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An MRI-based articulatory characterization of Kannada coronal consonant contrasts

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1 Abstract

This paper investigates production mechanisms of a complex set of coronal consonant contrasts in Kannada, with the goals of (i) testing previous theoretical distinctive feature approaches to coronals and (ii) documenting this relatively phonetically under-studied Dravidian language.

An extensive corpus of articulations was collected by static MRI midsagittal from two female speakers, including a full set of Kannada place and manner contrasts in five vowel contexts. Articulatory modelling was used to determine a small set of components responsible for the implementation of various consonant classes, including the place sets of dentals, retroflexes, and alveolopalatals, and manner sets of stops, fricatives, nasals, liquids, and glides. Overlaid average contours were used for the traditional phonetic classification of consonants, while dispersion ellipses were employed to capture consonants' susceptibility to vowel coarticulation.

The results provide evidence for some of the distinctive feature characterizations of coronals (e.g. constriction location and tongue body height distinctions for dentals and retroflexes), while disconfirming others (tongue dorsum backing for retroflexes). They also largely confirm previous descriptive phonetic accounts of Kannada consonants (including the merger of retroflex and alveolopalatal sibilants), while at the same time identifying somewhat unexpected articulatory patterns (such as dorsal constrictions for /v/, /h/, and /r/).

All the images and articulatory contours are made publicly available.

Keywords

articulation, coronals, Kannada, MRI, distinctive features

2 Introduction

A rapid development of various articulatory methodologies over the last few decades has revolutionised the fields of phonetics and phonology, considerably enriching our understanding of the variation observed in the production of sounds within and across languages. Yet, the majority of articulatory work done so far has focused on a handful of languages, most of which are native to Europe. Thus, among articulatory phonetic studies published in major journals between 2000 and 2019, more than one third focus on English, and more than two thirds focus on Indo-European languages spoken in Europe (with the bulk being major Germanic and Romance languages) (Kochetov, 2020). Given this linguistic bias, it remains to be shown whether empirical findings and theoretical generalizations obtained based on major European languages can extend to a wider range of sound pattern types. As part of our general effort to document articulatory structures of less studied languages, we have developed a static MRI corpus of sounds in Kannada, a Dravidian language spoken in India. Apart from being phonetically under-documented, Kannada is phonologically interesting in having a robust set of coronal phonemic contrasts, with dentals and retroflexes in particular, occurring with various manners of articulation. Articulatory mechanisms involved in the production of retroflexes as well as their phonological representations are topics of an ongoing debate (as reviewed below). An important goal of this work, therefore, is to shed light on the production mechanisms of Kannada consonant contrasts, focusing on coronals of different places and manners of articulation. This is done by employing recent MRI techniques and computational modelling (Labrunie *et al.*, 2018). This work thus aims to add significantly to the insights obtained in recent articulatory research on Kannada retroflexes (Kochetov *et al.*, 2014; Irfana, 2017) and similar contrasts in other related (Narayanan *et al.*, 1999; Scobbie *et al.*, 2013) and unrelated languages (Tabain, 2012; Tabain *et al.*, 2018).

2.1 Coronal consonant contrasts and distinctive features

Coronal place contrasts, such as distinctions between dentals, alveolars, retroflexes, and alveolopalatals, have been a major focus of the distinctive feature theory in phonology for several decades (e.g. Lahiri *et al.*, 1984; Paradis *et al.*, 1991; Hall, 2011). The main goal of this theory is to supply a minimal set of articulatory (or auditory) parameters that (i) distinguishes phonemic contrasts within and across languages and (ii) accounts for respective sounds' phonological patterning (distribution within a word, alternations with other sounds, etc.). Considering various articulation-based distinctive feature proposals, researchers generally agree that retroflexes are more distinct from dentals than from alveolopalatals (Chomsky *et al.*, 1968; Sagey, 1986; Hamilton, 1996); Gnanadesikan, 1994; Arsenault, 2008). That is, the number of distinctive feature differences is generally greater for the dental-retroflex contrast than for the retroflex-alveolopalatal contrast.

Among the key characteristics noted to distinguish dentals and retroflexes are (i) the location of the constriction along the palate: the binary feature [+anterior] for dentals and [-anterior] for retroflexes (Chomsky *et al.*, 1968; Sagey, 1986; Hall, 1997); the privative features [dental], [postalveolar], [palatal], often combined with underspecification for some of them (Hamilton, 1996; Gnanadesikan, 1994); (ii) the spatial extent of the

constriction between the tongue and the roof of the mouth [+distributed] for dentals and [-distributed] for retroflexes (Chomsky *et al.*, 1968; Hall, 1997); (iii) the part of the tongue making the constriction – whether it is the tip, the blade, or the underside ([apical], [laminal], or [sublaminal] (Hamilton, 1996; Gnanadesikan, 1994); (iv) the orientation of the tongue tip ([tip up] for retroflexes and [tip down] for dentals (Gafos, 1999; Hamann, 2003); and (v) the shape of the front portion of the tongue ([tongue middle down] for retroflexes, Hamann, 2003); or [convex] for dentals and [concave] for retroflexes, Arsenault, 2008). Further, some researchers proposed that retroflexes are characterised by (i) a distinct involvement of the posterior portion of the tongue: a backing of the tongue body: features [dorsal] or [back] (Bhat, 1974; Gnanadesikan, 1994; Hamann, 2003; Arsenault, 2008) and (ii) a raising of the tongue dorsum: [high] (Hamann, 2003), as well as (iii) a concomitant lowering of the tongue body for sublaminal retroflexes in particular: [low] (Arsenault, 2008). Finally, retroflexes were noted to be consistently produced with a sublingual cavity, although this is considered to be a consequence of their characteristic tongue tip curling (Hamann, 2003).

Many of the noted features are also relevant for the distinction between retroflexes and alveolopalatals. Specifically, unlike retroflexes, alveolopalatals can be classified as [+distributed] (given their extensive tongue-palate contact: Chomsky *et al.*, 1968; Hall, 1997), [laminal] and [tip down] (given the involvement of the blade and the direction of the tip: Hamilton, 1996; Gnanadesikan, 1994; Gafos, 1999; Hamann, 2003), and [convex] (given the overall shape of the tongue body: Arsenault, 2008). Further, alveolopalatals were noted to be distinguished by a configuration of the posterior portion of the tongue, which could be the reverse of retroflexes: a fronting and/or raising of the tongue body: [-back] and [high] (Hall, 1997; Arsenault, 2008). The two types of consonants, however, are assumed to share an important characteristic – the general location of the constriction, as reflected in the feature specifications [-anterior] (Chomsky *et al.*, 1968; Sagey, 1986) and [postalveolar] or [palatal] (Hamilton, 1996; Gnanadesikan, 1994). This characteristic distinguishes retroflexes and alveolopalatals from dentals (and alveolars). In addition, alveolopalatals are distinguished from dentals by their specification for the tongue body configuration [-back] and [high] (Hall, 1997; Arsenault, 2008), while sharing with the latter other features ([+distributed], [laminal], and [convex]). Overall, these differences amount to alveolopalatals being either equally distinct from retroflexes and dentals (Chomsky *et al.*, 1968; Sagey, 1986; Hall, 1997) or less distinct from retroflexes than from dentals (Hamilton, 1996; Gnanadesikan, 1994; Arsenault, 2008).

Overall, phonological proposals reviewed above agree in some respects and differ in others in identifying crucial distinguishing characteristics of coronal places, as well as relative amounts of these differences. An important goal of the current study is therefore to test some specific predictions of distinctive feature theories about the dental (/t̪ ɳ ʂ ʃ/), retroflex (/ʈ ɳ̠ ʂ̠ ʃ̠/), and alveolopalatal (/t̪ç ɳ̠(d) ç/) contrasts as produced by two speakers of Kannada. In particular, we will investigate which articulatory characteristics are important to distinguishing these contrasts – by both speakers and across five vowel contexts (/i e a o u/). We are also interested in speaker-specific strategies or differences in the realization of the contrasts, as well as in, presumably, non-essential articulatory differences

among consonants involving non-lingual articulators (the jaw, the lips, the velum, the larynx, etc.). Differences involving non-lingual articulators have been reported for coronal contrasts in other languages (as reviewed below).

With respect to the manner of articulation, it should be noted that distinctive feature theory proposals generally assume that place specifications are the same for consonants – whether they are stops, nasals, laterals, or fricatives. That is, for example, the retroflexes /ʈ, ɳ, ʂ, ʣ/ would share the same feature specification for place ([coronal, -anterior, -distributed]: Chomsky & Halle (1968), while differing in manner-specific features (such as [±sonorant, ±nasal], etc.). Whether this is true in general, and for our Kannada speakers specifically, is an open question, as previous articulatory studies have revealed manner-specific lingual and non-lingual differences in Kannada and other languages (as reviewed below).

2.2 Kannada consonants

2.2.1 Phonetic descriptions

Kannada is a Dravidian language spoken natively by over 43 million people, mostly in the southern Indian state of Karnataka (Census, 2011). Together with Tamil and Malayalam, it belongs to the Southern branch of the Dravidian language family (Krishnamurti, 2003).

The consonant inventory of Kannada is given in Table 1, based on previous reference grammar descriptions of the language sounds by Nāyaka (1967), Upadhyaya (1972), Schiffman (1983), and Sridhar (1990). Appendix F provides a summary table of these descriptive sources of Kannada phonology. In cases when the sources disagreed with their descriptions of consonants, we mostly followed Upadhyaya (1972), as the most detailed descriptive phonetic work, except for a few cases noted below.

Stops/affricates in Kannada contrast at five places of articulation: bilabial, dental, retroflex, (alveolo-)palatal, and velar, with three of the places being coronal (produced with the front or middle part of the tongue). Among these, /tʃ ʈʃ/ (also occasionally transcribed as /tʃ ʈʃ/) are classified as alveolopalatal affricates by most authors, and as palatal stops (/c ɟ/) by Nāyaka (1967). The full inventory of the literary (standard) Kannada also includes aspirated and breathy voiced stops. These sounds, however, are largely limited to Indo-Aryan loanwords, and are often neutralised with plain voiceless and voiced stops respectively (e.g. Schiffman, 1983). We, therefore, do not include them in Table 1.

Nasals occur phonemically at a small subset of these places – bilabial, dental, and retroflex. Alveolopalatal and velar nasals are also possible, yet non-phonemically, occurring before the corresponding stops/affricates: in [ɲtʃ], [ɲʈʃ], [ɲk], and [ɲŋ] (with square brackets indicating the non-phonemic status of the sequences).¹ Note that our classification of /ɲ/ as dental is consistent with Nāyaka (1967) but not with the other sources. The latter, including

¹ According to Sridhar (1990), /ɲ/ can be regarded as a marginal phoneme in conversational but not literary Kannada.

Upadhyaya (1972), classify the sound as alveolar (apical or laminal), and different from the nasal occurring before dental stops ([ṅṇ̇] and [ṇṇ̣]). As we will see, however, these differences are not observed in our data.

Descriptions of Kannada fricatives typically include a 3-way sibilant contrast among the anterior /ʃ/ and the posterior /ʂ/, and /ç/. However, the contrast between the latter two – the retroflex and the alveolopalatal – is reported to be frequently neutralised to either [ʃ] or [ç], at least in some dialects (Schiffman, 1983; Sridhar, 1990). In anticipation of our results, we place the anterior sibilant in the dental column, even though all previous descriptions classify it as alveolar. The other phonemic fricative is the glottal /h/ (or /ɦ/ according to Nāyaka (1967)). (The table does not include the fricatives /f/ and /z̤/, which occur exclusively in recent Urdu and English loanwords).

The language has a single rhotic, which is typically realised as a tap, or a trill when geminated. We will refer to it as /r/. There are two laterals – the dental /l̪/ and the retroflex /ɭ/. Our classification of the former sound as dental is consistent with Nāyaka (1967) and Sridhar (1990), but is different from Upadhyaya (1972) and Schiffman (1983), who refer to it as alveolar.

Finally, the approximants (glides) are /v/ and /j/. The former sound is reported to be realised as the bilabial [w] before non-front vowels (/a, a:, o, o:, u, u:/), at least for some speakers.

It should be noted that all retroflex stops and nasals are considered in the literature as sub-laminal post-alveolars/palatals – that is, produced with the underside of the tip behind the alveolar ridge. The details of the realization of the fricative /ʃ/ are less clear; but at least Sridhar (1990) mentions that the sound is apical, rather than sub-apical.

Most consonants can be geminated, with geminate versions occurring only between vowels. All consonant phonemes can occur word-medially between vowels (where consonants can occur as singletons or geminates). All but /ŋ/ and /ɭ/ can occur word-initially. None of the consonants occur word-finally (with vowel epenthesis used to avoid final consonants). There is a small number of onset consonant clusters and hetero-syllabic sequences; however, these are mainly limited to loanwords from Sanskrit or English, or arise due to vowel deletion in conversational speech (Upadhyaya, 1972; Sridhar, 1990).

Kannada has 11 phonemic vowels: short /i e æ a o u/ and long /i: e: a: o: u:/, with the status of /æ/ being marginal (Schiffman, 1983).

Table 1. The ‘core’ consonant inventory of Kannada based on previous descriptions

	Labial		Coronal				Dorsal	Glottal
	Bilabial	Labiodental	Dental	Alveolar	Retroflex	Alveolopalatal	Palatal	Velar
Stop	p b		t̪ d̪		t̠ d̠			k g
Affricate						tʃ dʒ		
Nasal	m		ɳ		ɳ̠	[ɲ]		[ŋ]
Fricative			ʃ		ʃ̠ (or ʃ̠ ~ ʃ̠)	ç		h
Trill/tap				r				
Lateral approximant			l̪		l̠			
Approximant		v [v/w]					j	

2.2.2 Articulatory studies

Unlike other major Dravidian languages, Kannada has received relatively little attention in articulatory phonetic studies. To our best knowledge, there exist no X-ray or static palatography data on the language. This is in contrast to Tamil, for which there have been a number of such studies: X-ray with or without static palatography by Švarný *et al.* (1955), Balasubramanian (1972), and Ladefoged *et al.* (1983), as well as static palatography by Ramasubramanian *et al.* (1971), Balasubramanian *et al.* (1972), and Balasubramanian (1972). More recent articulatory investigations of Tamil sounds made use of electropalatography (EPG Krull *et al.*, 1996), EPG and static palatography (McDonough *et al.*, 2009), MRI (Smith *et al.*, 2013), and a combination of MRI, articulography (EMA), and static palatography (Narayanan *et al.*, 1999). While considerably less numerous, studies of Malayalam have made use of static palatography (Dart *et al.*, 1999) and ultrasound (Scobbie *et al.*, 2013; Irfana, 2017). Contrary to this, articulatory investigations of Kannada have been largely limited to the work by the first author and colleagues – a series of studies using an ultrasound and EMA dataset from 10 Kannada speakers collected in Mysore, India. These studies investigated the production of voiceless geminate dentals, retroflexes, and (alveolo-)palatals (Kochetov *et al.*, 2014; Kochetov *et al.*, 2016; Kochetov *et al.*, 2018), exploring tongue shape differences among the consonants in terms of place and manner of articulation.

Overall, these studies confirmed the robust contrasts between dentals and retroflexes typical of Dravidian languages (Švarný *et al.*, 1955; Ladefoged *et al.*, 1983), as well as between dentals and alveolopalatals. One interesting finding was that the production of Kannada retroflexes did not involve the backing of the tongue body/dorsum, as is commonly assumed of retroflexes (Bhat, 1974; Hamann, 2003; Arsenault, 2008; see above) or retroflex-like articulations (like the North American English /ɹ/: Narayanan *et al.*, 1997). In fact, the tongue dorsum for the Kannada /t̠/ in Kochetov *et al.* (2014) was in a more front position compared to /t̠/ or to the rest position,

suggesting that the tongue backing is not obligatory for retroflexes. A similar lack of the tongue dorsum retraction was observed for Kannada nasals and laterals in Kochetov *et al.* (2018). Another finding was that tongue shapes for coronals differed somewhat depending on the manner of articulation. For example, the nasals /ŋ, ɲ/ tended to be produced with a more advanced or lower tongue dorsum compared to the laterals /ɭ, ʎ/ and stops /ʈ, ʈʰ/, and more so for dentals than retroflexes. These differences presumably reflected different aerodynamic requirements involved in the production of distinct manner classes and their interactions with requirements imposed by the place contrasts.

However, these and other observations made using ultrasound should be taken with caution, as they rely on an inherently partial view of the tongue and limited information about other articulators (as discussed further below). Such information, however, is important, as the involvement of the jaw and other non-lingual articulators have been noted to be important for certain place contrasts and their variation across manners. For example, Tabain (2012) found that retroflexes and alveopalatals in Arrernte (Australian Aboriginal) were produced with a lower and higher jaw, respectively, compared to each other, as well as compared to their dental and alveolar counterparts. Presumably, the jaw lowering facilitates the curling of the tongue tip towards the hard palate for retroflexes, while the jaw raising assists with producing an extensive laminal contact with the palate for alveopalatals. While combining ultrasound imaging with EMA can partly resolve some of these limitations (by tracking the lips and the jaw, as done by Tabain, 2012), we are still faced with a rather limited sampling of the sagittal section vocal tract.

2.3 Predictions

Based on descriptive accounts and articulatory studies of Kannada, reviewed above, we expect coronal articulations to fall into three major places with respect to the linguopalatal constrictions and tongue shapes (dentals/alveolars, retroflexes, and (alveolo)palatals). The dental-retroflex contrast is expected to exhibit more articulatory differences than the retroflex-alveopalatal and dental-alveopalatal contrasts. Specifically, we may expect to find the former contrast to be distinguished by a set of properties, among which are: the location and extent of the constriction between the tongue and the roof of the mouth (dental vs. post-alveolar or palatal), the part of the active articulator involved (apical, laminal, or sublaminal) and its shape or direction (the tongue middle down or not, convex or concave, tip-up or tip-down), the involvement of the posterior portion of the tongue (backing and lowering of the tongue body and raising of the tongue dorsum) and presence or absence of a sublingual cavity.

Within each coronal place, subtler differences in the tongue shape/constriction are expected across different manners of articulation, and most particularly between stops and nasals or laterals. Oral and nasal sounds would inherently differ in the position of the velum; they may also show some differences in other articulators, such as the jaw, the lips, and/or the tongue (Keating *et al.*, 1994; Mooshammer *et al.*, 2006; Tabain, 2012; see also Kochetov *et al.*, 2018). The need to channel air through the sides for laterals, as opposed to seal off the airflow for stops, would result in inherently different tongue shapes and jaw positions for these two types of consonants.

Considering retroflexes in particular, we predict these to be produced with a constriction behind the alveolar ridge and without a tongue dorsum/root backing (as observed in the ultrasound studies (Kochetov *et al.*, 2014; Kochetov *et al.*, 2018)). An exception to this can be presented by the fricative, which may not be distinguished by our speakers from the alveolopalatal fricative. Given some inconsistencies in the literature, a closer attention will be paid to the articulation of /ŋ/, /ʂ/, and /ɻ/ (which have been described as either dental or alveolar), as well as non-coronals /v/ (described as labiodental or bilabial-velar, depending on the vowel context) and /h/ (described as lacking a lingual constriction). Finally, we also predict consonants to show different degrees of coarticulation to adjacent vowels. Specifically, some tongue fronting and backing, expected next to front and back vowels respectively, is likely to be lesser for coronal consonants, and especially those with extensive linguopalatal contact (alveolopalatals and sublaminal retroflexes or those constrained by aerodynamic requirements, namely the trill and sibilant fricatives), compared to noncoronals that either lack a lingual constriction (labials and /h/) or share the primary articulator with vowels (velars) (Recasens, 1999).

3 Methodology

In this section, we present the methodological approach used in the present study to document and characterise the articulatory strategies implemented to produce the various contrast of interest in Kannada. We provide the pertinent information concerning the speakers, the corpus and the recording procedure. We then describe the pre-processing of the MRI images, namely the semi-automatic segmentation of the articulators, including head tilt correction. Next, we introduce the methods used to make sense of these data: comparison of mean consonant contours by overlay, illustration of the dispersion due to vocalic coarticulation and use of articulatory modelling to represent the contours in a compact interpretable way.

3.1 Speakers

The participants were two female native speakers of Kannada from the state of Karnataka, South India. Karnataka is the only state where Kannada is an official language and the main medium of instruction in schools. The speaker KMU was 25 years old, born and raised in the city of Mysore. At the time of the recording, she was a recent graduate of the University of Grenoble, having spent in France a total of 3 years. Apart from Kannada, she reported speaking Sanskrit, Hindi, English, and French. The speaker KD was 26 years old, born and raised in the city of Kalasa. She was a student at the University of Grenoble, having spent in France 2 years. She reported speaking English and Hindi as second and third languages. Both participants mentioned using their first language on a daily basis.

3.2 Recording setup

Magnetic Resonance Imaging (MRI) is a medical imaging technique that allows to observe all the speech articulators and the entire vocal tract, including the sublingual cavity, which is important for retroflex consonants (e.g. Narayanan *et al.*, 1999). While being constrained by participant sample size and other limitations, the MRI

method has some important advantages over the more commonly used in phonetics point-tracking or imaging methods. Indeed, although ultrasound tongue imaging has been used increasingly in studies of coronal consonant contrasts, the method does not provide enough reliable information about lingual constrictions made with the tongue tip or tongue underside/sublingual cavity (which are particularly important for retroflexes). Moreover, ultrasound usually provides very limited information about the palate, and the rest of the vocal tract (beyond the surface of the tongue), including the articulators such as the jaw, the lips, and the velum, which all are likely to be recruited in the production of coronal place and manner contrasts. It was therefore important for our purposes to use MRI in order to acquire images offering a larger coverage of articulators, for better characterising the articulatory strategies used to achieve robust consonantal contrasts, and analysing the interplay between place and manner of articulation and comparing the resistance to vocalic coarticulation between consonants.

Real-time MRI can nowadays easily generate large amounts of images (*e.g.* Narayanan *et al.*, 2014), but processing them to obtain a reliable segmentation of all speech articulators is still an arduous problem (*e.g.* Labrunie *et al.*, 2018). Therefore, we chose to record static single slice mid-sagittal images. We operated with a Philips Achieva 3.0T dStream scanner equipped with a 20 channel head-neck coil at the IRMaGe MRI facility, Grenoble, France. Turbo Spin Echo mode was used, with 85% half scan factor, no SENSE acceleration, 80° flip angle, shortest TR and TE (leading to actual values of 731 – 864 ms for TR and of 12 – 10 ms for TE), minimum water-fat shift, and a TSE factor of 38. The acquisition time was in the range of 6.58 – 6.95 s per image. This sequence produced single slice mid-sagittal images with a thickness of 4 mm covering a 192×256 mm² field of view with an isotropic 1 mm in-plane resolution. The image was framed to include the glottis and the main skull sinus regions (sphenoidal and frontal) in the vertical direction and the nose and the neck regions in the horizontal direction. This ensured to include the complete vocal tract as well as enough of the skull structures to allow the automatic tracking of its movements (*cf.* below for details).

Thus, although limited to data from two speakers, our corpus represents articulatory behaviour of these individuals in a considerable detail, and through this serves to document articulatory patterns of Kannada to an extent rarely available in the current literature.

The speakers were lying comfortably in a supine position on the MRI scanner bed. In order to minimise head movement, MRI-compatible foam cushions were wedged between the speakers' head and the MRI receiver coil. The speakers could watch a screen displaying the corpus items thanks to a mirror attached to the coil support.

