and English. This is the only articulatory/kinematic dataset of Kinyarwanda of which we are aware, and as such, it contributes not just to the phonological questions of interest but also to the phonetic knowledge of the language. Our findings are for the particular speaker under study. Although we do not have reason to expect our findings to be unique to this speaker, we have no direct evidence which would allow us to extend them to other speakers of this dialect (see Gick *et al.* 2006 for a recent acoustic and lingual ultrasound study on related topics in Kinande vowel harmony).

Stimuli. The target words for this study are given in Table I and the comparisons in Table II (seven additional words were recorded that are not analysed here).[8] Where possible, actual words of Kinyarwanda

[8] Duration of the vowels flanking [t] *vs.* [ⁿɖ] were not matched in the stimuli, because we had not anticipated finding retroflexion in the prenasalised stop when the data were collected.

research question	items compared
general articulation: [ʂ] *vs.* [s]	[βaʂata] [βasataze]
general articulation: [ʐ] *vs.* [z]	[βaʐaːta] [βazaːta]
general articulation: [ʈ] *vs.* [t]	[βataʈatá] [βasataze]
general articulation: [ⁿɖ] *vs.* [t]	[βasaːⁿɖaːze] [βasataze]
simple harmony: harmony context [ʂ] *vs.* non-harmony context [ʂ]	[βaʂaʂé] [βaʂata]
blocking consonants: blocking context [ⁿɖ t] *vs.* non-harmony context [ⁿɖ t]	[βasaːⁿɖaːʐe] [βasataʐe] [βasaːⁿɖaːze] [βasataze]
potential targets preceding blockers: blocking context [s] *vs.* non-harmony context [s]	[βasaːⁿɖaːʐe] [βasataʐe] [βasaːⁿɖaːze] [βasataze]
[ⁿɖ]'s non-trigger status: [ⁿɖ] context [s] *vs.* harmony context [ʂ] and non-harmony context [ʂ]	[βasaːⁿɖaːʐe] [βasaːⁿɖaːze] (pooled) [βaʂaʂé] [βaʂata] (pooled)
'transparent' non-coronal consonants: harmony context [m k] *vs.* failed harmony context [m k] *vs.* non-harmony context [m k]	[βaʂamáːʐe] [βaʂakáːʐe] [βasamáːʐe] [βasakáːʐe] [βasamáːze] [βasakáːze]
[ʈ]'s non-trigger status: [ʈ] context [s] *vs.* non-harmony context [s]	[βasaʈé] [βasazé]
'transparent' [ʈ]: harmony context [ʈ] *vs.* failed harmony context [ʈ] *vs.* non-harmony context [ʈ]	[βaʂaʈaʐe] [βasaʈaʐe] [βasaʈaze]

Table II

Target words compared for each research question. Where indicated, an item is pooled with the one immediately above it.

were used; only six nonce forms were used, all morphophonologically well-formed in the language. Words were pronounced in the carrier phrase [soma]__[gusa] 'read__only'. Words were separated into seven blocks. Each word occurred once within a block, resulting in seven tokens

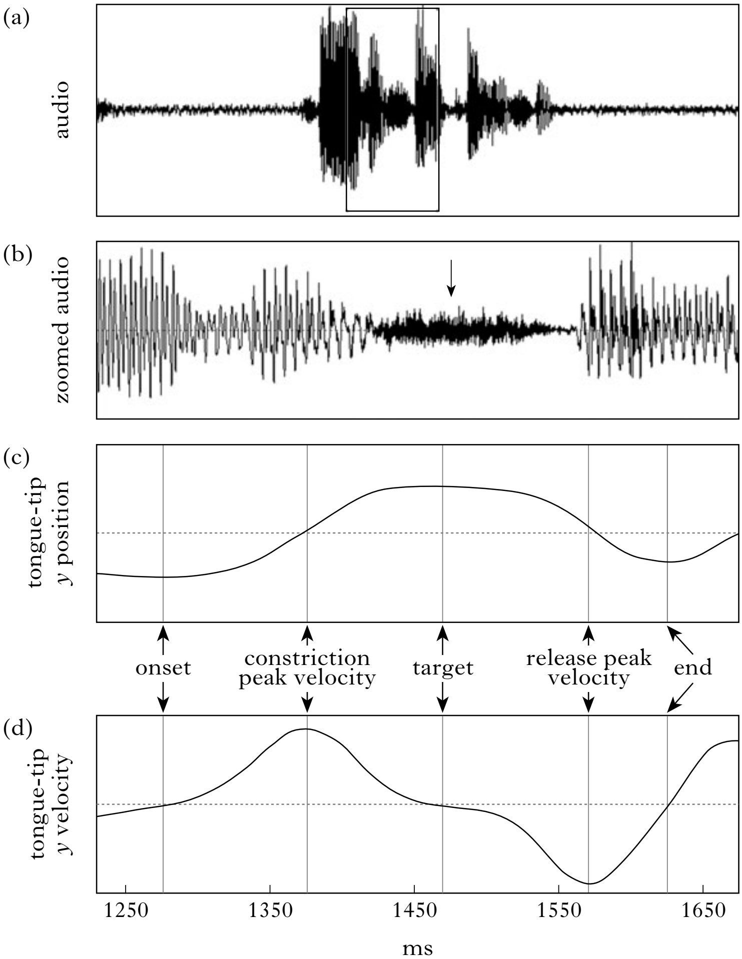

Figure 1

A token of [soma baṣata gusa] 'read (nonce word) only', showing the audio signal (a), zoomed audio signal (b), the tongue-tip *y*-position trajectory (c) and tongue-tip *y*-velocity trajectory (d). Maximum displayed tongue-tip *y* position is −15 mm and minimum is −26 mm. In the trajectories, the algorithmically defined timepoints of consonant onset, target and end (determined by velocity zero crossings) and of constriction and release peak velocities (determined by velocity extrema) are shown. The arrow indicates the [ṣ] of [baṣata].

for each word; the order within each block was randomised. Words were printed with their carrier phrases on a page that was presented to the subject to speak aloud at a normal speech rate.[9] Pairs of word forms in

[9] Phrases were presented to the subject in 'scientific' orthography, which is the same as Kinyarwanda's standard or 'common' orthography, except that it shows long vowels as a sequence of two identical vowel symbols and it marks high tones with an

which harmony has optionally applied or not applied between fricatives in non-adjacent syllables have the same meaning. The spelling of the stimuli indicated to the subject whether to produce the word with or without harmony. It was later verified that the speaker produced the form that matched the spelling by listening to the audio recording. Three stimuli are not included in the comparisons in the table, but were analysed in follow-up to results obtained for [ɽ]. The number of viable recordings for each word is notated in Table I. The total number of tokens collected for analysis in this study was 160.[10]

As is evident in Table II, the stimuli do not form a fully crossed factorial design. In order to test our hypotheses, we examine subsets of the data with specific contrasts that address the specific questions laid out in §1.2. In our analyses, we look at the data both globally and in specifically controlled segmental contexts.

Data analysis: kinematic landmarks. Kinematic landmarks were algorithmically identified for the alveolar and postalveolar consonants on the basis of the movement trajectory of the tongue-tip receiver in the vertical (y) dimension for the creation of the coronal consonant constriction. Over the course of a consonantal constriction and release, five significant articulatory landmarks were identified, based on tongue-tip y-velocity trajectory (see Fig. 1). Marking the onset of the constriction movement, a y-velocity zero-crossing occurs, generally during the acoustic interval of the preceding vowel. This is followed by a point at which y-velocity reaches a peak as the coronal constriction is taking place. Next, the consonant's constriction extremum is defined by a second y-velocity zero-crossing. As the constriction is released, a second y-velocity extremum occurs. The end of the interval of articulatory consonant release is identified by a third tongue-tip velocity zero-crossing.

Using a modified version of the Matlab-based MAVIS environment (Tiede *et al.* 1999) and a synchronised waveform display, the time and tip and blade y-position were recorded at each of the five articulatory landmarks for the consonant.[11] Figure 1 provides an example data token [baʂata] with the timepoints marked (onset, constriction peak velocity, target, release peak velocity, end). The interval from consonant onset to end is the constriction + release interval. Henceforth, we refer to this as the 'constriction interval'.

acute accent. Low tones are unmarked in the language's orthography and in our transcriptions. In our transcription of tone on long vowels, high-low tone sequences, which are realised as falling tones, are represented as [á:]. Double high tones and rising tones did not appear in our stimuli.

10 Six tokens were excluded due to misrecording or because the word was mispronounced. A recording error in the third block resulted in extra repetitions of some target words.

11 In one token of [βasaɽaʐe], no y-velocity extremum occurred to identify the release of the constriction for [ɽ], so this consonant was excluded from measurements.

