Kochetov *et al.* (submitted) An MRI-based articulatory analysis of the Kannada dental-retroflex contrast. The Journal of the International Phonetic Association.

Supplementary material S1: Acoustic validation of static MRI recordings

This document provides results of formant (F2 and F3) measurements for vowels preceding (V1) and following (V2) the normally-produced and sustained dental and retroflex consonants (C) by both speakers.

Method

Audio recordings made during the MRI sessions with an optical microphone positioned close to the speaker's lips and using a denoising procedure Kahana, Paritsky *et al.* (2003)). The audio signal sampled at 16000 Hz was annotated in Praat (Boersma & Weenink (2021)), marking onsets and offsets of preceding and following vowels /a i e o u/. This was done for both normal (non-sustained) and sustained productions. As mentioned in the text (Section 2.3), the speakers had to repeat each VCV word twice normally and then to sustain the consonant in the last repetition for the approximately 6.9 s duration of the scan. As our MRI images were based on the latter, a comparison between acoustic properties of sustained and normal productions was taken to assess the naturalness of these productions. We examined F2 and F3 formants, as primary correlates of vowel front/back and dental/retroflex contrasts, respectively. These formants were automatically extracted at 10 equally-spaced time points throughout preceding and following vowels (V1 and V2). Values beyond 3 standard deviations from the mean for each vowel by each speaker (less than 3% of the data) were considered to represent formant tracking errors, and were therefore excluded from the analysis. The package *ggplot2* (Wickham (2009)) was used to plot vowel formants in time using `geom_smooth()` using the 'loess' method. The plots below provide formant values for V1 and V2 by manner and vowel phoneme, focusing on place differences.

Results: F2

As shown in the following figures, the place contrast is not consistently distinguished by F2: both coronal places are characterised by higher values (rising transitions in V1 and falling transitions in V2) next to back vowels /a, o, u/ and slightly lower values (falling transitions in V1 and rising transitions in V2) next to front vowels. These patterns are similar for the normal and sustained conditions. (Note that somewhat wider confidence intervals, represented in grey, in the sustained condition are due to fewer tokens used – one repetition per item, compared to two repetitions for the normal condition.)

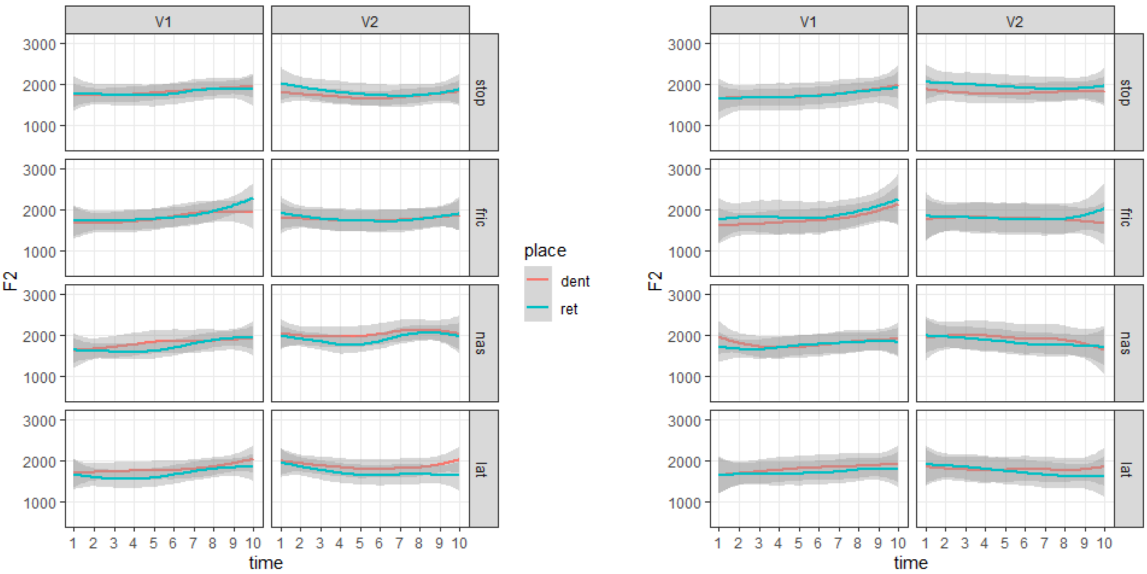

Figure 1. F2 (Hz) for speaker KMU throughout the vowels before (V1) and after (V2) dental and retroflex consonants by manner across five vowel contexts, separately for normal (left) and sustained (right) conditions.

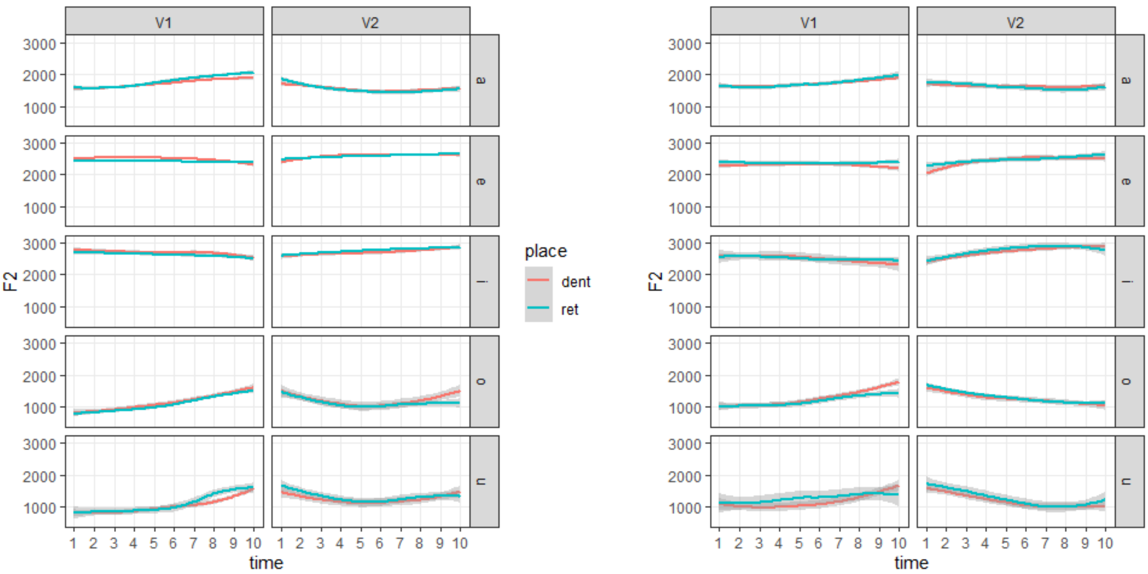

Figure 2. F2 (Hz) for speaker KMU throughout the vowels before (V1) and after (V2) dental and retroflex consonants by vowel context across four manners, separately for normal (left) and sustained (right) conditions.

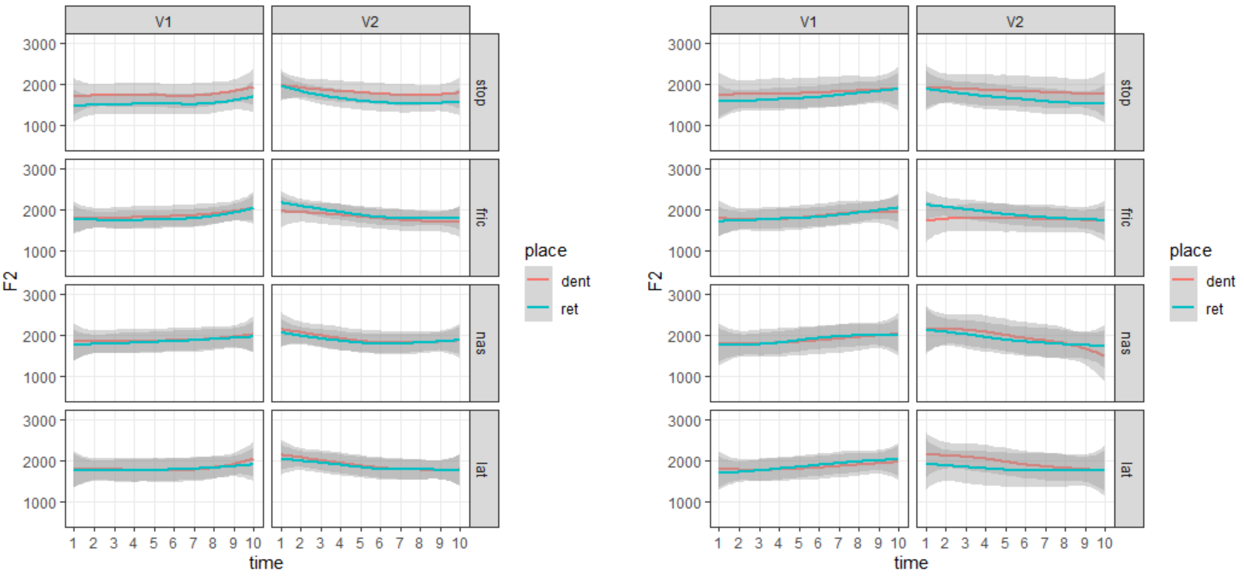

Figure 3. F2 (Hz) for speaker KD throughout the vowels before (V1) and after (V2) dental and retroflex consonants by manner across five vowel contexts, separately for normal (left) and sustained (right) conditions.

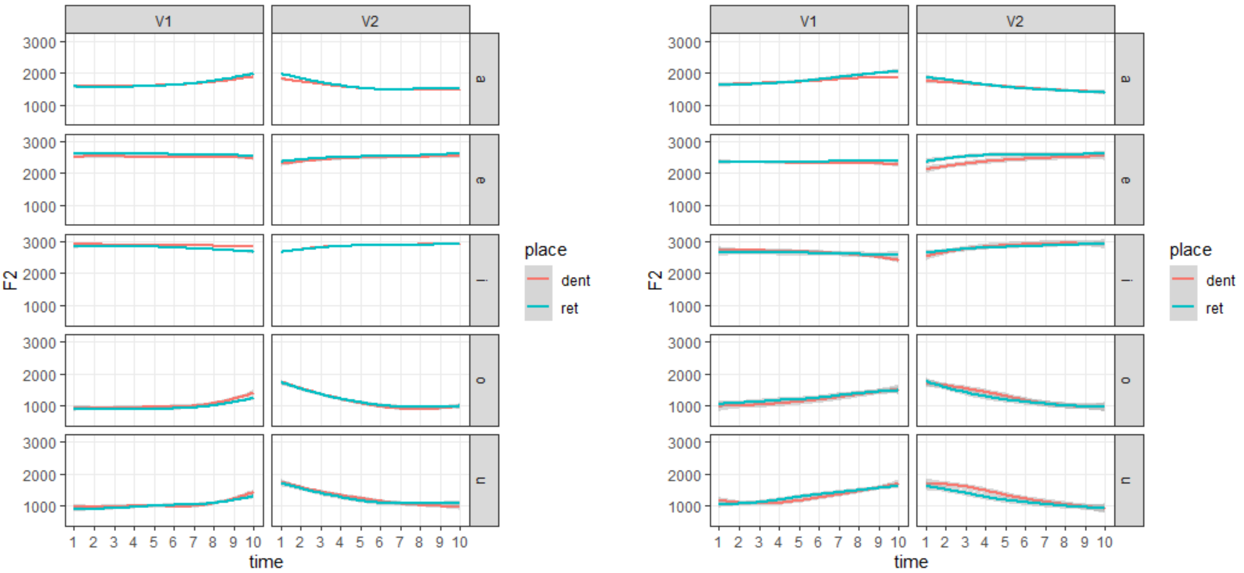

Figure 4. F2 (Hz) for speaker KD throughout the vowels before (V1) and after (V2) dental and retroflex consonants by vowel context across five vowel contexts, separately for normal (left) and sustained (right) conditions.

Results: F3

As shown in the following figures, the place contrast is distinguished by lowering transitions before retroflexes. Exceptions include the fricatives (by KMU) and front vowel contexts, for both normal and sustained conditions. Differences in the following vowel are also observed for some manners/vowel contexts, but are much lesser in magnitude.

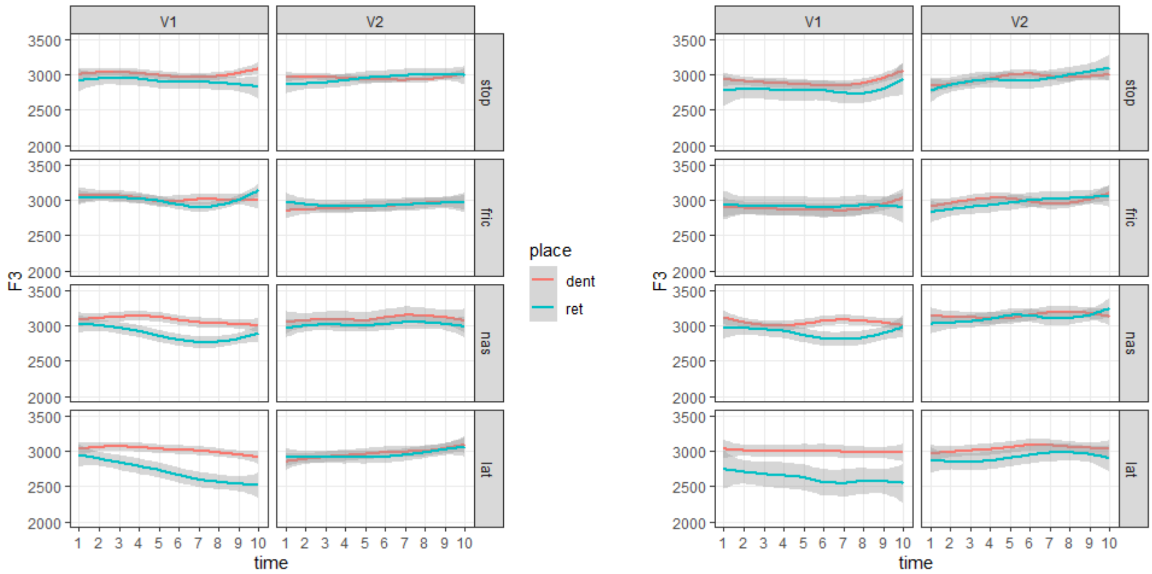

Figure 5. F3 (Hz) for speaker KMU throughout the vowels before (V1) and after (V2) dental and retroflex consonants by manner across five vowel contexts, separately for normal (left) and sustained (right) conditions.

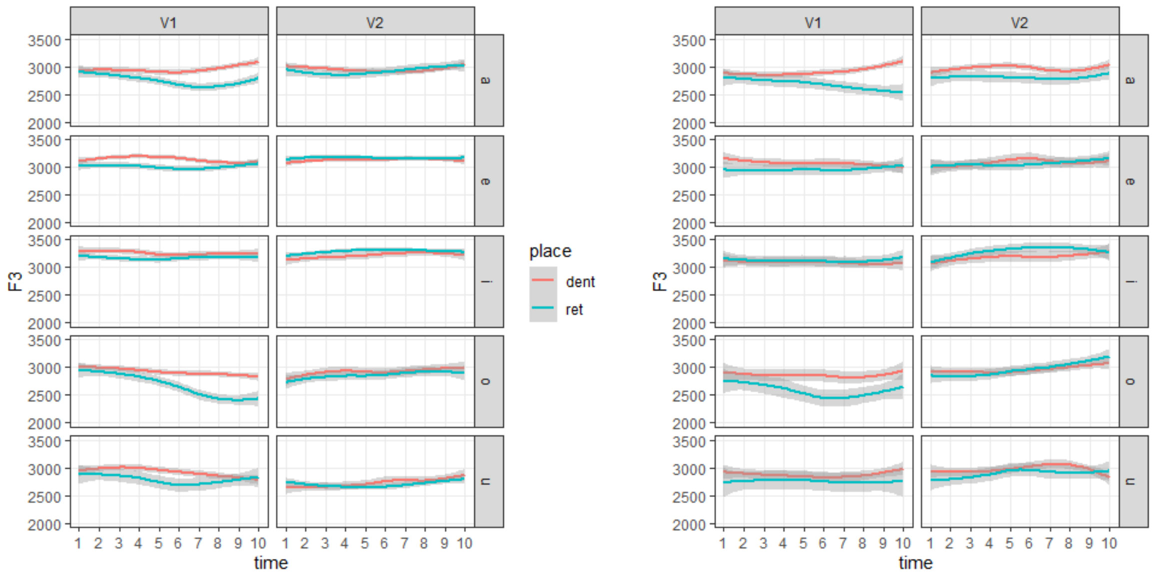

Figure 6. F3 (Hz) for speaker KMU throughout the vowels before (V1) and after (V2) dental and retroflex consonants by vowel context across four manners, separately for normal (left) and sustained (right) conditions.