3.3 Corpus and procedure

While focusing on the above-mentioned coronal contrasts, the recorded corpus was designed to include Kannada consonants of all places of articulation (including labials, velars, and laryngeals, see Table 1), occurring in the same five vowel contexts. This was necessary in order to develop comprehensive articulatory models of coronal consonants, taking into account the full range of articulatory positions (Badin *et al.*, 2002). Specifically, the corpus

contained 17 consonant phonemes /p t̪ k t̪ɕ ʃ ç ɣ h m ŋ ŋ̣ l̪ r v j/ (excluding the voiced cognates that are difficult to sustain) embedded in symmetric V_V contexts with the five short vowels /i e a o u/. This produced 85 nonsense items, five for each consonant (e.g. [aʈa], [iti], [uʈu], [ete], and [oto]).² To further explore place differences in nasals, we included 25 items with sequences of homorganic nasals and stops/affricates: [mb ŋ̣̄ ŋ̣̄ ɲ̣̄ ŋ̣̄] (e.g. [aŋ̣̄ɕa], [iŋ̣̄ɕi], [uŋ̣̄ɕu], [eŋ̣̄ɕe], [oŋ̣̄ɕo]), which will be referred to below as /m(b) ŋ̣̄(d) ŋ̣̄(d) ɲ̣̄(ɕ) ŋ̣̄(g)/. Although limited to data from two speakers, our corpus represents articulatory behaviour of these individuals in a considerable detail, and through this serves to document articulatory patterns of Kannada to an extent rarely available in the current literature.

The wordlist was prepared in consultation with both participants prior to the first recording session. The words were transcribed using the Kannada orthography and presented on a computer screen, seen by the speaker lying in the MRI machine via a mirror. Immediately before the recording sessions, the speakers were asked to read through the list aloud several times, to ensure that they were comfortable producing all words in the MRI machine. Task performance was monitored through audio communication standardly available on the MRI scanner, complemented with MRI-compatible audio recording to allow later checking. As well, reconstructed images were displayed immediately after each recording and could be inspected to check their quality and their relevance.

For the recordings, the speakers were instructed to repeat the utterances twice in a natural manner and then to freeze the consonant in the last repetition for the 6.9 s duration of the scan.³ The scan was launched as soon as the operator heard that the consonant articulation was being maintained. This protocol ensured that the consonant was truly coarticulated with the vowel. A single recording was made for each item, except for items with the affricate /t̪ɕ/. There, two recordings were made: one during the occlusion (designated as /t̪ɕ/) and one during the frication portion (/ç(t̪ɕ)/) of the sound. Altogether, 110 tokens were recorded (one for each non-affricate item and two for each affricate item).

In order to retrieve the contours of the teeth, which cannot be distinguished from the air on MRI, a few additional reference articulations where the soft tissues are in contact with the teeth were recorded: upper lip rolled around the upper incisors, lower lip rolled around the lower incisors, tongue pressed against the incisors. These images allowed us to determine the contours of the teeth to appear in contrast to the soft tissues.

² Short rather than long vowels were used, given the lesser frequency of the latter in words and phonotactic restrictions on sequences of two long vowels (N. Sreedevi, p.c., November 2018).

³ The relative length of the scanning time was the reason not to include voiced stops/affricates, as it is hardly possible to maintain voicing for the 6.9 seconds. It was assumed that the voiced and voiceless counterparts would have very close articulations.

3.4 Semi-automatic contour segmentation

Semi-automatic segmentation of the main speech articulators (jaw, lips, tongue, velum, etc.) from the MRI images was performed according to the method described in Labrunie *et al.* (2018). First, the boundaries of the upper teeth and hard palate as well as those of the lower teeth and jaw bone were manually outlined on the reference images, using B-splines and control points, in order to serve as reference rigid contours. Besides, the unwanted head movements of translation parallel to the midsagittal plane and of rotation around the left-right direction were automatically determined and counterbalanced for all images, in order to realign the skull structures and in particular the hard palate on the same chosen reference image; this was realised by an automatic procedure that minimises the average difference of pixel intensities in the skull region between the reference image and the aligned image (*cf.* Labrunie *et al.* (2018) for details).

A set of 60 images was then automatically selected by means of unsupervised ascending hierarchical clustering to optimally represent the whole corpus (*cf.* Labrunie *et al.*, 2018). All contours were manually segmented for these images. The rigid contours (jaw and hyoid bone) were positioned by means of rotation and translation, while deformable contours were edited using B-splines. In addition, specific anatomical landmarks were located by the expert in order to determine coherent extremities for some of the articulators (*e.g.* tongue tip, junction of tongue root and epiglottis, *subnasale* for the upper lip or *submentale* for the lower lip (*cf.* Bishara *et al.*, 1995)). The processing of each image took about 10-15 minutes for the trained MRI expert phonetician to perform.

The data were subsequently used to train modified Active Shape Models that could predict the contours from the images for the rest of the corpus (Labrunie *et al.*, 2018). All contours were finally checked and manually corrected if needed. In addition, three anatomical landmarks were positioned by the expert: N2 for the upper limit of the upper lip, LL for the lower limit of the lower lip, and TT for the extremity of the tongue. Figure 1 illustrates the resulting contours for one of our speakers, as well as these landmarks. The contours converted to centimetres were all aligned on the same hard palate and each resampled with a number of points fixed for each articulator, using the landmarks as extremities when needed. This resampling ensures the possibility to reliably compare contours and build models based on methods requiring a fixed number of variables, such as Principal Component Analysis (PCA). Appendix A provides individual images with overlaid contours as exemplified in Figure 1 for all phones for both speakers.

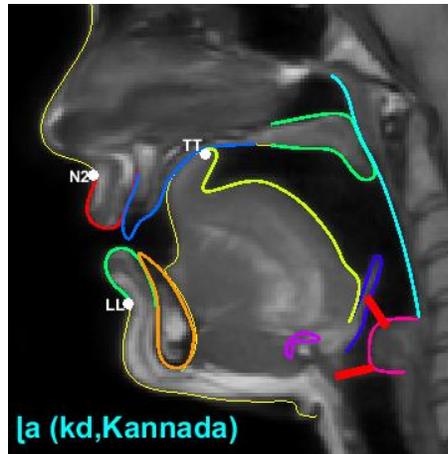


Figure 1: Articulator contours superimposed on a midsagittal image of /l/ in /a|a/ (speaker KD). Resampled contours are identified by different colors, in a clockwise rotation along the vocal tract walls: upper lip, palate, velum, nasopharyngeal wall, laryngeal articulator (in reference to the laryngeal articulator Model, Esling (2005), Esling et al. (2019)⁴), epiglottis (though it is not an active articulator, cf. Esling et al. (2019)), hyoid bone, tongue, jaw, and lower lip. The original contours available for the image are traced in yellow lines. The three anatomical landmarks are displayed with white dots. Two red thick lines have been added to facilitate the interpretation of the laryngeal region: the aryepiglottic folds (top) and the vocal folds (bottom) that cannot be seen in such a midsagittal image correspond to the extremities of the epilaryngeal tube.

3.5 Head tilt correction

The automatic procedure mentioned above aligns images on the reference image so as to make sure that the skull structures coincide, but it cannot fully control for the change of head tilt, *i.e.* the angle between the skull and a plane parallel to the spine or posterior wall of the pharynx. As we found, the head tilt had a fairly large influence on the shape of all articulators. We have therefore implemented a head tilt correction procedure, based on linear articulatory modelling, considering the head tilt movement as an articulatory component (*cf.* section 3.7 for a

⁴ Note that what we call here ‘laryngeal articulator’ for convenience corresponds to the contours of the variable region of contact of the rear structures of the larynx in the midsagittal plane, namely the transverse and oblique arytenoid muscles and the aryepiglottic folds. During phonation, the laryngeal constrictor mechanism may tighten these muscles slightly, reinforcing the lateral cricoarytenoid contraction necessary to bring the vocal folds into line (Esling et al., 2019). Concomitantly, the visible contact region in the midsagittal plane increases with increasing constriction, whereas it may be considerably reduced during breathing. The horizontal movements of the anterior edge of this region are thus related to vocal fold adduction and to constriction, while its vertical movements are related to vertical movements of the larynx (usually upwards with constriction and downwards during breathing or breathiness). Tracking this contour can thus provide information about laryngeal position and vocal fold state.

definition of articulatory models), though not directly related to speech. The head tilt $PhTilt$ was estimated as the z-scored horizontal coordinate of the intersection of the pharyngeal wall measured along a fixed horizontal line just above the larynx region. The contribution of this articulatory variable to the (x / y) coordinates of all articulators was then modelled by a linear regression on $PhTilt$. Figure 2 displays the nomogram of this component, *i.e.* the changes in contours when $PhTilt$ varies from -3 to +3): we can observe that the influence of $PhTilt$ decreases from the back to the front of the vocal tract. The head tilt correction then consisted in removing this contribution from the original data. Appendix B illustrates the effects of this head tilt correction for some extreme cases.

Further analysis or modelling of the whole set of contours was finally performed on the resulting residues. Note that we checked that all the analyses were actually not much influenced by this correction.

Note also that sometimes the speaker's head was not fully aligned with the mid-sagittal plane – due to subsequent motion of the speaker, which produced parallax errors that could not be compensated for, and which resulted in slight deformations visible in the front region (nose, lips and incisors).

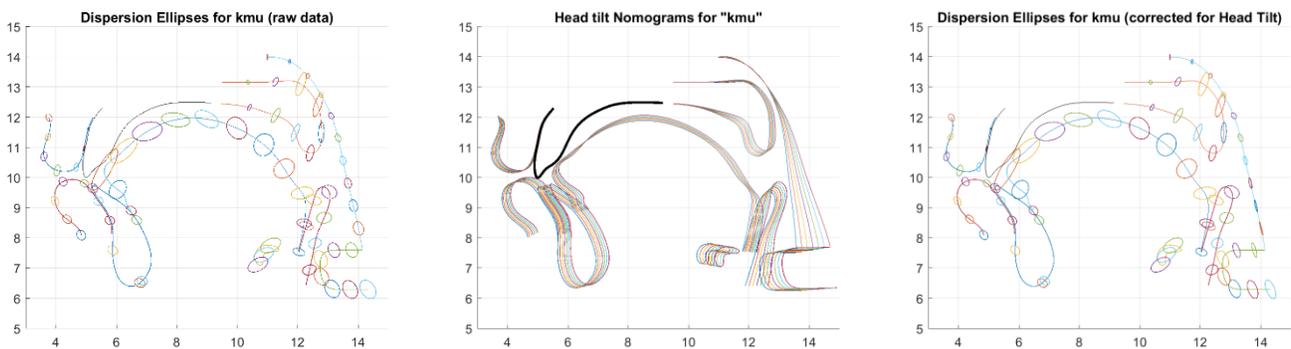


Figure 2. Illustration of the head tilt correction. Left: dispersion ellipses of raw contours plotted for every 15th point; middle: nomogram of the effect of the head tilt variation; right: dispersion ellipses of the corrected contours (speaker KMU).

3.6 Analysis methods

This section presents the various analytical and modelling methods developed and used in this study, namely display of dispersion ellipses, superposition of individual or mean contours, and articulatory modelling.

3.6.1 Superposition of contours

The simplest – though very useful – approach to comparing articulations and characterising coarticulatory effects consists in superposing various contours on the top of each other. Though this approach is speaker dependent, since normalising articulatory contours across different speakers is difficult (*e.g.* Serrurier *et al.*, 2019), the superposition of individual or mean contours for each speaker is very meaningful, as exemplified in Figure 3. Note that the alignment of the images insures that the articulator shapes can be directly compared to each other for a

given speaker. For example, we can see in the Figure 3 that velars /k/ and /ŋ(g)/ are produced with roughly the same lingual gesture – a tongue dorsum closure at the boundary between the hard and soft palates (but extending slightly further back for /k/). The positions of the jaw and the lips are relatively similar too. The differences, on the other hand, are in the position of velum/uvula (high for /k/ and low for /ŋ(g)/), as well as the hyoid bone, and, less consistently, the epiglottis and the glottis.

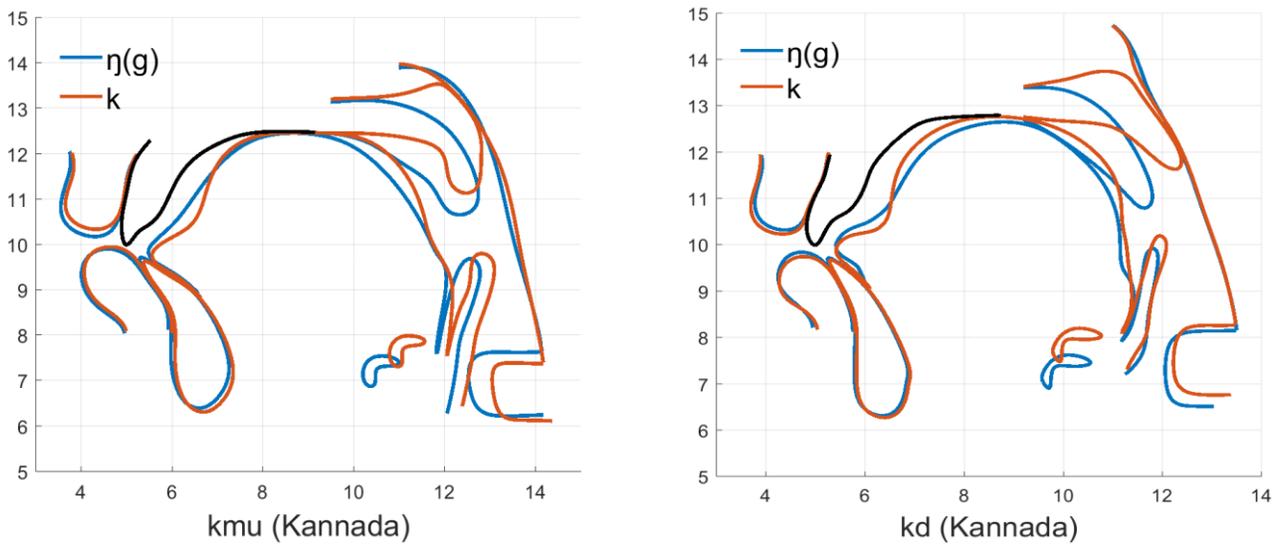


Figure 3. Sample midsagittal mean contours superposition (speaker KD).

3.6.2 Dispersion ellipses

One aim of the work being to characterise the robustness to vocalic coarticulation and compare this robustness between consonants, it was interesting to go one step further from the simple comparison of contours by superposition, and to find ways to estimate the variance of the contours. One classical approach to determine this variance for the tongue is Smoothing Spline ANOVA(SS-ANOVA) (e.g. Davidson, 2006 or Mielke, 2015): this method, applied to contours extracted from ultrasound images, aims to determine confidence interval around the average of contours over several repetitions of the same articulation, and then to compare the different articulations. In practice, the number of repetitions for each item largely amounts to a dozen [8 for Davidson, and apparently more than 20 for Mielke, counting from his Fig. 2], and the variance of the repetitions of the same articulations is low. Besides, the method is useful for contours without large bends – which is the case for contours extracted from ultrasound images where the tip and the root of the tongue are not well visible and thus not taken into account. In its version working with Cartesian X/Y coordinates of the contours (Davidson, 2006), SS-ANOVA works only if $Y = f(X)$ is an injective function of X, i.e. each Y has no more than one corresponding X. As this is not the case of all regions of the tongue due to the large curvature of the vocal tract, Mielke (2015) developed an SS-ANOVA method based on polar coordinates. It is indeed more suitable, but still cannot properly work for

retroflex articulations. The extensive contours that we have obtained from our MRI data have complex shapes that cannot be dealt with using SS-ANOVA; moreover, since we aim to study vowel coarticulation, the variance of the repetition of the consonants for the five vowels is large; finally, we have unfortunately only five items for each consonant, which is not suitable for proper statistical analysis.

As we were not able to use SS-ANOVA for our contours, we resorted to a less sophisticated approach to present vocalic coarticulation effects on a consonant in a comprehensive way, as proposed in Badin *et al.* (2019): we display the mean of the articulations of the same consonant over all vocalic contexts of interest, with a representation of the associated dispersion of contour points, by means of dispersion ellipses drawn at ± 2 standard deviations around the mean points. This display is illustrated in Figure 4 where we can observe that the tongue tip for / η / has a low variance, whereas the tongue blade region is much more variable.

Appendix C provides the dispersion ellipses for all consonants for both speakers, which can serve as reference.

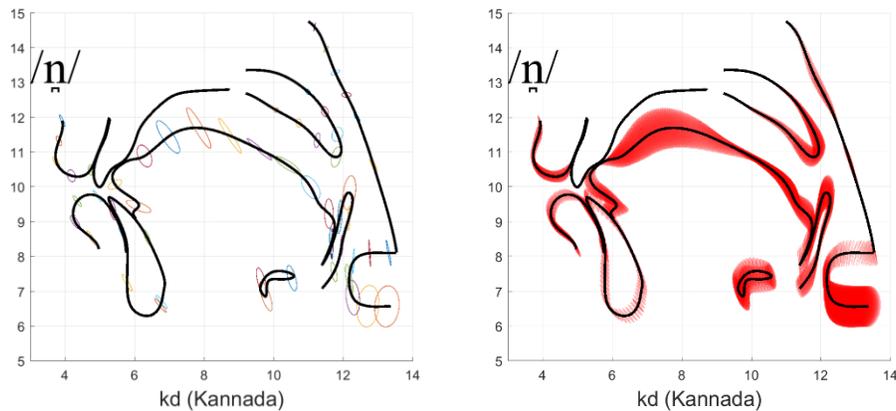


Figure 4. Example of dispersion ellipses around the points of the mean contour for / η / (speaker KD). Left: only one point every 15th is selected in order to better illustrate the method; right: all points are selected, which allows to see the outlines of the ± 2 standard deviations region.

3.7 Articulatory modelling

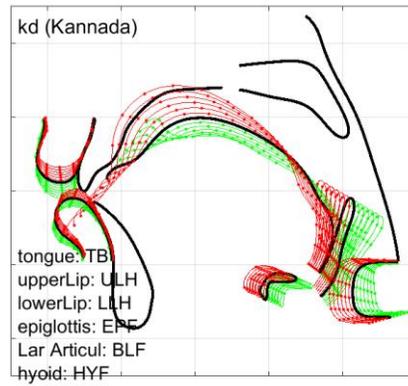
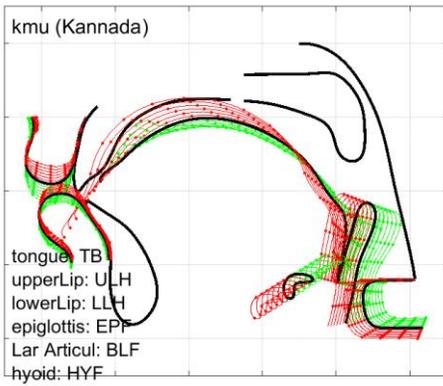
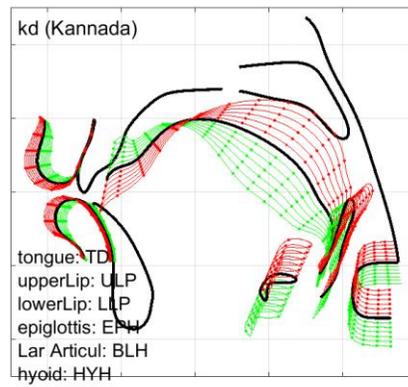
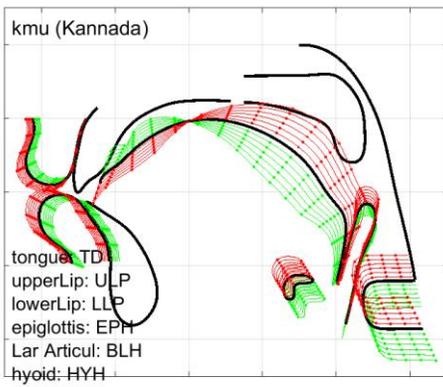
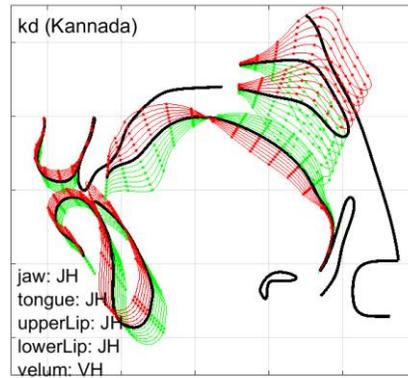
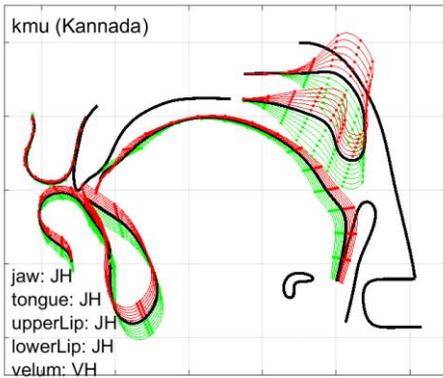
3.7.1 Principles of articulatory modelling

Due to their complexity, the articulatory contours are difficult to characterise in a meaningful and relevant manner for speech. Articulatory modelling obviously constitutes a way to deal with this issue, as it offers the possibility to boil down the apparent articulatory complexity to a few basic components. As reviewed in Serrurier *et al.* (2019), linear articulation models based on principal component analysis (PCA) have been successfully used for long to extract and characterise the basic articulatory components of a speaker (*e.g.* Lindblom *et al.*, 1971 or Serrurier *et al.*, 2008). Such an approach allows to exploit correlations between different shapes of speech organs observed in the tasks in order to determine the independent degrees of freedom (DoF) of the articulators. These DoF correspond to the simple gestures that are linearly uncorrelated and can be performed independently of each other by the

articulators (*cf.* Beautemps *et al.*, 2001). In this study, we used guided PCA which aims to take into account the sole correlations related to biomechanisms while excluding correlations clearly related to pure control strategies (Beautemps *et al.*, 2001). Note that Silva *et al.* (2016) proposed the “use of objective measures to compare the configurations assumed by the vocal tract during the production of different sounds”; for each speaker, they measured distances in the midsagittal plane at a number of specific locations and normalised them by the maximal distance for each speaker. While this approach might be suitable for normalization purposes, it tends to miss the proper semantics of articulatory parameters.

For each speaker, we have built articulatory models of all segmented organs following the approach described by Badin *et al.* (2002) or Serrurier *et al.* (2019). The jaw control parameters, *JH* (jaw height) and *JA* (jaw advance), are the z-scored values of the vertical and horizontal coordinates of the lower incisors. Parameter *JH* is also used as the first control parameter of the tongue. Its main effect is a tongue rotation around a point in the back of the tongue (see Figure 5). The next two parameters, tongue body *TB*, and tongue dorsum *TD*, are extracted by PCA from the tongue contour coordinates, excluding the tongue tip region, from which the *JH* contribution has been removed. They control respectively the front/high vs. back/low and flattening vs. arching/bunching movements of the tongue (see Figure 5). The last two parameters, tongue tip fronting *TTF*, and tongue tip height *TTH*, are extracted by PCA from the tongue contour coordinates from which the *TB* and *TD* contributions have been removed (see Figure 5). For the upper and lower lips, the z-scored values of the protrusion (*ULP*, *LLP*) and height (*ULH*, *LLH*) measurements have been used as control parameters in complement to the *JH* component. This approach leads to somehow lower performances than using the first two PCA components of the *JH* residue (*cf.* section 3.7.2 and Table 2), but ensures a better interpretation of these components in terms of phonetics. The models of the other organs (velum, pharynx, hyoid, epiglottis and laryngeal articulator) are simply controlled by their first two PCA components.