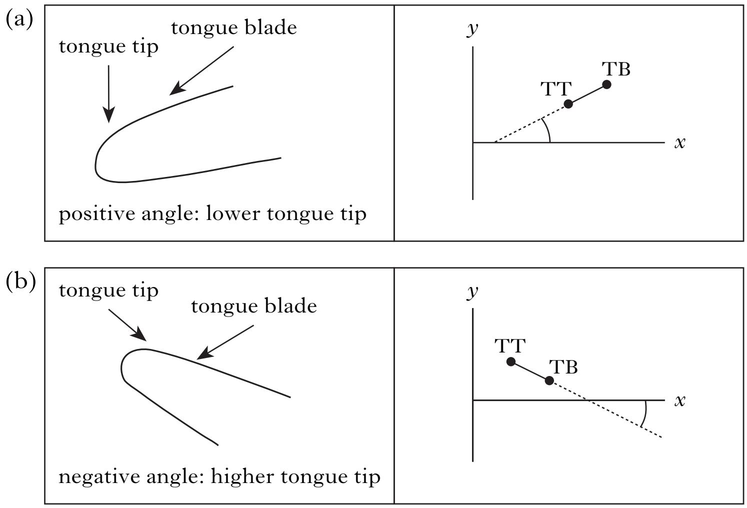

Figure 2

Illustration of a positive angle measurement (a) and negative angle measurement (b). Left panels depict the height of tongue tip (TT) relative to tongue blade (TB) in the occlusal plane. The corresponding coordinate systems showing the angle measured are depicted in the right panels.

Statistical testing. In statistical tests, the levels for the harmony context factor varied as appropriate for the particular question under examination, but they included the following, using the labels identified in §1.2: harmony, non-harmony, failed harmony, blocking, [ⁿɖ] and [ɽ]. Consonant identity was an additional factor in many tests. For statistical tests, a criterial p value was set at $p < 0{\cdot}05$.

Preanalysis testing. Inspection of a variety of measures derived from the five articulatory landmarks identified a measure we call 'mean angle', in (7a), as the ideal articulatory variable of interest for our questions about the articulation of consonants in Kinyarwanda coronal harmony. To identify the interval for the bilabial and velar consonants under study ([m k]), the acoustic beginning and end were marked using information from the speech signal spectrogram and waveform, giving rise to the separate definition in (7b).[12]

[12] The beginning of [m] was marked at the onset of weak nasal formants in the spectrogram. In the waveform this corresponded to a reduction in amplitude and a change in the waveform pattern from that of the preceding vowel. The end of [m] was marked at the onset of (i) the following vowel formants in the spectrogram, (ii) increased intensity and (iii) an alteration in the waveform pattern with high-frequency components. The beginning of [k] was marked at the onset of a silent interval, corresponding to closure. The end of the stop was marked at the release, signalled by a burst transient.

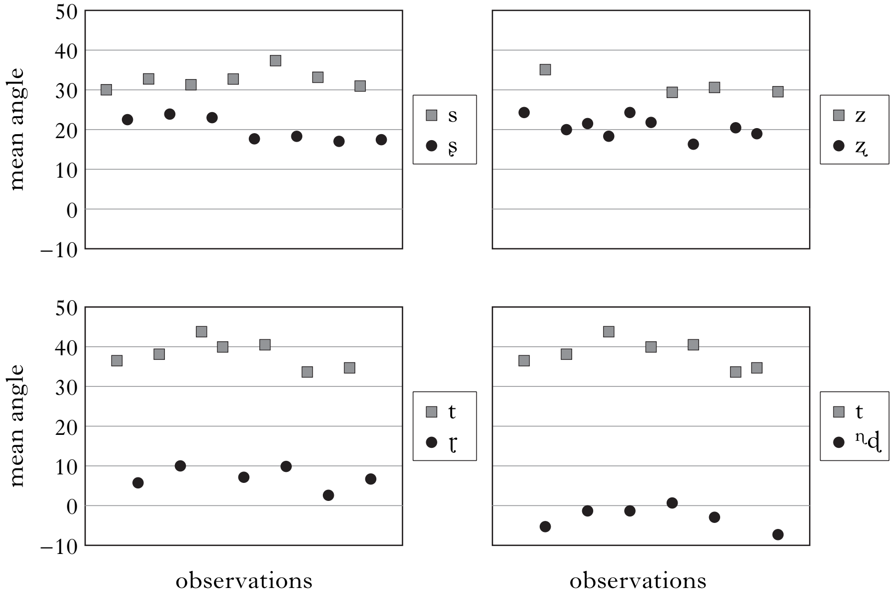

Figure 3

Scattergrams for the variable of mean angle showing observations for different tokens of the relevant segments as produced by the subject speaking aloud the target words for the research question of 'general articulation' in Table II: [s ʂ], [z ʐ], [t ʈ], [t ^{n}ɖ].

(7) a. *Mean angle*
Mean of the angle (in degrees) formed by the line defined by the *x* (horizontal) and *y* (vertical) positions of the transducers adhered to the tongue tip and tongue blade relative to the occlusal plane over the entire constriction interval.

b. *Mean angle for* [m] *and* [k] *intervals*
Mean of the angle (in degrees) formed by the line defined by the *x* and *y* positions of the transducers adhered to the tongue tip and tongue blade relative to the occlusal plane over the [m] or [k] consonant's acoustic interval.

Crucially, the mean angle variable reliably and robustly distinguishes the alveolar and retroflex consonant series (see §3.1), and directly characterises the tongue tip-blade orientation. In other kinematic research, Wiltshire & Goldstein (1997) used an angle measurement for comparison of dental and retroflex consonants in Tamil.

Figure 2 illustrates relative orientations of the tongue tip and tongue blade that correspond to positive *vs.* negative angles and their corresponding coordinate systems. The midsagittal section of the occlusal plane forms the *x*-axis, with the positive direction pointing to the posterior of

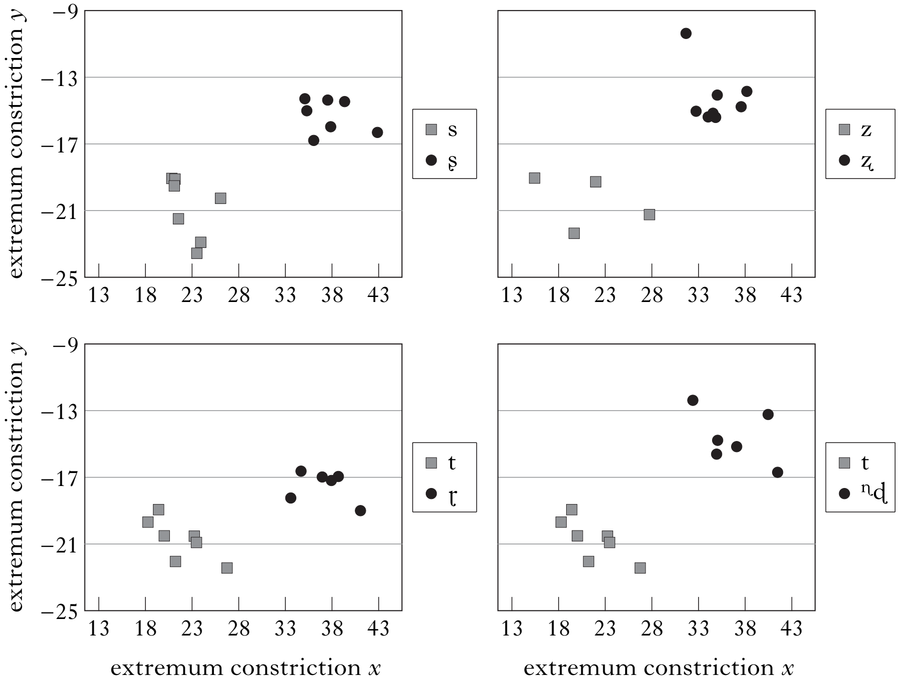

Figure 4

Scattergrams for the variables of tongue-tip extremum constriction position *x* and *y* for [s ʂ], [z ʐ], [t ʈ], [t ⁿɖ].

the mouth. The positive direction of the *y*-axis points to the top of the oral cavity. The *x*- and *y*-positions of the tongue tip and blade transducers define a line. The angle between this line and the *x*-axis was measured. Positive angle values correspond to a lower tongue tip relative to blade, i.e. when the *y*-coordinate of the tongue blade transducer is higher than that of the tongue tip (a). The lower the tongue tip in relation to the blade, the greater the angle. Conversely, when the tongue tip is higher than the blade, the angle measured is negative (b). The lower the negative angle value, the higher the tongue tip is in relation to blade. When the transducers adhered to the tongue tip and tongue blade are level with each other, i.e. their value for *y* is the same, the angle is zero. Alveolar consonants are characterised by a tip-blade angle that is greater than that in retroflex postalveolar consonants, whose tip is raised.