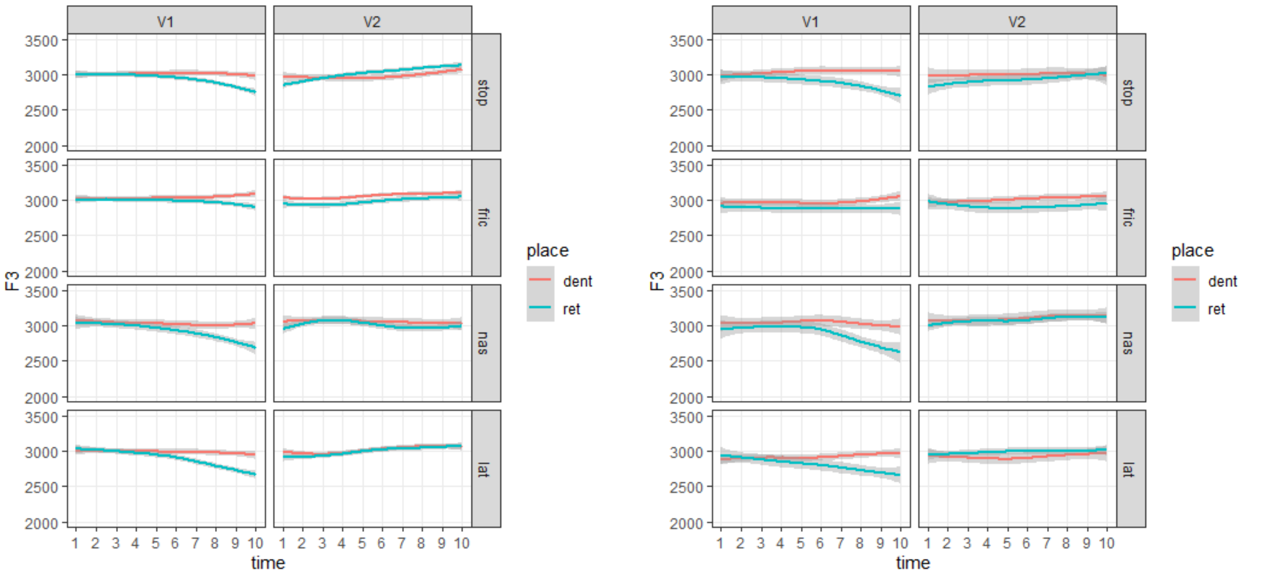

Figure 7. F3 (Hz) for speaker KD throughout the vowels before (V1) and after (V2) dental and retroflex consonants by manner across five vowel contexts, separately for normal (left) and sustained (right) conditions.

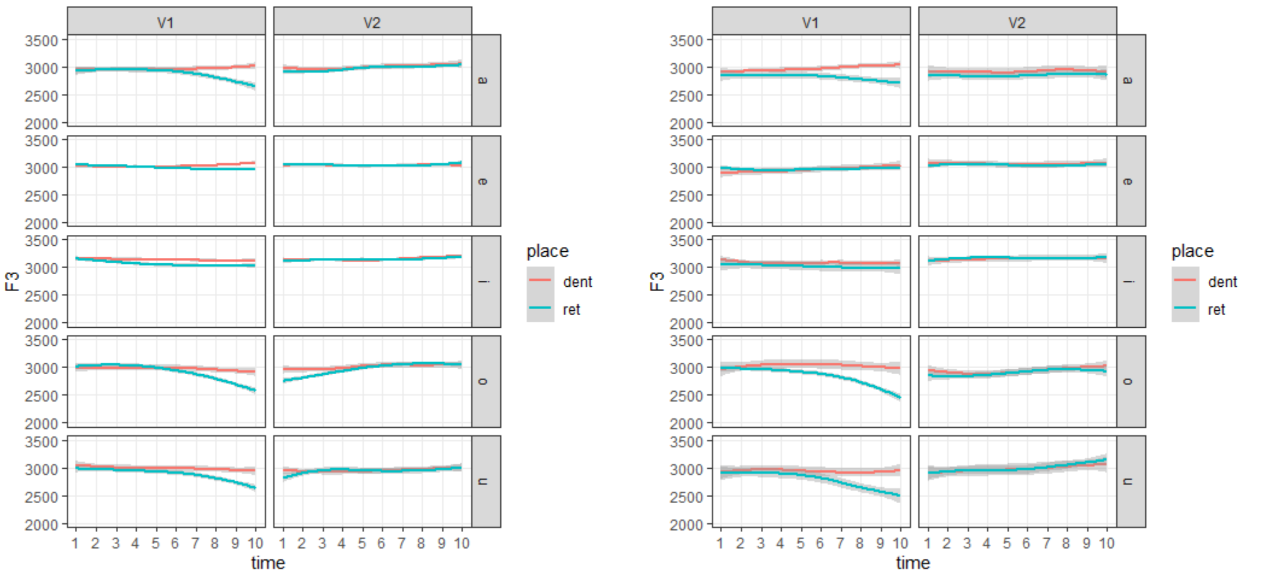

Figure 8. F3 (Hz) for speaker KD throughout the vowels before (V1) and after (V2) dental and retroflex consonants by vowel context across four manners, separately for normal (left) and sustained (right) conditions.

Conclusion

The lack of consistent differences in F2 and the presence of F3 differences at the offset of the preceding vowel are consistent with previous observations about the dental-retroflex contrast in Kannada (Kochetov, Tabain *et al.* (2018)) and other South Asian languages (e.g. Dave (1977); McDonough & Johnson (2009); Narayanan, Byrd *et al.* (1999)). So is the effect of front vowels on the contrast (Hamann (2003)). The fact that these patterns clearly appear in both normal and sustained conditions confirm the relative naturalness of the productions in the static MRI recordings.

References

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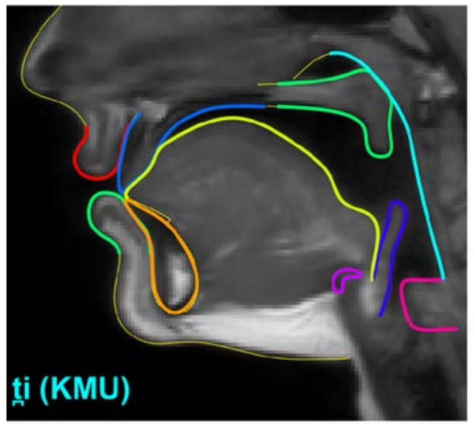
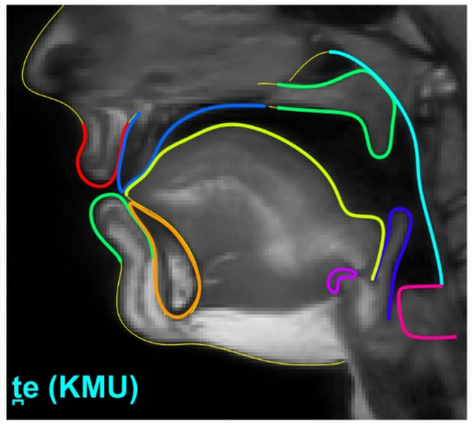
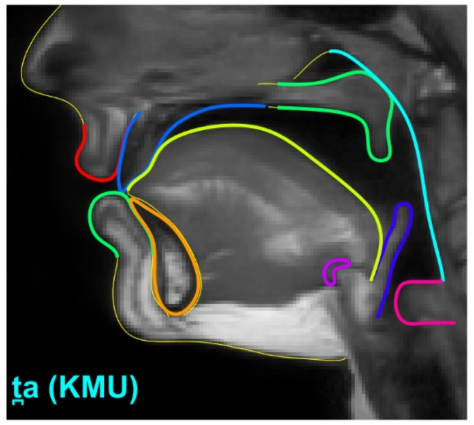
Supplementary material S2: MRI images overlaid with contours

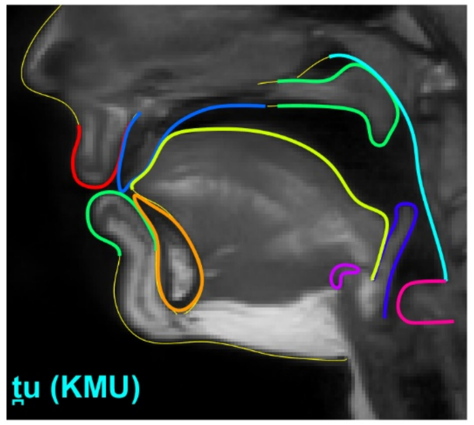
This document displays articulator contours superimposed on midsagittal MRI images (as in Figure 1 of the main text) for eight consonants (/t̪ ʈ s̪ ʂ n̪ ɳ l̪ ɭ/) in five vowel contexts (/i e a o u/), separately by speaker. Resampled contours are indicated by different colours, in a clockwise rotation along the vocal tract walls: upper lip, palate, velum, naso-oropharyngeal wall, laryngeal articulator, epiglottis, hyoid bone, tongue, jaw, and lower lip. The original contours are displayed in thin yellow lines. See Section 2.4 of the main text for further details.