To illustrate the general behaviour of these models, we generated articulatory nomograms, *i.e.* displays of the articulator shapes across the range of control parameters of the model. Figure 5 displays nomograms associated with the components of the various articulators. As we can see in the first two images, the *TD* parameter controls the arching movement of the posterior region of the tongue towards the velum, accompanied by some lowering of the tongue blade. The second two images show that the *TTF* parameter is responsible for the lowering of the middle region of the tongue and the fronting of its back region, which seems to be crucial for the raising and retraction of the tongue tip during retroflexion.



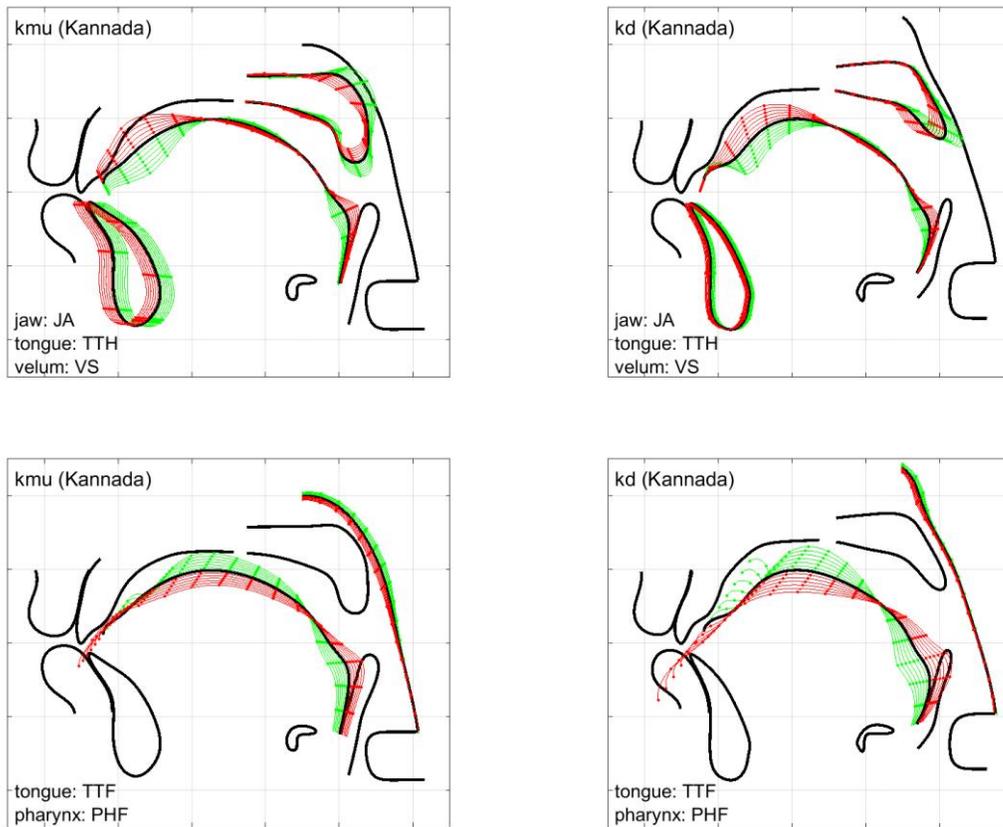


Figure 5. Nomograms of all articulators for both speakers (left KMU, right KD). Articulatory nomograms of jaw, tongue, lips and velum are displayed as the variations of their shapes for control parameters varying from -3 to +3 by 0.5 steps. Mean contours are drawn in black lines, contours for negative parameter values in green, and those for positive values in red. Every 10th point is displayed with dots to illustrate the movements of the models points.

3.7.2 Assessment of the articulatory models

The models have been evaluated in terms of cumulative relative variance explained (VarCum) and of Root Mean Square contour reconstruction Error (RMSE). Table 2 displays the results of the evaluation. These results are consistent with previous similar models elaborated on another speaker (Badin *et al.*, 2006). Overall, the model reconstruction is accurate, with an explained variance between 66 and 98 % (99.8% for the hyoid), and an RMSE between 0.02 and 0.10 cm. Table 2 displays also the performances of the raw PCA models with the same number of parameters as in the guided models for each organ: we observe that the guided models are suboptimal, with a loss of performance with respect to the PCA models between 2.0 and 29.7 %, and 0.02 to 0.04 cm RMSE. The lower performance for the lips may be ascribed to the slight lack of accuracy in the position of the *submentale* marker (see 3.7.2.1).

In order to assess the similarity of articulatory strategies, the Pearson correlation coefficient between the two speakers was estimated for all parameters. Values in Table 2 show that the tongue strategy is rather similar (0.75 for *TB*, 0.55 for *TD*, up to 0.70 for *TTF*, though the jaw is not as much correlated; see the column “Correl.”). Other important similarities are found for the velum (0.90 for *VH*) or for the upper lip (0.59 for *ULP*). These similarities are confirmed by the nomograms in Figure 5.

3.7.2.1 Analysis of robustness to extremities errors for the articulatory models

For three specific organs, i.e. the tongue and both lips, the resampling process may introduce errors due to the uncertainty of the localisation of extremities by means of the anatomical landmarks (N2, LL, TT). In order to assess this problem, we have simulated pointing errors for these points and determined the consequences. The projections of the three points N2, LL and TT on the manually edited contours, which are used as anchor points for the resampling of the contours, have been shifted along the contours by an amount randomly chosen in a given range (from 0.1 to 0.5 cm) for the whole corpus. In addition to the original contour data (i.e. no shift), we have obtained another five data sets with increasing error ranges. We have then applied the standard guided PCA modelling approach to each of the six sets articulations, for speaker KD.

We have then made various comparisons of the models obtained from the five datasets with the original one: (cumulated) relative variance explained by each component (VarExCum), RMS reconstruction errors, informal observations of the nomograms, correlations between the articulatory parameters for the different sets.

We observed a very negligible influence of the random shifts of TT on the tongue models and performances. Oppositely, a larger influence of extremities was observed for the lip models. The model on the original data reaches a variance explanation of 94.0% and 92.4% respectively for the upper and lower lips with RMS of 0.026 and 0.038 cm respectively.

Another interesting comparison is the correlation, over the whole corpus, of the articulatory parameters. We have observed that for the lips models a general decrease of the correlations when the extremities shift range increases. The correlations are higher than 0.94 for the ± 0.1 cm range, and higher than 0.66 for the ± 0.2 cm range. We note that for higher ranges some of the correlations are swapped: *ULP* for the ± 0.2 cm range is correlated with *ULH* at 0.94, or *LLH* is correlated with *LLP* at -0.96. This reflects the fact that the variance of the data, which has been increased by the random shifts, is distributed differently between the first two PCA components.

This was also reflected in the nomograms. A careful inspection of these figures revealed the approximate continuity of semantics (protrusion or height movements) of the components for the different datasets with little dispersion of the markers, and some swaps between some of the components. In conclusion, there are no problems for the tongue, while lips models start to be less reliable for shift ranges greater than ± 0.3 cm, which are not likely to be produced by the expert.

Table 2. Performances of the articulatory models by organ parameter (Param.) and speaker (VarEx = relative variance explained by the component; VarCum = cumulative explained variance); figures for the total number of parameters used in the models for each organ are marked in bold. The correlations between KMU and KD parameters are given in the last column; correlations above 0.50 are indicated in bold. In the extra lines for articulators processed with the guided PCA, the performance of the raw PCA model with the same number of parameters is given in non-italics.

Organ	Param.	KMU			KD			Correl
		VarEx (%)	VarCum (%)	RMS (cm)	VarEx (%)	VarCum (%)	RMS (cm)	
jaw	JH	51.8	51.8	0.11	88.9	88.9	0.05	0.18
	JA	35.3	87.1	0.05	4.5	93.4	0.04	0.38
	PCA 2		<i>98.6</i>	<i>0.02</i>		<i>99.5</i>	<i>0.01</i>	
tongue	JH	2.2	2.2	0.35	7.3	7.3	0.43	0.18
	TB	54.6	56.8	0.23	41.5	48.8	0.32	0.75
	TD	19.7	76.5	0.17	19.3	68.1	0.25	0.55
	TTF	12.6	89.1	0.12	23.4	91.5	0.13	0.70
	TTH	17.2	93.7	0.09	26.3	94.4	0.10	0.46
	PCA 5		<i>96.4</i>	<i>0.07</i>		<i>96.4</i>	<i>0.08</i>	
upperLip	JH	1.2	1.2	0.10	15.3	15.3	0.10	0.18
	ULP	21.0	22.2	0.09	29.2	44.5	0.08	0.59
	ULH	44.1	66.3	0.06	30.0	74.5	0.06	0.16
	PCA 3		<i>96.0</i>	<i>0.02</i>		<i>98.1</i>	<i>0.02</i>	
lowerLip	JH	26.7	26.7	0.12	56.9	56.9	0.09	0.18
	LLP	33.0	59.7	0.09	13.6	70.5	0.08	-0.02
	LLH	11.3	71.0	0.07	9.1	79.6	0.06	0.32
	PCA 3		<i>91.6</i>	<i>0.04</i>		<i>92.9</i>	<i>0.04</i>	
velum	VH	83.5	83.5	0.08	93.0	93.0	0.08	0.90
	VS	11.5	95.0	0.04	4.9	97.9	0.04	-0.01
pharynx	PHH	84.3	84.3	0.04	88.9	88.9	0.03	0.27
	PHF	6.6	90.9	0.03	5.1	94.0	0.02	-0.06
hyoid	HYF	76.0	76.0	0.14	81.6	81.6	0.12	-0.68
	HYH	23.9	99.9	0.01	18.2	99.8	0.01	0.22
epiglottis	EPF	57.1	57.1	0.13	49.7	49.7	0.16	0.49
	EPH	23.2	80.3	0.09	37.0	86.7	0.08	-0.03
lar articul	LAH	75.7	75.7	0.11	53.3	53.3	0.14	0.20
	LAF	16.8	92.5	0.06	35.8	89.1	0.07	0.33

3.7.3 Radar display of articulatory parameters

We have seen that the articulatory parameterization allows to characterise each articulation with a small number of articulatory parameters. Ideally, we would have applied ANOVA to these articulatory parameters to assess the differences between consonants. Unfortunately, each consonant is available in only five vowel contexts, which prevents a pertinent use of ANOVA. Therefore, inspired by Silva *et al.* (2014), we use a *spider* or *radar* chart to

display the main articulatory parameter values simultaneously in a compact way: the superposition of two or three sets of such displays allows a comparison of articulations in terms of main articulatory components, as illustrated in Figure 6. In such plots, values for each component are the means over five vowel contexts; along each radius, the values increase from the minimum on the inner polygon (corresponding to the green contours on the nomograms, Figure 5) to zero on the intermediate polygon, to the maximum on the outer polygon (corresponding to the red contours in the nomograms). For instance Figure 6 shows that the differences between /ŋ(g)/ and /k/ for KMU are mainly related to the velum height (VH, /k/ > /ŋ(g)/), hyoid bone fronting (HYF, /ŋ(g)/ > /k/), and to a lesser degree to other components, including the laryngeal articulator height (LAH), jaw height (JH), upper lip protrusion (ULP, /ŋ(g)/ > /k/), upper lip height (ULH, /k/ > /ŋ(g)/), and the tongue dorsum (TD, /k/ > /ŋ(g)/). For KD, the main differences are in the velum height, the hyoid bone height (HYH), and to a lesser degree in the upper lip protrusion (all /k/ > /ŋ(g)/).

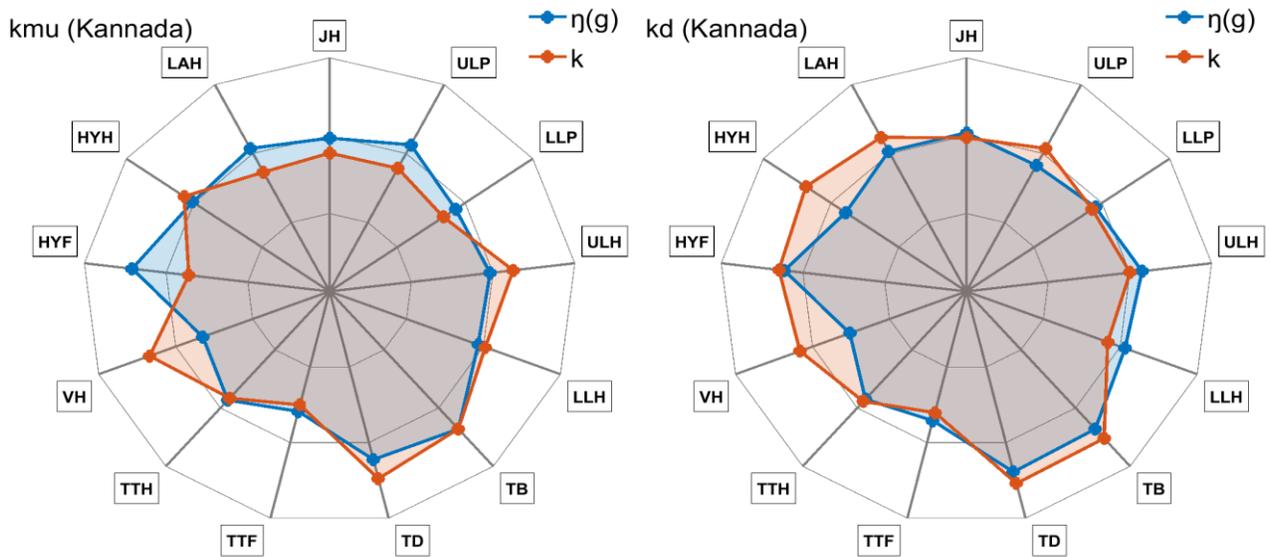


Figure 6. Example of radar charts (KMU left, KD right).

4 Results

The presentation of results is organised by place differences (Section 4.1), manner differences (Section 4.2), and patterns of coarticulation (Section 4.3). Within the first two sections, the results are further sub-divided by types of contrast – by manner, place, or both.

4.1 Place differences within manner classes

4.1.1 Place contrasts in stops/affricates

4.1.1.1 Contrasts among coronals

The results for coronal stops/affricates are presented in Figure 7, separately by speaker. Overlaid average articulator contours are displayed on the left, while radar displays are presented on the right. In each case, we begin by providing general descriptions of three articulations represented in overlaid contours, and follow by a review of differences in articulatory parameters based on radar displays. In articulatory descriptions, we are using the delineation of upper and lower articulator areas from Catford (1988).

For KMU, we can see that /t̥/ can be described as an apico-laminal denti-alveolar/post-alveolar stop, as the constriction is produced by both the tip and the blade, and extends over a large area from the upper teeth to the post-alveolar region. The consonant is produced with an overall convex tongue, a somewhat raised tongue body, and a slightly more retracted lower posterior part of the dorsum. The second consonant, /t/, is an apical/sublaminal post-alveolar stop, as it is apparently produced with both the tip and the underside in the postalveolar area. Its tongue shows a small concavity between the blade and the tongue body; the tongue body and the tongue dorsum are convex, and overall similar to /t̥/. Among other characteristics of this consonant are the considerably lowered/retracted jaw, a lowered/less protruded lower lip, and a small sublingual cavity. The third consonant, the affricate /t(t̥)/ is produced as an apico-laminal denti-alveolar/post-alveolar stop, with the constriction being similar to /t̥/, but extending slightly further back. Its tongue is convex and considerably raised (palatalised) compared to the other stops; the posterior portion of the tongue (its tongue dorsum) is similar to that of /t̥/ (and more fronted than for /t̥/, while the root is fronted compared to the other two consonants. In addition, the affricate is produced with a lowered larynx, and both lips being considerably protruded. The somewhat higher/more front position of the hyoid bone appears to reflect the raising of the tongue body. Turning to articulatory parameters illustrated in the radar plot, differences among the three consonants are mainly related to the components *TTF* (the tongue tip is the most front for /t̥/, compared to /t/ and /t(t̥)/), *TB* (the tongue body is the highest for /t(t̥)/ and the lowest for /t/), and *LLP* and *LLH* (the lower lip is most protruded and highest for /t(t̥)/ and least protruded and lowest for /t/).

For KD, /t̥/ can also be classified as an apico-laminal denti-alveolar stop; it has a relatively flat/weakly convex tongue shape, a raised/retracted dorsum, and a slightly retracted root. /t/ is an apical/sublaminal post-alveolar/prepalatal stop (thus showing a contact somewhat further than for KMU), with a concavity between the blade and the tongue body, and a convex tongue body/middle, and a somewhat flattened/fronted tongue dorsum. It also shows a slightly lower/retracted jaw, a sublingual cavity, and a weaker velopharyngeal port closure, compared to the other consonants. /t(t̥)/ is an apico-laminal denti-alveolar/post-alveolar stop, which is strongly palatalised (showing a considerably raised and fronted, strongly convex tongue body). The tongue middle and the dorsum for this consonant are flattened, while the jaw is fronted and the lips are protruded. The tongue-palate

contact for /t(t̤)/ is quite extensive. Considering articulatory parameters in the radar plot, differences are mainly related to *TTF* (the tongue tip is most retracted for /t/), *TTH* (the tongue tip is the lowest for /t/), *TB* (the tongue body is the highest for /t(t̤)/), *TD* (the tongue dorsum is the least arched for /t(t̤)/), and *LLP* (the lower lip is most protruded for /t(t̤)/).

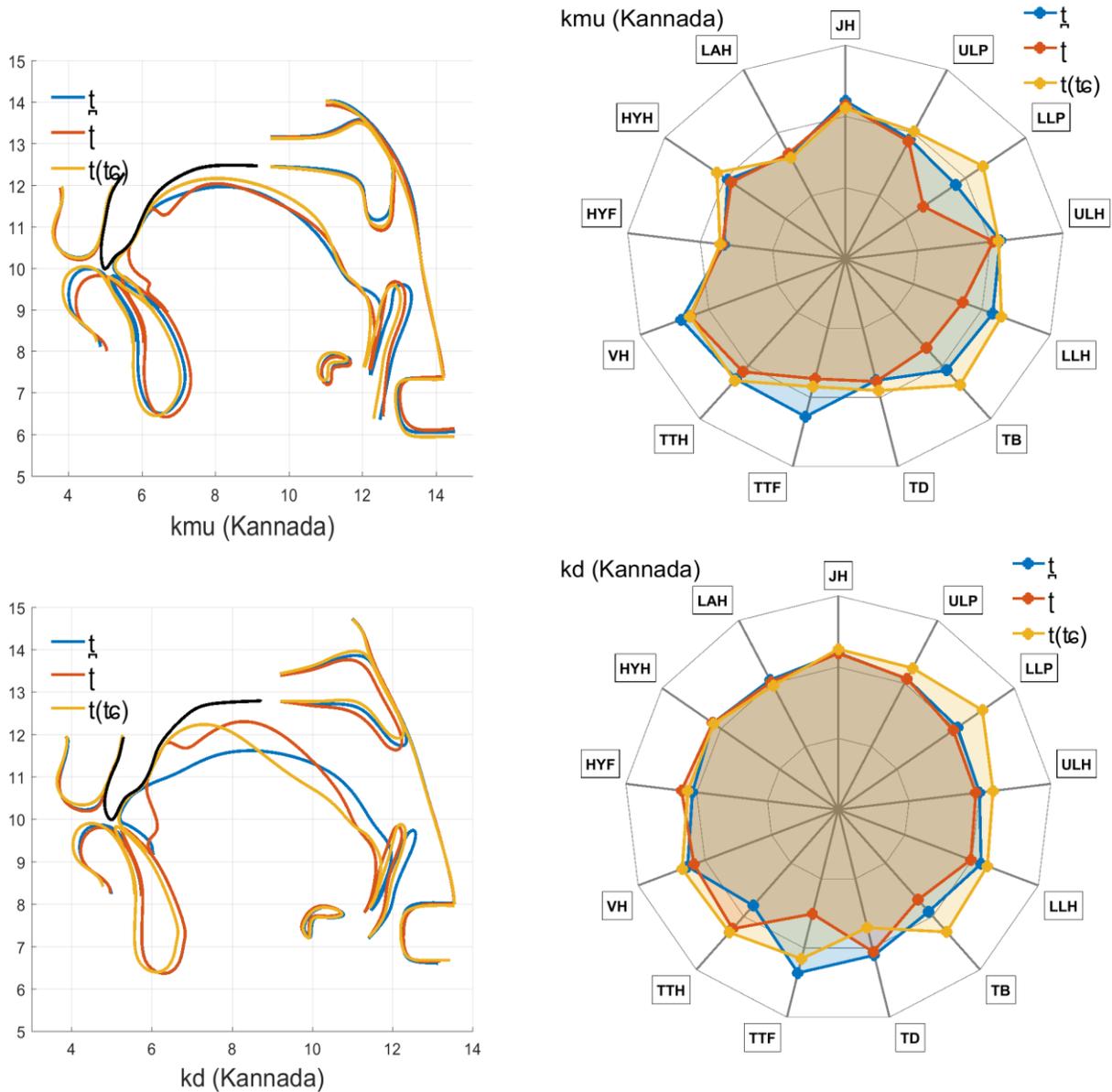


Figure 7. Overlaid average contours (left) and radar displays of articulatory parameters (right) for stops/affricate at the dental /t/ vs. retroflex /t̤/ vs. alveolopalatal /t(t̤)/ places for both speakers (top KMU, bottom KD).

Overall, both speakers consistently distinguish the dental vs. retroflex contrast by the fronting/backing movement of the tongue tip and the raising/lowering movement of the tongue body, while differing in their use of additional components to implement this contrast.

Note that some between-speaker differences in the components used to implement the dental vs. retroflex contrast can be attributed to somewhat different articulatory targets for both sounds. As seen in Figure 7 (left column), the /t̪/ constriction is more posterior for KMU (the tongue blade contact extending from the upper teeth to the alveolar ridge) than for KD (primarily the tip touching the upper teeth). For /ɖ/, the patterns are reversed: the constriction is more anterior for KMU (the tip touching the alveolar/post-alveolar region) than for KD (the tip or the underside contact extending further into the post-alveolar region). Somewhat unexpectedly, one of the tokens of /t̪/ (/it̪i/) was produced by KD with a lower velum (as would be expected for /ŋ/): this is possibly a strategy for maintaining the voicing – that is a secondary cue to retroflexion in Kannada – during the sustained consonant. Interestingly, similar nasalization of the retroflex /t̪/ was observed in a separate MRI dataset from two Malayalam speakers.

It is also worth noting that neither speaker produces /t̪/ with a noticeable backing of the tongue dorsum or tongue root, relative to /t̪/, as might be expected of retroflexes (see Section 1). In fact, the opposite is observed for KD. This is consistent with observations made by Kochetov *et al.* (2014) based on ultrasound data. The considerably higher tongue body and – for KD – the more front tongue dorsum/root than for /t̪/ is consistent with ultrasound results reported by Kochetov *et al.* (2016). Importantly, however, the MRI data further show that these contrasts are not limited to differences in tongue posture, but involve other parameters, such as small-scale adjustments of the lips and the velum.