3 Results

3.1 The articulation of postalveolar consonants under study

To evaluate the geometry of the tongue tip-blade in the alveolar and postalveolar consonant pairs [s ʂ], [z ʐ], [t ⁿɖ], [t ʈ], scattergrams

	mean	SD	count
mean angle [s]	32·61	2·38	7
mean angle [z]	31·15	2·68	4
mean angle [ʂ]	19·98	3·00	7
mean angle [ʐ]	20·66	2·65	9
mean angle [t]	38·16	3·55	7
mean angle [ɽ]	7·09	2·89	6
mean angle [ⁿɖ]	−2·88	3·02	6
minimum angle [s]	24·56	3·86	7
minimum angle [z]	19·64	2·19	4
minimum angle [ʂ]	9·34	3·03	7
minimum angle [ʐ]	8·95	3·73	9
minimum angle [t]	28·41	4·93	7
minimum angle [ɽ]	−17·79	5·27	6
minimum angle [ⁿɖ]	−22·71	5·49	6
maximum angle [s]	39·11	3·83	7
maximum angle [z]	39·39	4·39	4
maximum angle [ʂ]	32·13	4·52	7
maximum angle [ʐ]	34·11	4·69	9
maximum angle [t]	47·37	4·70	7
maximum angle [ɽ]	34·56	4·91	6
maximum angle [ⁿɖ]	25·41	2·50	6

Table III

Means table for tongue tip-blade angle in contexts independent of coronal harmony. Measurements are from tokens of the following: [s] in [βasataze], [ʂ] in [βaʂata], [z] in [βazaːta], [ʐ] in [βaʐaːta], [t] in [βasataze], [ɽ] in [βataɽatá], [ⁿɖ] in [βasaːⁿɖaːze].

were generated to compare measurements for the mean angle variable (Fig. 3) and, for descriptive purposes, the articulatory variable of tongue-tip extremum constriction position, plotting *x*-position against *y*-position (Fig. 4).

As can be seen, the variables of mean angle and extremum constriction position differentiate postalveolar from alveolar consonants. The post-alveolar fricatives are produced with a tongue-tip position that is higher and more retracted at the target timepoint than the alveolar fricatives. This is also true of the flap and prenasalised stop in comparison to [t]. (There was one exception: for the variable of extremum constriction position *y*, one token's value for [t] fell in the lower range of values observed for [ɽ].)

All fricatives show a positive mean angle in Fig. 3. The mean angle for the tongue tip-blade over the consonant constriction interval was lower

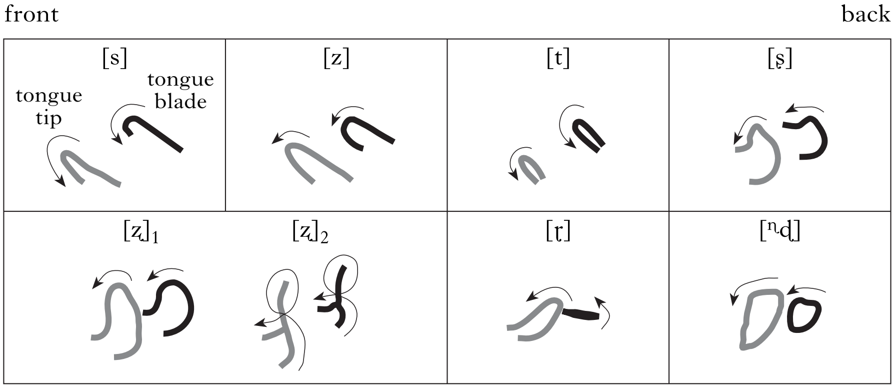

Figure 5

Sample position trajectories of the tongue tip and blade for consonants under study for the research question of general articulation. View is of the head from the left. Arrows indicate direction of movement. The intervals for which trajectories are shown are from the points of minimum tongue tip height preceding and following the target constriction. All retroflex consonants are generally produced in a counterclockwise direction, from back-to-front, although [ʐ] is sometimes produced with a slight clockwise rotation near the peak of constriction. Two types of curvature path were witnessed for [ʐ], indicated as [ʐ]$_1$ and [ʐ]$_2$.

in postalveolar consonants, indicating that the tongue tip is higher relative to tongue blade in the postalveolar consonants than in alveolar ones. Table III gives details of the mean and standard deviation for the following variables for tongue tip-blade angle within the consonant constriction interval: mean angle, minimum angle and maximum angle. The latter is defined in (8). The minimum angle variable is defined in the same way, with ‘minimum’ in place of ‘maximum’.

(8) *Maximum angle*

Maximum value for the angle formed by the line defined by the *x* and *y* positions of the transducers adhered to the tongue tip and tongue blade (relative to the occlusal plane) within the constriction interval.

The maximum angle during a constriction interval corresponds to the point at which the tongue tip is lowest relative to the tongue blade; the minimum angle corresponds to the point at which the tongue tip is highest relative to the blade. These measurements provide information about tip-blade angle extrema that occurred during the consonants' production. Figure 5 provides a visual record of the course of tongue tip and blade movement during the consonants' production.

The minimum angle occurring during a postalveolar fricative is positive. However, minimum angles for [ɽ] and [^{n}ɖ] are consistently negative.

The postalveolar flap and prenasalised stop therefore involve retroflex articulations in which the tongue tip is markedly up and raised higher than the tongue blade. A static palatogram made for this subject's [ⁿɖ] showed that the rearmost extent of linguo-palatal contact was in line with the secondmost-posterior molar – indicating that the tongue is high in the palatal vault – and that the contact is extended forward, as seen in Fig. 5, consistent with a strongly retroflex articulation.[13] On the other hand, the postalveolar fricatives involve retroflex postures in which the tongue tip is only slightly curled up. That the tongue tip was indeed curled up was verified on a separate occasion by inserting a toothpick through the centre of the subject's mouth during production of each postalveolar fricative. The toothpick touched the underside of the tongue, indicating the presence of tongue-tip raising.

In characterising tongue tip-blade orientation in postalveolar consonants, Ladefoged & Maddieson (1996) and Ladefoged (2005) draw a distinction between strong retroflexion, similar to what we found in [ɽ] and [ⁿɖ], and intermediate retroflexion, which we found in the postalveolar fricatives of Kinyarwanda, where the tongue tip is raised to produce a sublingual cavity, but is curled up to a lesser degree. In 'retroflex' articulations of the latter type, the tongue tip is raised higher than the blade than in alveolars, but the tip is not necessarily higher than the blade. The practice of Ladefoged & Maddieson (1996) and Ladefoged (2005) is to transcribe fricatives of this type with the (non-IPA) symbols [ṣ ẓ]. Here we use the standard IPA transcriptions [ʂ ʐ], but a transcription system that distinguishes two degrees of retroflexion would be more precise.

Other examples of fricatives with the lesser degree of retroflexion are found in Standard Chinese and Polish. Our classification of Kinyarwanda postalveolar fricatives as retroflexes of this kind rather than alveolo-palatals (or alveo-palatals) is consistent with articulatory findings on fricative contrasts in these languages. Ladefoged & Maddieson (1996: 151) present x-ray tracings of Chinese for alveolar fricatives and two postalveolar fricative series, characterised as 'flat postalveolar (retroflex)' and 'palatalised postalveolar (alveolo-palatal)'. Alveolo-palatal fricatives show a higher tongue body than retroflex ones, and the tongue-body raising drags the blade higher than in alveolars. Ladefoged & Maddieson (1996: 154) also present diagrams of three coronal fricative series in Polish (based on x-ray data from Puppel *et al.* 1977), using the same descriptive labels as for those in Chinese. Given Ladefoged & Maddieson's diagrams and articulatory descriptions, we expect an alveolo-palatal fricative to present a shape where tongue tip is lower relative to blade than in alveolar

[13] In addition to the kinematic data we collected for this study's subject, we examined the articulation of [ⁿɖ] in another native speaker of Kinyarwanda by inserting a toothpick through the centre of the speaker's mouth during the stop's production. The toothpick made contact with the underside of the tongue, indicating the presence of tongue-tip raising. An investigation with more subjects would be necessary to determine whether variation exists across speakers or dialects in the place of articulation and tongue shape for this stop.

fricatives. Yet this is not what we found in our articulatory data for Kinyarwanda; rather, postalveolar fricatives showed a higher tip relative to blade than alveolars. This is consistent with our characterisation of Kinyarwanda postalveolar fricatives as retroflex in shape.

Further, Walker & Mpiranya (2006) report that F3 is lower in a vowel preceding a postalveolar fricative than in one preceding an alveolar fricative in Kinyarwanda. As they note, this is consistent with a retroflex classification for these consonants. Walker & Mpiranya also find evidence of F3 lowering in a vowel preceding the flap.

While we have no reason to believe that our subject is unique in his production of the consonants under study, it is conceivable that some speakers produce them as non-retroflex, with postalveolar alveolo-palatal fricatives. However, given that auditory distinctions in this region can be subtle and that no instrumental data has yet confirmed that description, it is very possible that previous descriptions classifying them as alveolo-palatal were articulatorily inaccurate in this regard.

To summarise, our findings indicate that postalveolar fricatives in Kinyarwanda are produced with a geometry that involves a higher tongue tip relative to blade in comparison to alveolar fricatives, leading us to classify them as retroflexes. In addition, the tongue tip is positioned higher and further back for postalveolar fricatives than for alveolar fricatives. The same contrasts hold of the flap and prenasalised stop *vs*. [t]. In the flap and prenasalised stop, the tongue tip is raised higher than the blade at a point during the constriction formation, while in the postalveolar fricatives, the height of the tongue tip remains lower than the blade, i.e. they involve a lesser degree of retroflexion than [ɽ] or [^{n}ɖ].