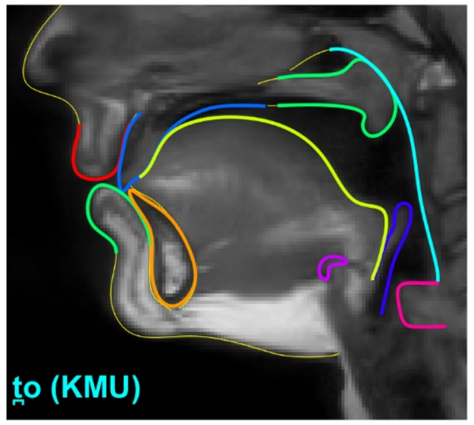
Speaker KMU

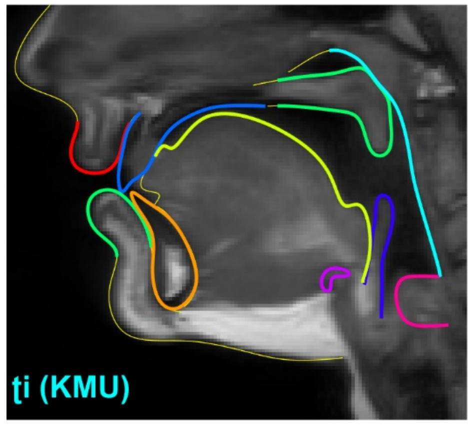


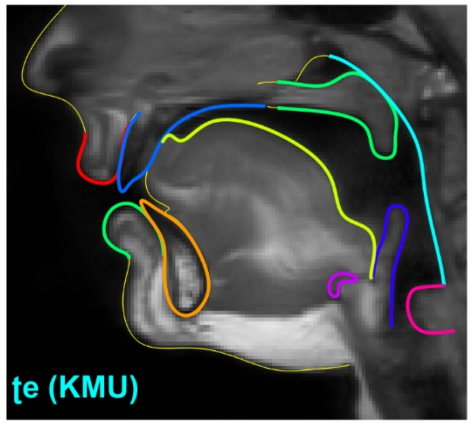


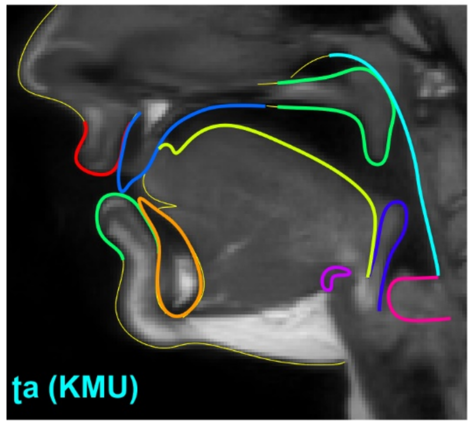


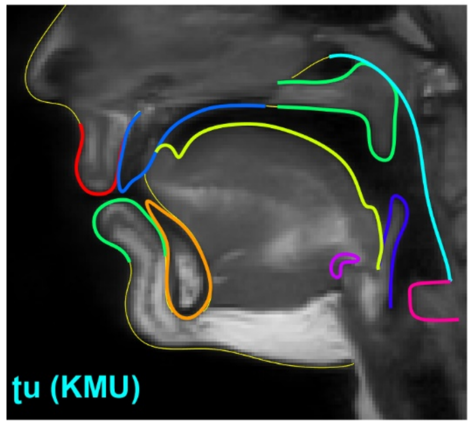


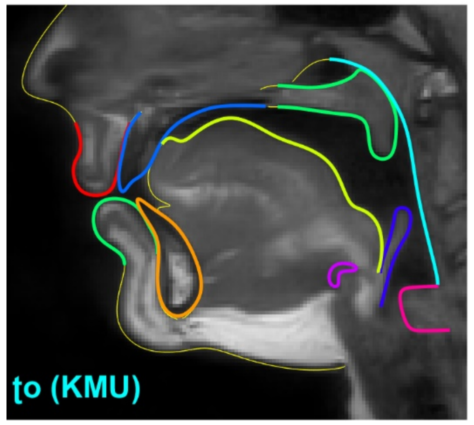


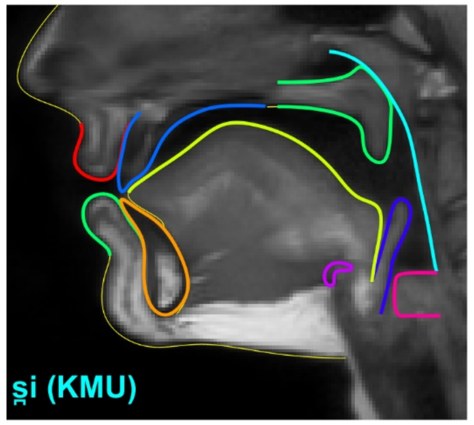


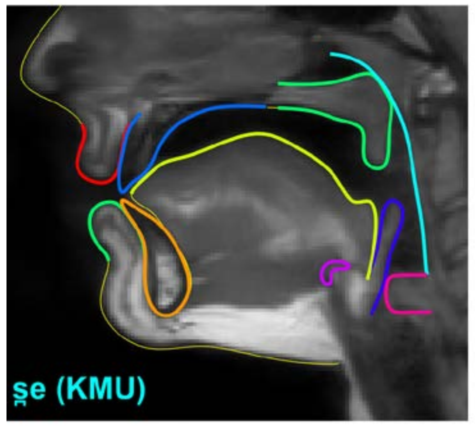


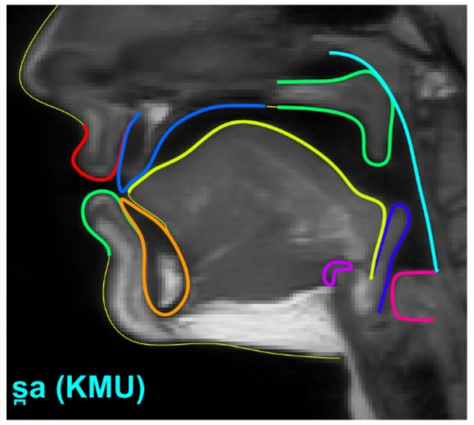


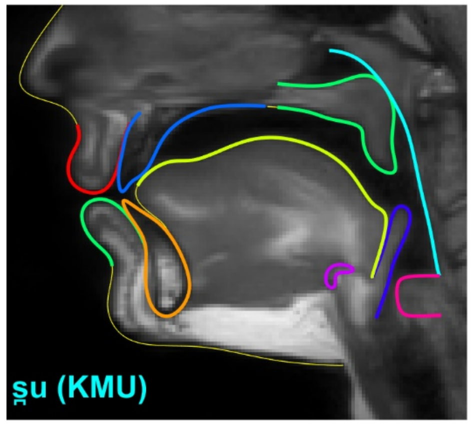


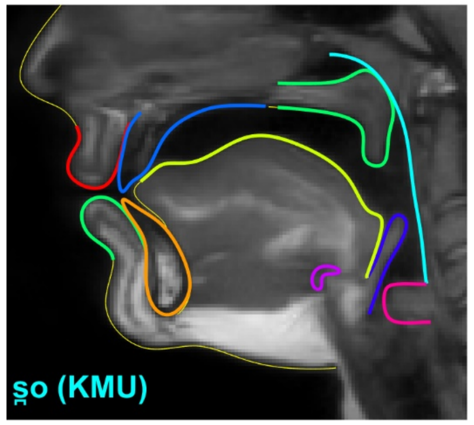


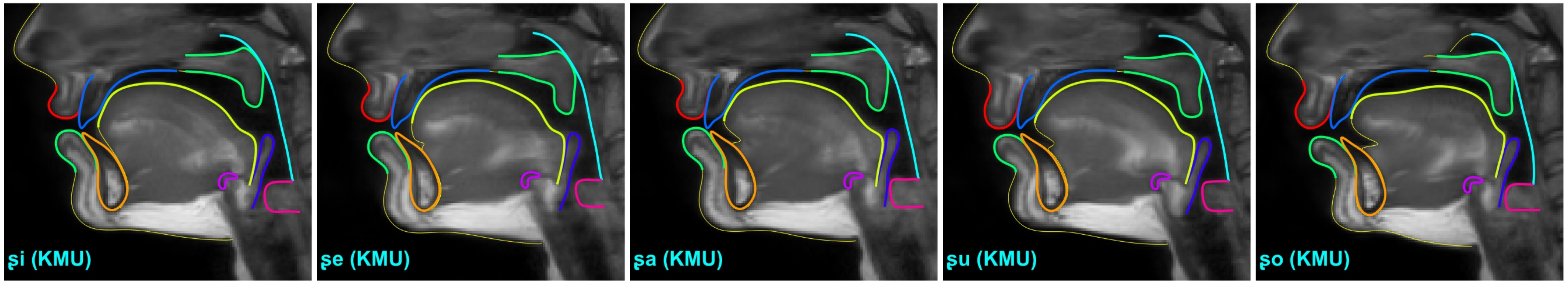








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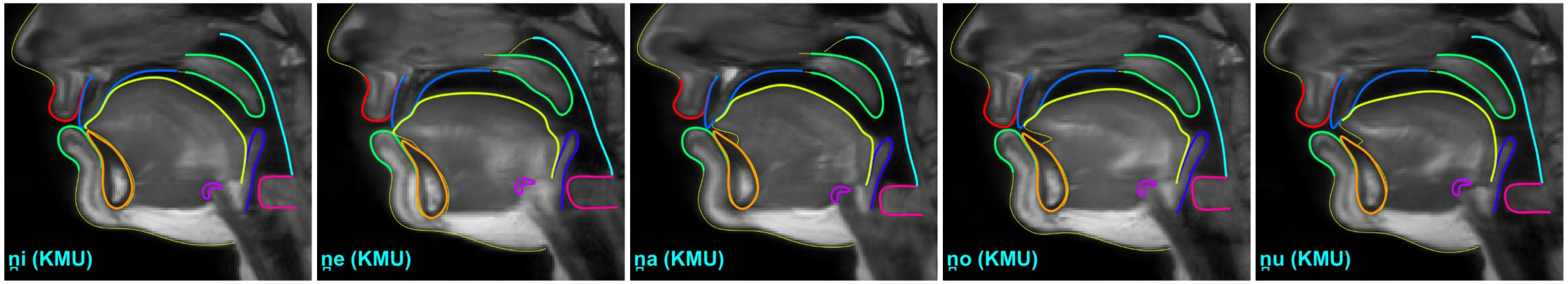
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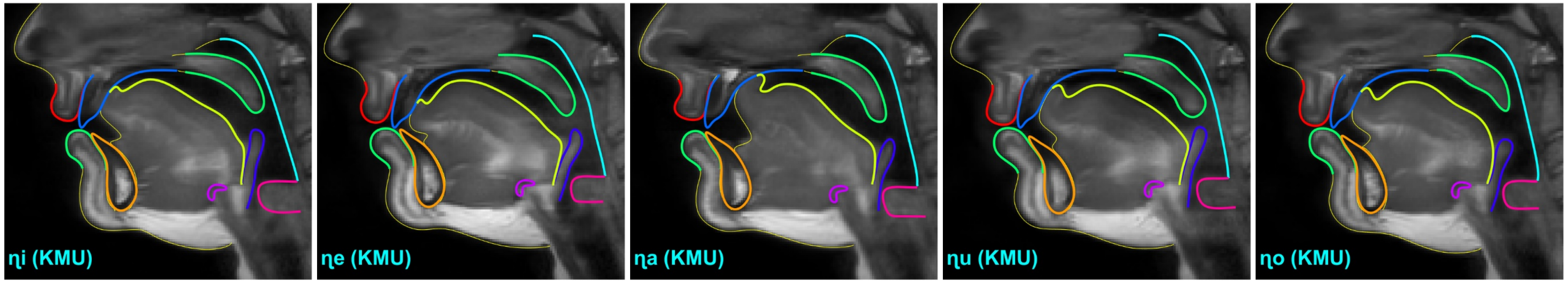
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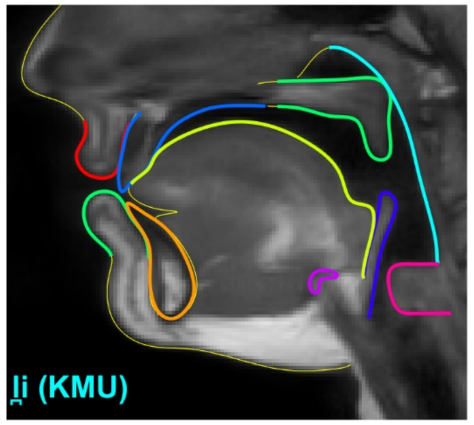
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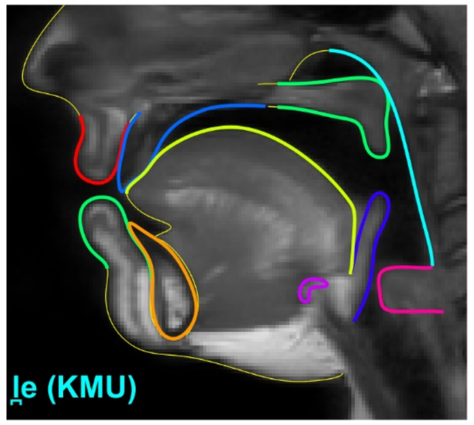
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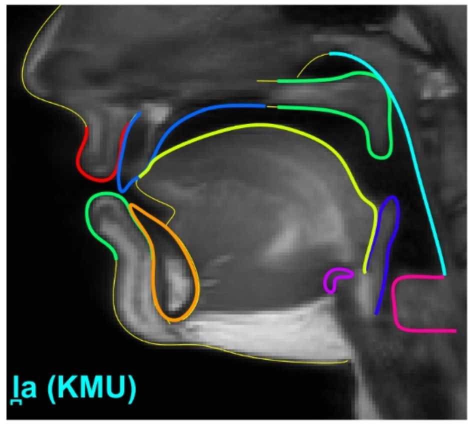
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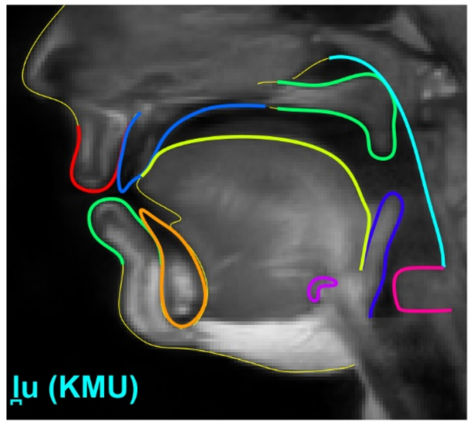
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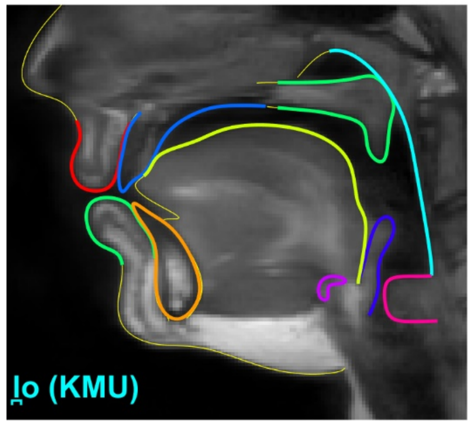
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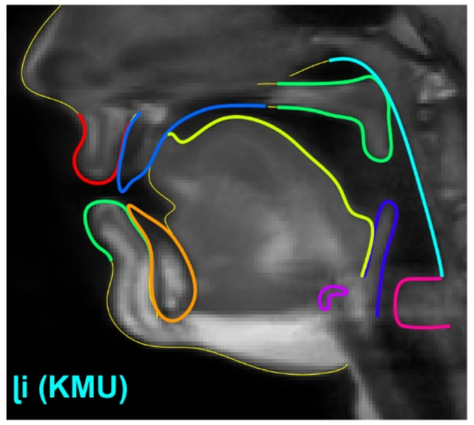
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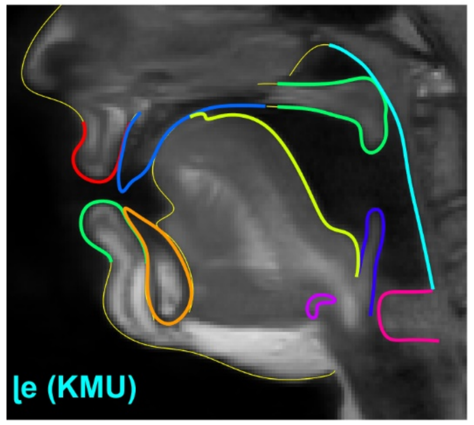
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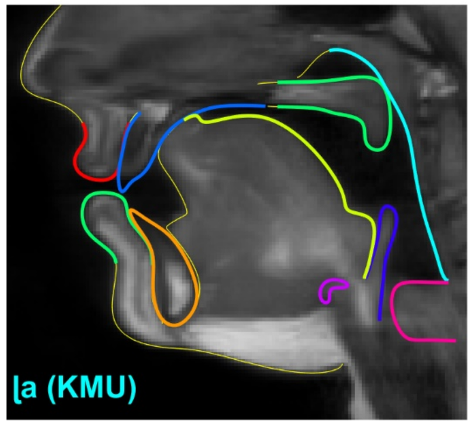
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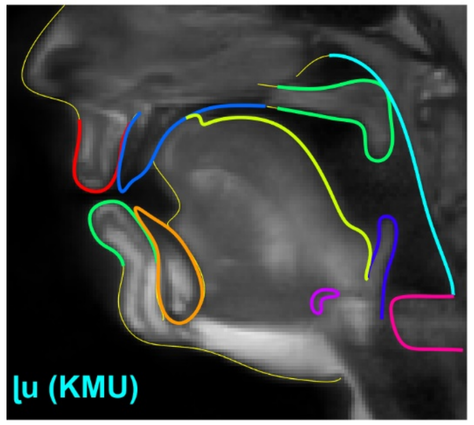
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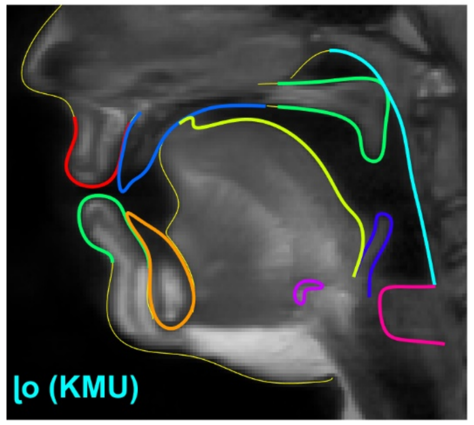
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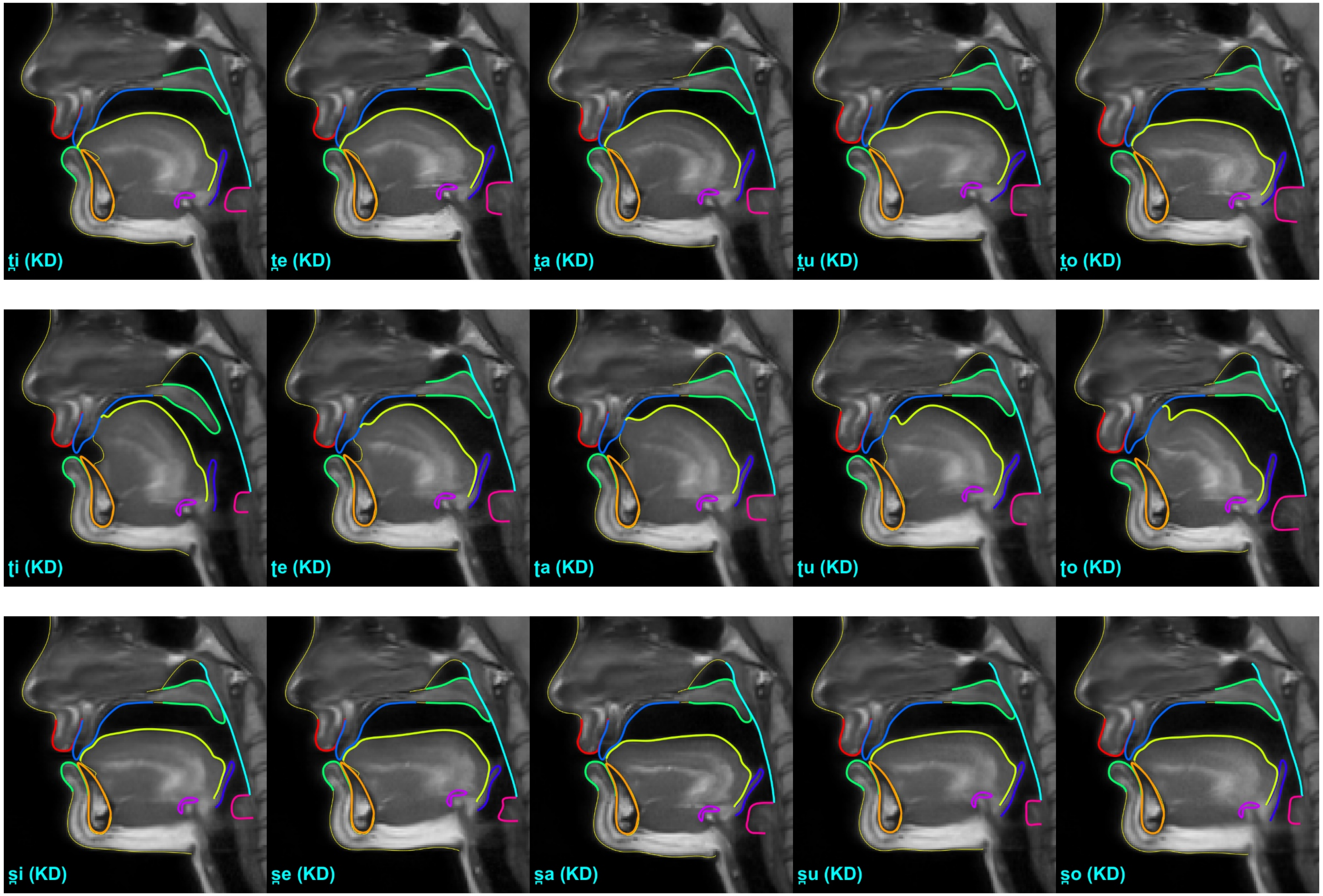
Speaker KD



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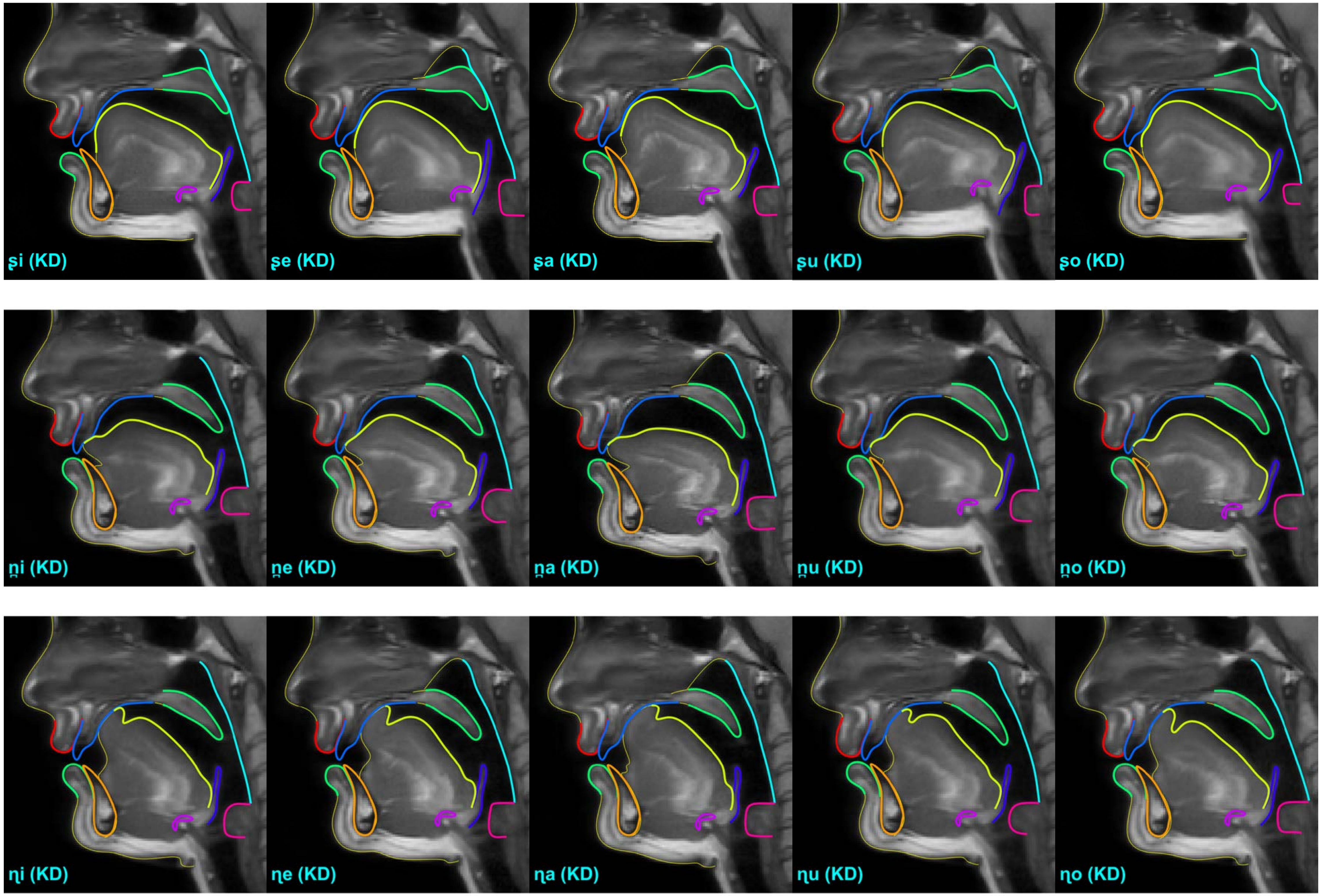

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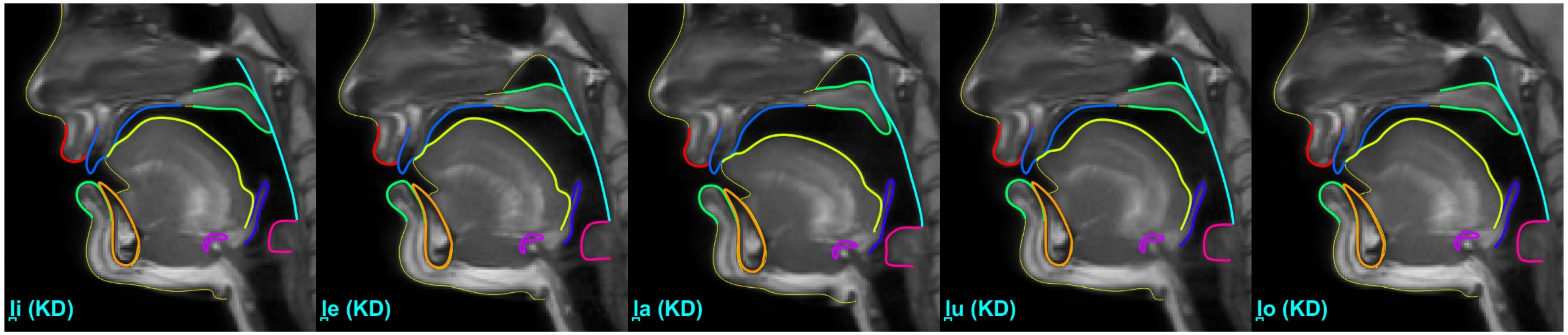
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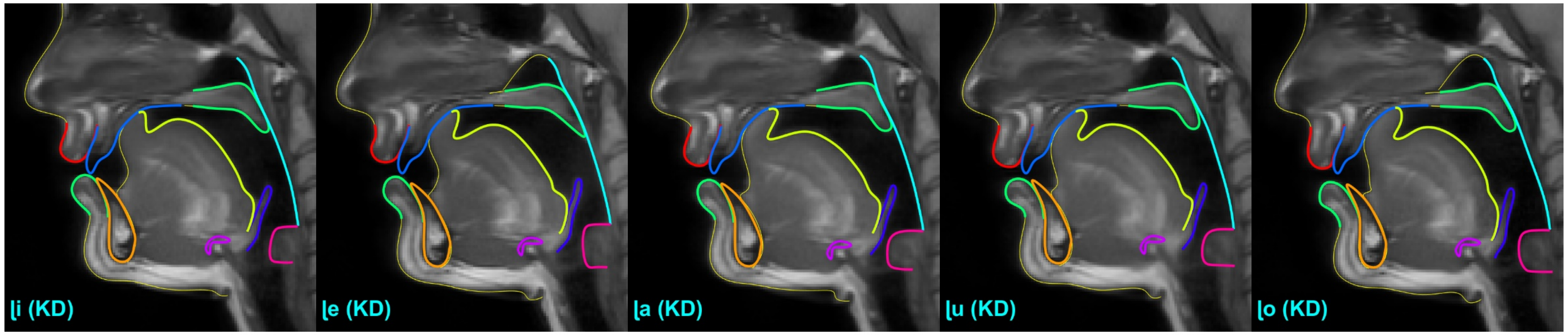
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Supplementary material S3: Tongue Constriction location plots

The figures in this document constitute a complement to Figure 3 of the main article. They display articulatory contours and tongue tip constriction values for eight consonants (/t̪ ʈ s̪ ʂ n̪ ɳ l̪ ɭ/) in five vowel contexts (/i e a o u/), separately by speaker. The parts of tongue and hard palate represented by thicker lines correspond to the tongue constriction defined in more details in section 2.5 of the main article; as well the angle of the straight line that crosses the constriction in its middle constitutes a measure the constriction location.