4.1.1.2 Other contrasts

While our focus here is on coronal contrasts, it is worth considering articulatory parameters distinguishing coronals from non-coronals. Among other place contrasts in stops, both speakers differentiated the bilabial /p/ from the lingual /t̪/ primarily by *ULH* (a lower position of the upper lip). They differentiated /k/ from /t̪/ by *TD* (a higher tongue dorsum for the velar) and *TTF* (a more retracted tongue tip for the velar). It should be also noted that the velar stop was produced by both speakers with a fairly front constriction – in the posterior palatal, rather than the velar region. KD in particular, produced /k/ with the fronting of the entire tongue and the epiglottis, as well as some raising of the hyoid bone and the laryngeal articulator. Additional figures can be found in Appendix D.

4.1.2 Place contrasts in nasals

4.1.2.1 Contrasts among coronals

The results for coronal nasals – dental, retroflex, and alveolopalatal (phonetic) – are presented in Figure 8.

For KMU, /ŋ̪/ can be described as an apico-laminal denti-alveolar nasal, produced with a weakly convex tongue body, and convex tongue dorsum. /ŋ/ is an apical/sublaminal post-alveolar (and possibly prepalatal) nasal, with

a concavity between the blade and the tongue body, a convex front portion of the tongue body, and a flattened tongue dorsum. It also shows somewhat less protruded lips and a sublingual cavity. /ɲ(ɕ)/ is an apico-laminal denti-alveolar nasal, which is weakly palatalised (showing a convex and slightly raised tongue body). The tongue dorsum is convex as well, while being very similar in shape to /ɲ/; the jaw is somewhat raised/fronted, while the lips are more protruded. All three nasals, as expected, show a widely open velopharyngeal port. In the radar plot, we can see that the differences among three nasals are mainly related to *TTF* (the tongue tip is most posterior for /ɲ/, compared to /ɲ/ and /ɲ(ɕ)/), *TB* (the tongue body is the least front/high for /ɲ/, at least in its posterior region, however, also related to a concomitant retraction of the tip region, as can be seen in the *TB* nomogram in Figure 5), and to a lesser degree in *TD* (the tongue dorsum is somewhat less arched for /ɲ/ at the mid and lower further back) and *LLP* (the lower lip is most protruded for /ɲ(ɕ)/ and least protruded for /ɲ/).

For KD, /ɲ/ is an apico-laminal denti-alveolar nasal, with a relatively small area of contact. The tongue shows a slight concavity between the blade and the tongue body, a moderately convex tongue body and the tongue dorsum. /ɲ/ is a sublaminal prepalatal/palatal nasal (with the contact produced by a strongly curled tongue in a fairly posterior portion of the palate). The tongue-palate contact is extensive. The tongue shows a substantial concavity between the blade and the tongue body, while the tongue body middle is convex and the tongue dorsum is flattened/fronted. Other characteristics of the consonant include a somewhat lowered/backed jaw, a slightly retracted tongue root, a lowered larynx, and a large sublingual cavity. /ɲ(ɕ)/ is an apico-laminal denti-alveolar nasal, which is palatalised (produced with a raised convex tongue body); the tongue dorsum is moderately convex (being similar to /ɲ/ and more posterior than for /ɲ/), while the jaw is raised/fronted, and the lower lip slightly protruded. The higher position of the hyoid bone for /ɲ(ɕ)/ seems to reflect the raising/fronting of the tongue body, while the lower position of this organ (as well as the larynx) for /ɲ/ is likely due to the lowering of the tongue dorsum. All three nasals are produced with a widely open velopharyngeal port. As seen in the radar plot, parameter differences among three nasals are mainly related to *TTF* (the tip is the most posterior for /ɲ/), *TB* (the tongue body is the most retracted/lowest for /ɲ/ and the most advanced/highest for /ɲ(ɕ)/), and *LLH* (the lower lip is the higher for /ɲ(ɕ)/). In addition, we can notice a general lowering of the hyoid bone and the laryngeal articulator for the retroflex /ɲ/ (seen on *HYH* and *LAH*).

Thus, both speakers make use of *TTF* and *TB* to distinguish the dental vs. retroflex contrast in nasals, while showing smaller and less consistent differences between the alveolopalatal and the dental (mainly involving articulators other than the tongue). Note that the retroflex /ɲ/ is produced with a considerable tongue tip curling behind the alveolar ridge (sub-apical postalveolar/palatal), and more so for KD than KMU. Both speakers also show some fronting/lowering of the tongue dorsum for /ɲ/, compared to the other two articulations (and this difference is more extensive than was observed for stops). Unexpectedly, the alveolopalatal nasal is produced by KD with a more extended upper teeth contact than the dental nasal. Note also that the constriction location for the

alveopalatal nasal, as produced by both speakers, is less extensive than we observed for the palatal affricate, and hardly overlaps with that of the retroflex counterpart.

Among other coronal contrasts involving nasals, no difference was observed between /ɲ/ and /ɲ(d)/, nor between /ŋ/ and /ŋ(d)/. The lack of the former difference is in contrast with previous descriptions, which attribute to these consonants distinct places – alveolar and dental respectively (Upadhyaya (1972): /n/ vs. /ɲ(d)/).

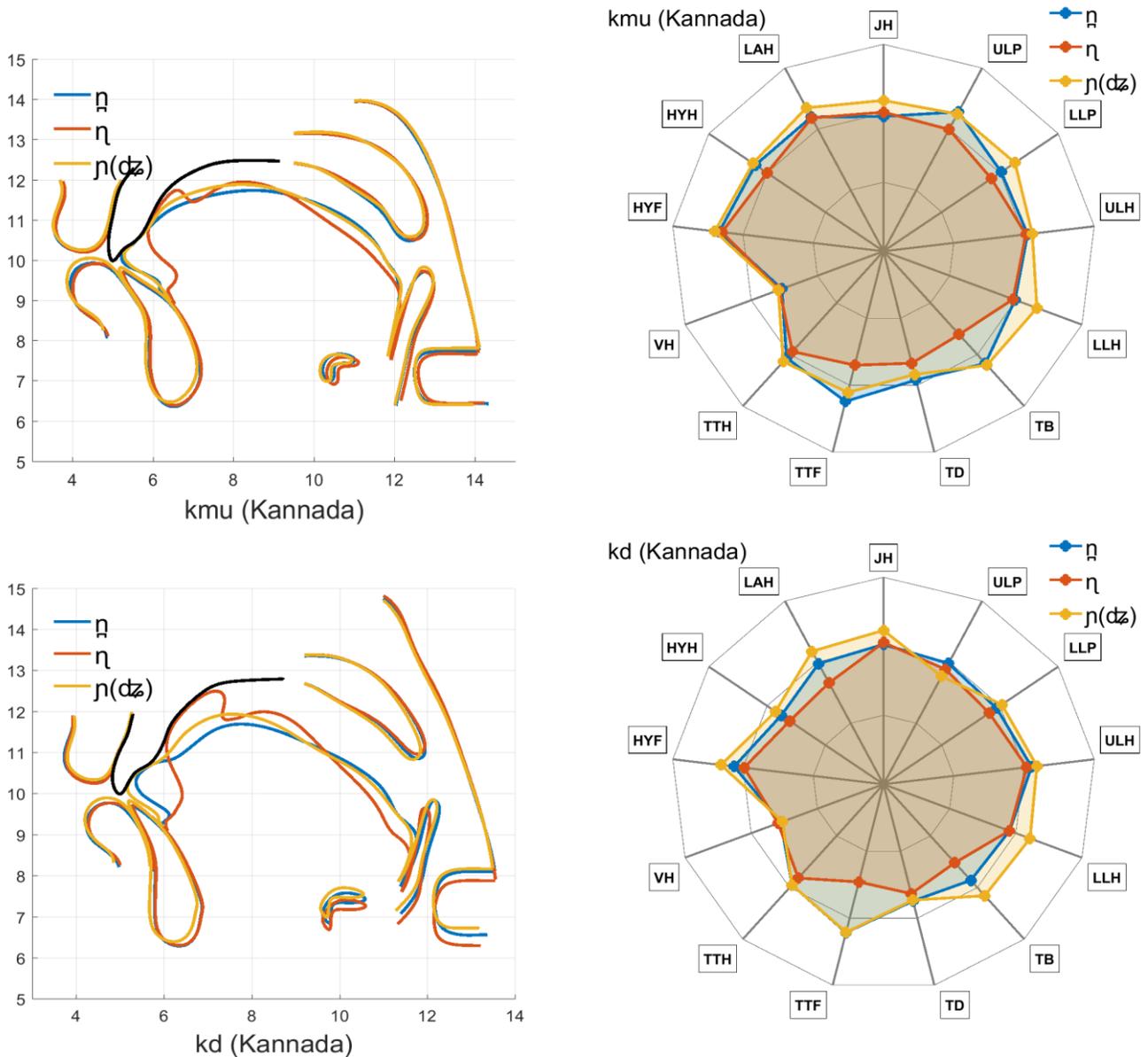


Figure 8. Overlaid average contours (left) and radar displays of articulatory parameters (right) for nasals at the dental /ɲ/ vs. retroflex /ŋ/ vs. alveopalatal /ɲ(d)/ places for both speakers (top KMU, bottom KD).

4.1.2.2 Other nasal contrasts

Among place contrasts involving non-coronal stops, /m/ was differentiated from coronal nasals by *ULH* (a lower position of the upper lip for /m/). /ŋ(g)/ was different from /ŋ/ primarily in *TD* (a higher tongue dorsum), and *TTF* (a more retracted tongue tip). These differences are fully expected for contrasts between coronals and labials/velars. No difference was observed between /m/ and a nasal in the nasal + stop cluster (/m(b)/). Further additional figures can be found in Appendix D.

4.1.3 Place contrasts in fricatives

4.1.3.1 Contrasts among coronals

The results for coronal fricatives – the phonemically dental, retroflex, and alveolopalatal sibilants – are presented in Figure 9.

For KMU, /ʃ/ is a laminal denti-alveolar fricative, with a flattened anterior portion of the tongue body (and a very weak concavity between the blade and the tongue body). The middle of the tongue is fairly convex, while the larynx is lowered. /ʃ/ is a laminal alveolar/post-alveolar fricative, with the entire tongue raised and convex. It also shows a slightly fronted jaw and a raised/protruded lower lip. The constriction and the tongue shape for /ç/ are almost identical to /ʃ/, with the differences being in a slightly more protruded tongue tip and more fronted jaw for the former. Both /ʃ/ and /ç/ show a relatively extensive constriction area and a small sublingual cavity. In terms of parameters shown in the radar plot, differences between the fricatives are mainly related to *TTH* (the tip is the lowest for /ʃ/ compared to /ʃ/ and /ç/) and *TTF* (the tip is the most advanced for /ʃ/). The posterior sibilants /ʃ/ and /ç/ show hardly any differences in the tongue parameters, while exhibiting some minor difference in *LLH* (a somewhat higher lower lip for /ç/).

For KD, /ʃ/ is an apico-laminal denti-alveolar fricative, with a very flat tongue behind the constriction, a somewhat raised and convex tongue dorsum, a slightly retracted tongue root, and lowered larynx. /ʃ/ is a laminal alveolar/post-alveolar fricative, which is strongly palatalised (with a substantially raised and fronted tongue body, which is strongly convex). The tongue dorsum is flattened, while the tongue root is slightly fronted, and lips are protruded. As for the other speaker, the articulation of /ç/ by KD is near-identical to /ʃ/, with the difference being mainly in a slightly more protruded tongue tip and a higher lower lip for the alveolopalatal. Both consonants show relatively extensive constriction areas. Most parameter differences, based on the radar plot, are between /ʃ/ on the one hand and /ʃ/ and /ç/ on the other. Primarily, these differences are in *TTH* (the tongue tip is the lowest for /ʃ/), *TTF* (the tongue tip is the most advanced for /ʃ/), *TB* (the tongue body is least front/lower for /ʃ/), and *TD* (the tongue dorsum is most arched for /ʃ/). In addition, both lips show the least protrusion for /ʃ/ compared to the other two sibilants (*LLP* and *ULP*). Differences between /ʃ/ and /ç/ are essentially absent, with the exception of the relatively minor ones involving *LLH* and *HYF* (the lower lip is slightly higher and the hyoid being more back for /ç/ than /ʃ/).

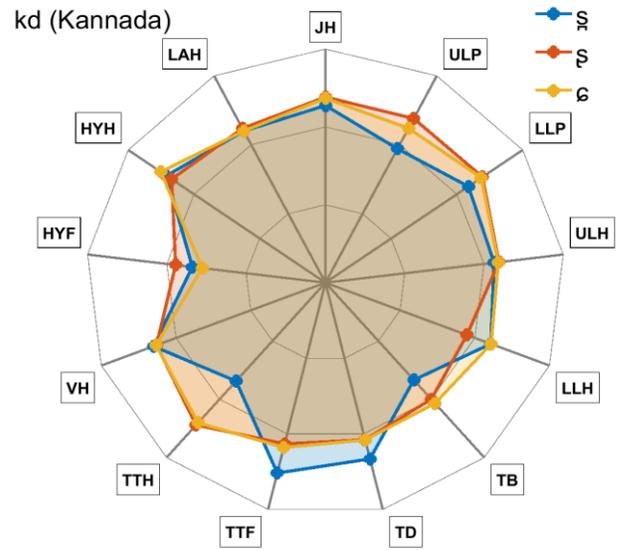
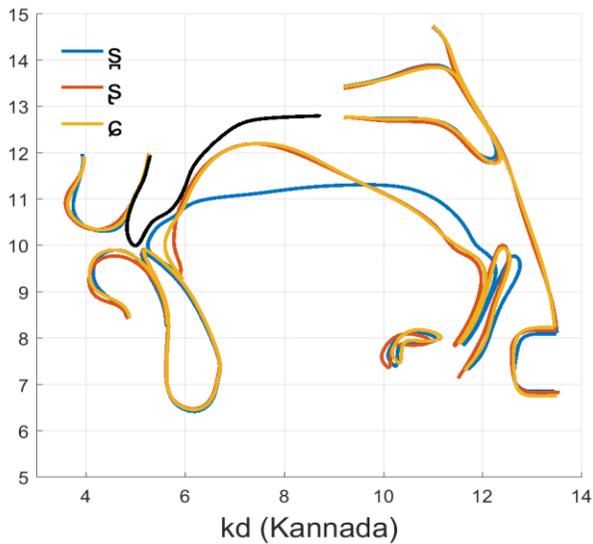
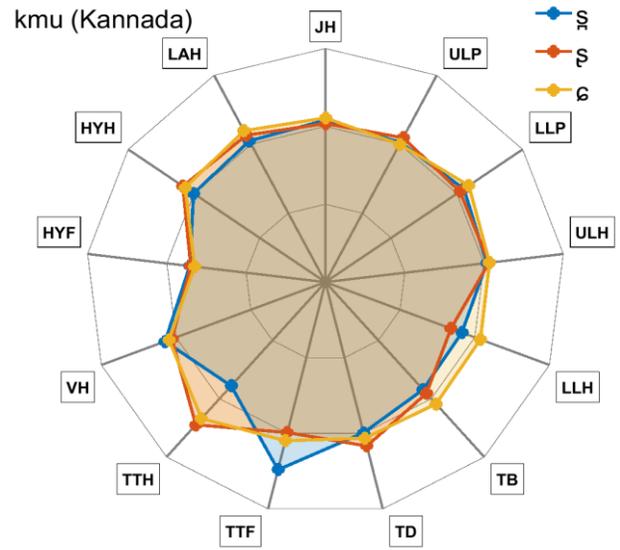
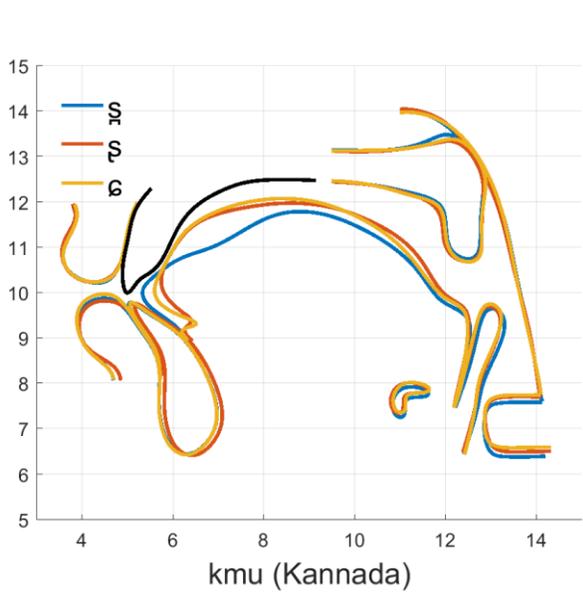


Figure 9. Overlaid average contours (left) and radar displays of articulatory parameters (right) for sibilant fricatives /ʃ/, /ʂ/ and /ç/ for both speakers (top KMU, bottom KD).

In sum, both speakers made use of the vertical and horizontal tongue tip position components to differentiate between the anterior and posterior sibilants (/ʃ/ vs. /ʂ/ and /ç/), while showing no clear lingual differences between the two posterior consonants (yet some small differences in the lower lip position). For both speakers, the sounds /ʃ/ and /ç/ are realised as alveolopalatals (produced with the tongue blade approximating the alveolar

ridge/post-alveolar region) rather than retroflexes. The tongue shape configurations used by each speaker for these consonants, however, are somewhat different (e.g. a more fronted and convex tongue body for KD than KMU).

Recall that the occurrence of such a merger was reported in previous descriptions to occur in at least some dialects of Kannada (Schiffman, 1983; Sridhar, 1990). Further, it should be noted that /ʂ/ is produced by our speakers as dental (with the tip/blade approaching the upper teeth). This is contrary to previous descriptions of this sound as alveolar (*cf.* Upadhyaya (1972), among others).

Turning to differences between the fricative /ç/ and the frication component of the affricate, /ç(tç)/ (Figure 10), we can see that, for KMU, /ç(tç)/ has a similar (laminal alveolar/post-alveolar) constriction to /ç/, while a much lower, flatter tongue body/middle. It also shows a somewhat weaker lip rounding, a more lowered larynx, and tighter velum constriction. These differences can be attributed to the influence of the stop portion of the affricate. In terms of parameters, the frication portion of the affricate shows a more advanced tongue tip (*TTF*), a lower tongue body (*TB*), a slightly lower and less protruded lower lip (*LLH* and *LLP*), a lower laryngeal articulator (*LAH*), and – somewhat unexpectedly – a slightly lower position of the velum (*VH*).

For KD, the constriction for /ç(tç)/ is somewhat more front and more extensive than for /ç/. As for KMU, the tongue body for /ç(tç)/, as well as its larynx are somewhat lower than for /ç/. The two consonants also show differences in the position of the hyoid. Parameter differences between the two sounds are relatively small, and involve primarily the lower position of the laryngeal articulator (*LAH*), a higher position of the hyoid (*HYF*), and slightly lower tongue body (*TB*) for the frication component of the affricate.

In sum, both speakers distinguish the two sounds in the relative position of the tongue body and the laryngeal articulator, while also employing some individual strategies.

4.1.3.2 Other contrasts

A comparison of /h/ to coronal fricatives suggested that it had a lingual constriction. In particular, the tongue dorsum for /h/, produced by both speakers, was considerably higher than for the other fricatives, approaching the posterior part of the hard palate or the velum. The tongue body for /h/ also tended to be higher (while the tongue tip being lower and retracted) than for the sibilants. That is, the consonant was rather a velar fricative [x] (or palatal [ç] in [ihi]). KD also showed a lower/more back jaw position for /h/ and an advanced uvula (presumably facilitating the achievement of the velar constriction). Additional figures can be found in Appendix D.

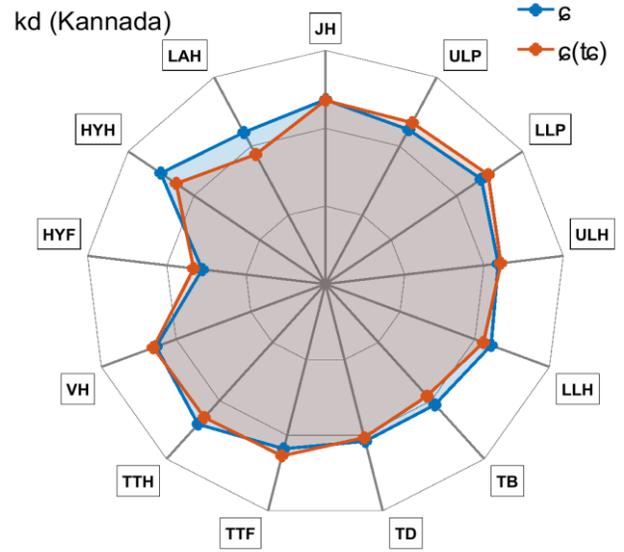
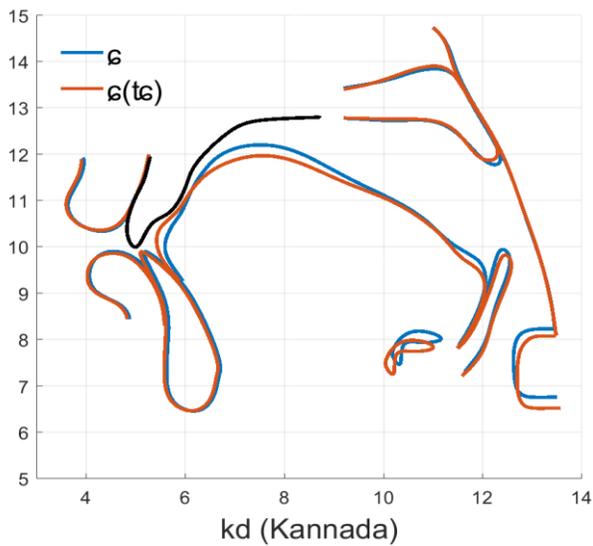
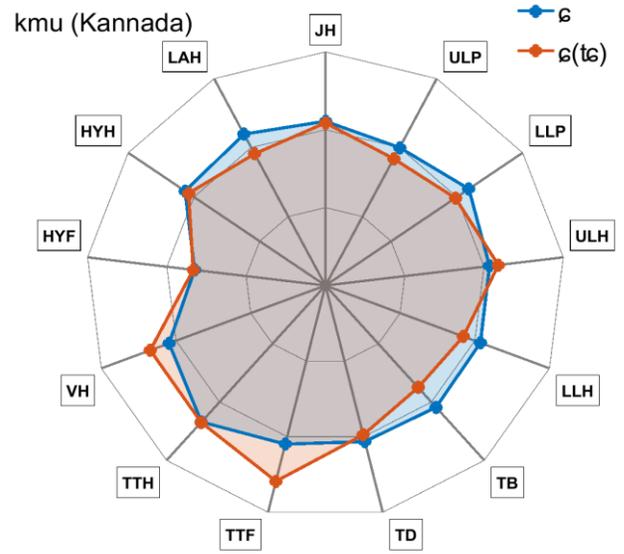
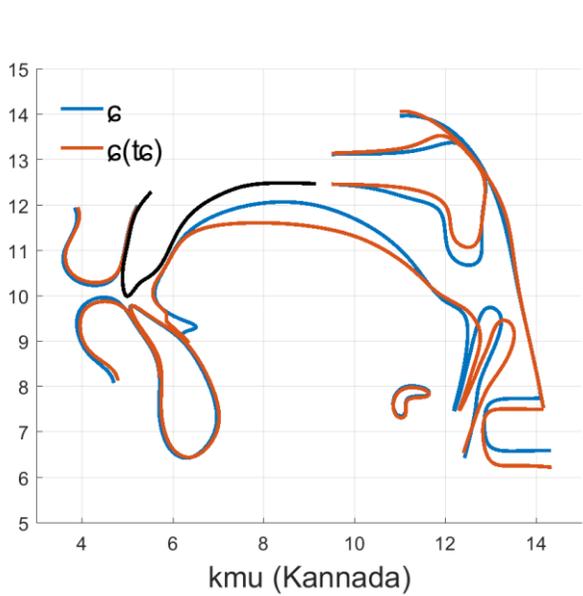


Figure 10. Overlaid average contours (left) and radar displays of articulatory parameters (right) for the sibilant fricative /ç/ and the frication of /tç/ for both speakers (top KMU, bottom KD).