3.2 Articulations in contexts for (potential) coronal harmony

The first approach we take in the statistical analysis is an overarching comparison across forms containing disyllabic stems in which no consonant intervenes between the test consonant and the following conditioning consonant. Disyllabic stems were examined first because they include the context in which harmony is obligatory, where the trigger and target are in adjacent syllables. Mean angle was examined in the first coronal fricative in tokens of the following words: [βaʂaʂé] (retroflex fricative; harmony context), [βasaɽé, βasazé, βazaːta] (alveolar fricative; non-harmony context) and [βaʂata, βaʐaːta] (retroflex fricative; non-harmony context). A one-way ANOVA found a significant effect of the factor of context on the fricatives' mean angle ($F(2, 39) = 9{\cdot}576$, $p = 0{\cdot}0004$). Figure 6 compares the group mean for each context, showing, as expected, that the means for the retroflex fricative groups were lower than that of the alveolar fricatives. Post hoc Fisher's PLSD tests indicate that these differences are significant (for alveolar, non-harmony *vs*. retroflex, harmony, $p = 0{\cdot}0059$, and for alveolar, non-harmony *vs*. retroflex, non-harmony, $p = 0{\cdot}0002$). Further, as expected, the retroflex groups did not differ significantly ($p = 0{\cdot}83$).

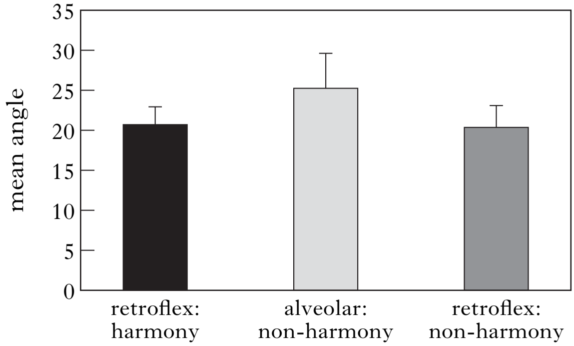

Figure 6

Mean angle by harmony context factor. Error bars mark standard deviation.

3.2.1 *Fricative targets.* In what follows we explore further comparisons with respect to the specific hypotheses of interest. Narrowing our focus to a more controlled segmental context, mean angle was examined in the retroflex fricatives in the second syllable in tokens of [βa**ʂ**aʂé] (harmony context) and [βaʂata] (non-harmony context). A one-way ANOVA found no significant effect of the factor of context on mean angle in these groups (F(1, 12) = 0·27, p = 0·62). This is consistent with reports that retroflex fricatives that occur in a harmony target context are not distinct in their tip-blade posture from their counterparts in non-harmony contexts. The Appendix provides means and standard deviations for the variables of mean angle, minimum angle and maximum angle for the research questions examined in §§3.2.1–4.

3.2.2 *Blocking stops.* To examine the effect of intervening consonants, we turn our attention to trisyllabic stems, which include the following contexts: blocking, non-harmony, [^{n}ɖ], harmony and failed harmony. With regard to blocking consonants, we explore whether there is a difference in the tip-blade geometry during coronal stops in blocking context *vs.* non-harmony context. To address this issue, we consider mean angle for [^{n}ɖ] and [t] in [βasaː^{n}ɖaːʐe, βasataʐe] (blocking context) and [βasaː^{n}ɖaːze, βasataze] (non-harmony context). To test for effects on the dependent variable of mean angle, a two-factor ANOVA was used, with factors of harmony context (levels: blocking, non-harmony) and consonant (levels: [^{n}ɖ], [t]). Harmony context did not show a significant effect (F(1, 22) = 0·06, p = 0·8). The factor of consonant was significant (F(1, 22) = 579·02, p < 0·0001). This was expected, because [t] and [^{n}ɖ] are produced with different mean angles for tongue tip-blade (§3.1). No interaction was found between harmony context and consonant (F(1, 22) = 0·3, p = 0·59). These results suggest that coronal harmony does not systematically alter the tip-blade articulation of [^{n}ɖ] and [t]. Given that [t] did not show a distinct articulation across the blocking and non-harmony contexts, we interpret that it is not a target for retroflex harmony. While [ⁿɖ] also did not show a distinct mean angle in these contexts, whether it is a target of coronal harmony is a more complicated matter, because it is already retroflex. We return to this issue in §4.2.

Our next question is concerned with whether there is a difference in tongue tip-blade angle in alveolar fricatives that occur in a non-harmony context *vs*. alveolar fricatives that occur prior to a retroflex fricative with an intervening blocking consonant. Mean angle for [s] was measured in tokens of the same words as those that were examined for blocking stops above. A two-factor ANOVA was used with mean angle as the dependent variable and factors of harmony context and consonant, as above. The factor of context was not significant ($F(1, 22) = 1{\cdot}033$, $p = 0{\cdot}32$). This is consistent with the claim that retroflex fricatives do not cause harmony in an alveolar fricative in blocking context. The factor of consonant was significant, presumably due to different articulatory influences from a following [t] *vs*. [ⁿɖ] ($F(1, 22) = 53{\cdot}1$, $p < 0{\cdot}0001$), but no interaction was found between harmony context and consonant ($F(1, 22) = 0{\cdot}004$, $p = 0{\cdot}95$).

As harmony is optional in non-adjacent syllables, even if harmony were available across [t] and [ⁿɖ], there should be an option available to produce a potential target as alveolar. Nevertheless, the evidence for blocking by coronal stops is twofold. First, Kinyarwanda speakers explicitly report that a variant retroflex pronunciation of an alveolar fricative in blocking context is not available. Second, our kinematic data indicates no evidence of systematic (partial) retroflexion of an alveolar fricative caused by a retroflex fricative in blocking context.

To test whether [ⁿɖ] triggers harmony, we compared the mean angle for [s] pooled across tokens of [βasaːⁿɖaːʐe] and [βasaːⁿɖaːze] ([ⁿɖ] context) to the mean angle for [ʂ] pooled across tokens of [βaʂata] and [βa**ʂ**aʂé] (the [ʂ] in the second syllable). A one-way ANOVA revealed a significant difference between the two groups ($F(1, 25) = 12{\cdot}97$, $p = 0{\cdot}0014$). The mean tip-blade angle during [s] preceding [ⁿɖ] was significantly greater (less retroflex) than the mean angle during [ʂ]. We did not find that retroflexion in [ʂ] was distinct across harmony ([βa**ʂ**aʂé]) and non-harmony contexts ([βaʂata]); if [ⁿɖ] had triggered harmony, we would have expected to find no difference in the retroflexion in the preceding coronal fricative from that of [ʂ] in other contexts. Nevertheless, we have seen that the execution of retroflexion can differ to some extent across consonants. If [ⁿɖ] were to trigger harmony in a target fricative in such a way as to produce some geometry particular to this trigger, even greater retroflexion might be expected in the target than when harmony was triggered by a retroflex fricative, as [ⁿɖ] has a lesser mean angle. Yet this is not what we found. In addition, the fricative in the second syllable of [βasaːⁿɖaːʐe] and [βasaːⁿɖaːze] is reported by Kinyarwanda speakers to be [s] and not [ʂ].

3.2.3 *Transparent bilabial and velar consonants.* In examining transparent consonants, we first implemented an overarching test of words

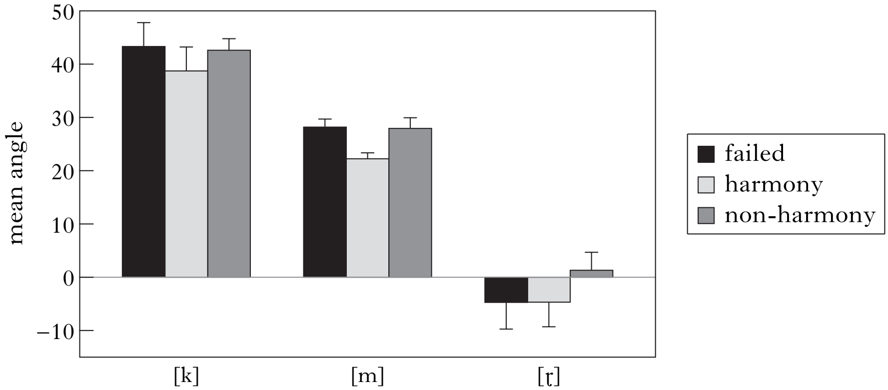

Figure 7

Mean angle by consonant ([k m ɽ]) and harmony factor (harmony, failed harmony, non-harmony). Error bars mark standard deviation.

containing [m], [k] or [ɽ] in the following contexts: harmony ([βaʂamáːʐe, βaʂakáːʐe, βaʂaɽáːʐe, βaʂaɽaʐe]), failed harmony ([βasamáːʐe, βasakáːʐe, βasaːɽaːʐe, βasaɽaʐe]) and non-harmony ([βasamáːze, βasakáːze, βasaɽaze]). A two-factor ANOVA tested the dependent variable of mean angle with factors of harmony context (levels: harmony, failed harmony, non-harmony) and consonant (levels: [m, k, r]). Figure 7 compares the means for each consonant, split by context. A main effect of context was found ($F(2, 69) = 11{\cdot}163$, $p < 0{\cdot}0001$). The factor of consonant was also significant ($F(2, 69) = 899{\cdot}06$, $p < 0{\cdot}0001$), as expected. This is because a qualitative difference was found in the retroflex shape of [ɽ] *vs.* postalveolar fricatives. Also, the articulation of bilabial consonants is independent of the tongue, but velar consonants involve raising of the tongue body, which was anticipated to raise the tongue blade to some extent, as indeed occurred. An interaction between the factors of harmony context and consonant was found ($F(4, 69) = 2{\cdot}706$, $p = 0{\cdot}037$). This, too, was expected, given the different shape of retroflexion in [ɽ].