Tongue tip constriction geometry determination

First, we describe in details the approach to determine the TTC geometry. The determination of the constriction location along the vocal tract on real contour data is prone to noise, as small details in contours may induce the location of the minimum to vary in an irrelevant or unrealistic way. As well, determining useful constriction lengths and cross-dimensional distances may be prone to errors. We have therefore adopted a method based on a low frequency approximation of the constriction tube impedance *LFI*[1] (*cf.* Fant (1960), p. 80) to smooth out acoustically irrelevant details. First, we divided the vocal tract into a chain of quadrilaterals hooked on points which sample both inner and outer contours (see Figure 1): their lengths, computed along the VT midline of the midpoints (see Figure 2) and transverse distances constitute a sampling of the midsagittal function. Then, we considered the region with a cross-dimensional distance below a given threshold (0.5 cm)[2] (see Figure 3 for the midsagittal image, and Figure 4-top for the midsagittal distance along the VT midline), and computed the LFI for each quadrilateral in this region (see Figure 4-mid): the centre of the constriction was considered as the section upstream and downstream of which the cumulated LFI are equal (Figure 5-bottom displays the cumulated LFI, the horizontal line marking the half of the total). Next, the whole constriction duct was considered as the set of all contiguous sections with an LFI below a given ratio of the maximum LFI (1/20), which provides its acoustically equivalent length. Finally, we computed the cross-dimension of the constriction duct as the cross-dimension of a uniform tube having the same length and the same cumulated LFI over all the quadrilaterals belonging to the constriction. The centre of the constriction coordinate was finally expressed as the angle of this point in reference to the centre of the vocal tract, referred to as *TTCL* (Tongue Tip Constriction Location) in the following. The results of this approach are illustrated in Figure 5, where the constriction limits are outlined by coloured contours on the inner and outer walls, and the centre of the constriction is marked by a radial line. The acoustically equivalent length will be referred to as *TTClength*, while the cross-dimension of the acoustically equivalent constriction duct will be referred to as *TTCD*.

In the figures, the top line displays *TTCL* (Loc) in °, *TTCD* (Dist) in cm, and *TTClength* (Leng) in cm.

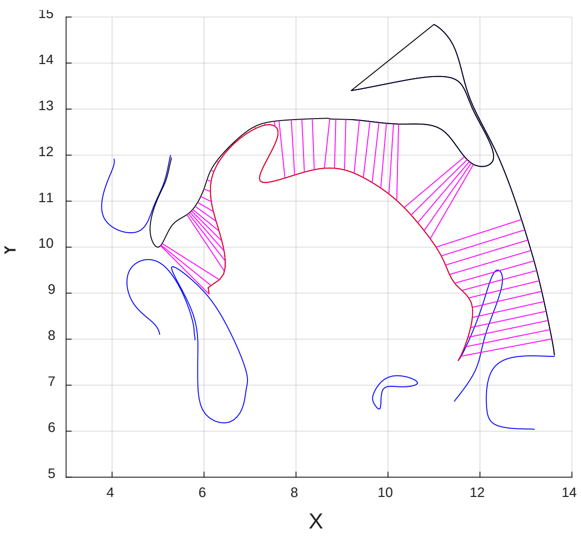


Figure 1. Articulatory contours and quadrilaterals representing the midsagittal function (for better visibility, every 10th quadrilateral only is shown).

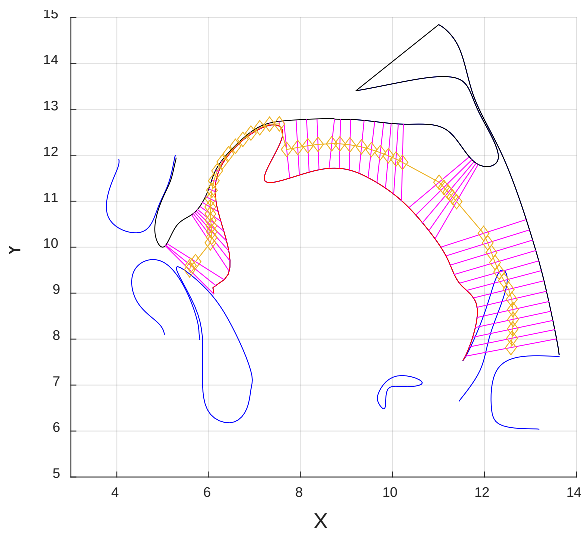


Figure 2. Same as Figure 1, with segments on the midline added.

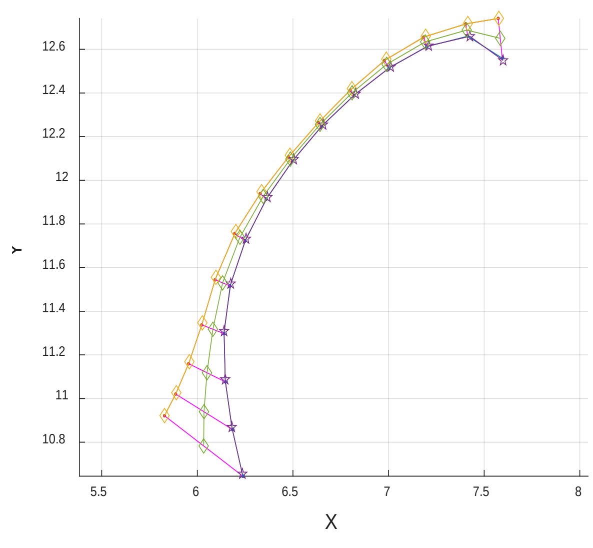


Figure 3. Zoom of Figure 2 on the constriction area.

[1] as its length divided by the square of the cross-sectional distance.

[2] Note that if more than one region was eligible, the most front one was selected, with some exceptions, in particular for velar articulation for which the back constriction was selected even though there might be tighter constriction in the front.

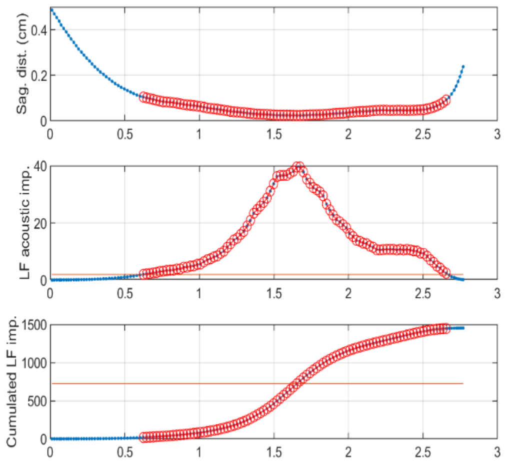


Figure 4. Top: midsagittal distance as a function de the curvilinear abscissa along the VT midline in the vicinity of the constriction (for distance below 0.5 cm). Mid: LFI along the midline (the horizontal red line is 1/20 below the maximum of LFI. Bottom: cumulated LFI along the midline (the horizontal red line is at half the total LFI).

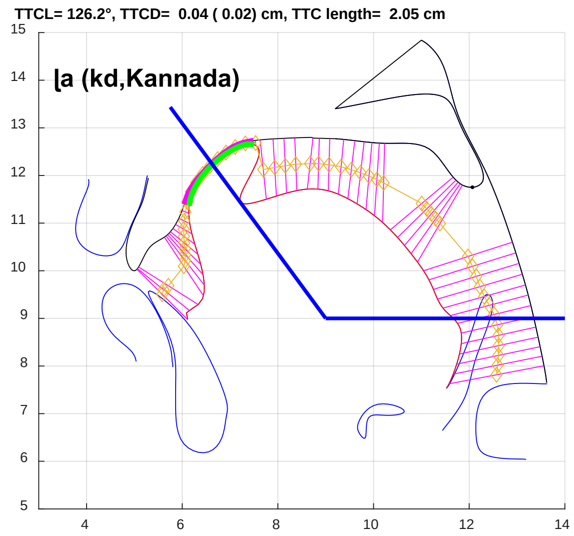
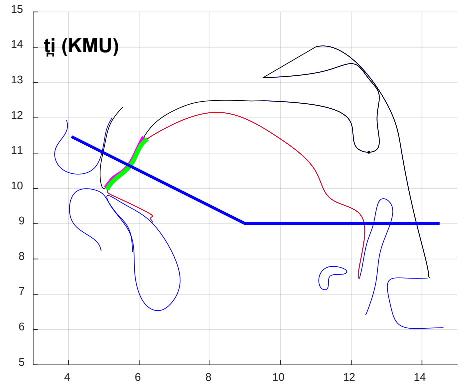


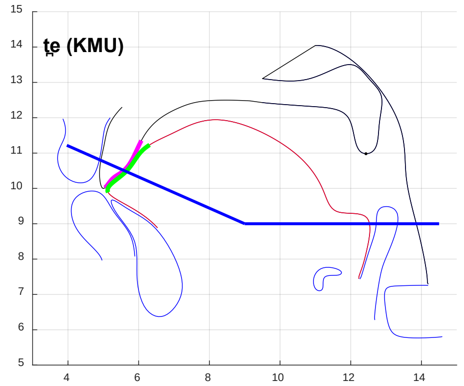
Figure 5. Same as Figure 2, with contours of the constriction in thick lines (cyan for the palate, green for the tongue) and the polar grid lines (thick blue) allowing the determination of TTCL in °.