4.1.4 The liquids (the rhotic and the laterals)

While the contrast between laterals and rhotics represents a manner distinction, the Kannada rhotic /r/ is alveolar, and is thus distinct from both laterals (dental and retroflex) in place. We therefore include this consonant in the three-way place contrast of liquids, the results for which are presented in Figure 11.

For KMU, /r̥/ is an apico-laminal denti-alveolar/post-alveolar lateral approximant, produced with a relatively extensive tongue-palate contact. It has a weakly convex tongue shape, and a small sublingual cavity. /r/ is an apical alveolar trill, produced with a minimal contact. It is velarised, as the convex-shaped dorsum is strongly

raised and retracted. The front portion of the tongue is relatively flat, the jaw is raised/fronted, and the larynx is slightly raised as well. The consonant is produced with a considerable sublingual cavity. /ɭ/ is an apical/sublaminal post-alveolar/prepalatal lateral approximant (with the constriction being more posterior and more extensive than for other retroflexes produced by this speaker). The tongue for the consonant shows a weak concavity between the blade and the tongue body; the front portion of the tongue body is convex, while the tongue dorsum is flattened. The consonant is produced with a considerably lowered larynx and a large sublingual cavity. It shows an extensive tongue (sublaminal)-palate contact. A higher hyoid bone for /r/ is an apparent side-effect of raising the tongue dorsum, while a lower hyoid for /ɭ/ is due to the tongue dorsum lowering for this consonant. Overall, the tongue shapes liquids show greater differences than seen above for stops, nasals, and fricatives. As the radar plot indicates, the contrasts among the liquids are captured by multiple components: *TTF* (the tongue tip is most retracted for /ɭ/ and most advanced for /ɭ̥/), *TB* (the tongue body is the most back/lowest for /ɭ/ and the most front/highest for /ɭ̥/), *TD* (the tongue dorsum is the least arched for /ɭ/ and the most arched for /r/), and *JH* (the jaw is the highest for /r/). In addition, the hyoid bone is the lowest for /ɭ/ and the highest, as well as more back, for /r/, and the laryngeal articulator is the lowest for /ɭ/ (the components *HYH*, *HYF*, and *LAH*).

For KD, /ɭ̥/ is an apical alveolar lateral approximant that is weakly palatalised (showing a convex fronted tongue body). It also shows a moderately convex tongue dorsum, a lowered/retracted jaw, and a small sublingual cavity. /r/ is an apical alveolar trill, which is velarised, although the raising and retraction of the tongue dorsum are not as extensive as for KMU. The front portion of the tongue shows a weak concavity; the jaw is raised/fronted, the larynx is raised, and there is a considerable sublingual cavity. The higher position of the hyoid reflects the raising of the tongue dorsum. /ɭ/ is a sublaminal prepalatal/palatal lateral approximant, characterised by strong curling of the tongue and an extensive linguopalatal contact. The tongue shows a strong concavity between the blade and the tongue body, a convex front/middle portion of the tongue body, a somewhat flattened tongue dorsum, and a slightly retracted tongue root. There is a large sublingual cavity, and the larynx is substantially lowered. The most robust articulatory components differentiating the contrast involve *TTF* (the tip is most retracted for /ɭ/), *TTH* (the tip is the highest for /ɭ̥/, and the lowest for /ɭ/), *TB* (the tongue body is the most back/lowest for /ɭ/), *TD* (the tongue dorsum is most arched for /r/), *JH* (the jaw is the highest for /r/ and the lowest for /ɭ̥/), as well as *LLH* and *LLP* (the lower lip is the lowest and least protruded for /ɭ̥/). In addition, /r/ is produced by this speaker with the highest and most advanced hyoid bone (*HYH* and *HYF*), and the highest laryngeal articulator (*LAH*). The latter articulator is also lower for /ɭ/ than /ɭ̥/.

In sum, both speakers make use of *TTF*, *TB*, and *LAH* to distinguish the retroflex lateral from its dental counterpart (and often /r/), while differing in their supplementary strategies (*TD*, *TTH*, lower lip, or hyoid). Both speakers distinguish the alveolar rhotic from both liquids by *TD*, *JH*, and the hyoid position (both vertical and horizontal), as well as, less consistently, by the laryngeal articulator. The extensive rhotic-lateral non-lingual differences are likely due to manner rather than place distinctions.

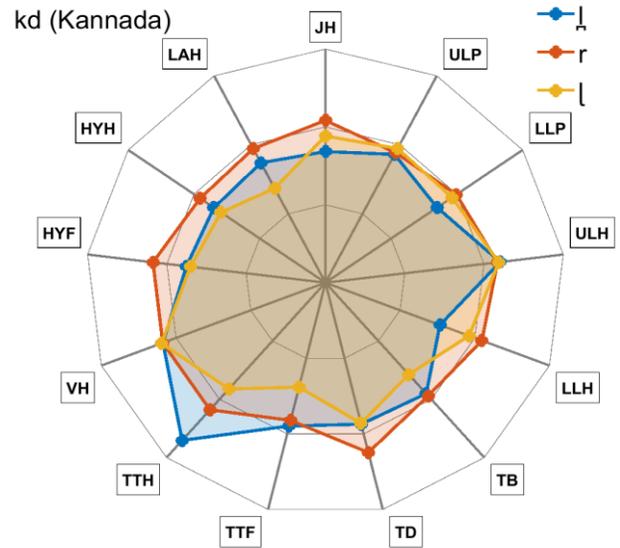
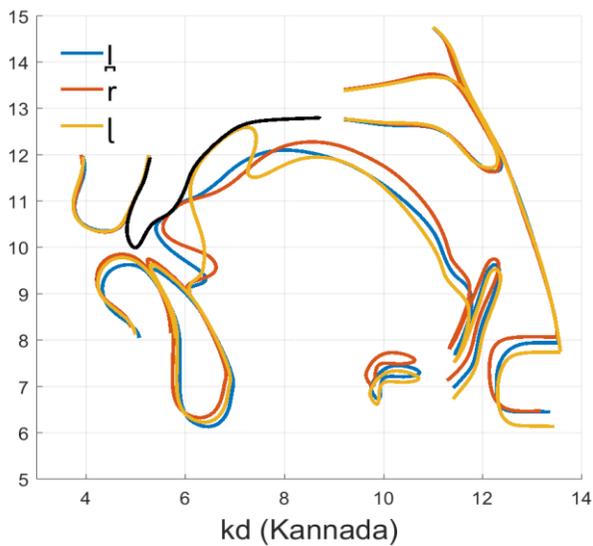
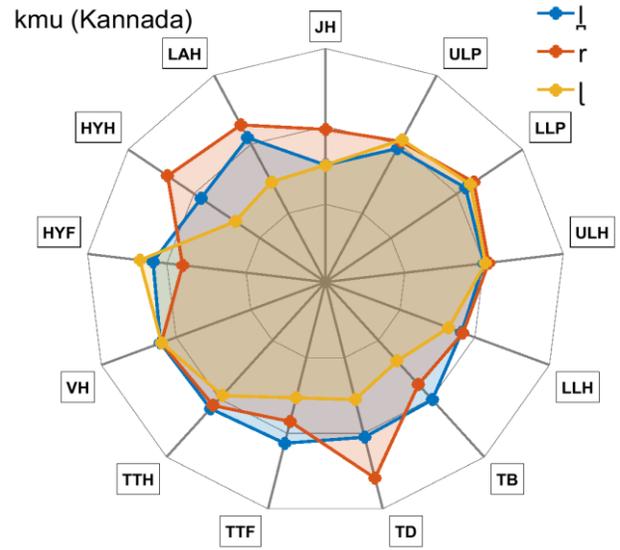
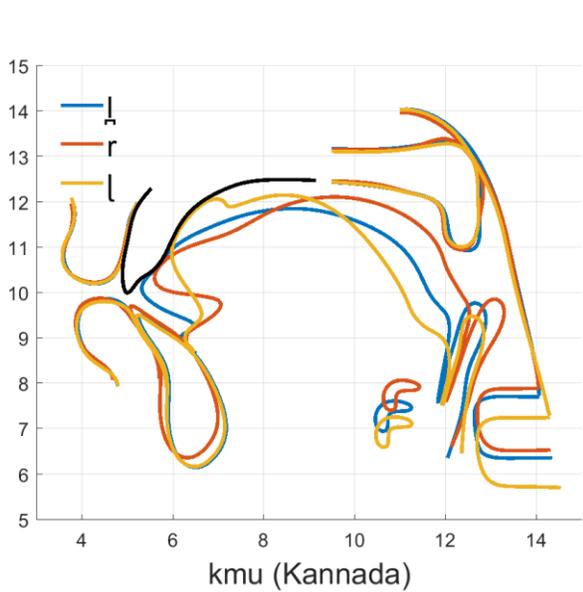


Figure 11. Overlaid average contours (left) and radar displays of articulatory parameters (right) for the liquids – the dental lateral /l/ vs. alveolar rhotic /r/ vs. retroflex lateral /r/ for both speakers (top KMU, bottom KD).

It should be noted that the rhotic is produced by our speakers as a trill, even though phonemically it varies between a trill and a tap (Upadhyaya, 1972). As seen in Figure 11, this sound was articulated by both speakers as an apical alveolar, consistent with previous descriptions. While the consonant has not been previously described as velarized, the related arching of the tongue dorsum for rhotics is a common strategy used to stabilise the tongue during the tip vibration (Recasens, 1999).

The constriction location for the dental lateral /l̥/ is similar to the rhotic for KD (apical alveolar or denti-alveolar), while being more front and with a more extended contact (laminal dental) for KMU. This inter-speaker variation reflects conflicting opinions about the classification of this sound as either ‘dental’ (Nāyaka (1967); Sridhar (1990) or ‘alveolar’ (Upadhyaya, 1972; Schiffman, 1983). For both speakers, however, /r/ and /l̥/ are clearly different from the retroflex /ɭ/, a sub-laminal post-alveolar/palatal. The relatively low jaw position for laterals is expected, as it facilitates the lowering of the tongue sides (Keating *et al.* (1994) for English and Swedish; Mooshammer *et al.* (2006) for German; Recasens (2012) for Catalan; Tabain (2012) for Arrernte). The situation with trills is less clear, partly due to fewer studies of these consonants. Presumably, a raised jaw can facilitate the trilling of the tongue tip against the alveolar ridge. Indeed, Keating *et al.* (1994) reported a somewhat higher jaw for the Swedish trill /r/ compared to /l/ (yet lower than for coronal stops and fricatives). Beňuš *et al.* (2011), on the other hand found that the syllabic trill /r/ and lateral /l/ in Slovak had similarly low position.

4.1.5 Glides

For both speakers, /j/ was produced an antero-dorsal palatal (rather than an alveolopalatal) – having an anterodorsal constriction in the prepalatal or palatal regions. The tongue had a strongly convex anterior portion and a strongly advanced tongue dorsum, with the tongue tip held against the lower front teeth. Compared to the other glide, labiodental /v/, the palatal had a fronted root, a fronted/raised jaw, a more front lower lip, and a raised larynx. Based on radar plots, differences between the two involved *LLH* (a higher and/or more retracted lower lip, approaching the upper teeth, for /v/), *TB* (a higher tongue body for /j/), *TD* (a less arched tongue dorsum for /j/), *HYF* (a more advanced hyoid for /j/), *LAH* (a more raised laryngeal articulator for /j/), and the epiglottis (more front for /j/). Additional figures can be found in Appendix D.

The involvement of the lower lip in the production of /v/ is an interesting finding, as this indicates that the consonant is produced by both speakers as labiodental (regardless of the vowel context), rather than alternating between labiodental and labial-velar (in front and central/back vowel contexts, respectively; Upadhyaya (1972). At the same time, this consonant was found to be produced with a considerably backed and raised tongue dorsum (to an extent greater than for the other labials, /p/ and /b/). This indicates that the consonant is really a hybrid between /v/ and /w/ (combining the labiodental and velar constrictions), and apparently regardless of the vowel context.

4.1.6 Summary (coronals)

General differences observed in this section are summarised below by specific place-of-articulation contrasts in coronals, with some of the main generalizations presented in Table 3. Here we list the differences that held for the majority of pairwise comparisons.

4.1.6.1 *The dental vs. retroflex contrast*

Given the observed lack of retroflexion in /ʂ/, we will discuss here only the contrast in stops, nasals, and laterals. As seen in Table 3 (a), for both speakers, *TTF* serves to differentiate dentals and retroflexes across three manners of articulation (stops, nasals, and laterals). Not surprisingly, the tongue tip moves forward for dentals, while moving backwards for retroflexes. The contrast is also largely distinguished by *TB*: for stops, nasals, and laterals produced by KMU, and nasals and laterals produced by KD. In all these cases, the retroflexes show a lower/less front tongue body compared to the dentals.

The speakers differed in their other strategies in producing the contrast. KMU made use of *LLP* (for stops and nasals) and *TD* (for nasals and laterals): retroflexes were produced with a lesser lower lip protrusion and a less arched tongue dorsum than dentals. Together with the lack of *TD* differences for KD, these results confirm an earlier observation that Kannada retroflexes are produced without a tongue dorsum backing/arching (Kochetov *et al.* (2014). In addition, KD made use of *TTH* (for stops and laterals) and *LAH* (for nasals and laterals), with both the tongue tip and the laryngeal articulator being lower for retroflexes than dentals. The lowering of the larynx is likely related to the characteristic tongue shape for retroflexes – retraction of the tongue tip and the blade, and some lowering/fronting of the tongue body.

4.1.6.2 *The dental vs. alveolopalatal contrast*

Recall that this contrast involves stops/affricates, nasals (including the phonetic [ɲ]), and fricatives. There was overall more variability between the speakers and across manners in distinguishing this contrast. As seen in Table 3, only *LLP* was shared by the speakers: alveolopalatals (the affricate and the nasal for KMU, and the affricate and the fricative for KD) were produced with greater lip protrusion than their dental counterparts. As both /t(ʈ)/ and /ç/ are sibilants, the lip protrusion here is likely an additional strategy for producing posterior sibilant constrictions, rather than alveolopalatals in general. Stops/affricates and fricatives produced by KMU were also distinguished by *TTF* (less fronting for palatals). Stops, fricatives, and nasals produced by KD were differentiated by *TB* (higher/more front for palatals). In addition, the latter speaker used *TTH* and *TD* to differentiate the contrast in stops and fricatives (a higher tip and a less arched dorsum for palatals), and also used *LLH* to differentiate the contrast in nasals and fricatives (a higher lower lip for palatals). The fronting and raising of the tongue dorsum for alveolopalatals, as shown by KD, is expected of these sounds. The result also confirms previous ultrasound findings for the closure of /ʈ/ (Kochetov *et al.*, 2014). The lack of tongue body difference for KMU, however, is unexpected. It should be noted that this speaker showed relatively little differentiation in tongue positions for coronals in general.

Table 3. A summary of main differences for place contrasts, as exhibited by both or one of the speakers, with ratios of relevant comparisons presented in parentheses.

Contrasts	Both speakers	KMU only	KD only
a. dental vs. retroflex (stops, nasals, laterals)	<i>TTF</i> dental > retroflex (6/6) <i>TB</i> dental > retroflex (5/6)	<i>TD</i> dental > retroflex (2/3) <i>LLP</i> dental > retroflex (2/3)	<i>TTH</i> dental > retroflex (2/3) <i>LAH</i> dental > retroflex (2/3)
b. dental vs. alveopalatal (stops/affricates, nasals, fricatives)	<i>LLP</i> alveopalatal > dental (4/6)	<i>TTF</i> dental > alveopalatal (2/3)	<i>TB</i> alveopalatal > dental (3/3) <i>TTH</i> alveopalatal > dental (2/3) <i>TD</i> dental > alveopalatal (2/3)
c. retroflex vs. alveopalatal (stops, nasals)	<i>TB</i> alveopalatal > retroflex (4/6) <i>LLH</i> alveopalatal > retroflex (4/6)	<i>LLP</i> alveopalatal > retroflex (2/3)	<i>TTF</i> alveopalatal > retroflex (2/3)
d. dental vs. alveolar (lateral vs. rhotic)	<i>TD</i> alveolar > dental (2/2) <i>JH</i> alveolar > dental (2/2) <i>HYH</i> alveolar > dental (2/2)		

4.1.6.3 The retroflex vs. alveopalatal contrast

Again, given the lack of retroflexion in /ʂ/, we will first consider the contrast in stops and nasals. As seen in Table 3 (c), both speakers distinguished retroflexes and alveopalatals by *TB*, which was expectedly higher/more front for the latter class. This, together with the use of this parameter for the dental-retroflex contrast, points to a robust tongue body difference between retroflexes and the other coronals. For KMU, the contrast was also distinguished by *LLP* (more protrusion for palatals). Recall that this was also the parameter that distinguished dentals and alveopalatals in most of the cases. KD, in contrast, differentiated retroflexes and alveopalatals by *TTF* (more tip fronting for the latter).

Turning to fricatives, the near-lack of the /ʂ/ vs. /ç/ contrast (at least in the tongue configuration) is not an unexpected outcome. As noted above, a (near-)merger of the two sounds has been previously observed in the literature, at least for some varieties of Kannada (Schiffman, 1983; Sridhar, 1990). The finding of some differences

in the lower lip raising *LLH* exhibited by both speakers, nevertheless suggests that the merger of the contrast may not be complete.

4.1.6.4 *The dental vs. alveolar contrast*

Finally, the dental-alveolar contrast between /ɺ/ and /r/ was distinguished consistently by a series of parameters, including lingual and non-lingual ones (see Table 3 (d)). This fairly robust difference is likely due to the accompanying manner differences between the lateral and the rhotic. The use of secondary articulation (velarization for /r/ and possibly some palatalization for /ɺ/) is another factor.

Altogether, none of the articulatory parameters could distinguish all coronal place contrasts. Among the most commonly used parameters, however, were (not unexpectedly) the lingual gestures such as the tongue tip fronting, tongue body, and tongue dorsum. Among the non-lingual parameters, we observed a moderate use of the lower lip protrusion and the occasional use of the larynx, jaw height, and the hyoid fronting/raising. The rather limited use of the jaw height for place contrasts is somewhat unexpected, as this articulator was previously observed to distinguish at retroflexes (produced with a lower jaw) and alveolopalatals (produced with a higher jaw) from each other and from other coronals in Arrernte (Tabain, 2012), based on EMA data. Perhaps the lack of these effects reflects different strategies used to produce Kannada retroflexes, or can be attributed to these particular speakers, who in general showed little jaw variation. It may also be the case that the task of sustaining articulations used in this study has reduced the movement of the jaw.

4.2 Manner differences

4.2.1 *Contrasts among coronals*

We now turn to manner differences within place classes, focusing on coronals. The results are presented by places of articulation; as before, descriptions of average contours are presented first, followed by descriptions of radar plots, separately for each speaker.

4.2.1.1 *Dentals*

Figure 12 presents results for dentals of three manners of articulation – the stop, nasal, and lateral (with the dental fricative /ʃ/ examined further below).

We can see that for KMU, all three dentals have a very similar constrictions and tongue shapes, with the stop being somewhat more different from the sonorants – having a slightly more extensive contact, a higher position of the front portion of the tongue, a less retracted tongue dorsum, a more retracted tongue root (as well as the hyoid), a somewhat higher jaw, and a considerably lower larynx. In contrast, the nasal and the lateral are remarkably similar in their profiles, except for the open velopharyngeal port for the former. In addition, /ɺ/ shows a somewhat lower jaw and a more protruded lower lip. In terms of articulatory parameters, the differences among the dentals involve primarily the components *VH* (the velum is the lowest for /ŋ/), *JH* (the jaw is the lowest for /ɺ/ and the highest for /t/), and to a lesser extent *ULP* (the upper lip is most protruded for /ŋ/) and *LLH/LLP* (the lower lip is the

highest for /t/ and the lowest for /l̥/; it is least protruded for /t̥/. In addition, the hyoid (*HYF*) is more retracted, while laryngeal articulator (*LAH*) is lowered for /t̥/ compared to the other consonants.

For KD, the dentals have a similar constriction at the upper teeth and alveolar ridge, but the location of the constriction is more front (and more extensive) for the stop, and somewhat more posterior for the lateral (and more extensive than for the nasal). In terms of the tongue shape, the lateral is produced with a more raised tongue body/middle (i.e. some palatalization) than the other two consonants, while the stop and the lateral differ primarily in the greater/lesser raising/retraction of the tongue dorsum, respectively. The raising of the latter articulator for the stop is a likely conditioning factor for the raising of the hyoid. The nasal, as expected, shows the velum lowering, while the lateral shows a lowered jaw, a lowered lower lip, and a slightly lowered larynx. Parameter differences for this speaker involve *VH* (the velum is the lowest for /ŋ/), *TTH* (the tongue tip is the highest for /l̥/), *TTF* (the tongue tip is most retracted for /l̥/), *TD* (the tongue dorsum is most arched for /t̥/), *JH* (the jaw is the lowest for /l̥/ and the highest for /t̥/), and for *LLH/LLP* (the lower lip is the highest for /t̥/ and the lowest for /l̥/). In addition, the hyoid is the highest for /t̥/, while the laryngeal articulator is lower for /l̥/ than the other consonants (*HYH* and *LAH*).

In sum, both speakers make the expected use of the velum height to distinguish the dental nasal from its non-nasal counterparts. Most other differences, however, contrast the stop and the lateral (such as the jaw height, the lower lip and the laryngeal articulator position), with the nasal often patterning in between, or with either of the other two consonants.

Comparing the stop and the fricative, /t̥/ and /s̥/, multiple differences were observed for both speakers (Figure 13). For KMU, both consonants have at least a portion of their constriction in the dental region (with that for the stop extending further, as far as the postalveolar region). The convex shape of the tongue body for the stop contrasts with the relatively flat shape for the fricative, is a likely requirement for directing airflow towards the upper teeth. The tongue dorsum, in contrast, is somewhat more retracted for the fricative. The latter consonant also shows a more fronted/lowered jaw, a less raised lower lip, a more raised larynx, and the velum extending somewhat lower. Many of these differences are captured by the articulatory parameters: *TTH*, *TB*, *JH*, *LLH*, and *VH* (all higher for the stop), as well as *TTF*, *TD*, and *LLP* (higher for the fricative). For KD, most differences were similar to KMU: a flatter tongue body, a more convex, retracted tongue dorsum, a more front jaw, and a more raised larynx for the fricative. In terms of the parameters, differences were observed in *TB* and *HYF* (higher for the stop), as well as for *TTF*, *TD*, *ULH*, *LLP*, and *HYH* (higher for the fricative).