Next we narrowed our focus to the items containing non-coronal consonants [m] and [k]. A two-factor ANOVA for mean angle was used, where the independent factors were again harmony context and consonant. A main effect for both context ($F(2, 36) = 13{\cdot}09$, $p < 0{\cdot}0001$) and consonant ($F(1, 36) = 286{\cdot}18$, $p < 0{\cdot}0001$) was found, as expected. However, there was no interaction between the factors of harmony context and consonant ($F(2, 36) = 0{\cdot}35$, $p = 0{\cdot}71$).

Post hoc Fisher's PLSD tests reveal that mean angle in the harmony context was significantly different from both the failed harmony context ($p < 0{\cdot}0001$) and the non-harmony context ($p < 0{\cdot}0001$). No significant difference for mean angle was found between the failed harmony and non-harmony contexts ($p = 0{\cdot}39$). The mean angle during [m] and [k] was smaller (more retroflex) in the harmony context than in the other contexts.

These results are indicative that an angle associated with retroflexion actually occurs during intervening 'transparent' bilabial and velar consonants.

To follow up, the mean tip-blade angle during [m] in the harmony context was compared with the mean angle of [ʂ] and [ʐ] in tokens of words where they occur independent of harmony: [βaʂata] and [βaʐaːta]. The intent was to examine whether the mean angle during 'transparent' [m] was distinct from that of retroflex fricatives. Mean angle for [m] alone was compared with the fricatives, because, as mentioned above, its distinctive consonantal constriction is formed independently of the tongue. A one-way ANOVA tested first whether the mean angle for [ʂ] *vs*. [ʐ] was different in [βaʂata] and [βaʐaːta]. No significant difference was found ($F(1, 14) = 0{\cdot}23$, $p = 0{\cdot}64$). Next, a one-way ANOVA tested for a difference in mean angle during [m] in the harmony context *vs*. mean angles for [ʂ] and [ʐ] (pooled). No significant difference was found ($F(1, 21) = 3$, $p = 0{\cdot}1$). These findings are consistent with the retroflexed tip-blade angle being systematically sustained over the interval that separates the harmonising retroflex sibilants, even though it does not produce a reported perceptible effect for intervening consonants.

While mean angle during 'transparent' [m] in the harmony context (mean = 22·23) was similar to that of retroflex fricatives ([βaʂata, βaʐaːta]; mean = 20·36), mean angle during 'transparent' [k] in the harmony context was noticeably greater (mean = 38·72). This is presumably due to biomechanical articulatory coupling during [k] in the harmony context, such that when the tongue body raises to produce the velar constriction, the tongue blade is dragged along with it.

We had a closer look at the tongue-tip posture of [k], to verify that it was raised in harmony contexts. Tongue-tip *y*-position was examined at the acoustic centre of [m] and [k] (i.e. the extremum constriction position variable in *y* for these consonants) in the harmony and non-harmony contexts. The consonant centre for [m] and [k] was taken as the midpoint in duration from the consonant's beginning to its end (based on acoustic boundary markings). With tongue-tip *y*-position as the dependent variable, a two-factor ANOVA was used to test for effects of consonant and harmony context. As expected, for tongue-tip *y*-position, the context factor was significant ($F(1, 24) = 22{\cdot}74$, $p < 0{\cdot}0001$), but no significant difference was found for the factor of consonant ($F(1, 24) = 0{\cdot}35$, $p = 0{\cdot}56$). There was no interaction between the factors of context and consonant ($F(1, 24) = 0{\cdot}38$, $p = 0{\cdot}54$). These results confirm that a raised tongue tip is present in both [m] and [k] in the harmony context (means: [m]: −22·06 (SD = 1·46), [k]: −21·39 (SD = 1·9)), while a lower tongue-tip posture occurs in the non-harmony context (means: [m]: −24·37 (SD = 1·21), [k]: −24·39 (SD = 1·31)). Further, tongue-tip position shows no significant difference across the bilabial and velar consonants within harmony contexts and within non-harmony contexts.

To sum up, bilabial and velar consonants show a mean angle with higher tongue tip relative to blade during harmony contexts *vs*. contexts where harmony does not occur. During 'transparent' [m], the mean angle is not distinct from that of the Kinyarwanda retroflex fricatives. During [k], mean angle is affected to some extent by tongue-body raising, but during 'transparent' [k] it is nevertheless closer to that of a retroflex fricative than during [k] in non-harmony context. Our interpretation is that aspects of a retroflex tip-blade posture are systematically present during so-called transparent non-coronal consonants.

3.2.4 *The retroflex flap.* To investigate [ɽ]'s reported failure to trigger retroflex harmony, we examined whether mean angle differed in the sibilant in the second syllable in tokens of [βasaɽe] ([ɽ] context) and [βasaze] (non-harmony context). With mean angle as the dependent variable, a one-way ANOVA showed no effect of context ($F(1, 12) = 1{\cdot}35$, $p = 0{\cdot}27$). This result is consistent with the claim that [ɽ] is not a trigger.

Our next question relates to the apparent transparency of [ɽ]. In contexts where harmony transmits across [ɽ], this consonant is not perceived as different from its occurrence in the non-harmony context. To examine whether [ɽ] is affected by harmony, we compared its mean angle in tokens of [βaʂaɽaʐe] (harmony context), [βasaɽaʐe] (failed harmony context) and [βasaɽaze] (non-harmony context). With mean angle as the dependent variable, an ANOVA tested for differences across the three contexts. A main effect was found ($F(2, 19) = 10{\cdot}13$, $p = 0{\cdot}001$). Post hoc tests examined context pairs for differences. Mean angle in the harmony context (mean = −7·21) was significantly different from the non-harmony context (mean = 1·31) ($p = 0{\cdot}001$).[14] More remarkably, mean angle in the failed harmony context (mean = −7·61) *vs.* the non-harmony context was significantly different ($p = 0{\cdot}0009$), while the mean angle of [ɽ] in the contexts of failed harmony *vs.* harmony did not show a significant difference ($p = 0{\cdot}86$). This differs from the findings for 'transparent' [m] and [k]. For [m] and [k], mean angle differed in the harmony context *vs.* the failed harmony context, but it was not distinguished in the failed harmony context *vs.* the non-harmony context. Thus for [ɽ] the failed harmony

[14] Noting the increase in the retroflexion of [ɽ] in harmony contexts, an anonymous reviewer asks if the value for the tongue-tip extremum constriction position variable in *y* for [ɽ] in the harmony context is close to that of the retroflex fricatives. The reviewer also asks whether the value for this variable for [k] in the harmony context is close to that of the retroflex fricatives. If the values were close, the reviewer suggests that could be taken as support for using this variable instead of mean angle as the one to index retroflexion in Kinyarwanda. The mean value for tongue-tip extremum constriction position in *y* for [ʂ] and [ʐ] was −14·79 (SD = 1·43) (pooled, based on [βaʂata, βaʐaːta]), whereas for [ɽ] in the harmony context it was −17·81 (SD = 1·52) (*vs.* −18·54 in the non-harmony context (SD = 1·38)), and for [k] in the harmony context it was −21·39 (SD = 1·9) (*vs.* −24·39 in the non-harmony context (SD = 1·31)). The difference between the value for [ɽ] in the harmony context *vs.* [ʂ]/[ʐ] was significant, as tested by a one-way ANOVA ($F(1, 21) = 19{\cdot}4$, $p = 0{\cdot}0002$). Likewise, the difference in the value for [k] in the harmony context *vs.* [ʂ]/[ʐ] was significant, as tested by a one-way ANOVA ($F(1, 20) = 78{\cdot}23$, $p < 0{\cdot}0001$). We thus did not find evidence indicating that extremum constriction position variable in *y* for tongue tip is the appropriate articulatory variable for retroflexion in Kinyarwanda.

context groups with the harmony context, but for [m] and [k] it groups with the non-harmony context.

We consider three interpretations with respect to the results for 'transparent' [ɽ].