Speaker KMU

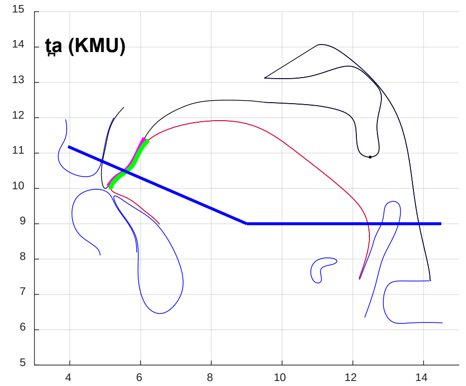
Loc 153.4°, Dist 0.04 cm, Leng 1.87 cm



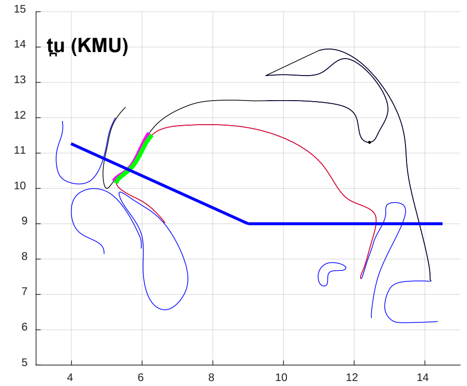
Loc 156.2°, Dist 0.08 cm, Leng 1.78 cm



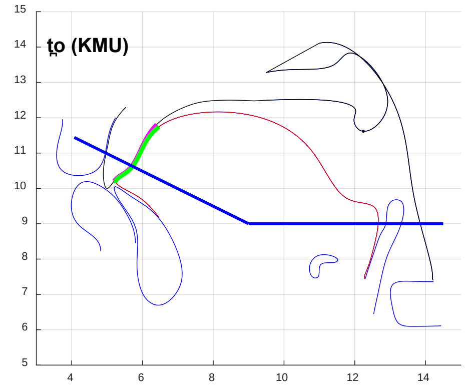
Loc 156.6°, Dist 0.05 cm, Leng 1.78 cm



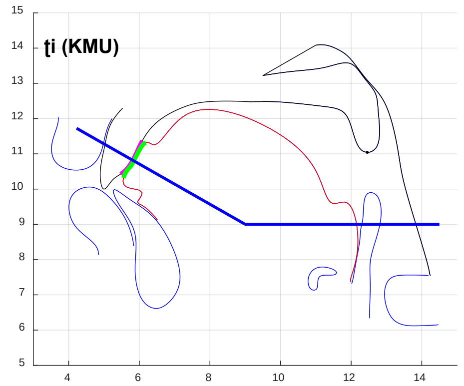
Loc 155.7°, Dist 0.04 cm, Leng 1.74 cm



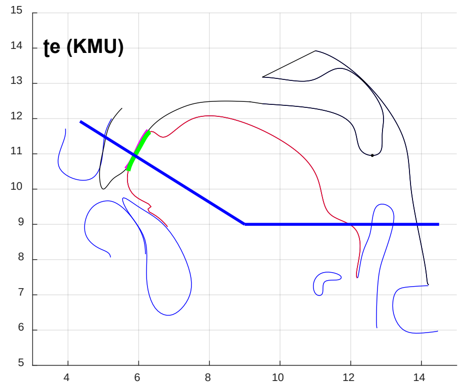
Loc 153.6°, Dist 0.03 cm, Leng 2.06 cm



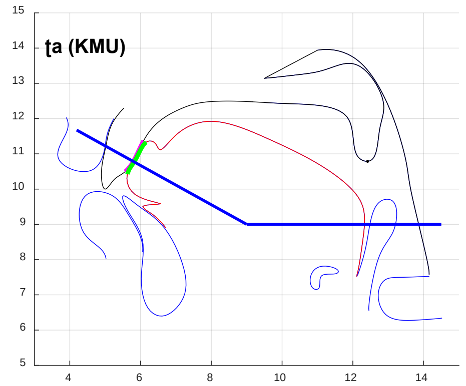
Loc 150.3°, Dist 0.04 cm, Leng 1.18 cm



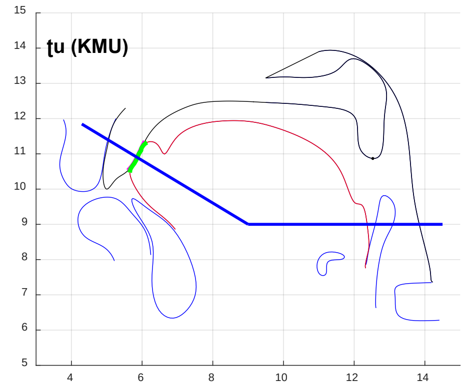
Loc 147.9°, Dist 0.03 cm, Leng 1.29 cm



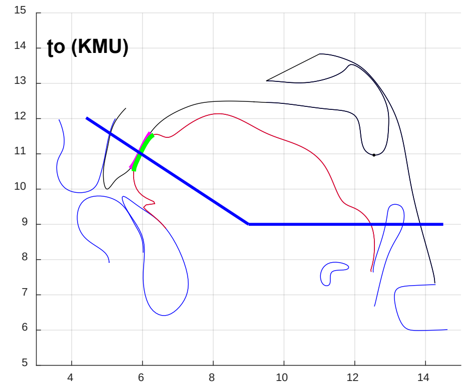
Loc 150.9°, Dist 0.03 cm, Leng 1.06 cm



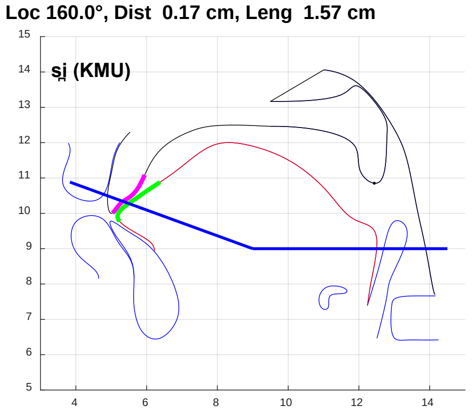
Loc 148.8°, Dist 0.02 cm, Leng 1.00 cm



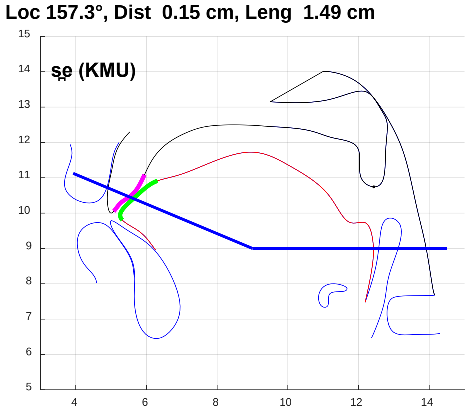
Loc 146.6°, Dist 0.04 cm, Leng 1.20 cm



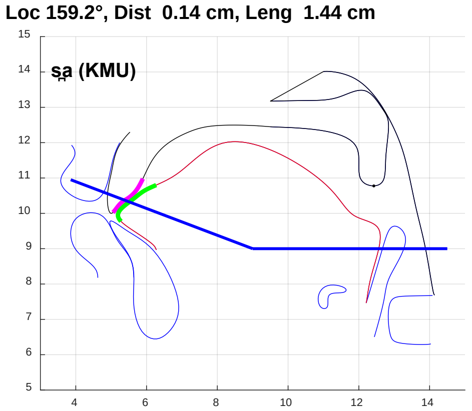
Loc 160.0°, Dist 0.17 cm, Leng 1.57 cm



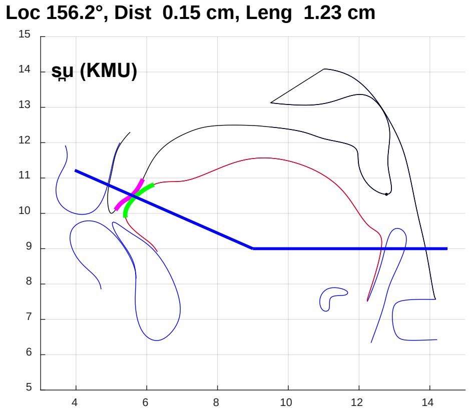
Loc 157.3°, Dist 0.15 cm, Leng 1.49 cm



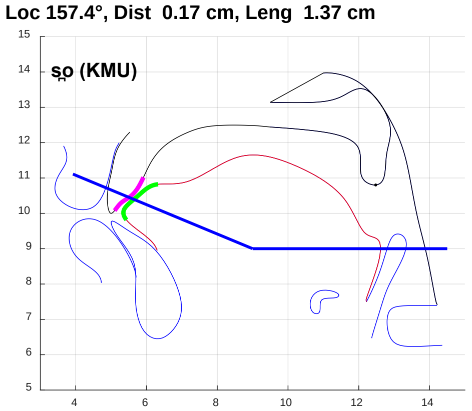
Loc 159.2°, Dist 0.14 cm, Leng 1.44 cm



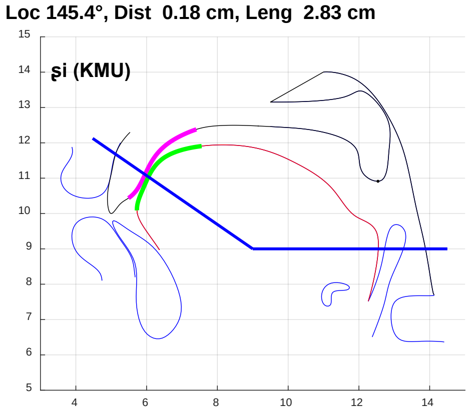
Loc 156.2°, Dist 0.15 cm, Leng 1.23 cm



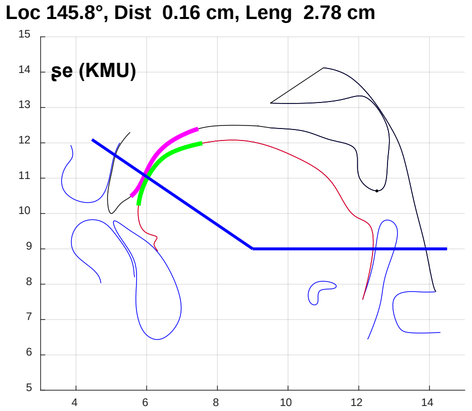
Loc 157.4°, Dist 0.17 cm, Leng 1.37 cm



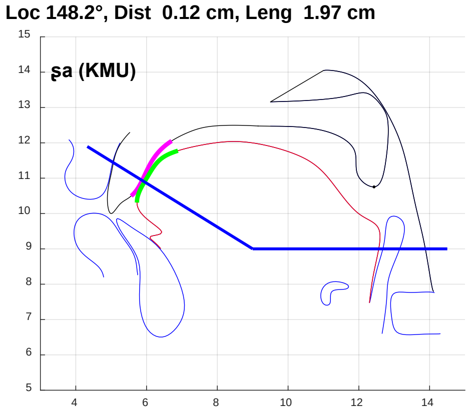
Loc 145.4°, Dist 0.18 cm, Leng 2.83 cm



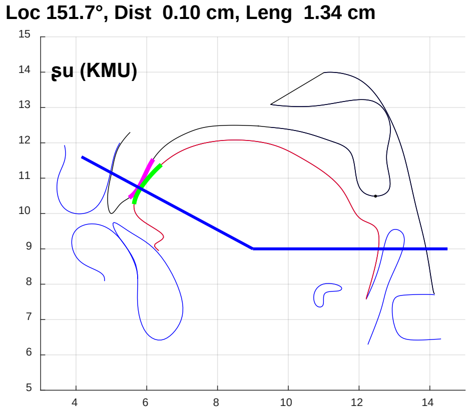
Loc 145.8°, Dist 0.16 cm, Leng 2.78 cm



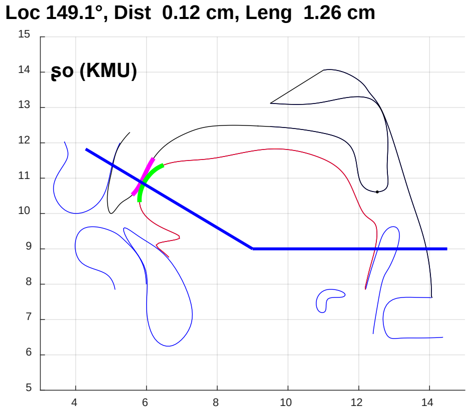
Loc 148.2°, Dist 0.12 cm, Leng 1.97 cm

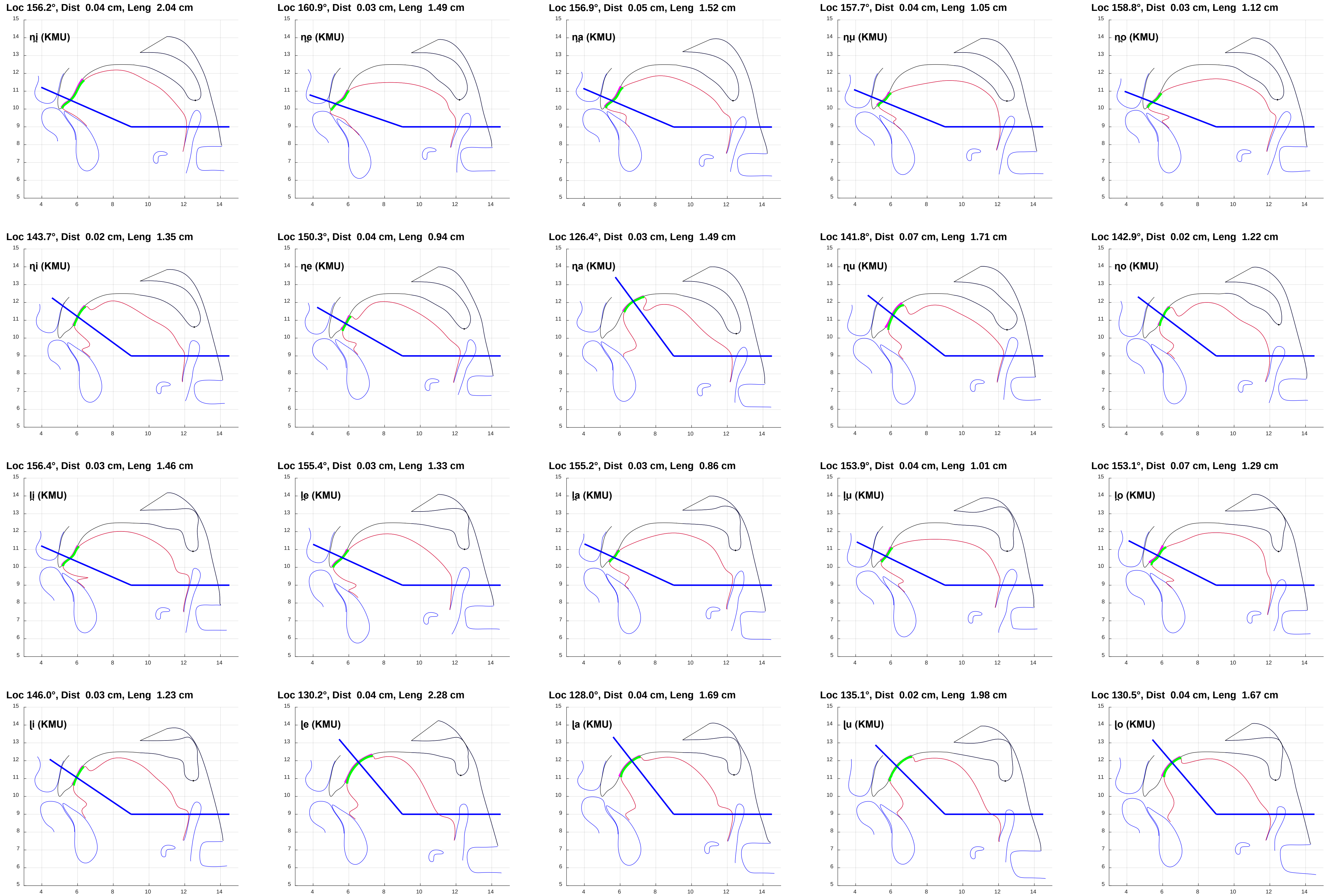


Loc 151.7°, Dist 0.10 cm, Leng 1.34 cm



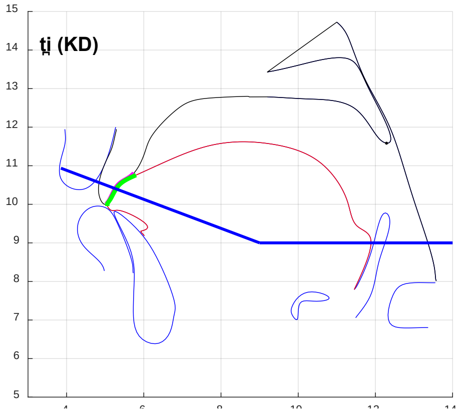
Loc 149.1°, Dist 0.12 cm, Leng 1.26 cm



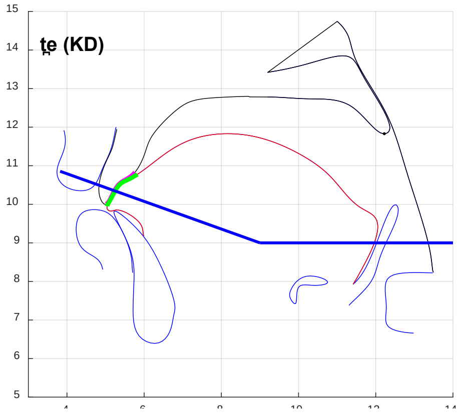

Loc 156.2°, Dist 0.04 cm, Leng 2.04 cm
ɳ̪i (KMU)
Loc 160.9°, Dist 0.03 cm, Leng 1.49 cm
ɳ̪e (KMU)
Loc 156.9°, Dist 0.05 cm, Leng 1.52 cm
ɳ̪a (KMU)
Loc 157.7°, Dist 0.04 cm, Leng 1.05 cm
ɳ̪u (KMU)
Loc 158.8°, Dist 0.03 cm, Leng 1.12 cm
ɳ̪o (KMU)
Loc 143.7°, Dist 0.02 cm, Leng 1.35 cm
ɳi (KMU)
Loc 150.3°, Dist 0.04 cm, Leng 0.94 cm
ɳe (KMU)
Loc 126.4°, Dist 0.03 cm, Leng 1.49 cm
ɳa (KMU)
Loc 141.8°, Dist 0.07 cm, Leng 1.71 cm
ɳu (KMU)
Loc 142.9°, Dist 0.02 cm, Leng 1.22 cm
ɳo (KMU)
Loc 156.4°, Dist 0.03 cm, Leng 1.46 cm
l̪i (KMU)
Loc 155.4°, Dist 0.03 cm, Leng 1.33 cm
l̪e (KMU)
Loc 155.2°, Dist 0.03 cm, Leng 0.86 cm
l̪a (KMU)
Loc 153.9°, Dist 0.04 cm, Leng 1.01 cm
l̪u (KMU)
Loc 153.1°, Dist 0.07 cm, Leng 1.29 cm
l̪o (KMU)
Loc 146.0°, Dist 0.03 cm, Leng 1.23 cm
ɭi (KMU)
Loc 130.2°, Dist 0.04 cm, Leng 2.28 cm
ɭe (KMU)
Loc 128.0°, Dist 0.04 cm, Leng 1.69 cm
ɭa (KMU)
Loc 135.1°, Dist 0.02 cm, Leng 1.98 cm
ɭu (KMU)
Loc 130.5°, Dist 0.04 cm, Leng 1.67 cm
ɭo (KMU)