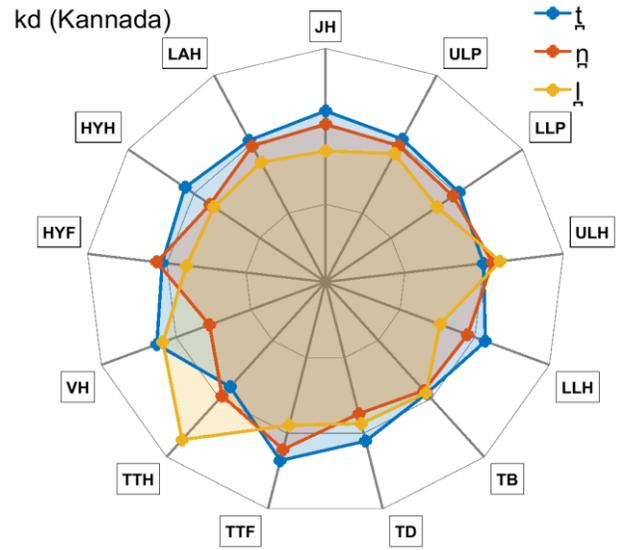
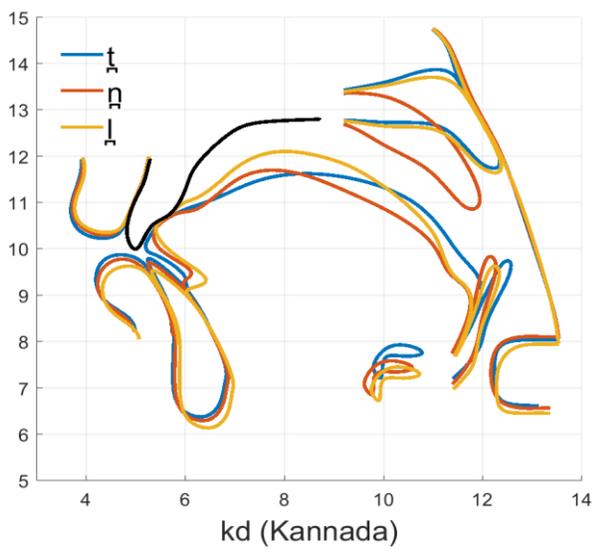
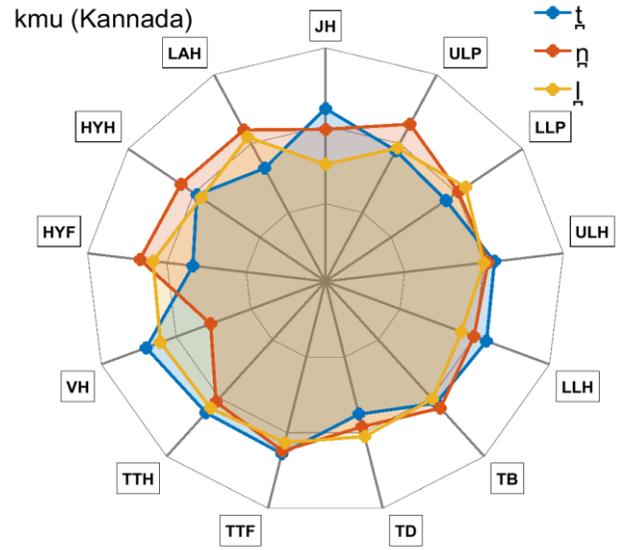
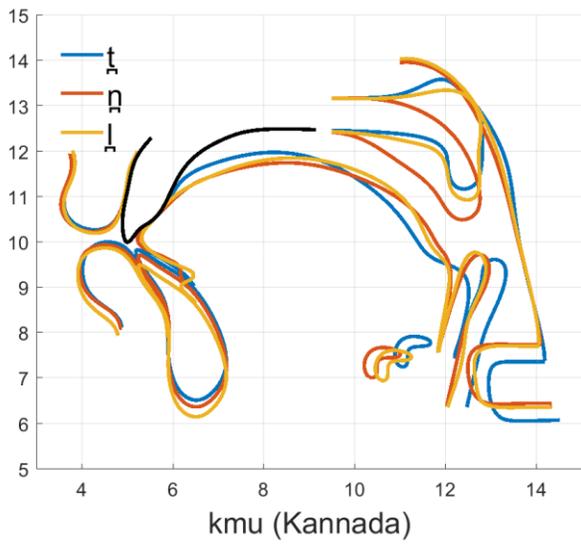


Figure 12. Overlaid average contours (left) and radar displays of articulatory parameters (right) for stops, nasals, and laterals at the dental place for both speakers (top KMU, bottom KD).

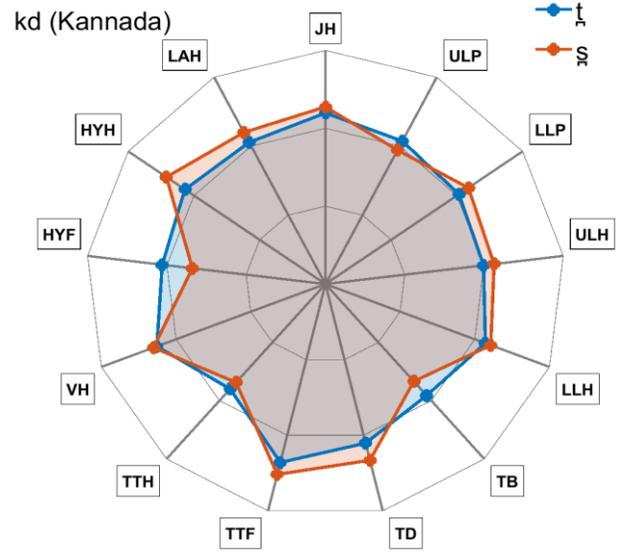
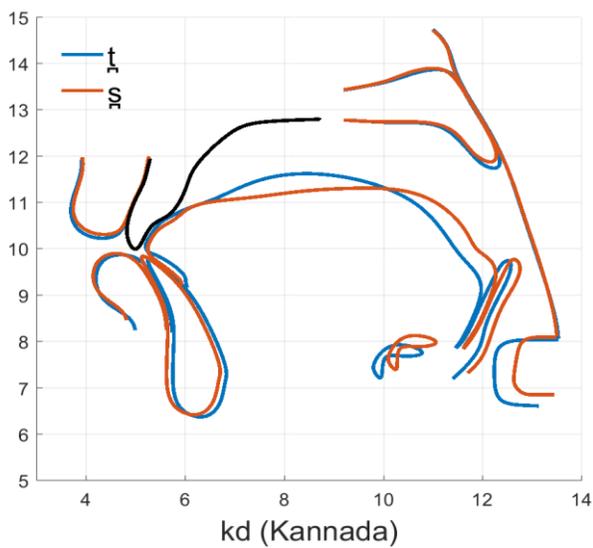
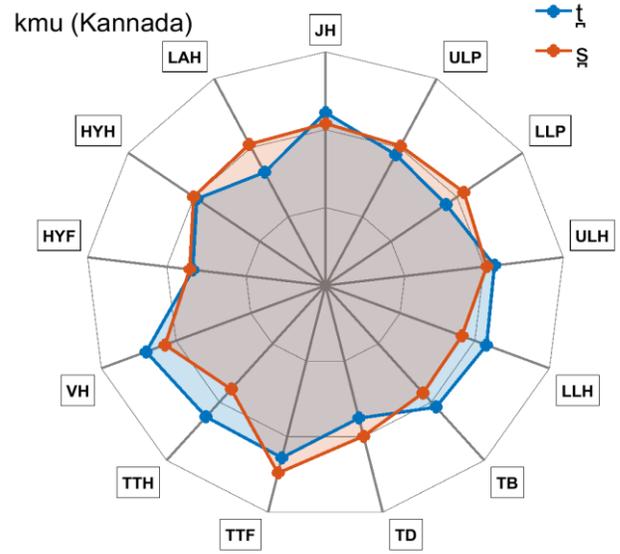
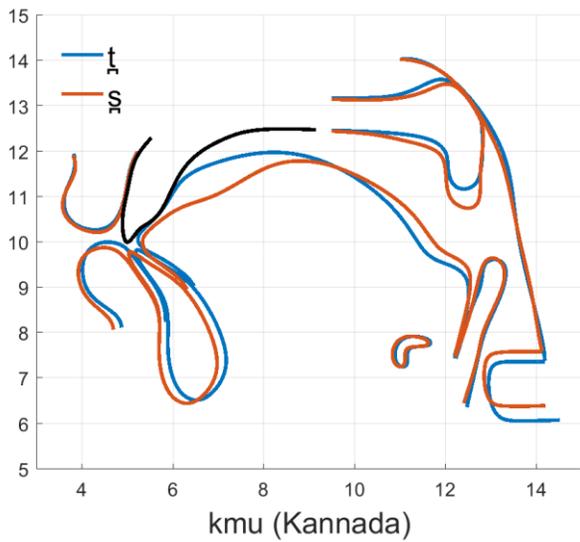


Figure 13. Overlaid average contours (left) and radar displays of articulatory parameters (right) for stops, and fricative at the dental place for both speakers (top KMU, bottom KD).

4.2.1.2 Retroflexes

The results for the 3-way manner contrast in retroflexes are illustrated in Figure 14. We can see that for KMU, constriction locations are progressively more posterior in the order stop > nasal > lateral. While the contact for the stop is clearly in the post-alveolar area, the contact for the lateral is more in the prepalatal area, and the contact for the nasal is in-between. Otherwise, the tongue shapes for the consonants are rather similar, with the consonant having the most posterior constriction, /l/, showing a somewhat higher tongue middle and more flattened tongue dorsum (as well as a lower hyoid). The stop has a more retracted tongue root (and the hyoid), and a more backed

jaw and the lower lip. The lateral shows a lower jaw, a more protruded lower lip, and a considerably lower larynx. Apart from the expected velar lowering, the nasal shows a considerably raised larynx. In terms of the parameters, manner differences for the speaker are primarily manifested in *VH* (the velum is the lowest for /ŋ/ than for the oral consonants), *TB* (the tongue body is the lowest/most back for /ʌ/), *JH* (the jaw is the lowest for /ʌ/), and *LLP/LLH* (the lower lip is least protruded for /t/ and most protruded for /ʌ/, as well as most raised for /ŋ/). In addition, the hyoid is the lowest for /ʌ/ and the most retracted for /t/, while the laryngeal articulator is the highest for /ŋ/ and the lowest for /ʌ/ (*HYH*, *HYP*, and *LAH*).

For KD, the constriction is similar for the nasal and the lateral in being considerably more posterior (and showing greater tongue tip curling) than for the stop. This roughly corresponds to the degree of the concavity in the front portion of the tongue (being the greatest for the lateral). The middle portion of the tongue is raised the highest for the stop, while the tongue dorsum is most flattened for the nasal. Despite the rather different constrictions between /t/ and /ʌ/, the shape of the posterior portion of the tongue is rather similar (weakly convex), while the same part of the tongue for /ŋ/ is considerably flattened. The stop also shows a somewhat fronted root, a slightly fronted jaw, more protruded lips, a raised hyoid, and a higher larynx. The nasal and the lateral, on the other hand are relatively similar in terms of the non-lingual articulators, except for the configuration of the velopharyngeal port. Parameter differences for the speaker are primarily related to *VH* (the velum is the lowest for /ŋ/), *TTH* (the tongue tip is the highest/most front for /t/ than the other consonants), *TD* (the tongue dorsum is the least arched for /ŋ/ and the most arched for /t/), and *JH* (the jaw is the highest for /t/ and the lowest for /ʌ/). In addition, the hyoid is the highest and most front for /t/, while being most back for /ʌ/, and the laryngeal articulator is the highest for /t/ while being the lowest for /ʌ/.

In sum, both speakers expectedly differentiate nasal and non-nasal retroflexes by the velum opening, with KD also making use of the tongue dorsum. For both speakers, the stops are differentiated from laterals (and occasionally nasals) by the position of the jaw, the hyoid, and the laryngeal articulator, all of which were higher for /t/ than /ʌ/. Speakers are also different in the use of other articulators to distinguish manner contrasts.

It is notable that while the constriction location for dentals, as produced by both speakers, shows relatively little manner-specific variation, constrictions for retroflexes differ considerably, being more anterior for the stop and more posterior for the nasal and lateral. As a result, the overall amount of the non-retroflex vs. retroflex lingual contrast was greater for nasals and laterals compared to stops.

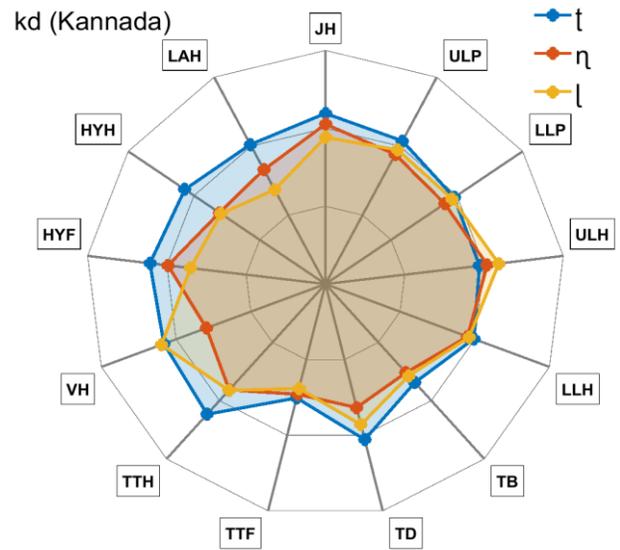
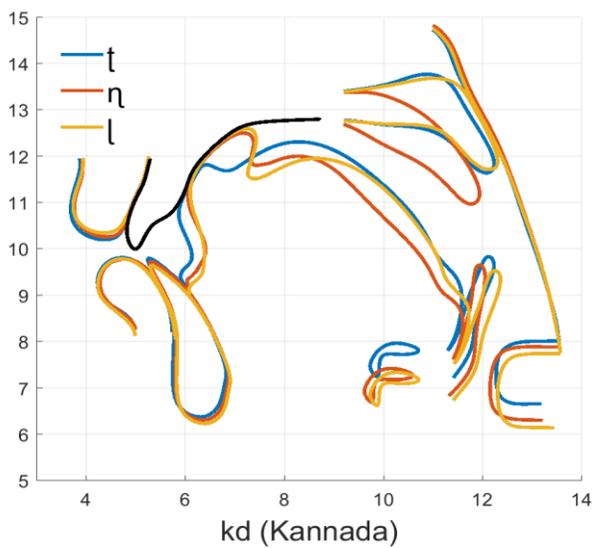
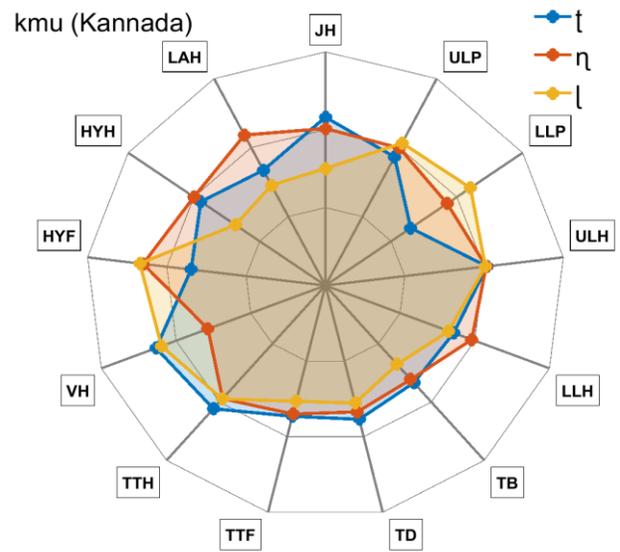
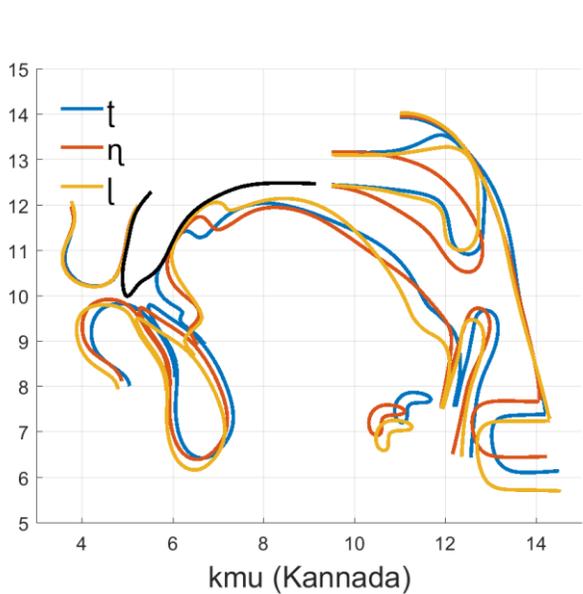


Figure 14. Overlaid average contours (left) and radar displays of articulatory parameters (right) for stops, nasals, and laterals at the retroflex place for both speakers (top KMU, bottom KD).

4.2.1.3 Alveolopalatals

Figure 15 illustrates manner differences among three alveolopalatals – the affricate /t(ɕ)/ (occlusion), the allophonic nasal in /ɲ(dʒ)/, and the fricative /ç/.

We can see that for KMU, all three consonants are produced with the blade making a laminal constriction primarily in the post-alveolar region of the palate and a strongly raised and fronted tongue body. The constriction extends further for the nasal and particularly for the stop (covering the upper teeth and the alveolar ridge, in addition to the post-alveolar region), compared to the fricative. The tongue body is raised higher for /t(ɕ)/ and lower for

/ɲ(ɕ)/ (with /ç/ being intermediate). The tongue root is more retracted for /t(ɕ)/ and /ç/ than for the nasal, and this corresponds to the retraction of the hyoid. The larynx is lowered for /t(ɕ)/ compared to the other consonants. As expected, the velum is much lower for /ɲ(ɕ)/ for the other consonants. While showing a complete velopharyngeal closure for /ç/, the velum for this consonant extends further down than for /t(ɕ)/. Based on the radar plot, the consonants show differences in a wide range of parameters: *VH* (the velum is the lowest for /ɲ(ɕ)/ and the highest for /t(ɕ)/), *TTH* (the tongue tip is somewhat lower for /ɲ(ɕ)/), *TTF* (the tongue tip is somewhat less front for /t(ɕ)/), *TB* (the tongue body is the highest/most front for /t(ɕ)/ and the lowest/most back for /ç/), *TD* (the tongue dorsum is more arched for /ç/), *LLH* (the lower lips is lower for /ç/), *ULP* (the upper lip is higher for /ɲ(ɕ)/), *HYF* (the hyoid is most front for /ɲ(ɕ)/), and *LAH* (the larynx is the highest for /ɲ(ɕ) and the lowest for /t(ɕ)/).

Like KMU, KD shows an overall similar constriction location (concentrated in the alveolar/post-alveolar region) for the three consonants, and this constriction is also more extensive for the affricate and the nasal than for the fricative. All three show a strong raising and fronting of the tongue body and a flattened tongue dorsum. Yet, the body is raised less for /ɲ(ɕ)/, while the dorsum is somewhat retracted for /ç/. This consonant also shows a somewhat retracted tongue root and backed/raised hyoid. For /ɲ(ɕ)/, the lips are less protruded, the larynx slightly lowered, while the velum is considerably lowered. The parameters show differences in *VH* (the velum is the lowest for /ɲ(ɕ)/), *TTH* (the tongue tip is lower for /ɲ(ɕ)/), *TB* (the tongue body is the highest/most front for /t(ɕ)/), as well as *LLP/ULP* (both lips are less protruded for /ɲ(ɕ)/). In addition, we observe clear differences in the position of the *HYH/HYF* (with the hyoid being the highest and more back for /ç/ and the lowest and most front for /ɲ(ɕ)/), and *LAH* (being the lowest for /t(ɕ)/).

In sum, both speakers make use of *VH* (as expected) to differentiate the nasal from the non-nasal alveolopalatals; they also make use of *TB* and *LAH* to distinguish the affricate from the other consonants, and of *TTH*, *HYH/HYF*, and *LAH* to distinguish the nasal.

A comparison of the affricate components – occlusion and frication – shows that, for KMU (upper panel of Figure 16), the latter component is produced with a less extensive constriction, a lower tongue body, a more retracted tongue dorsum, a less raised lower lip, and a higher larynx. In terms of the parameters, this corresponded to differences in *TTF* (the tongue tip is more advanced/higher for /ç(ɕ)/), *TB* (the tongue body is higher/more front for /t(ɕ)/), as well as *LLH* and *LLP* (the lower lip is raised higher and more protruded for /t(ɕ)/). In addition, the laryngeal articulator (*LAH*) is higher for /ç(ɕ)/.

For KD, differences between the two articulations also involved the extent of the constriction and the tongue dorsum backing, as manifested in the parameters *TB* (the tongue body is higher/more front for /t(ɕ)/) and *TD* (the tongue dorsum is more arched for /ç(ɕ)/). Finally, the hyoid bone (*HYF*) is more front for /t(ɕ)/ than for /ç(ɕ)/.

Overall, both speakers used *TB* to differentiate the two components, while showing some individual strategies in the use of other components. The lower tongue body position for the frication component is expected, given the need to channel airflow towards the lower teeth.

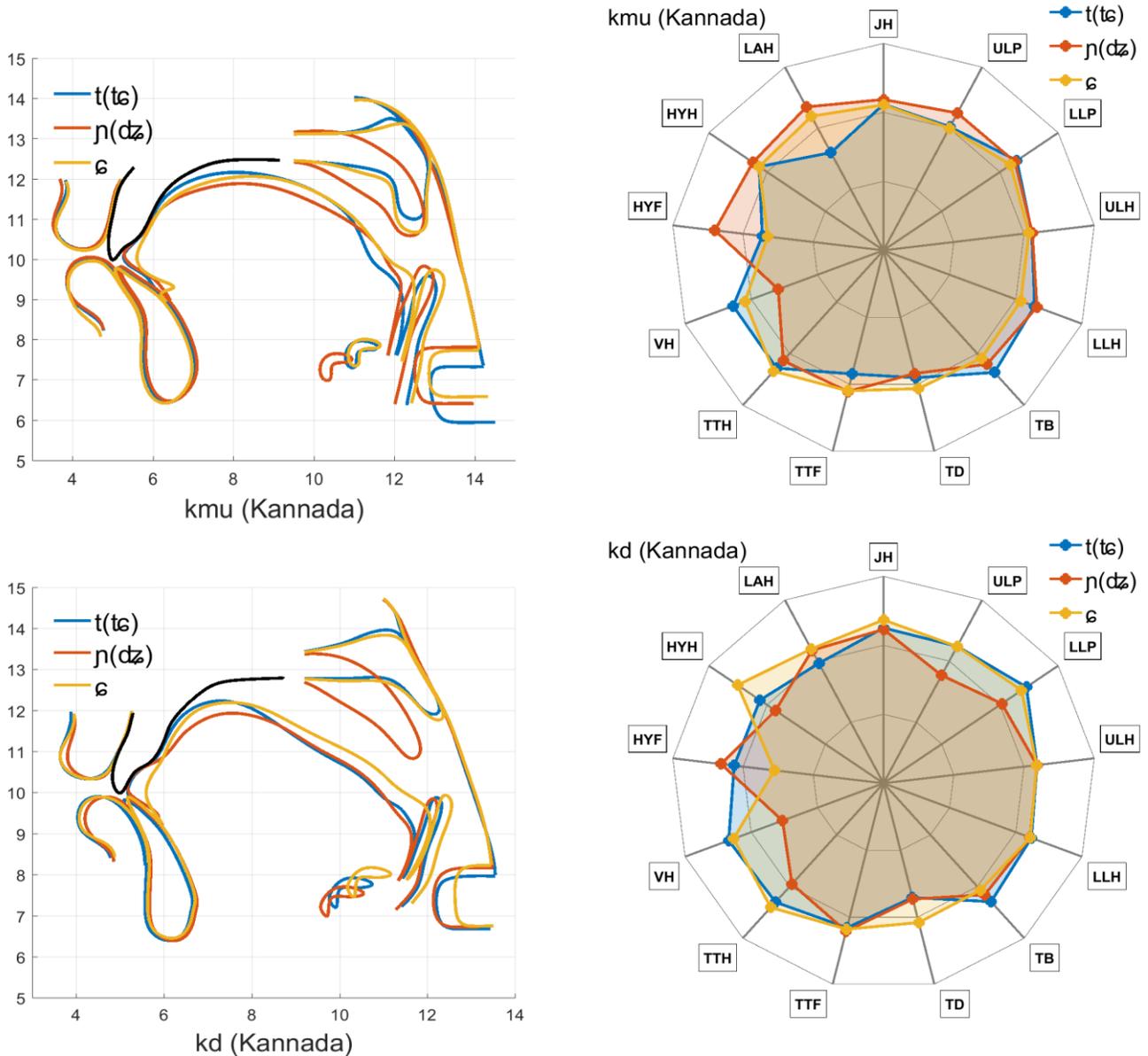


Figure 15. Overlaid average contours (left) and radar displays of articulatory parameters (right) for the affricate occlusion /t(tʃ)/ vs. nasal /ɲ(dʒ)/ vs. alveolopalatal fricative /ʃ/ for both speakers (top KMU, bottom KD).