(9) a. [ɽ] is targeted by harmony from a following retroflex fricative, unlike [m] and [k], which are influenced by harmony only if a preceding consonant is targeted.
  b. [ɽ]'s retroflexion is reduced in non-harmony contexts because of biomechanical interaction with the non-retroflex tip-blade posture of alveolar fricatives in flanking syllables.
  c. [ɽ] undergoes significant biomechanical interaction with the retroflex posture of a retroflex consonant in a following syllable, while [m] and [k] do not.

Comparison of the mean angle of [ɽ] in various contexts does not lend support to (9b). Because this issue with [ɽ] was not anticipated, data were not collected with [ɽ] between syllables containing non-coronal consonants within the same word. However, that context occurs in our data across word boundaries. Mean angle for [ɽ] in tokens of [βasamáːɽe gusa] is 14·12 (SD = 6·58). This mean angle is less retroflex than in the non-harmony context ([βasaɽaze]), where [ɽ] is flanked by alveolar fricatives (mean = 1·31). The results do not point to [ɽ] being the recipient of a comparatively strong articulatory influence from flanking alveolar fricatives for tip-blade angle posture (in the direction of having a lower tip relative to blade). When [ɽ] occurred in a context flanked by syllables with alveolar stops ([bataɽatá]), it also showed lesser mean angle retroflexion (mean = 7·09) than in the context of flanking alveolar fricatives. Further, the mean angle for [ɽ] in a syllable immediately preceding [ʐ] is similar whether the context is harmony or failed harmony. In the latter context, an alveolar fricative occurs in the preceding syllable without effect on the mean tip-blade angle of [ɽ]. These various findings argue against (9b), because they suggest that the alveolar fricatives have a comparatively weak articulatory influence on [ɽ] for tongue tip-blade.

The data we have available suggest that (9c) is not correct. In the words examined for 'transparent' [ɽ] above, [ɽ] occurred before a short vowel. We compared mean angle in [ɽ] in a syllable preceding a retroflex fricative where the consonants were separated by a long vowel rather than a short one. Mean angle for [ɽ] in [βaʂaɽáːʐe] (harmony context) was −1·8, while mean angle in [βasaːɽaːʐe] (failed harmony context) was −1·84. A one-way ANOVA found no significant difference across these contexts ($F(1, 12) = 0{\cdot}001$, $p = 0{\cdot}98$). If the lack of difference in mean angle for [ɽ] in harmony context *vs.* failed harmony context was simply because of biomechanical interaction with a following retroflex fricative, we might well expect a difference in mean angle to emerge when the intervening vowel is long, while given our findings for non-coronal consonants in harmony context, any effect on retroflexion in [ɽ] caused by harmony between retroflex fricatives in flanking syllables is expected to be systematically present. Vowel-length differences should not alter an effect on retroflexion that is due to harmony. However, biomechanical interaction is sensitive to proximity in time, and could be weaker across a long vowel than a short one. The lack of difference for mean angle during [ɽ] in harmony and failed harmony contexts even before a long vowel therefore suggests that it is targeting of [ɽ], as in (9a), rather than biomechanical interaction that underlies the effects involving [ɽ].

The data actually support a drop-off in strength of biomechanical articulatory influence across a long *vs.* a short vowel. Mean angle for [ɽ] in words where a short vowel intervenes between [ɽ] and [ʐ] (means: [βaʂaɽaʐe] = −7·21; [βasaɽaʐe] = −7·61) is lower than in words where a long vowel intervenes (means: [βaʂaɽáːʐe] = −1·79; [βasaːɽaːʐe] = −1·84). These results are consistent with a weakening of biomechanical interaction across a long vowel simultaneous with equivalent 'targeting' of [ɽ] in retroflex harmony in harmony and failed harmony contexts.[15] We conclude that of the hypotheses under consideration it is (9a) that is best supported by the available data. That is, we speculate that [ɽ] is targeted by harmony from a following retroflex fricative, unlike [m] and [k], which are only affected by harmony if a preceding consonant is targeted.

4 Discussion

4.1 Blocking and transparency in the harmony system

The theoretical issues that motivated this study involve the phonological representations for coronal harmony and their relation to the existence of blocking and transparency in the Kinyarwanda system. Our study found that the retroflex fricatives that occur in a target context for harmony are not distinct in mean angle from those that occur outside harmony contexts. This is consistent with the view that harmony affects fricatives in a categorical fashion, as would be expected for a phonological phenomenon. Our findings are consistent with reports that blockers in Kinyarwanda genuinely prevent coronal harmony from operating across them; also that

15 To test the validity of (9a) *vs.* (9c), it might seem that the best items to compare would be the mean angle for [ɽ] in a syllable preceding a retroflex fricative (e.g. [βasaɽaʐe]) *vs.* [ɽ] in a non-adjacent syllable preceding a retroflex fricative (e.g. a form like hypothetical [βaɽamaʐe]). If the mean angle for [ɽ] did not show a significant difference in these contexts, this could support (9a) over (9c), because it is possible that biomechanical articulatory interaction from [ʐ] would not reach that far, while harmony does show the capacity to extend beyond adjacent syllables. However, if the mean angle for [ɽ] were different in the two contexts, the results would not be conclusive, because retroflex harmony is optional in non-adjacent syllables, and there would be no way to signal to the speaker of the words whether to 'apply' harmony or not in a form like [βaɽamaʐe] (as the spelling and perception of [ɽ] would be the same in both cases). Also, biomechanical interaction could be an interfering factor, causing a difference in mean angle even if harmony did occur. As we had not anticipated the issues we uncovered surrounding [ɽ], we did not collect data with sequences like that in [βaɽamaʐe], but we note that this would be valuable in future research.

non-retroflex blockers ([t]) are not affected by harmony, and that retroflex blockers ([ⁿɖ]) do not trigger harmony. These conclusions hold, conservatively, at least for the consonants examined, and, by extension, for all reported blockers. On the issue of transparency, we found that characteristics of a retroflex tongue tip-blade posture were systematically sustained during 'transparent' bilabial and velar consonants when they occurred between harmonising fricatives. These findings point to Kinyarwanda coronal harmony involving a continuous retroflex gesture whose duration extends from the target consonant to the trigger consonant.

These results bear on the assessment of a Gesture Extension model *vs*. a Repeated Gesture model for Kinyarwanda harmony. Under the Gesture Extension proposal, the retroflex gesture persists continuously over the interval separating a harmonising target consonant and trigger, even though it might not yield a perceptible effect on intervening segments. Gesture Extension thus predicts that a retroflex tip-blade posture will occur during non-coronal consonants that are perceived as transparent. This prediction is borne out by our findings.

Under the Repeated Gesture proposal, the retroflex gesture is interrupted by intervening segments, and separate instances of the gesture occur for the trigger and target consonants. This model does not predict that transparent non-coronal segments will show a retroflex gesture. Our finding that these transparent consonants actually display retroflexion therefore does not support a Repeated Gesture representation. The existence of a retroflex posture during [m] or [k] in the harmony context would require an independent explanation.

While phonological assimilation is one way in which segments can acquire articulatory properties of a following segment, biomechanical interaction among articulators is another possible source.[16] We have reason to believe that the sustained retroflexion we found during transparent non-coronal consonants was not due to the latter. We did not find evidence that anticipatory biomechanical interaction with retroflexion – which is typically stronger than perseveratory effects[17] – produced a significant effect on [m] and [k] in the failed harmony context (*vs*. non-harmony), nor did it approach significance ($p = 0{\cdot}39$). Further, our comparison of mean angle during [ɽ] preceding a retroflex fricative pointed to a drop-off in

16 If 'coarticulation' causes an actively controlled articulatory manoeuvre to be present, then we do not see an important distinction between assimilation and coarticulation for the issues at hand. However, coarticulation could be understood as referring to biomechanical coupling among articulators. Such coupling could cause articulatory behaviour at a point where it is not represented in the abstract linguistic structure. It is this type of contextual articulatory influence that we contrast with assimilation.