Speaker KD

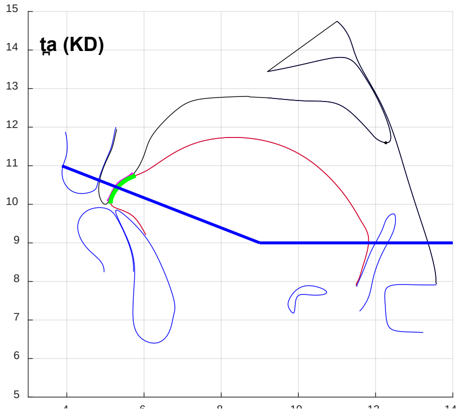
Loc 159.4°, Dist 0.02 cm, Leng 1.13 cm



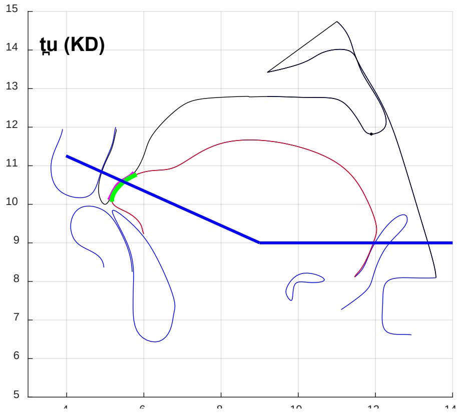
Loc 160.3°, Dist 0.02 cm, Leng 1.18 cm



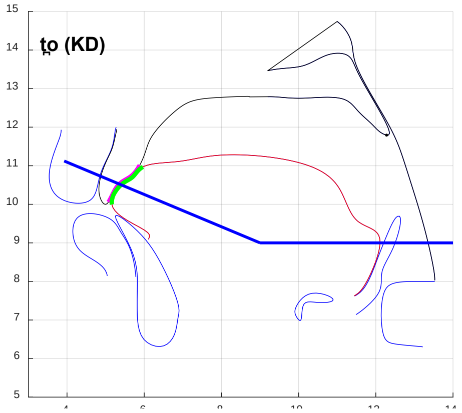
Loc 158.7°, Dist 0.02 cm, Leng 1.03 cm



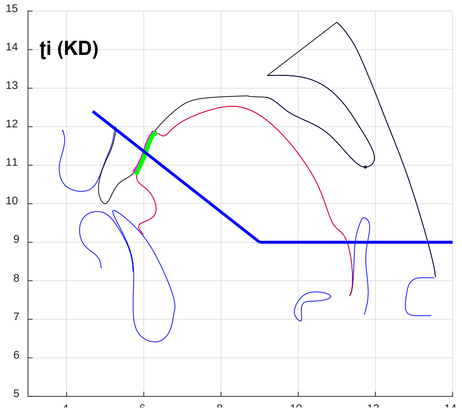
Loc 155.8°, Dist 0.03 cm, Leng 1.01 cm



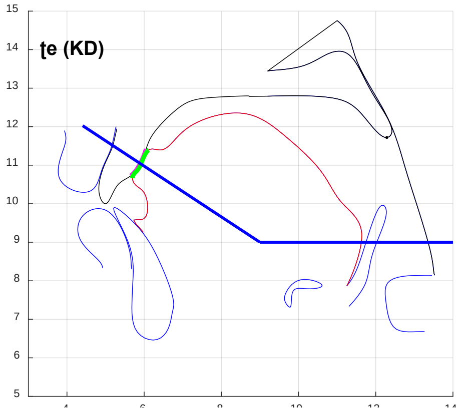
Loc 157.3°, Dist 0.04 cm, Leng 1.31 cm



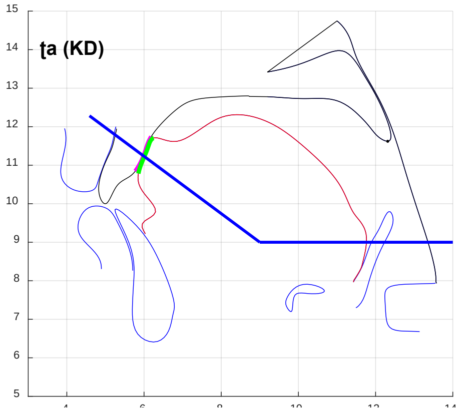
Loc 141.8°, Dist 0.03 cm, Leng 1.22 cm



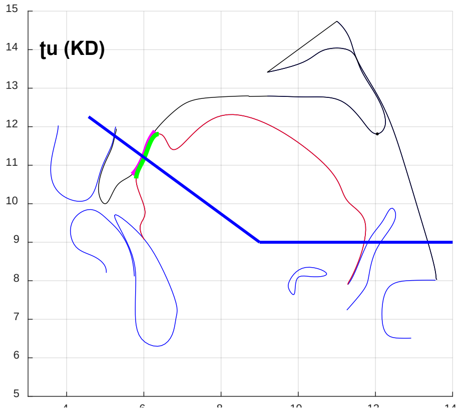
Loc 146.6°, Dist 0.02 cm, Leng 0.84 cm



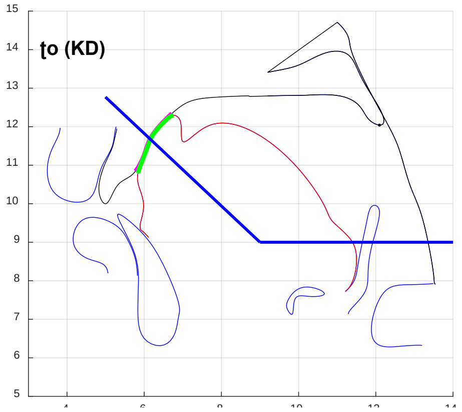
Loc 143.4°, Dist 0.03 cm, Leng 1.02 cm



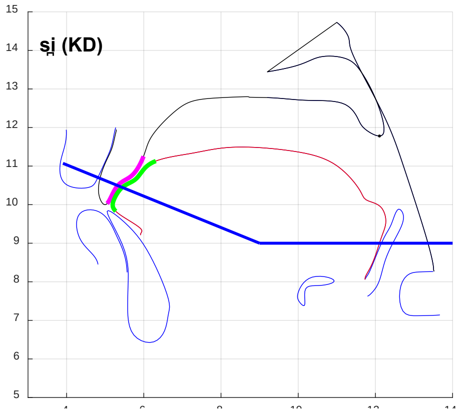
Loc 143.7°, Dist 0.05 cm, Leng 1.31 cm



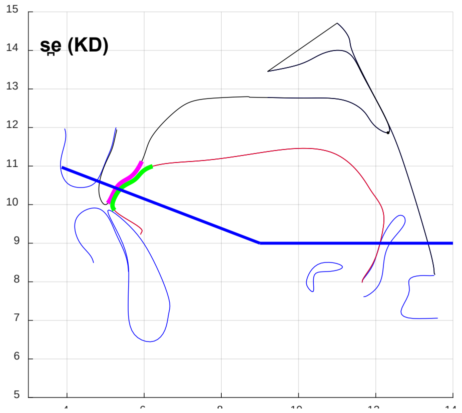
Loc 136.7°, Dist 0.02 cm, Leng 1.82 cm



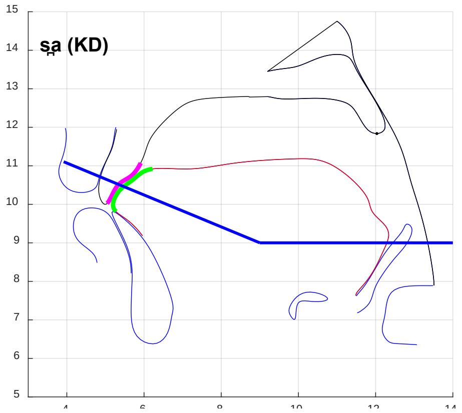
Loc 157.9°, Dist 0.13 cm, Leng 1.70 cm



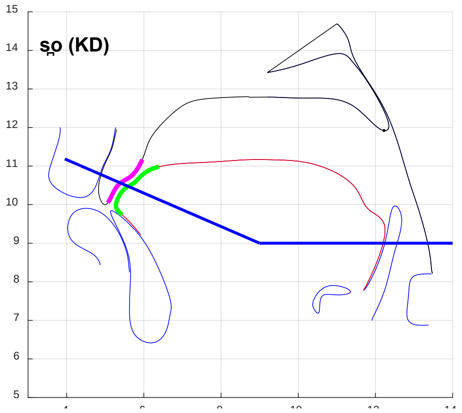
Loc 159.0°, Dist 0.11 cm, Leng 1.54 cm



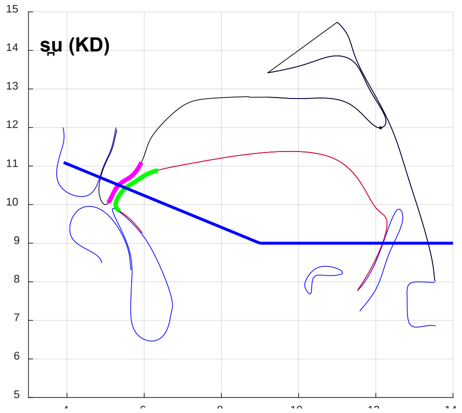
Loc 157.5°, Dist 0.12 cm, Leng 1.51 cm



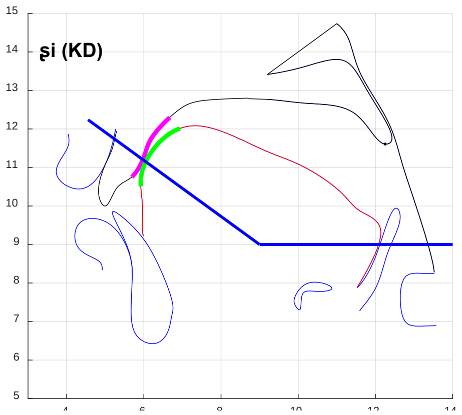
Loc 156.6°, Dist 0.20 cm, Leng 1.65 cm



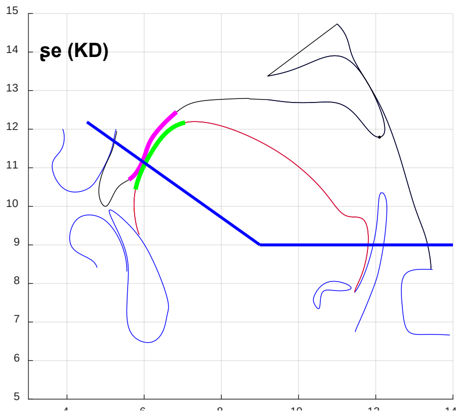
Loc 157.6°, Dist 0.19 cm, Leng 1.52 cm



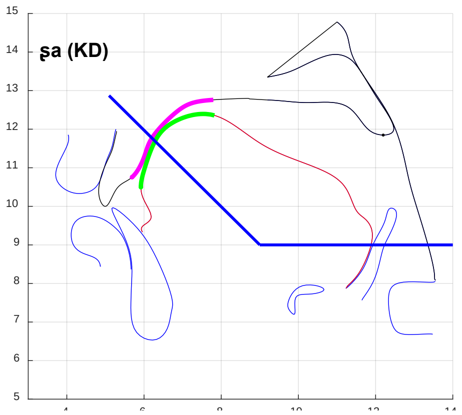
Loc 143.9°, Dist 0.15 cm, Leng 1.89 cm



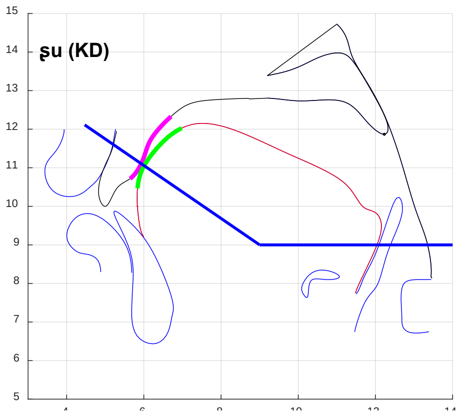
Loc 144.6°, Dist 0.14 cm, Leng 2.22 cm



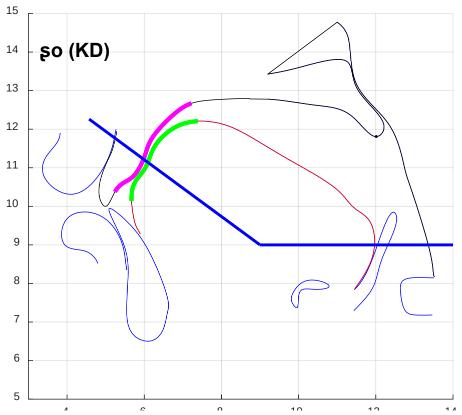
Loc 135.3°, Dist 0.14 cm, Leng 3.13 cm



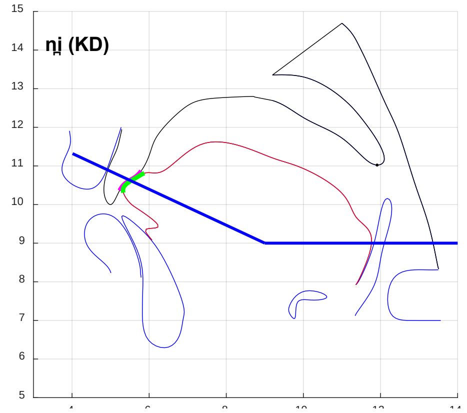
Loc 145.5°, Dist 0.16 cm, Leng 1.98 cm



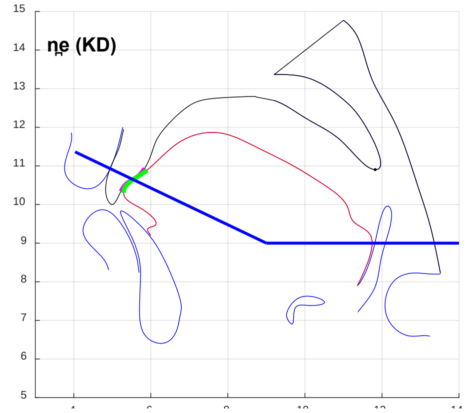
Loc 143.6°, Dist 0.18 cm, Leng 3.00 cm



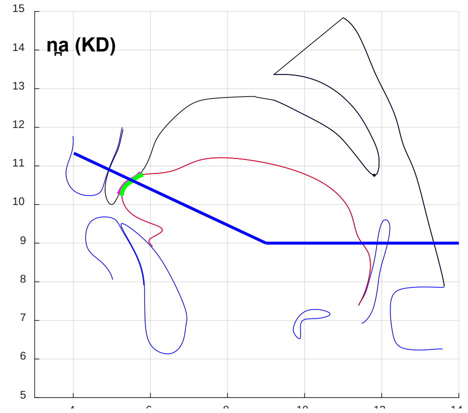
Loc 155.1°, Dist 0.04 cm, Leng 0.79 cm



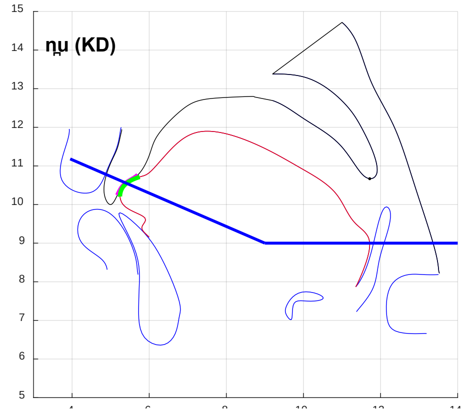
Loc 154.6°, Dist 0.03 cm, Leng 0.89 cm



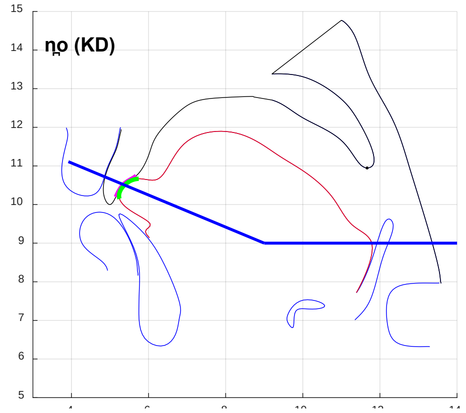
Loc 154.9°, Dist 0.03 cm, Leng 0.82 cm



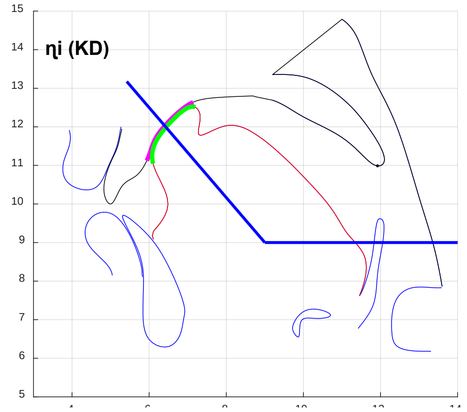
Loc 156.6°, Dist 0.03 cm, Leng 0.78 cm



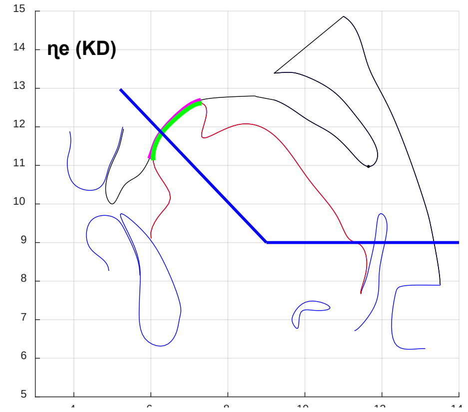
Loc 157.4°, Dist 0.04 cm, Leng 0.81 cm



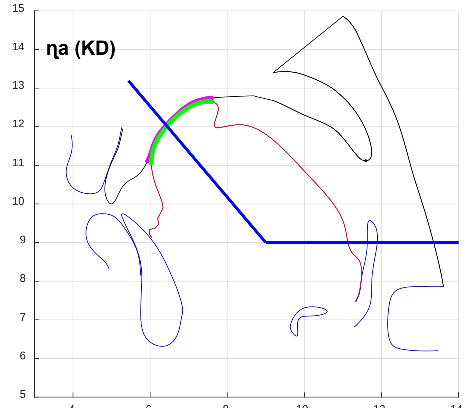
Loc 130.6°, Dist 0.05 cm, Leng 2.00 cm



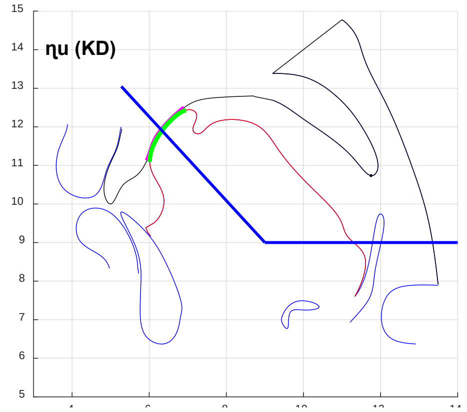
Loc 133.7°, Dist 0.04 cm, Leng 2.10 cm



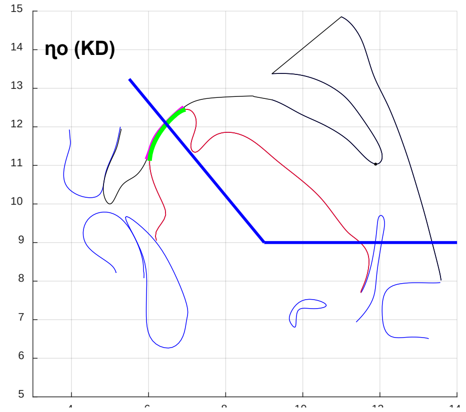
Loc 130.4°, Dist 0.04 cm, Leng 2.59 cm



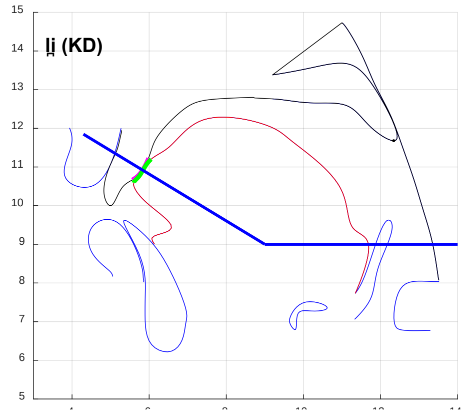
Loc 132.6°, Dist 0.03 cm, Leng 1.73 cm



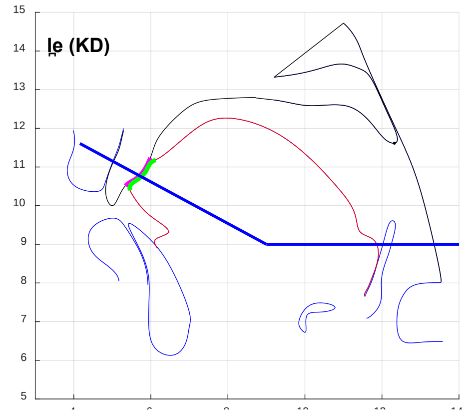
Loc 129.6°, Dist 0.03 cm, Leng 1.71 cm



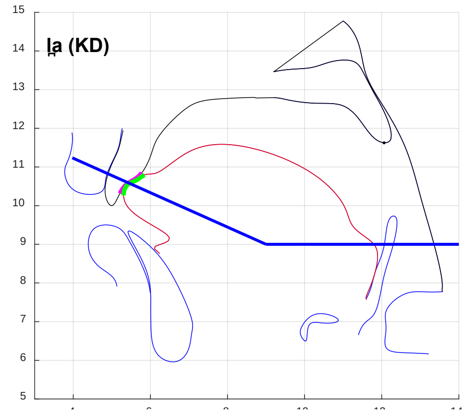
Loc 148.8°, Dist 0.03 cm, Leng 0.75 cm



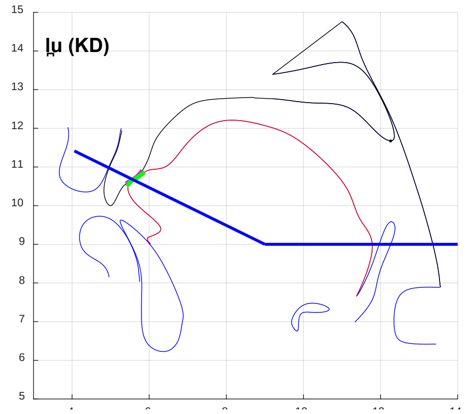
Loc 151.7°, Dist 0.05 cm, Leng 1.04 cm



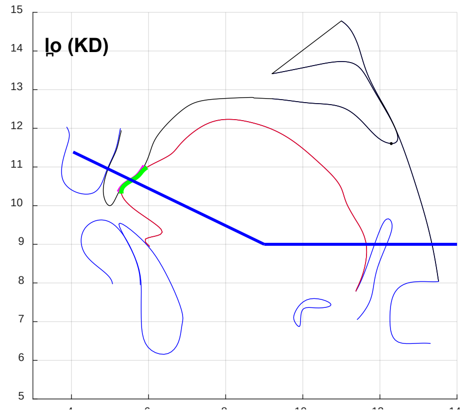
Loc 156.0°, Dist 0.04 cm, Leng 0.82 cm



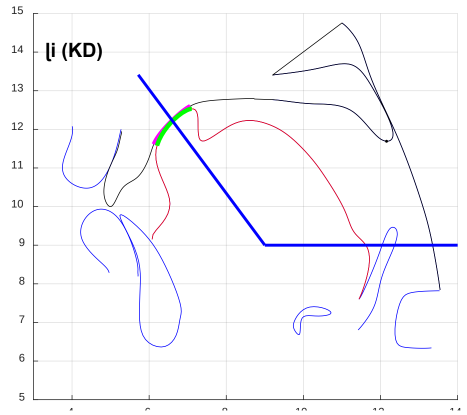
Loc 154.0°, Dist 0.03 cm, Leng 0.58 cm



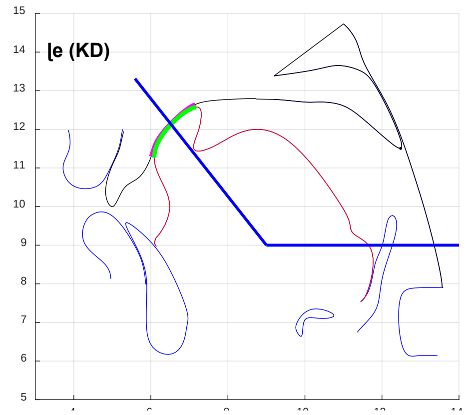
Loc 154.3°, Dist 0.02 cm, Leng 0.99 cm



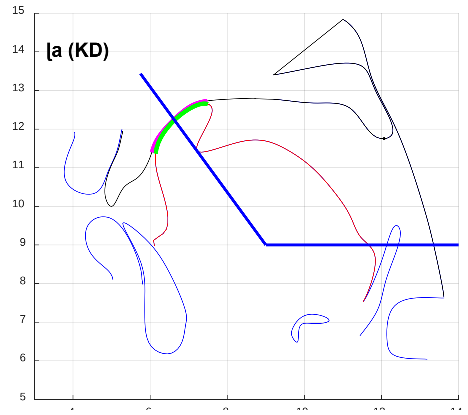
Loc 126.7°, Dist 0.03 cm, Leng 1.39 cm



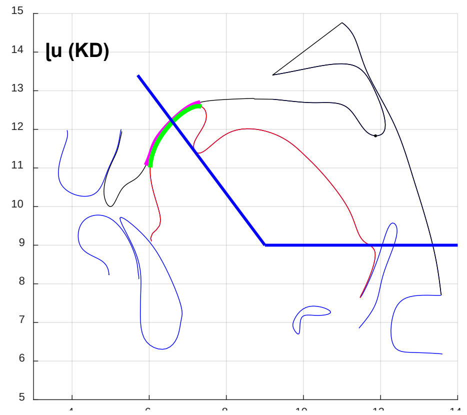
Loc 128.3°, Dist 0.03 cm, Leng 1.83 cm



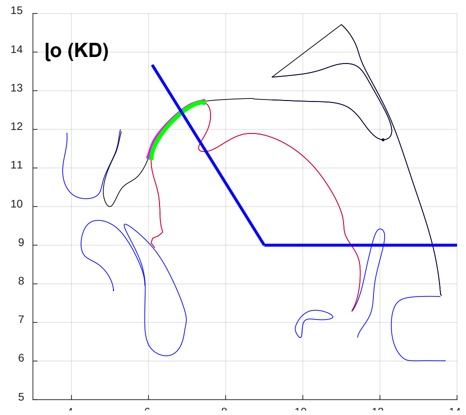
Loc 126.2°, Dist 0.04 cm, Leng 2.05 cm



Loc 126.9°, Dist 0.05 cm, Leng 2.25 cm



Loc 121.9°, Dist 0.03 cm, Leng 2.22 cm



Kochetov et al. (submitted) An MRI-based articulatory analysis of the Kannada dental-retroflex contrast. The Journal of the International Phonetic Association.

Supplementary material S4: Results of LMER models and `rpart` classification matrices

This document provides formulae and outputs (likelihood ratio tests) of Linear Mixed Effects models and pairwise tests described in the sections 3.1 and 3.2 of the main text. It also includes confusion matrices for `rpart` classification from the same sections. The data used in the analysis are provided in the supplementary file S4. The R packages used are `ggplot2`, `lme4`, `phia`, `lmerTest`, and `rpart` (see the main text for references).

Analyses by place

Sample formulae:

- lmer(TTF ~ Place + (1|Manner) + (1|V), kn_kmu) -> fit
- Anova(fit)

Results: Speaker KMU

Table 1. LMER model comparisons for the analysis of place (dental and retroflex) based on all constriction parameters and articulatory components for the full set and the set without fricatives produced by speaker KMU (Analysis of Deviance Table, Type II Wald χ^2 tests, significance levels: '' <.001, '**' <.01, '*' <.05).***

	Full set				Set without fricatives			
	Chisq	Df	Pr(>Chisq)		Chisq	Df	Pr(>Chisq)	
TTCL	69.021	1	< 2.20E-16	***	49.639	1	1.85E-12	***
TTClength	0.4707	1	0.4927		0.2843	1	0.5939	
TTCD	3.9032	1	0.04819	*	2.4	1	0.1213	
TTF	127.54	1	< 2.20E-16	***	92.058	1	< 2.2e-16	***
TTH	0.291	1	0.5896		11.1	1	0.000863	***
TB	37.274	1	1.03E-09	***	97.543	1	< 2.2e-16	***
TD	4.7912	1	0.02861	*	12.347	1	0.000442	***
HYH	0.7296	1	0.393		0.9699	1	0.3247	
JA	4.0184	1	0.04501	*	1.6997	1	0.1923	
JH	0.0135	1	0.9075		4.00E-04	1	0.9837	
VH	1.988	1	0.1585		0.7288	1	0.3933	
LAH	3.1354	1	0.07661		4.7948	1	0.02855	*

Results: Speaker KD

Table 2. LMER model comparisons for the analysis of place (dental and retroflex) based on all constriction parameters and articulatory components for the full set and the set without fricatives produced by speaker KD (Analysis of Deviance Table, Type II Wald χ2 tests, significance levels: '' <.001, '**' <.01, '*' <.05).***

	Full set				Set without fricatives			
	Chisq	Df	Pr(>Chisq)		Chisq	Df	Pr(>Chisq)	
TTCL	311.32	1	< 2.2e-16	***	319.28	1	< 2.2e-16	***
TTClength	48.355	1	3.56E-12	***	35.372	1	2.72E-09	***
TTCD	0.4453	1	0.5046		1	1	0.3173	
TTF	221.07	1	< 2.2e-16	***	256.28	1	< 2.2e-16	***
TTH	0.0937	1	0.7595		2.8845	1	0.08943	
TB	6.9171	1	0.008537	**	49.414	1	2.07E-12	***
TD	4.7376	1	0.02951	*	0.8816	1	0.3478	
HYH	3.6427	1	0.05632		3.0904	1	0.07876	
JA	0.6106	1	0.4345		0.1425	1	0.7058	
JH	2.9289	1	0.08701		1.4771	1	0.2242	
VH	0.263	1	0.6081		0.046	1	0.8302	
LAH	5.7811	1	0.0162	*	9.8878	1	0.001664	**

Table 3. Confusion matrices for consonant classification by Place based on constriction parameters for (a) the full dataset and (b) without fricatives, separately by speaker; dent =dental, ret = retroflex.

	C	*Speaker KMU*			*Speaker KD*		
		dent	*ret*	*correct*	*dent*	*ret*	*correct*
a.	t̪	5	0	100%	5	0	100%
	ʈ	0	5	100%	0	5	100%
	s̪	5	0	100%	5	0	100%
	ʂ	0	5	100%	0	5	100%
	n̪	5	0	100%	5	0	100%
	ɳ	0	5	100%	0	5	100%
	l̪	5	0	100%	5	0	100%
	ɭ	0	5	100%	0	5	100%
	Mean			*100%*			*100%*
b.	t̪	5	0	100%	5	0	100%
	ʈ	0	5	100%	0	5	100%
	n̪	5	0	100%	5	0	100%
	ɳ	0	5	100%	0	5	100%
	l̪	5	0	100%	5	0	100%
	ɭ	0	5	100%	0	5	100%
	Mean			*100%*			*100%*

Table 4. rpart confusion matrices for consonant classification by Place based on articulatory components for (a) the full dataset and (b) without fricatives, separately by speaker; dent =dental, ret = retroflex.

	C	KMU			KD		