Finally, we also compared the alveolopalatal affricate /t(tʃ)/ and the palatal glide /j/. The two consonants clearly differed in the part of the tongue being used (the blade vs. the tongue front) and the constriction location (a more anterior area extending from the upper teeth to the post-alveolar region vs. the pre-palatal area). For /j/, the entire tongue was advanced, rather than mainly the tongue body. For both speakers, the contrast was manifested by *TTH*

(a lower tongue tip for /j/), *TB* (a higher/more front tongue body), and *HYH* (a lower hyoid for /j/). In addition, *KMU* differentiated the contrast by *TD* (a less arched tongue dorsum for /j/), while *KD* did it by *TTF* (a more retracted tongue tip for /j/), and *LLH/LLP* (a more lowered/less protruded lower lip for /j/). Additional figures can be found in Appendix D. In general, this shows that /j/ is different from /t(tɕ)/ and other alveolopalatals not only in manner but in place, and thus a phonetic classification of the letter as “palatal” (Nāyaka, 1967) is not fully accurate.

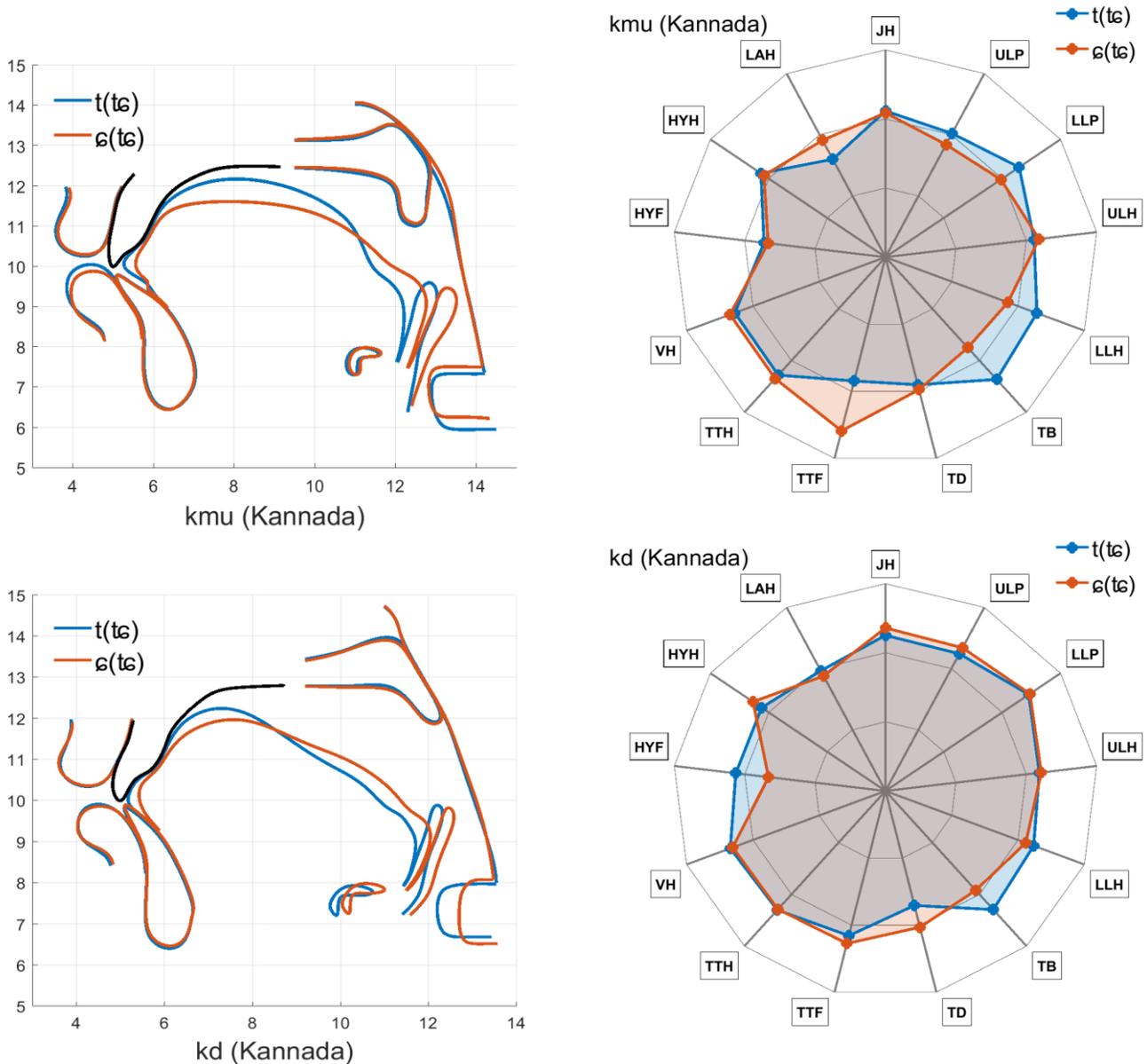


Figure 16. Overlaid average contours (left) and radar displays of articulatory parameters (right) for the alveolopalatal affricate occlusion /t(tɕ)/ vs. the alveolopalatal affricate frication /ɕ(tɕ)/ for both speakers (top KMU, bottom KD).

4.2.2 Other contrasts

While focusing on coronals, it is also worth considering manner differences in non-coronals, as some of these are independent of place. Among the labials, manner differences between /p/ and /m/ were manifested by both speakers in the *VH* component (a lower velum for /m/) and the *HYH/HYF* components (a higher/more posterior hyoid for the stop). Differences between /p/ and /v/ involved a type of labial constriction – bilabial vs. labiodental, as manifested by a combination of the *ULH/ULP* and *LLH/LLP* components, as well as some differences in the tongue position (a somewhat lower *TT* and more arched *TD* for the glide; as discussed above).

Among velars, the /k/ vs. /ŋ(g)/ contrast was, as expected, exhibited by the *VH* component (a lower velum for the nasal), but also by *HYH/HYF* (a higher/more posterior hyoid for the stop) and of the tongue dorsum (a somewhat more arched dorsum for the stop). The tongue dorsum contact with the velum/palate was somewhat more extensive for the stop than the nasal.

Finally, a superimposition of /h/ and /k/ articulators showed in general similar profiles, but with a somewhat higher tongue body, a more arched tongue dorsum, and a more advanced tongue tip for the stop compared to the fricative. The relative similarity of the profiles further confirms that /h/ was produced by our speakers with a velar constriction. Additional figures can be found in Appendix D.

4.2.3 Summary

General differences observed in this section are summarised below by specific manner contrasts in coronals, illustrated in Table 4.

4.2.3.1 Stop vs. nasal

For both speakers, the stop vs. nasal contrast was consistently distinguished – across three manners – by *VH*. Not surprisingly, nasals were produced with a lower velum than stops. In addition, both speakers showed manner differences in the position of the hyoid bone, although somewhat differently: stops produced by *KMU* showed the hyoid backing, while stops produced by *KD* showed the hyoid raising (and this involved both coronal and non-coronal contrasts). Other differences were speaker-specific. *KMU* stops showed a consistently lower *LAH* for all three places, and lesser *LLP* (for dental and retroflex) stops than nasals. *KD* showed more *TT* raising for (retroflex and palatal) stops compared to nasals, and a more arched *TD* and higher jaw for stops than nasals (of the dental and retroflex places). Note that differences between Kannada stops and nasals in the tongue dorsum arching were previously observed using ultrasound (Kochetov *et al.*, 2018). However, given the lack of such differences in *KMU*'s productions, we can conclude that this distinction is optional. The lack of consistent jaw position difference in our data (apart from dentals, /t̪/ > /ŋ/) is also only partly consistent with previous findings for other languages, such as English, German, and Arrernte (Keating *et al.*, 1994; Mooshammer *et al.*, 2006; Tabain, 2012). As mentioned above, this could be related to the task of sustaining articulations; however, this does not explain the presence of jaw differences in contrasts involving laterals (see below).

Table 4. A summary of main differences for manner contrasts, as exhibited by both or one of the speakers, with ratios of relevant comparisons presented in parentheses.

Contrasts	Both speakers	KMU only	KD only
a. stop/affricate vs. nasal (dental, retroflex, alveolopalatal)	<i>VH</i> stop > nasal (6/6)	<i>HYF</i> nasal > stop (3/3) <i>LAH</i> nasal > stop (3/3) <i>LLP</i> nasal > stop (2/3)	<i>HYH</i> stop > nasal (3/3) <i>TTH</i> stop > nasal (2/3) <i>TD</i> stop > nasal (2/3) <i>JH</i> stop > nasal (2/3)
b. stop vs. lateral (dental, retroflex)	<i>JH</i> stop > lateral (4/4)	<i>LLP</i> lateral > stop (2/2) <i>HYF</i> lateral > stop (2/2)	<i>TD</i> stop > lateral (2/2) <i>HYH</i> stop > lateral (2/2) <i>LAH</i> stop > lateral (2/2)
c. nasal vs. lateral (dental, retroflex)	<i>VH</i> lateral > nasal (4/4) <i>JH</i> nasal > lateral (4/4)	<i>LLH</i> nasal > lateral (2/2)	<i>LAH</i> nasal > lateral (2/2)

4.2.3.2 Stop vs. lateral

For both speakers, the stop vs. lateral contrast was consistently distinguished by *JH*: both dental and retroflex stops were produced with a higher jaw position than the corresponding laterals. Both speakers also exhibited manner differences in the position of the hyoid, however, again, in a somewhat different direction: the organ showed some backing for KMU's stops, while raising for KD's stops (as well as advancement for KD's retroflex /t̪/). There were other individual differences distinguishing manner contrasts. KMU made use of *LLP* (which was higher for laterals), while KD made use of *TD* (a more arched dorsum for stops) and *LAH* (a higher laryngeal articulator for stops).

4.2.3.3 Nasal vs. lateral

The lowering of the velum for nasals served as the main differentiator of the nasal vs. lateral contrast for both speakers. In addition, both speakers differentiated the manner contrast by *JH*: laterals were consistently produced with a lower jaw than nasals. Speakers differed in the use of other parameters. Thus, laterals were produced by KMU with a lower *LLH*, and by KD with a lower *LAH*. The two strategies are likely related, as they presumably facilitate the lowering of the tongue sides and/or extending the tongue dorsum. Notably, some lingual differences were also observed at least for some places: KD produced /ɺ̥/ with a less front and higher tongue tip than /ɺ̥̃/, and produced /ɺ̥/ with a more arched dorsum than /ɺ̥̃/. On the other hand, KMU differentiated /ɺ̥/ from /ɺ̥̃/ by a lower/less front tongue body.

Overall, differences observed for the nasal vs. lateral contrast were less numerous than the differences for the stop vs. lateral contrast. This indicates that (apart from the velar lowering) nasals are in a sense intermediate between stops and laterals. This is likely because these categories involve active articulatory adjustments: raising of the jaw/larynx to make an aerodynamically tight closure for stops and a lowering of the same articulators and extending the tongue in order to produce lateral airflow. Neither of these adjustments are necessary for nasals, which are sufficiently differentiated by the velum lowering.

Note that stop-lateral differences were previously reported for other languages (English and Swedish: Keating *et al.*, 1994; Arrernte: Tabain, 2012). In these studies, tongue shape differences between stops and laterals were also observed, with the latter showing some tongue dorsum/root retraction needed for lateral compression. Such an effect is not clearly present in our data (apart from KD's tongue dorsum difference); nor was it observed in the ultrasound study of this Kannada contrast (Kochetov *et al.*, 2018). The lack of such difference is possibly in a greater lowering of the jaw, neutralising the tongue retraction effect.

Among other manner contrasts, the palatal glide was rather different from the alveolopalatals, as manifested most clearly by the tongue body and the tongue tip position. The labiodental glide /v/ was also different from the labial stop /p/, not only in their lip configurations, but also in the relative position of the tongue. An unexpected result, already mentioned above, was the finding of a velar-like realization of /h/. Recall that all previous accounts described the sound as a glottal fricative.

Taken together, most frequently and consistently used parameters distinguishing manner contrasts were the velum height (lowering for nasals) and the jaw height (lowering for laterals). KMU also tended to employ lower lip protrusion (stronger protrusion for nasals) and hyoid fronting (retraction for stops), while KD frequently made use of the tongue dorsum (more bunching for stops), the hyoid height (raised hyoid for stops), and the larynx articulator (lowered larynx for laterals).

4.3 Resistance and susceptibility to vowel coarticulation

As mentioned in the Introduction, coronals were expected to be relatively resistant to coarticulation, and particularly those produced with an extensive contact along the palate (alveolopalatals and sublaminal retroflexes) or constrained by aerodynamic requirements (fricatives and the trill). In contrast, labials and laryngeals, which lack a lingual constriction, and velars, which share the primary articulator with vowels, were expected to be highly susceptible to coarticulation (Recasens, 1999). Our quantitative examination of variance by articulator (see above) did not reveal clear and consistent clustering of articulations by place or manner. Nevertheless, we observed some general tendencies in the expected directions, at least with respect to lingual variability.

As we can see in Figure 17, in most cases the speakers produced coronal stops, fricatives, and /r/ with a relatively stable tongue (exhibiting little variation; with /tʃ/ by KMU and /t/ by KD being exceptions). Non-coronals, such

as /p/, /k/, /v/, and /h/, on the other hand, were largely produced with much greater lingual variation. This broadly confirms our prediction. Further additional figures can be found in Appendix C.

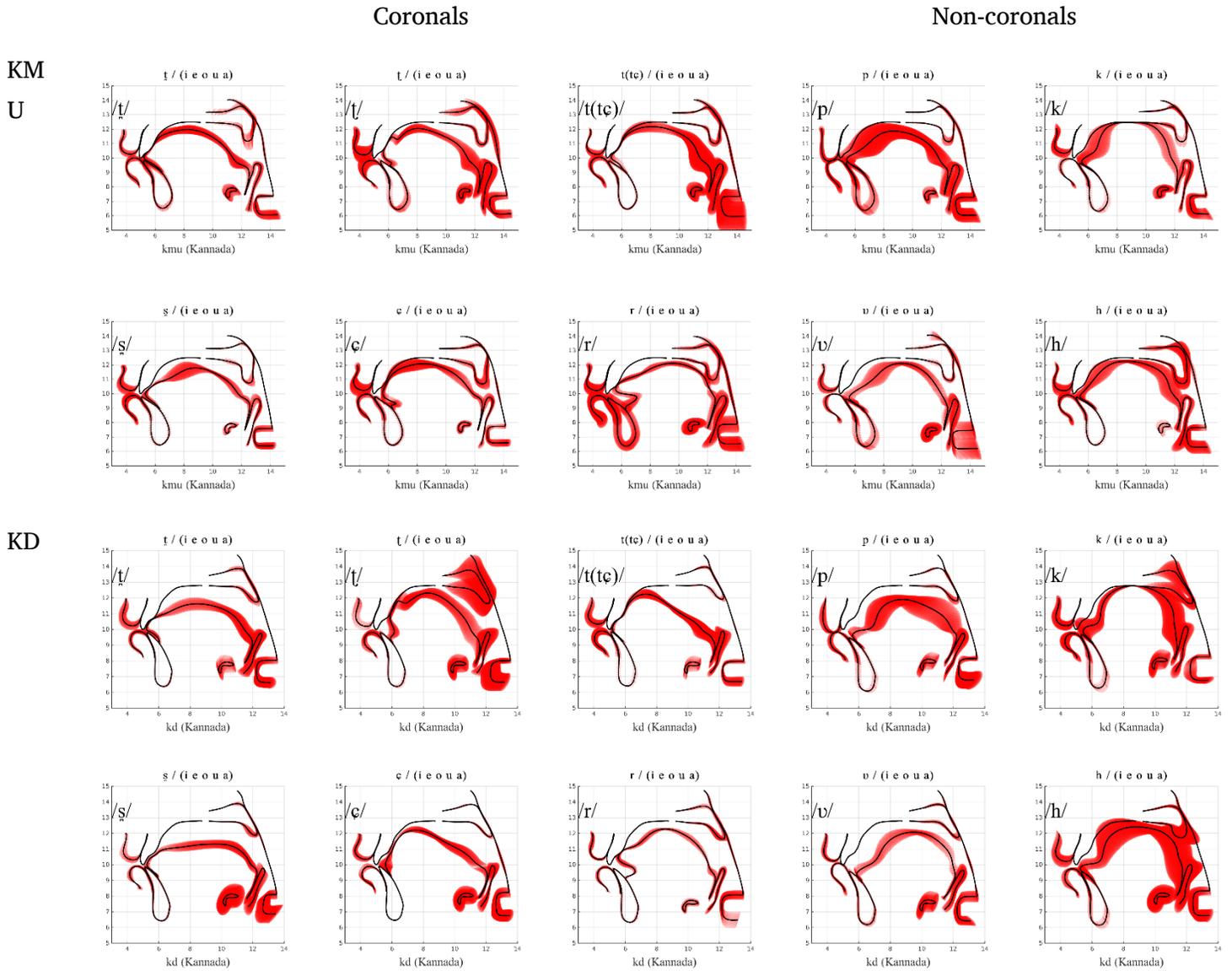


Figure 17. Dispersion ellipses with ± 2 standard deviations for sample coronal and non-coronal consonants illustrating resistance/susceptibility to coarticulation (top KMU, bottom KD). The dense set of ellipses allows to see the outlines of the variability.

5 Discussion

5.1 Evaluating proposals about distinctive features

An important goal of this study was to examine coronal contrasts in Kannada in light of previous proposals on distinctive features for dentals, retroflexes, and alveopalals. As reviewed in the Introduction, one general prediction shared by distinctive feature theory approaches is that some contrasts are more distinct than others. In particular, most researchers agree that retroflexes are essentially more different from dentals than alveopalalals, as predicted by numbers of distinctive feature differences. There is less agreement, on the other hand, about alveopalalals, which are predicted to differ more from dentals than retroflexes by some phonologists, or equally different from those two segment classes by others.

Given some variation across consonants of different manners of articulation and differences between speakers observed in our results, it is not easy to conclusively confirm or disconfirm these predictions. Nevertheless, considering speaker-specific differences shared by most manners of articulation within a class, we can say that the first prediction is confirmed: retroflexes are more different from dentals than alveopalalals. The first contrast is differentiated by both speakers using four parameters, three of which are lingual (for KMU: *TTF*, *TB*, *TD*, and *LLP*; for KD: *TTF*, *TB*, *TTH*, and *LAH*). The second contrast is differentiated by both speakers using three parameters, only one or two of which are lingual (for KMU: *TB*, *LLH*, and *LLP*; for KD: *TB*, *LLH*, *TTF*).

Considering contrasts involving alveopalalals, our results are somewhat contradictory. The alveopalalal-dental contrast was manifested by KMU using only two parameters, with one of them being lingual (*LLP* and *TTF*); it was manifested by KD by four parameters, most of which were lingual (*LLP*, *TB*, *TTH*, and *TD*). Thus, it appears that the contrast is less distinct than the retroflex-alveopalalal contrast for one speaker (3 parameters; see above), contradicting both previous proposals. For the second speaker, the alveopalalal-dental contrast is more distinct than the alveopalalal-retroflex contrast, confirming one of the proposals (Hamilton, 1996; Gnanadesikan, 1994; Arsenault, 2008).

Taken together, these results confirm the greater distinctiveness of the dental-retroflex contrast, while indicating that contrasts of dentals and retroflexes with alveopalalal are more variable.

5.1.1 *The dental-retroflex contrast*

Turning to predictions based on specific features, recall that the dental-retroflex contrast was predicted to differ in a number of features corresponding to crucial articulatory characteristics. These include (1) the location and extent of the constriction between the tongue and the roof of the mouth (dental vs. post-alveolar or palatal), (2) the part of the active articulator involved (apical, laminal, or sublaminal) and its shape or direction (the tongue middle down or not, convex or concave, tip-up or tip-down), as well as (3) the involvement of the posterior portion of the tongue (backing and lowering of the tongue body and raising of the tongue dorsum) and (4) the presence or absence of a sublingual cavity.

Starting with the constriction location, our interpretation of overlaid average contours suggested consistent differences between the dentals and retroflexes produced by our two Kannada speakers. As expected, dentals /t̪ n̪ l̪ s̪/ were produced by both speakers in the denti-alveolar region (extending into the postalveolar region for some of the consonants produced by KMU). In contrast, retroflexes /t̪̠ n̪̠ l̪̠ s̪̠/ were articulated further back – in the post-alveolar or (pre)palatal area (with /s̪̠/, not being a true retroflex, showing a somewhat more anterior constriction – alveolar/post-alveolar). Overall, the contrast was more distinct for KD than KMU (as the speakers’ retroflexes tended to differ in the amount of retraction – to an area just behind the alveolar ridge or towards the hard palate). The contrast was also more distinct for sonorants (nasals and laterals) than stops, as produced by both speakers. This is because retroflex stops tended to be more anterior (post-alveolars) compared to sonorants, whose constrictions tended to extend to the prepalatal/palatal regions. Both kinds of results have been reported for Kannada. Ultrasound data in Kochetov *et al.* (2014) suggested that speakers varied in their constriction locations for retroflex stops: 3 speakers in that study produced these sounds as clear post-alveolars, 4 as (pre)palatals, and the other three as intermediates between these two categories. A more posterior tongue tip constriction for /ŋ/ and /l/ compared to /t/ was also found for the same speakers in Kochetov *et al.* (2018), which is also consistent with the X-ray study of Tamil retroflexes by Švarný *et al.* (1955). It is possible that a more anterior position constriction for stops favours the aerodynamics of burst production, allowing for a greater bracing of the tongue sides against the upper teeth.