17 Retroflex articulations tend to induce greater effects in preceding segments than in following ones. Audible cues to retroflexion are biased to the preceding segment, particularly a preceding vocoid (see Steriade 2001 for a review). Also, a study of retroflex stops across three languages found a more posterior articulation at the onset of the closure than at the release (Krull *et al*. 1995). This suggests there should be stronger anticipatory biomechanical interaction effects of retroflexion than carry-over effects.

biomechanical articulatory influence across a long vowel *vs.* a short vowel. Therefore, if biomechanical interaction were the source of retroflexion during [m] and [k] in the harmony context, where they preceded a long vowel, it would be surprising that we found evidence of a retroflex posture during [m] that was not distinct from that of retroflex fricatives, while at the same time we found no evidence that biomechanical articulatory influence from a retroflex fricative caused retroflexion in a preceding non-coronal consonant in the failed harmony context. In addition, if the retroflexion in transparent [m] were solely the product of biomechanical influence in the harmony context, it could be expected to show a lesser degree of retroflexion than that of a retroflex fricative. Our results instead suggest a phonological assimilatory source that causes retroflexion in transparent consonants in harmony contexts.[18] That is, they point to the existence of a systematic and sustained retroflex posture during the transparent consonant, as expected under Gesture Extension.[19]

Because the Gesture Extension model posits a retroflex gesture to be continuously active during the interval from target to trigger, it offers a straightforward explanation for the blocking of harmony by alveolar stops and affricates and palatals (blocking by [ⁿɖ] is addressed below). A retroflex tip-blade gesture distinguishes retroflex consonants from alveolars. Producing retroflexion during an intended alveolar will thus interfere with a fundamental dimension of the consonant's articulation, and it has the potential to produce perceptible effects. The production of a palatal or palatalised articulation has been observed to be antagonistic to retroflexion (Gafos 1996, Clements 2001, Flemming 2003, Hamann 2003). The blocking of Kinyarwanda harmony by certain coronal consonants could pose a difficulty for the Repeated Gesture model. Under a Repeated Gesture scenario, the harmony relation is postulated to exist only between triggers

18 A reviewer points out that it would be valuable to examine a labial or velar consonant when it is preceded by a retroflex belonging to the set of target consonants and followed by a consonant belonging to the set of triggers, but in a context where harmony is not expected to occur, for example, across a word boundary, as in [...ʐV]$_\omega$ [kVʂ...]$_\omega$. The question is whether the non-coronal consonant in this non-harmonic sequence shows a lesser degree of retroflexion than in the harmony context, as predicted by an analysis in which phonological harmony causes retroflexion in transparent consonants. Our data did not contain non-harmonic contexts in which we could test this, but it would be useful to examine cases of this kind in future research. Effects of word position could be a possible complicating factor that would need to be taken into consideration in investigating this.

19 It is worth asking whether the results we found could reflect some conscious behaviour on the part of the speaker. We regard it as highly improbable that the speaker had conscious control of the tongue-angle variable, i.e. of the relative geometric position of two sensors placed 7 mm apart on the tongue, especially while performing the automatic function of speech. In addition, the speaker had no conscious motive to bias the results one way or the other, as there was no pre-existing expectation for what would be found during transparent consonants – rather, we were investigating the viability of two possible models. Nevertheless, it is appropriate to be cautious about results from a single speaker, who was also an investigator. Future studies of Kinyarwanda coronal harmony with more speakers will be valuable.

and targets, and the harmonising gesture or feature is represented on these segments alone. The occurrence of blocking in Kinyarwanda, together with the persistence of retroflexion in transparent segments, points to a different conclusion for this harmony system, namely that in addition to the targets and triggers, intervening segments show involvement in the harmony – they either display the harmonising gesture or they prevent it from continuing through them.[20]

Our finding that a retroflex tip-blade posture is sustained in a significant and systematic manner during transparent non-coronal consonants resonates in certain respects with some articulatory research on vowel harmony. Instrumental investigation of certain vowels reported to be transparent in vowel harmony has revealed that they systematically display the harmonising property to at least some degree. Gick *et al.* (2006) examined transparent /a/ in the tongue-root harmony of Kinande, using lingual ultrasound imaging. Their findings revealed that /a/ shows advanced and retracted tongue-root articulations according to the dictates of the harmony system, and they conclude it is actually targeted in the harmony pattern. A study by Benus & Gafos (2007) investigated transparent vowels in the front-back harmony of Hungarian, using electromagnetic midsagittal articulometry and ultrasound (see also Gafos & Benus 2003, 2006, Benus *et al.* 2004). Their research investigated the articulation of transparent or 'neutral' vowels [i iː eː]. Among their findings were that transparent vowels in front harmony contexts show a tongue-body position that is significantly more advanced than in back harmony contexts. Further, in Hungarian, monosyllabic stems containing neutral vowels usually consistently select either front vowel suffixes or back vowel suffixes. The vowels in monosyllabic stems that regularly select front vowel suffixes had a more advanced tongue position than the corresponding vowels in roots that regularly select back suffixes (measured in the absence of suffixes). Benus & Gafos (2007) characterise these systematic differences in the neutral vowels' articulation as subphonemic properties, usually not perceived.

Like the findings of this vowel harmony research, transparent segments in Kinyarwanda coronal harmony show subphonemic differences in articulation in accordance with the harmony system. While significant differences conditioned by harmony context are observed in the 'transparent' segments across these studies, we may wonder whether the magnitude of the harmonising gesture in transparent segments is as great as in reported targets of harmony. There is reason to expect the magnitude

[20] In a re-examination of the Repeated Gesture model together with discussion of some particular modifications to its implementation, Hansson (2006, 2007) identifies the possibility that blocking could occur in harmony involving Repeated Gesture representations. However, for Kinyarwanda coronal harmony, Hansson (2007) notes drawbacks for this approach in capturing the patterning of [ɽ] and the segment classes that function as blockers in the system. Even if these could be resolved, the Repeated Gesture model would still be faced with the problem that transparent non-coronal consonants in Kinyarwanda present a retroflex gesture.

could be lesser in at least some languages. In the above vowel harmonies, the harmonising property is not perceived or is less salient on the transparent vowels. This could be due to a lesser activation of the harmonising gesture in the transparent vowel. Other factors such as the gesture's lack of perceptible effect on the particular segment or the influence of the lexical contrast system (Ní Chiosáin & Padgett 1997, 2001) could also play a role.

The transparent non-coronal consonants in our data bear on this issue for coronal harmony. We found no significant difference in the mean angle during [m] in harmony contexts *vs.* during a phonologically retroflex fricative. This suggests that the magnitude of the retroflex gesture during transparent [m] is not distinct from that during trigger or target fricatives. However, in [k], tongue-body raising for the velar closure also raises the tongue blade, causing the mean tip-blade angle to be less retroflex in the harmony context than during a retroflex fricative. At the same time, the mean angle during [k] in the harmony context was more retroflex than in the non-harmony context, and no difference was found in tongue-tip raising for [m] *vs.* [k] in harmony contexts. To understand these effects, we suggest that the gesture producing a retroflex tip-blade angle could be realised in a range of magnitudes over the interval from trigger to target. During [m], the independence of retroflex tip-blade posture and bilabial closure allows the retroflex gesture to have a magnitude equivalent to that of a retroflex fricative. During [k], the stop involving the tongue body occurs simultaneously with a retroflex posture. As these two postures are not entirely independent, the result could be some reduction in magnitude of the retroflex gesture during this consonant in harmony contexts.[21] Despite this potential for varying degrees in magnitude of retroflexion over the harmony interval in Kinyarwanda, it seems that a definite degree of retroflexion is certainly present. And in turn, consonants that are incompatible with retroflexion in this language's system block retroflex harmony.

Thus, while our study finds support for a Gesture Extension model for Kinyarwanda coronal harmony, we see a benefit to elaborating this with a more nuanced view allowing for a certain range of gestural magnitude; this may be language-particular. Whether it is appropriate to augment phonological representations with information about the degree of gestural activation is a question that we leave for future research.

4.2 The status of [ɽ] and [ⁿɖ] in Kinyarwanda harmony

Our investigation of [ɽ] found results consistent with reports that it does not trigger harmony. This supports a divide in Kinyarwanda retroflex consonants with respect to trigger status: while [ʂ ʐ] are triggers, [ɽ] and [ⁿɖ] are not. On the question of the transparency of [ɽ], our results support

[21] In related work on the articulation of retroflexion, Wiltshire & Goldstein (1997) found that the angle of orientation for retroflex consonants in Tamil varies to some extent, depending on vowel context.

an interpretation that it is actually targeted by harmony from a following retroflex fricative.

Because retroflex [ɽ] and [ⁿɖ] pattern differently from [ʂ ʐ] in certain ways in Kinyarwanda harmony, it is valuable to compare these two consonants with respect to blocking effects and target status. Our data suggest that [ⁿɖ] blocks retroflex harmony, but [ɽ] does not. This difference might have a source in their different strictures. Related to this are our findings that differences exist in the retroflex posture of [ʂ ʐ] *vs.* [ⁿɖ ɽ] and that a retroflex posture is present during the interval between harmonising consonants. Retroflexion from a fricative could thus be expected to affect [ⁿɖ] and [ɽ] in harmony contexts, but these consonants' manner difference could affect their potential to submit to harmony. Stone (1991) has argued that anterior tongue bracing against the palate provides a base that facilitates the execution of certain tongue shapes and movements. On the assumption that [ⁿɖ] involves more palate contact and bracing than [ɽ], its retroflex posture could be more fixed across phonological contexts than that of [ɽ]. Thus, while [ɽ] could be more flexible in its execution of retroflexion across contexts, consistent with its failure to obstruct harmony, [ⁿɖ] could interrupt Gesture Extension-based retroflex harmony by virtue of its rigid retroflex posture.[22] This interpretation is supported by the difference in mean angle for [ɽ] preceding a retroflex fricative *vs.* preceding an alveolar fricative (means: [βasaɽaʐe] = −7·61; [βasaɽaze] = 1·31), while mean angle for [ⁿɖ] is comparatively close in parallel contexts (means: [βasaːⁿɖaːʐe] = −3·39; [βasaːⁿɖaːze] = −2·85).[23]

Historical factors could also contribute to blocking by [ⁿɖ] but not [ɽ]. In closely related Kirundi (Ntihirageza 1993) and Kiha (Harjula 2004), the prenasalised coronal stop is reported to be alveolar, not retroflex. While this description merits further instrumental study in these

22 The prenasalised fricative [ⁿʐ] can trigger retroflex harmony, as in [-ʂoːⁿʐi] 'victim of famine'. This signals that the closure that occurs during the prenasalisation phase of a fricative does not block harmony. What we suggest could produce the blocking effect in [ⁿɖ] is the bracing that accompanies a full (oral) stop consonant, together with the retroflex posture of [ⁿɖ] that differs to some degree from retroflexion during fricatives.