		dent	ret	correct	dent	ret	correct
a.	t̪	4	1	80%	5	0	100%
	ʈ	0	5	100%	0	5	100%
	s̪	5	0	100%	3	2	60%
	ʂ	1	4	80%	0	5	100%
	n̪	4	1	80%	5	0	100%
	ɳ	0	5	100%	0	5	100%
	l̪	3	2	60%	5	0	100%
	ɭ	0	5	100%	0	5	100%
	Mean			*88%*			*95%*
b.	t̪	5	0	100%	5	0	100%
	ʈ	1	4	80%	0	5	100%
	n̪	5	0	100%	0	5	100%
	ɳ	0	5	100%	5	0	100%
	l̪	5	0	100%	5	0	100%
	ɭ	0	5	100%	0	5	100%
	Mean			*97%*			*100%*

Analyses by manner

Sample formulae:

- lmer(TTCL ~ Manner + (1|Place) + (1|V), kn_kmu) -> fit
- Anova(fit)
- testInteractions(fit, pairwise="Manner", adjustment="bonferroni")

Results: Speaker KMU

Table 5. LMER model comparisons for the analysis of manner (stops, fricatives, nasals, and laterals) based on all constriction parameters and articulatory components for the full set and the set without fricatives produced by speaker KMU (Analysis of Deviance Table, Type II Wald χ2 tests, significance levels: '' <.001, '**' <.01, '*' <.05).***

	Chisq	Df		Pr(>Chisq)	
TTCL	16.864	3		0.000754	***
TTClength	3.0265	3		0.3876	
TTCD	282.39	3	<	2.20E-16	***
TTF	40.508	3		8.32E-09	***
TTH	3.2158	3		0.3595	
TB	7.0945	3		0.06895	
TD	15.02	3		0.0018	**

HYH	163.13	3	<	2.20E-16	***
JA	24.284	3		2.18E-05	***
JH	38.282	3		2.46E-08	***
VH	278.76	3	<	2.20E-16	***
LAH	32.376	3		4.36E-07	***

Table 6. Results of pairwise comparisons by manner (stops, fricatives, nasals, and laterals) based on all constriction parameters and articulatory components for speaker KMU ('' <.001, '**' <.01, '*' <.05).***

		Value	Df	Chisq	Pr(>Chisq)	
TTCL	stop-fric	-1.03	1	0.2001	1	
	stop-nas	2.44	1	1.1232	1	
	stop-lat	7.62	1	10.9543	0.005603	**
	fric-nas	3.47	1	2.2716	0.790578	
	fric-lat	8.65	1	14.1159	0.001031	**
	nas-lat	5.18	1	5.0621	0.146724	
TTCD	stop-fric	-0.106	1	181.2258	<2e-16	***
	stop-nas	0.003	1	0.1452	1	
	stop-lat	0.003	1	0.1452	1	
	fric-nas	0.109	1	191.629	<2e-16	***
	fric-lat	0.109	1	191.629	<2e-16	***
	nas-lat	0	1	0	1	
TTF	stop-fric	-0.75	1	13.5843	0.001369	**
	stop-nas	0.1	1	0.2415	1	
	stop-lat	0.52	1	6.5301	0.063638	
	fric-nas	0.85	1	17.4482	0.000177	***
	fric-lat	1.27	1	38.9512	2.61E-09	***
	nas-lat	0.42	1	4.26	0.234116	
TD	stop-fric	-0.92	1	11.4945	0.004188	**
	stop-nas	-0.09	1	0.11	1	
	stop-lat	-0.11	1	0.1643	1	
	fric-nas	0.83	1	9.3555	0.013339	*
	fric-lat	0.81	1	8.9101	0.017016	*
	nas-lat	-0.02	1	0.0054	1	
HYH	stop-fric	-0.11	1	0.3091	1	
	stop-nas	-1.93	1	95.1671	< 2.2e-16	***
	stop-lat	-1.74	1	77.3519	< 2.2e-16	***
	fric-nas	-1.82	1	84.6282	< 2.2e-16	***
	fric-lat	-1.63	1	67.8809	1.04E-15	***
	nas-lat	0.19	1	0.9223	1	
JA	stop-fric	-1.78	1	23.0963	9.25E-06	***
	stop-nas	-0.55	1	2.2051	0.825332	
	stop-lat	-0.7	1	3.5719	0.352592	
	fric-nas	1.23	1	11.0284	0.005384	**

	fric-lat	1.08	1	8.5026	0.021279	*
	nas-lat	-0.15	1	0.164	1	
JH	stop-fric	0.39	1	1.1773	1	
	stop-nas	0.63	1	3.0721	0.47787	
	stop-lat	2.08	1	33.4877	4.30E-08	***
	fric-nas	0.24	1	0.4458	1	
	fric-lat	1.69	1	22.1071	1.55E-05	***
	nas-lat	1.45	1	16.274	0.000329	***
VH	stop-fric	0.71	1	22.2703	1.42E-05	***
	stop-nas	2.34	1	241.9034	< 2.2e-16	***
	stop-lat	0.41	1	7.4264	0.03856	*
	fric-nas	1.63	1	117.3777	< 2.2e-16	***
	fric-lat	-0.3	1	3.9761	0.27691	
	nas-lat	-1.93	1	164.5602	< 2.2e-16	***
LAH	stop-fric	-1.29	1	15.5192	0.00049	***
	stop-nas	-1.62	1	24.4748	4.52E-06	***
	stop-lat	-0.37	1	1.2767	1	
	fric-nas	-0.33	1	1.0156	1	
	fric-lat	0.92	1	7.8934	0.029769	*
	nas-lat	1.25	1	14.5717	0.00081	***

Results: Speaker KD

Table 7. LMER model comparisons for the analysis of manner (stops, fricatives, nasals, and laterals) based on all constriction parameters and articulatory components for the full set and the set without fricatives produced by speaker KD (Analysis of Deviance Table, Type II Wald χ2 tests, significance levels: '' <.001, '**' <.01, '*' <.05).***

		Chisq	Df	Pr(>Chisq)	
TTCL	Manner	62.35	3	1.85E-13	***
TTClength	Manner	27.151	3	5.47E-06	***
TTCD	Manner	394.31	3	< 2.20E-16	***
TTF	Manner	132.29	3	< 2.20E-16	***
TTH	Manner	5.51	3	0.138	
TB	Manner	3.3742	3	0.3374	
TD	Manner	82.843	3	< 2.20E-16	***
HYH	Manner	207.81	3	< 2.20E-16	***
JA	Manner	51.038	3	4.80E-11	***
JH	Manner	72.18	3	1.46E-15	***
VH	Manner	216	3	< 2.20E-16	***
LAH	Manner	48.883	3	1.38E-10	***

*Table 8. Results of pairwise comparisons by manner (stops, fricatives, nasals, and laterals) based on all constriction parameters and articulatory components for speaker KD ('***' <.001, '**' <.01, '*' <.05).*

		Value	Df	Chisq	Pr(>Chisq)	
TTCL	stop-fric	0.22	1	0.0178	1	
	stop-nas	6.82	1	17.103	0.000212	***
	stop-lat	10.89	1	43.6073	2.41E-10	***
	fric-nas	6.6	1	16.0174	0.000377	***
	fric-lat	10.67	1	41.8632	5.87E-10	***
	nas-lat	4.07	1	6.0911	0.081521	
TTClength	stop-fric	-0.827	1	24.4427	4.59E-06	***
	stop-nas	-0.235	1	1.9737	0.960353	
	stop-lat	-0.205	1	1.5019	1	
	fric-nas	0.592	1	12.5251	0.002409	**
	fric-lat	0.622	1	13.8267	0.001203	**
	nas-lat	0.03	1	0.0322	1	
TTCD	stop-fric	-0.124	1	284.4128	<2e-16	***
	stop-nas	-0.008	1	1.1838	1	
	stop-lat	-0.007	1	0.9064	1	
	fric-nas	0.116	1	248.8982	<2e-16	***
	fric-lat	0.117	1	253.208	<2e-16	***
	nas-lat	0.001	1	0.0185	1	
TTF	stop-fric	-1.12	1	37.4177	5.72E-09	***
	stop-nas	0.32	1	3.0545	0.48308	
	stop-lat	0.93	1	25.7993	2.27E-06	***
	fric-nas	1.44	1	61.8538	2.22E-14	***
	fric-lat	2.05	1	125.3572	< 2.2e-16	***
	nas-lat	0.61	1	11.0994	0.005181	**
TD	stop-fric	-0.39	1	4.2841	0.230819	
	stop-nas	1.2	1	40.5598	1.14E-09	***
	stop-lat	0.63	1	11.1793	0.004963	**
	fric-nas	1.59	1	71.2077	< 2.2e-16	***
	fric-lat	1.02	1	29.3044	3.71E-07	***
	nas-lat	-0.57	1	9.1513	0.014913	*
HYH	stop-fric	-0.73	1	16.1699	0.000347	***
	stop-nas	1.35	1	55.3004	6.21E-13	***
	stop-lat	1.47	1	65.5686	3.37E-15	***
	fric-nas	2.08	1	131.2767	< 2.2e-16	***
	fric-lat	2.2	1	146.8609	< 2.2e-16	***
	nas-lat	0.12	1	0.4369	1	
JA	stop-fric	-0.99	1	14.3885	0.000892	***
	stop-nas	0.3	1	1.3213	1	
	stop-lat	0.82	1	9.8713	0.010073	*
	fric-nas	1.29	1	24.4301	4.62E-06	***
	fric-lat	1.81	1	48.0954	2.44E-11	***

	nas-lat	0.52	1	3.9697	0.277963	
JH	stop-fric	-0.43	1	4.511	0.202066	
	stop-nas	0.47	1	5.3893	0.121564	
	stop-lat	1.21	1	35.7196	1.37E-08	***
	fric-nas	0.9	1	19.7615	5.26E-05	***
	fric-lat	1.64	1	65.6181	3.28E-15	***
	nas-lat	0.74	1	13.3598	0.001542	**
VH	stop-fric	-0.23	1	1.9776	0.9579	
	stop-nas	1.89	1	133.5364	<2e-16	***
	stop-lat	0.06	1	0.1346	1	
	fric-nas	2.12	1	168.0149	<2e-16	***
	fric-lat	0.29	1	3.1439	0.4573	
	nas-lat	-1.83	1	125.1925	<2e-16	***
LAH	stop-fric	-0.53	1	3.0614	0.481048	
	stop-nas	0.67	1	4.8923	0.161862	
	stop-lat	1.47	1	23.5503	7.30E-06	***
	fric-nas	1.2	1	15.6937	0.000447	***
	fric-lat	2	1	43.5935	2.43E-10	***
	nas-lat	0.8	1	6.975	0.049595	*

Table 9. rpart confusion matrices for consonant classification by Manner based on constriction parameters, separately by speaker; cells with largely incorrect classification are shaded; fric = fricative, nas = nasal, lat = lateral.