In terms of distinctive features, our results provide support for specifications of the dental-retroflex contrast that make use of features referring to constriction locations – the binary feature [±anterior] and privative features [dental], [postalveolar], and [palatal]. Given the observed across-/within-speaker and across-manner variation, however, the use of the latter set of features is somewhat problematic. Thus, based on our data, retroflexes for some speakers of Kannada would need to be specified for [postalveolar], while for other speakers as [palatal]. Similarly, stops would be more commonly specified as [postalveolar], while nasals and laterals as [palatal]. While this may not be something unusual in task-dynamic models (e.g. Proctor *et al.*, 2010), the use of different features for similar phonemic contrasts runs against the usual assumptions of the distinctive feature theory. In this sense, the use of the relative feature [±anterior] is more appropriate, although it should be mentioned that its traditional definition refers a specific articulatory landmark – the alveolar ridge (Chomsky *et al.*, 1968).

In terms of the part of the active articulator – the tip or the blade, we also observed consistent differences between dentals and retroflexes (again, excluding the fricatives). While /t̪ n̪ l̪/ in our data were classified as apico-laminals (with /l̪/ by KD being apical), /t̪̠ n̪̠ l̪̠/ were clearly realised as apical/sublaminal (combining the tip and the underside) or just sublaminal. The frequent (although not exclusive) use of the underside for Kannada retroflexes was observed – rather indirectly – in the ultrasound study of stops by Kochetov *et al.* (2014), as well as noted to be characteristic of Dravidian retroflexes in general (Ladefoged *et al.* (1983) for Tamil and Telugu stops; Švarný *et al.* (1955) and Balasubramanian (1972) for Tamil stops, nasals, and laterals; Scobbie *et al.* (2013) for Malayalam

liquids). Overall, we can interpret the results as providing support for the use of privative features [laminal] on the one hand and [apical]/[sublaminal] on the other to characterise the dental-retroflex contrast. Less clear is the choice between the latter two features, as they appear to be subject to manner-specific and/or individual variation. It should be noted that the feature [apical] can also characterise the alveolar rhotic in our data, as it was clearly produced with the tongue tip.

In terms of the extent of constriction area along the sagittal line, we found a rather inconsistent evidence for the use of the feature [\pm distributed]. This is because not all dentals (/ɳ/ by both speakers, and /ɺ/ by KD) were produced by our speakers with extensive contact ([+distributed]), and not all retroflexes were produced with considerably lesser contact ([-distributed]; e.g. as /ɻ/ by both speakers, and /ŋ/ by KD). The latter variation is due to the fact that sublaminal contact (which was more commonly observed for sonorant retroflexes) can be fairly extensive, and thus the feature might be of use for apical but not for sublaminal retroflexes. Note that for fricatives, the distinction was in fact the opposite of what is expected, with a greater constriction extent for /ʂ/ being due to the alveolopalatal production of this sound.

Recall that dentals and retroflexes were also proposed to be distinguished by the convexity/concavity of the front portion of the tongue (Hamann, 2003; Arsenault, 2008). Our results in general support this distinction. Dentals were produced by both speakers with an overall weakly or moderately convex tongue, both in its front and back portions (although note the relatively flat or weakly concave tongue for /ʂ/). Retroflexes, on the other hand, were produced with a small or moderate concavity between the blade and the tongue body (which was greater for sonorants, given the more extensive tongue tip retraction). This concavity was uniformly accompanied by a convexity in the front portion of the tongue body (or the tongue middle), and a relatively flat or mildly convex tongue dorsum. As the concavity was produced by active lowering of the tongue body (as reflected in the *TD* parameter in our results), together with the retraction of the tongue tip, this provides support for (Arsenault (2008)'s specification of (sublaminal) retroflexes for the feature [low]. Note, however, the tongue body for retroflexes is not necessarily lower than for dentals, and in fact the middle part of the tongue tends to be higher than for the latter (see e.g. /ɽ/ vs. /ɻ/ for KD in Figure 7 or /ɺ/ vs. /ɻ/ for KMU in Figure 10). This weakens the support for [low], which is the feature commonly used to characterise the low tongue position for vowels like /a/. Another contradiction in our data is the tongue dorsum (or body) backing, the characteristic advocated in a number of proposals (Bhat, 1974; Gnanadesikan, 1994; Hamann, 2003; Arsenault, 2008). Specifically, the feature specification [dorsal, back] (e.g. Arsenault, 2008) implies a tongue position similar to a back vowel like /ɑ/, /o/, or /u/ (with the latter being specifically consistent with Hamann (2003)'s proposal of tongue body backing and dorsum raising). Although we did not directly compare tongue shapes for retroflexes and these vowels, it was evident that none of the retroflex articulations in our data were characterised by tongue dorsum backing or raising, as observed for the trill, or relative to dentals and alveolopalatals. In fact, the opposite was frequently observed, as dentals tended to show a more convex, slightly retracted tongue dorsum than retroflexes. While unexpected in

the context of feature theories, this result is consistent with previous findings of the ultrasound investigations of Kannada retroflexes (Kochetov *et al.*, 2014; Kochetov *et al.*, 2018), as well as an X-ray study of retroflexes in Tamil (Švarný *et al.*, 1955). The lowering and advancing of the tongue dorsum in these cases appear to serve to stabilise the tongue so that the flapping forward movement of the tongue tip/blade can be produced effectively. At the same time, we cannot exclude the possibility that this lowering/fronting of the dorsum is a side effect of sustaining the retroflex articulation or gemination (as in the studies mentioned above). It is therefore important to obtain some dynamic data on the Kannada retroflex production.

Another observation to note is that retroflexes in our data were not distinguished by the retraction of the tongue root, as might be expected based on previous studies of the English retroflex approximant /ɻ/ (Narayanan *et al.*, 1997). In fact, dentals and retroflexes of the same manner were hardly different from each other in this articulator, with a possible exception of the laterals /ɭ/ and /ɮ/ produced by KD (more retracted root for the retroflex). At the same time, some root retraction was characteristic of coronal stops in general, with the likely purpose of facilitating the build-up of air-pressure.

It should be mentioned that the full range of observations about the tongue convexity/concavity and its relative position could not be made using methods like EMA and ultrasound, given their either sparse spatial sampling or the lack of reflexion of sound waves from concave surfaces. Another important advantage of MRI as a method is that it allows us to observe presence or absence of a sublingual cavity, one of the key characteristic of retroflex consonants (Hamann, 2003). Our results showed that, indeed, the retroflexes /ɻ ɺ ɽ/ were produced with such a cavity, which ranged in its size from relatively small or moderate for the stop to moderate or large for the sonorants. The size of the cavity in these cases was directly related to the degree of the retraction of the tongue tip. In contrast, the dental stop and nasal, /t̪, n̪/, lacked a sublingual cavity, as the tongue was positioned at the foundation of the lower teeth. At the same time, both speakers produced the dental lateral /ɭ/ with a small or moderate sublingual cavity (although much lesser in size than for /ɮ/); they also did it for the alveolar rhotic /r/. This suggests that this characteristic is not unique to retroflexes, but is also shared by anterior coronals of certain manners of articulation (which require a specific positioning of the tongue – for lateral airflow or trilling). Perhaps a more appropriate generalization is therefore that retroflexes have a larger sublingual cavity than dentals/alveolars of the same manner of articulation.

Our finding that the contrast was consistently distinguished by only two parameters – the tongue tip fronting and the tongue body lowering (see Table 4) – suggests that the constriction location and the height of the tongue are the most important characteristics of the contrast. If this is the case, the corresponding features referring to place ([±anterior] or [dental] and [post-alveolar/palatal]) and tongue position ([dorsal, high/low]) should be the main distinguishing properties of the contrast. A retraction of the tongue tip accompanied by the lowering of the tongue body for retroflexes can plausibly produce all other characteristic properties, such as an apical/sublaminal constriction, a concave tongue shape, and a sublingual cavity. The individual use of other parameters – the tongue

dorsum fronting and the lower lip spreading by KD, and the tongue tip raising and larynx lowering by KD – suggests some secondary strategies, likely supporting the realization of the two key features.

5.1.2 *The retroflex-alveolopalatal contrast*

Recall that phonological approaches predict that retroflexes and alveolopalatal share the same place of articulation ([-anterior] or [postalveolar]/[palatal]), while contrasting in essentially all the other characteristics mentioned above: the extent of the constriction ([±distributed], apicality/laminality, concavity/convexity, and the position of the posterior portion of the tongue to fronting and/or raising of the tongue body and/or dorsum ([dorsal, ±back, ±high]).

Considering relevant same-manner contrasts involving stops/affricates and nasals (/t/ vs. /t(tʃ)/ and /ŋ/ vs. /ɲ(ɟ)/), the prediction of the same place of articulation is only partly correct. Constrictions for /t/ and /t(tʃ)/ in our data overlapped in the post-alveolar region, while extending into the more anterior, denti-alveolar region, for the affricate. Constrictions for /ŋ/ vs. /ɲ(ɟ)/, on the other hand, did not overlap: the alveolopalatal was produced in a more anterior place than the retroflex (denti-alveolar vs. post-alveolar or (pre)palatal). This contradicts the feature-based prediction; however, it should be noted that the more anterior realization of the alveolopalatal nasal can be attributed to this sound's allophonic status (as possibly a variant of /ŋ/). Considering the sibilants, /ʃ/ and /ç/, the lack of place distinction here (both were classified as alveolar/post-alveolar) is due to a different factor, an evident merger of the contrast in favour of the alveolopalatal by both speakers.

With respect to the part of the tongue involved in the constriction, the results confirmed the expected distinction between the apical or sublaminal retroflexes and (at least partly) laminal alveolopalatals. The laminal articulation was also characteristic of /ʃ/ and /ç/.

As with the dental-retroflex contrast, there was little evidence for the use of [±anterior], given the fact that sublaminal retroflexes (/ŋ/ in particular) showed a considerable extent of the constriction, while the alveolopalatals did not always do it (as /ɲ(ɟ)/ by KMU and /t(tʃ)/ by KD).

While retroflexes were produced with a concavity in the front portion of the tongue, alveolopalatals were consistently characterised by a relatively strong convexity of this tongue body, reflecting its palatalised (raised and fronted) configuration. This confirms the use of the features [concave]/[convex], as well as the use of [dorsal, +high, -back] for alveolopalatals (including fricatives). Interestingly, the tongue dorsum configuration did not systematically differentiate retroflexes from alveolopalatals (with the former showing a somewhat less convex configuration), which further confirms the lack of active tongue dorsum retraction for retroflexes.

As expected, the alveolopalatals /t(tʃ)/ and /ɲ(ɟ)/ lacked the sublingual cavity exhibited by the retroflexes /t/ and /ŋ/. However, both /ʃ/ and /ç/, which were realised as near-identical alveolopalatals, showed a small sublingual cavity for one of the speakers. This further confirms our observation that the presence of this property is not exclusive to retroflexes.

As the tongue body parameter was crucial to distinguishing the contrast in our data, we can consider that the feature specifications ([low] for retroflexes and [front] for alveolopalatals) to be the primary characteristic of the contrast. The use of a non-lingual parameter – the lower lip height (employed by both speakers) – is unexpected for this contrast, as it is not predicted by distinctive feature approaches. It is likely to be a secondary characteristic related (together with *LLP* for KMU) to the production of the sibilant noise for alveolopalatals.

5.1.3 *The dental-alveolopalatal contrast*

The dental-alveolopalatal contrast was predicted to be distinguished by the location of the constriction ([±anterior]) and their tongue body/dorsum configuration ([-back] and [high] for alveolopalatals), with the two classes of consonants sharing the feature values [+distributed], [laminal], and [convex].

Comparing the contrasts matched by manner – /ṭ/ vs. /t(ṭ)/, /ɲ/ vs. /ɲ(ḍ)/, and /ʃ/ vs. /ç/ – the place distinction was only partially observed in our data. Specifically, it was maintained by both speakers for the fricatives (denti-alveolar vs. alveolar/post-alveolar) and for the stops/affricates produced by KD (denti-alveolar vs. denti-alveolar/post-alveolar). In the other cases, both types of consonants were produced in the denti-alveolar region (extending into the post-alveolar region for /ṭ/ and /t(ṭ)/ produced by KMU). These, partly inconsistent differences, were manifested in our finding of the use of the tongue tip fronting parameter by one of the speakers and the tongue tip raising parameter by the other speaker.

As expected, no differences were observed between dentals and alveolopalatals in terms of the part of the tongue involved in the constriction: all stop/affricate and nasal counterparts were classified as apico-laminal, while the fricatives as laminal.

Also as expected, stops/affricates of both places were not distinguished by the amount of linguopalatal contact (with /ṭ/ and /t(ṭ)/ showing relatively much, and /ɲ/ vs. /ɲ(ḍ)/ relatively little of it). The fricatives, however, did show some differences, with /ç/ having a considerably more extensive constriction area compared to /ʃ/.

Both types of consonants were expected to show convexity in the front portion of the tongue, and this was confirmed by our results for stops/affricates and nasals. The degree of convexity, however, was relatively moderate for dentals compared to the alveolopalatals characterised by substantial tongue body raising and fronting. As expected, dentals lacked this secondary gesture, conforming the absence of [dorsal, high, front]. However, differences in the tongue body shape were relatively small for one of the speakers (KMU), and were not reflected in the tongue body raising parameter (in contrast to KD, who showed differences in both tongue body and tongue dorsum).

Unlike their stop and nasal counterparts, the dental fricative /ʃ/ showed a relatively flat front portion of the tongue, with some convexity in a more posterior region (the middle of the tongue). Its alveolopalatal counterpart /ç/, in contrast, was characterised by a clearly convex shape (and particularly for KD).

To summarise, Table 5 provides some key points of our evaluation of previously proposed phonetic characteristics of three coronal contrasts in light of the current results. In each cell, ‘yes’ and ‘no’ stand for the predicted or observed presence or absence of a difference, with ‘yes/no’ referring to partial differences/similarities. We can see that our results at least partly confirm most of the proposed differences/similarities involving non-fricative retroflexes (as contrasting with dentals and alveolopalatals). Exceptions to this include the constriction extent ([±distributed]) and the configuration of the posterior portion of the tongue (the expected [back] for the retroflex tongue body and [high] for the retroflex tongue dorsum). Our results for the contrast between dentals and alveolopalatals are largely consistent with feature proposals, while also showing some variation in some patterns, including those that are expected to crucially distinguish the contrast (the constriction location and the tongue body position). Finally, no expected differences were observed between retroflex and alveolopalatal fricatives, as these were merged by our speakers in favour of the latter place. While the results largely confirm many previous feature proposals for coronal contrasts, it should be kept in mind that our speakers showed considerable variation across manners of articulations and between each other. Thus, any characterization of place contrasts should take into account manner differences and individual strategies in the implementation of contrasts, which, in turn, can include combinations of lingual and non-lingual articulator parameters.

Table 5. A summary of predicted and observed characteristics for three coronal contrasts (pred. = predicted, obs. = observed).

Characteristic/feature difference	dental-retroflex		retroflex-alveolopalatal				dental- alveolopalatal	
	(/t̪ ɲ ʎ/ vs. /t̪ ɲ ʎ/)		(/t̪ ɲ/ vs. /t̪ ɲ(ɕ)/)		/ʃ/ vs. /ç/		(/t̪ ɲ ʃ/ vs. /t̪ ɲ(ɕ) ç/)	
	pred.	obs.	pred.	obs.	pred.	obs.	pred.	obs.
constriction location	yes	yes	no	yes/no	no	no	yes	yes/no
part of active articulator	yes	yes	yes	yes	yes	no	no	no
constriction extent	yes	no	yes	no	yes	no	no	yes/no
shape of the front part of the tongue	yes	yes	yes	yes	yes	no	no	no
tongue body/dorsum backing/fronting	yes	no	yes	no	yes	no	yes	yes/no

tongue body lowering/raising	yes	yes/no	yes	yes	yes	no	yes	yes/no
tongue dorsum raising/absence of it	yes	no	yes	no	yes	no	no	no
sublingual cavity/absence of it	yes	yes/no	yes	yes	yes	no	no	no

5.2 Re-examining the Kannada consonant inventory

Another goal of this study was to compare our results to previous descriptions of Kannada consonants, as well as previous articulatory studies of the language. Referring to Table 1 in the Introduction, we can say that the productions of our two speakers were largely consistent with the traditional phonetic descriptions of consonants in terms of places and manners of articulation (Nāyaka, 1967; Upadhyaya, 1972; Schiffman, 1983; Sridhar, 1990).

One obvious deviation of our results is in the finding that the glottal /h/ can be produced with a lingual constriction, as velar [x]. While this may be attributed to the nature of the task, the fact that both speakers produced a similar dorsal gesture in this case is of interest and requires further investigation.

Another somewhat unexpected finding is the use of a dorsal constriction for /ʋ/. Recall that this consonant is typically described as labial – produced with the lower lip articulated with the upper teeth (labiodental), or, at least in some vowel contexts and for some speakers, produced with both lips (bilabial). The dorsal ([w]-like) constriction was present in our results regardless of the vowel context, and so was the labiodental (but not bilabial) constriction. This indicates that for our speakers the consonant is a complex segment – labiodental-velar, produced with two approximant-like constrictions. In terms of the lingual position, this consonant is a counterpart of /j/, as both are crucially distinguished by the tongue body and tongue dorsum positions. The presence of dorsal constriction (albeit secondary – velarization) was also observed for the rhotic /r/. This has not been previously reported for Kannada.

The finding of the (near-)merger of /ɟ/ and /ɟ̥/ (in favour of the latter) is also notable, although not unexpected given previous reports of the absence of the contrast in some (non-standard) dialects (Schiffman, 1983; Sridhar, 1990). As both our participants are well-educated and have reported to speak a standard variety of Kannada, it remains to be seen whether the merger has become more common and whether the contrast is still maintained by younger speakers of the language.

The third sibilant, /ɟ̥/, was produced by both speakers as denti-alveolar (very similar in its constriction to /t̪/ and more anterior than for the alveolar /r/), and therefore the label ‘dental’ seems fully appropriate. This, however,

contradicts previous descriptions of the sound as alveolar (Nāyaka, 1967; Upadhyaya, 1972; Schiffman, 1983; Sridhar, 1990).

As discussed in the Introduction, the sources disagree about the place of articulation of /ɳ/ and /ɭ/. Some authors classify both of them as dental (Nāyaka, 1967; Sridhar, 1990), while others as alveolar (Upadhyaya, 1972; Schiffman, 1983). Our results showed that the ‘dental’ classification is more appropriate for the nasal, as produced by our speakers. It was similar in the constriction to /t̪/ and different from the proto-typical alveolar /r/. Moreover, the articulation for /ɳ/ was found to be identical to that of /ɳ(d̪)/, contrary to the expectation of a place difference (Upadhyaya, 1972). As for the lateral, both speakers showed for this consonant a constriction that is more posterior than for /t̪/ and /ɳ/, although not clearly alveolar. For one speaker, the lateral constriction was still classified as denti-alveolar, although somewhat retracted; for the other speaker, the constriction was classified as alveolar/post-alveolar, as it extended considerably further. This lends some support to previous descriptions of the consonant as being somewhat more posterior, while the finding of some inter-speaker variation helps to explain the lack of consensus among researchers.

Recall that previous descriptions are unanimous in classifying the retroflex stop, nasal, and lateral as sub-laminal post-alveolars or palatals. Our results showed that this is clearly the case for /ɳ/ and /ɭ/, while the constriction for /t̪/ is more anterior, and seems to have properties of both apical and sublaminar articulations. As mentioned above, these manner-specific differences were previously observed for Kannada retroflexes (Kochetov *et al.* (2018), based on ultrasound data for 10 speakers), as well as reported for the closely related Tamil (Švarný *et al.* (1955), based on X-ray data for one speaker).

Altogether, the current study confirms many descriptive and instrumental observations of Kannada consonants, while challenging others by highlighting previously unnoticed articulatory differences. By providing a detailed analysis and modelling for a full set of Kannada place and manner contrasts, this study contributes to the documentation of this, still fairly phonetically under-studied language.

5.3 Methodological contributions

The methodological approach taken in this work is based on already well established expertise and knowledge in MRI processing of speech data and articulatory modelling (e.g. Serrurier *et al.*, 2019). However, these techniques have been improved and extended in several useful ways. A procedure to correct for the head tilt variation due to speakers unwanted movements in the midsagittal plane has been implemented. Displays of the overlay of contours of consonants averaged over the vowel contexts allow simple direct comparisons of distinct articulations. The estimation of articulatory parameters – in relation with articulatory models for each speaker – that characterise each articulation has allowed to build radar displays offering an integrated view of these parameters, and thus an easy way to compare the contribution of each component for different phonemes. It is also worth mentioning the estimation of the correlations between the articulatory parameters for the two speakers that allows assessing the

degree of similarity of their articulatory strategies. Finally, we can also mention the representation of the coarticulatory resistance to vowel context by means of dispersion ellipses around mean contours. These techniques have helped partly overcoming the limitation due to the small number of observations preventing more extensive statistical analysis.

5.4 Concluding remarks

As mentioned in the Introduction, the use of articulatory methodologies has been important for increased phonetic documentation of languages, better understanding of the cross-linguistic typology of sound patterns, and the development of phonological theories. While much progress has been done, the bulk of existing articulatory work have examined a relatively small number of genetically related and geographically clustered languages. Questions remain as to whether previous empirical findings and theoretical generalizations reflect the variation observed in world languages. This study is part of a growing effort to provide extensive articulatory documentation of sound patterns of less studied – and typologically unusual – languages. Our extensive examination of Kannada consonants produced by two female speakers helped us confirm many previous phonetic descriptions of the language. Among the notable findings are the merger of retroflex and alveolopalatal fricatives and – less expected – the presence of dorsal (primary or secondary) constrictions for the laryngeal fricative, the labiodental glide, and the rhotic /r/. The results of our articulatory modelling allowed us to capture most of the observed variation using a small set of components. With respect to dentals and retroflexes in particular, we found that the tongue tip fronting/backing and the tongue body raising/lowering components were the key parameters defining the contrast, while also supplemented by individual strategies involving both lingual and non-lingual articulators. The contrast between retroflexes and alveolopalatals was crucially distinguished by the position of the tongue body, but not necessarily in the direction predicted by some feature approaches. This was primarily because of the lack of the tongue body/dorsum backing for retroflexes in our data, which was nevertheless consistent with previous ultrasound investigations of the language. Further, we observed considerable manner-specific differences in the realization of what is considered to be the same places of articulation. Many of these differences could not have been observed using other articulatory methods. The use of MRI is therefore fully appropriate for studying detailed place and manner differences in complex consonant inventories. Moreover, our study made important methodological enhancements to the method, which can be further developed and extended to articulatory studies of other languages. Given some obvious limitations of this study, its findings and generalizations for Kannada and coronal contrasts should be further validated using real-time MRI data, quantitative statistical analysis (such as the SS-ANOVA technique), and a larger sample of speakers.

6 Supplementary Files

The additional files for this article can be found as follows:

Appendix A. Images overlaid with contours for both speakers. DOI:xxx

Appendix B. Effects of head tilt correction. DOI:xxx

Appendix C. Dispersion ellipses for all consonants for both speakers. DOI:xxx

Appendix D. Comparison of mean contours with radar displays of articulatory parameters for both speakers. DOI:xxx

Appendix E. A summary of Kannada consonant classification based on current results and previous literature. DOI:xxx

7 Data and scripts

All MRI images and articulatory contours expressed in centimetres and aligned on the same reference hard palate for each speaker will be available. This archive includes a few matlab® scripts useful to display the contours.

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