23 The difference in retroflexion in [ʂ ʐ] *vs.* [ⁿɖ ɽ] might seem to suggest they are specified with phonological features (or gestures) distinguishing degree of retroflexion, i.e. something like [weak retroflex] and [strong retroflex] respectively, or different constriction location or shaping. A distinction along these lines could obtain the consonant pairs' difference in trigger status. However, it would not explain why [ɽ] does not obstruct retroflex harmony from fricatives and is actually targeted by harmony, while [ⁿɖ] blocks. Triggering by [ʂ ʐ] could instead be attributed to the contrastive status of retroflexion in these consonants, paralleling effects in certain other harmony systems (Dyck 1995, Walker 2005, Campos-Astorkiza 2007). Nevertheless, in future research it would be valuable to direct attention to whether differences in the geometry of retroflexion in different consonants affect their potential to interact in harmony. Also, if they do interact, in what manner, if any, do differences affect the geometry of retroflexion in the trigger or target? We saw some indications that this is relevant for target [ɽ] in Kinyarwanda, which warrants further investigation.

languages, it is possible that retroflexion in the Kinyarwanda prenasalised coronal stop is a relatively recent innovation. If the prenasalised coronal stop was actually [ⁿd] at the inception of retroflex harmony, then it would have been expected to block harmony by virtue of its alveolar articulation. When [ⁿd] later became [ᶯɖ] for some or all speakers of Kinyarwanda, its blocking status in the harmony could have remained a frozen property.[24]

While [ᶯɖ] blocks harmony, we may ask whether it is a target. Comparison with [ɽ], which we infer is a target, suggests that [ᶯɖ] is not. The retroflex flap shows a difference in mean angle preceding a retroflex fricative *vs.* preceding an alveolar fricative, but no significant difference was found for the mean angle of [ɽ] in the harmony context *vs.* the failed harmony context. Unlike [ɽ], no significant difference was found for the mean angle of [ᶯɖ] when it occurs followed by an alveolar fricative *vs.* followed by a retroflex fricative. The lack of difference for [ᶯɖ] across these contexts suggests that it is not targeted by harmony.

5 Conclusion

This study has provided a first glimpse into the articulation of transparent consonants in coronal harmony. Our research has found that coronal harmony in Kinyarwanda involves tongue tip-blade retroflexion. While this harmony audibly affects sibilant fricatives, a primary finding is that the retroflex articulation also persists during transparent consonants. The significance of these results reaches beyond the description of Kinyarwanda coronal harmony. This work adds to a growing body of experimental research on harmony that finds instrumental evidence of the harmonising property in transparent segments of certain harmony systems, even though it is not perceived during these segments.

On a comparative note, while our study of Kinyarwanda shows the necessity for a Gesture Extension model for certain coronal harmonies, it does not negate the possibility that coronal harmonies of other particular languages could best be represented in terms of a Repeated Gesture model. Studies of other consonant harmonies, such as laryngeal harmony and nasal harmony, point strongly to the existence of transparent segments in which the harmonising gesture is truly interrupted (Hansson 2001, Rose & Walker 2004), as predicted by the Repeated Gesture model. The same is true of patterns that produce full identity between consonants at a distance (Gafos 1996, 1998). These studies have postulated

[24] Given the consensus that nasal–obstruent sequences are composed of consonant clusters underlyingly (e.g. Coupez 1980, Downing 2005, Myers 2005), the blocking of retroflex harmony by [ᶯɖ] could also have a basis in its underlying representation. Prenasalised [ᶯɖ] is derived from /nd/ and /nɽ/ sequences. The occurrence of alveolar consonant(s) in the underlying representation could be connected to the blocking status of the derived stop.

representations involving separate gesture occurrences in the segments that show identity effects. Articulatorily based investigation of different harmonies in a variety of languages is therefore necessary in order to discover how transparent segments are produced in those systems and to evaluate which phonological representations are most consistent with the articulatory facts.

Appendix

Means table for tongue tip-blade angle. Contexts are related to questions involving coronal harmony. The section numbers in which the relevant questions are discussed are given in the left column.

			angle	mean	SD	count
simple harmony	[βa**ʂ**aʂé]	[ʂ]	mean	20·71	2·23	7
§3.2.1			minimum	10·09	3·33	
			maximum	33·10	3·38	
	[βaʂata]	[ʂ]	mean	19·98	3·00	7
			minimum	9·34	3·03	
			maximum	32·13	4·52	
blocking consonants	[βasataʐe]	[t]	mean	39·56	6·08	6
§3.2.2			minimum	32·43	7·99	
			maximum	45·66	4·73	
	[βasataze]	[t]	mean	38·16	3·55	7
			minimum	28·41	4·93	
			maximum	47·37	4·70	
	[βasaː^{n}ɖaːʐe]	[^{n}ɖ]	mean	−3·39	4·60	7
			minimum	−23·71	8·56	
			maximum	23·73	1·25	
	[βasaː^{n}ɖaːze]	[^{n}ɖ]	mean	−2·88	3·02	6
			minimum	−22·71	5·49	
			maximum	25·41	2·50	

			angle	mean	SD	count
potential targets preceding blockers §3.2.2	[βasataẓe]	[s]	mean	31·37	4·52	6
			minimum	24·17	5·76	
			maximum	39·30	7·46	
	[βasataze]	[s]	mean	32·61	2·38	7
			minimum	24·56	3·86	
			maximum	39·11	3·83	
	[βasaːⁿɖaːẓe]	[s]	mean	23·11	1·74	7
			minimum	11·91	0·85	
			maximum	32·27	2·00	
	[βasaːⁿɖaːze]	[s]	mean	24·20	2·51	6
			minimum	11·77	4·92	
			maximum	34·59	2·11	
[ⁿɖ]'s non-trigger status §3.2.2	[βasaːⁿɖaːẓe]/ [βasaːⁿɖaːze]	[s]	mean	23·62	2·11	13
			minimum	11·85	3·23	
			maximum	33·35	2·30	
	[βaṣata]/ [βa**ṣ**aṣé]	[ṣ]	mean	20·34	2·57	14
			minimum	9·71	3·08	
			maximum	32·62	3·87	
transparent [m] and [k] §3.2.3	[βaṣamáːẓe]	[m]	mean	22·23	1·12	7
			minimum	21·24	1·18	
			maximum	23·03	1·25	
	[βasamáːẓe]	[m]	mean	28·18	1·51	7
			minimum	27·24	1·39	
			maximum	28·79	1·59	
	[βasamáːze]	[m]	mean	27·94	2·42	8
			minimum	25·95	3·23	
			maximum	29·35	1·78	
	[βaṣakáːẓe]	[k]	mean	38·72	4·50	6
			minimum	31·27	5·02	
			maximum	41·48	4·55	
	[βasakáːẓe]	[k]	mean	43·31	4·49	7
			minimum	35·73	3·71	
			maximum	45·67	4·80	
	[βasakáːze]	[k]	mean	42·61	2·17	7
			minimum	36·60	2·63	
			maximum	44·57	2·21	

			angle	mean	SD	count
[ɽ]'s non-trigger status §3.2.4	[βasaɽé]	[s]	mean	22·65	2·66	7
			minimum	10·86	2·32	
			maximum	32·16	2·98	
	[βasazé]	[s]	mean	24·70	3·84	7
			minimum	12·75	3·33	
			maximum	34·32	4·61	
'transparent' [ɽ] §3.2.4	[βaʂaɽaʐe]	[ɽ]	mean	−7·21	4·75	8
			minimum	−16·91	5·00	
			maximum	9·40	6·07	
	[βasaɽaʐe]	[ɽ]	mean	−7·61	4·35	7
			minimum	−24·46	5·16	
			maximum	16·15	3·61	
	[βasaɽaze]	[ɽ]	mean	1·31	3·38	7
			minimum	−16·06	3·86	
			maximum	20·27	2·64	
	[βasaːɽáːʐe]	[ɽ]	mean	−1·84	4·00	7
			minimum	−23·74	6·25	
			maximum	21·50	2·57	
	[βaʂaɽaːʐe]	[ɽ]	mean	−1·79	2·28	7
			minimum	−16·44	2·79	
			maximum	18·01	4·31	

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