C	*Speaker KMU*					*Speaker KD*				
	stop	*fric*	*nas*	*lat*	*correct*	*stop*	*fric*	*nas*	*lat*	*correct*
t̪	3	0	2	0	60%	5	0	0	0	100%
ʈ	5	0	0	0	100%	4	0	1	0	80%
s̪	0	5	0	0	100%	0	5	0	0	100%
ʂ	0	5	0	0	100%	0	5	0	0	100%
n̪	0	0	5	0	100%	0	0	5	0	100%
ɳ	1	0	0	4	0%	0	0	5	0	100%
l̪	4	0	1	0	0%	1	0	4	0	0%
ɭ	0	0	0	5	100%	0	0	5	0	0%
Mean					*70%*					*73%*

Table 10. rpart confusion matrices for consonant classification by Manner based on articulatory components, separately by speaker; cells with largely incorrect classification are shaded.

C	*Speaker KMU*					*Speaker KD*				
	stop	*fric*	*nas*	*lat*	*correct*	*stop*	*fric*	*nas*	*lat*	*correct*
t̪	5	0	0	0	100%	5	0	0	0	100%
ʈ	5	0	0	0	100%	5	0	0	0	100%
s̪	1	4	0	0	80%	0	5	0	0	100%
ʂ	0	5	0	0	100%	2	3	0	0	60%

n̪	0	0	5	0	100%	1	0	0	4	0%
ɳ	0	0	5	0	100%	0	0	0	5	0%
l̪	1	0	0	4	80%	0	0	0	5	100%
ɭ	0	0	0	5	100%	0	0	0	5	100%
Mean					*95%*					*70%*

Speaker	Phon	C	V	Place	Manne	JH	ULP	ULH	VH	VS	PHH	PHF	HYH	HYF	LLP	LLH	JA	EPF	EPH	TB	TD	TTF	TTH	LAH	LAF	TTCL	TTCD	TTCle	TngTl	LBD	LBlen	LDD	TCL	TCD	TClen	CL	CD	Cleng	F1off	F2off	F3off	F1off	F2off	F3off	F2_F1	F3_F2
K1_KMU	ta	t	a	dent	stop	0.3	-1	0.7	0.6	-0.5	-1	-1	-0.9	0.5	-0.9	0.2	-0.2	-1.1	-0.3	0.4	-0.7	1	0.8	-0.9	-0.7	157	0.05	1.78	0.5	0.47	0.8	0.07	157	0.05	1.78	157	0.05	1.78	667	1877	2963	725	1811	3017	1086	1206
K1_KMU	te	t	e	dent	stop	-0.4	-1.3	-0.2	0.9	-0.1	-1.3	-1	-0.9	-0.9	-1.1	-0.2	-0.1	-1.4	-0.7	0.2	-0.9	1.7	0.2	-1.8	-0.1	156	0.08	1.78	0.5	0.37	0.92	0.16	156	0.08	1.78	156	0.08	1.78	486	2379	3032	522	2142	2886	1620	745
K1_KMU	ti	t	i	dent	stop	0.4	-0.3	1.1	0.9	0	-0.7	-0.4	-1.2	-1.2	-0.6	0.4	0.8	-0.7	0.1	0.9	-0.9	0.6	0.4	-1	-1.1	153	0.04	1.87	0.5	0.52	0.91	0.14	153	0.04	1.87	153	0.04	1.87	328	2665	3332	396	2596	3145	2201	549
K1_KMU	to	t	o	dent	stop	2	0.1	0.9	2.1	2.2	-0.7	-2.3	-0.9	1.2	-0.3	1.9	0.1	-1.4	0.4	-0.3	-0.5	-0.3	1.5	-0.9	-0.9	154	0.03	2.06	0.5	0.28	0.93	0.05	154	0.03	2.06	154	0.03	2.06	487	1479	3029	584	1626	2784	1042	1158
K1_KMU	tu	t	u	dent	stop	1	0.1	-0.4	1.5	1.3	-1	-0.9	-1.2	-0.4	-0.3	0.4	-0.8	-1.2	-0.1	0.1	-0.6	1	1	-0.8	-0.6	156	0.04	1.74	0.5	0.28	1.05	0.08	156	0.04	1.74	156	0.04	1.74	416	1282	2989	330	1497	2990	1167	1493
K2_KD	ta	t	a	dent	stop	0.8	-1.3	0.2	0.6	-1	-0.9	0.3	0.2	0.4	-0.6	0.7	-0.2	-0.4	0.5	0.1	0.2	0.9	-0.8	0.1	0.2	159	0.02	1.03	0.5	0.5	0.7	0.1	159	0.02	1.03	159	0.02	1.03	752	1724	2893	758	1841	2938	1083	1097
K2_KD	te	t	e	dent	stop	0.7	-0.2	0.6	0.8	-0.1	0.6	0.2	0.9	0.9	-0.2	0.3	0.3	-0.2	1.1	0.1	0.3	1.1	0.1	0.9	0.9	160	0.02	1.18	0.5	0.6	0.7	0.18	160	0.02	1.18	160	0.02	1.18	581	2387	3046	618	2264	2994	1647	729
K2_KD	ti	t	i	dent	stop	0.6	-0.8	0.7	0.6	-1.1	-0.5	0.9	-0.1	-0.4	-0.5	1	0.2	-0.4	-0.1	-0.1	0.2	1.2	-0.8	0.1	-0.6	159	0.02	1.13	0.5	0.6	0.71	0.08	159	0.02	1.13	159	0.02	1.13	436	2847	3155	519	2632	3058	2113	426
K2_KD	to	t	o	dent	stop	0	1.5	-1	0.8	0	-0.3	0.8	-0.1	-1	0.5	-0.5	-0.1	-1.2	0.2	-0.9	-0.3	1.6	0	-0.7	0.6	157	0.04	1.31	0.5	0.4	0.94	0.3	157	0.04	1.31	157	0.04	1.31	590	1141	2915	689	1071	3201	382	2130
K2_KD	tu	t	u	dent	stop	0.8	1	-0.3	1	0.6	-0.1	0.1	1	1.5	0.8	1	0.6	-0.8	0.6	-0.2	1	0.9	-1.3	0.5	1	156	0.03	1.01	0.5	0.34	0.91	0.16	156	0.03	1.01	156	0.03	1.01	479	1142	3009	542	1552	3042	1010	1490
K1_KMU	t_ra	T	a	ret	stop	0.5	-0.8	1.6	0.7	-0.9	-0.1	-0.5	-0.6	-0.3	-2.5	-0.1	-1.7	-0.5	0.8	-1.1	-0.5	-0.2	0.3	-0.4	-0.4	151	0.03	1.06	0.5	0.67	0.61	0.1	151	0.03	1.06	151	0.03	1.06	594	1883	2674	761	1794	2662	1033	869
K1_KMU	t_re	T	e	ret	stop	0.1	-1.5	0.3	0.6	-0.1	-1.7	1	-0.7	-1.5	-4.1	-2.2	-2	-0.9	-1.4	-1.2	-1.4	-0.9	-0.1	-1.7	-1.5	148	0.03	1.29	0.5	0.78	0.43	0.34	148	0.03	1.29	148	0.03	1.29	480	2464	3240	507	2502	3136	1995	634
K1_KMU	t_ri	T	i	ret	stop	1.6	0.7	1.9	0.9	0.4	-0.3	0.4	-0.5	-0.4	-0.4	0.9	-0.3	0.5	0.8	-0.8	-1.3	-1.1	0.3	-0.6	-0.8	150	0.04	1.18	0.5	0.6	0.91	0.08	150	0.04	1.18	150	0.04	1.18	351	2533	3302	440	2358	3053	1919	694
K1_KMU	t_ro	T	o	ret	stop	0.3	0	-1.6	0.8	-0.4	-1.5	0.9	-1.3	-0.5	-1.6	-1.1	-1.3	-1.6	0.4	-1.3	-0.6	-0.9	0.7	-1.5	-1.5	147	0.04	1.2	0.5	0.28	1.06	0.22	147	0.04	1.2	147	0.04	1.2	446	1484	2422	425	1284	2507	859	1223
K1_KMU	t_ru	T	u	ret	stop	0	-0.9	-1.5	1.1	-1.1	-0.9	-3.1	-1.5	1	-1.8	-1.3	-3	-0.6	0.8	-0.5	0.4	-1	0.5	-0.8	-1.9	149	0.02	1	0.5	0.38	0.86	0.23	149	0.02	1	149	0.02	1	426	1132	2438	483	1305	2337	822	1032
K2_KD	t_ra	T	a	ret	stop	0.9	-1	0.4	0.8	-0.9	-0.9	0.3	0.2	0.8	-0.6	0.9	0	-0.1	0.5	-1	0.9	-1.4	0.5	0.1	0.3	143	0.03	1.02	0.5	0.5	0.71	0.1	143	0.03	1.02	143	0.03	1.02	830	1867	2731	745	1969	2864	1224	895
K2_KD	t_re	T	e	ret	stop	1.1	-0.5	0.3	0.8	-0.6	0.2	0.3	0.5	1.4	-0.5	0.4	0.4	0.7	0.4	-0.7	0.6	-1.2	0.7	0.4	0.2	147	0.02	0.84	0.5	0.57	0.7	0.16	147	0.02	0.84	147	0.02	0.84	493	2660	2961	700	2309	3027	1608	718
K2_KD	t_ri	T	i	ret	stop	0.7	-0.8	0.4	-1.3	0.1	-0.2	0.1	-0.1	-0.8	-1	-0.2	0.5	0.9	-1.2	-0.9	-0.3	-1.8	1.4	1.2	-2	142	0.03	1.22	0.5	0.64	0.6	0.23	142	0.03	1.22	142	0.03	1.22	444	2773	3063	532	2761	3136	2229	375
K2_KD	t_ro	T	o	ret	stop	0.1	1.9	-1	1.1	1.4	-1.1	1.8	0	0.6	0.4	-1.3	-0.6	0.8	-0.4	-1.1	-0.9	-1.4	-0.1	-1.4	1.1	137	0.02	1.82	0.5	0.56	0.92	0.4	137	0.02	1.82	137	0.02	1.82	663	967	2716	708	1369	2550	661	1181
K2_KD	t_ru	T	u	ret	stop	0	1.1	-0.9	1	0.6	-0.5	0.2	1.5	1.5	0.9	0.2	0.1	0.1	0.4	-0.8	0.6	-1.4	1.1	0	0.9	144	0.05	1.31	0.5	0.36	0.9	0.28	144	0.05	1.31	144	0.05	1.31	455	1022	2789	561	1530	2647	969	1117
K1_KMU	na	n	a	dent	nas	0.8	0.5	1.3	-1.3	0.5	-0.5	-0.1	0.8	-0.9	0.3	0.6	-0.3	0.2	-0.3	0.1	-0.7	0.4	0.2	-0.3	0.5	157	0.05	1.52	0.5	0.51	1	0.1	157	0.05	1.52	157	0.05	1.52	789	1788	3160	772	1734	3167	962	1433
K1_KMU	ne	n	e	dent	nas	-1.9	-0.3	0.6	-1.3	0.7	0.8	3.4	1.1	1.6	-0.1	-0.5	-0.7	1.5	-0.5	1.3	-0.5	1.8	0.2	1.2	1.6	161	0.03	1.49	0.5	0.54	1.01	0.24	161	0.03	1.49	161	0.03	1.49	481	2423	3020	555	2330	3032	1776	702
K1_KMU	ni	n	i	dent	nas	0.8	-0.3	0.6	-1.4	-0.3	1.4	0.3	1.1	0.3	-0.3	1	-0.2	1	0.4	1.3	-0.5	-0.4	0.7	1	0.2	156	0.04	2.04	0.5	0.34	0.91	0.06	156	0.04	2.04	156	0.04	2.04	395	2629	3324	271	1916	2800	1645	884
K1_KMU	no	n	o	dent	nas	0.2	1.5	-0.9	-1.3	0.3	1	0.9	1.1	0.9	0.3	-0.1	0.7	0.6	-0.2	0.1	0.2	1	0.2	1	0.7	159	0.03	1.12	0.5	0.2	0.9	0.24	159	0.03	1.12	159	0.03	1.12	598	1426	2840	498	1590	3070	1092	1479
K1_KMU	nu	n	u	dent	nas	-0.6	1.8	-0.7	-1.6	-0.1	0.1	-0.1	0.9	1	-0.2	-0.8	-0.7	0.9	-1.2	-0.2	0.3	0.7	-0.2	0.1	0.5	158	0.04	1.05	0.5	0.36	1.02	0.28	158	0.04	1.05	158	0.04	1.05	545	1210	2801	552	1925	3099	1373	1174
K2_KD	na	n	a	dent	nas	-1.1	-0.8	0	-1.3	-0.6	-1	-2.4	-1.5	-0.8	-0.8	-1.1	0.1	-0.4	-1.2	-1.1	-1.4	1.2	-0.1	-1.4	-0.4	155	0.03	0.82	0.5	0.68	0.71	0.34	155	0.03	0.82	155	0.03	0.82	797	1855	3146	810	1928	3146	1117	1219
K2_KD	ne	n	e	dent	nas	0.7	-0.4	0.9	-1.3	-0.1	0.6	-0.7	-0.7	1	-0.2	0.3	0.3	0.4	0.2	-0.1	-0.6	0.6	0.1	0.4	0.7	155	0.03	0.89	0.5	0.69	0.7	0.2	155	0.03	0.89	155	0.03	0.89	605	2651	3094	697	2437	3161	1739	724
K2_KD	ni	n	i	dent	nas	0	-0.2	0.8	-1.2	-0.4	0.9	-0.2	-0.2	0.8	-0.9	-0.5	-0.5	0.5	0.6	-0.5	-0.6	0.6	-0.4	1.1	-0.3	155	0.04	0.79	0.5	0.77	0.6	0.27	155	0.04	0.79	155	0.04	0.79	425	2924	3117	594	2526	3033	1931	507
K2_KD	no	n	o	dent	nas	0.3	-0.3	-0.1	-1.3	0.6	-0.7	-0.5	-0.9	0.4	0	-0.1	0.1	-0.4	-0.8	-0.1	-0.8	0.6	-0.2	-0.8	0.3	157	0.04	0.81	0.5	0.54	0.7	0.25	157	0.04	0.81	157	0.04	0.81	658	1191	2900	702	1541	2891	839	1350
K2_KD	nu	n	u	dent	nas	0.4	0.2	0.3	-1.6	-0.5	0.5	0.6	-0.4	1.2	0.5	0.4	0.3	0.4	0.2	0.1	-0.7	0.5	0.1	0.4	0.6	157	0.03	0.78	0.5	0.55	0.8	0.21	157	0.03	0.78	157	0.03	0.78	594	1169	2834	663	1524	2718	862	1194
K1_KMU	n_ra	N	a	ret	nas	0.4	-0.1	0.8	-1.9	-0.6	-0.5	-0.5	1.2	-0.6	0.5	-0.7	1.7	-0.4	-0.9	-1.7	-1.6	-1.3	-0.7	-0.6	0.6	126	0.03	1.49	0.5	0.58	0.82	0.33	126	0.03	1.49	126	0.03	1.49	601	2092	2706	679	1880	2681	1201	800
K1_KMU	n_re	N	e	ret	nas	1.2	0.3	0.1	-1.3	0.2	1	0.8	0.9	0.7	-0.1	0.2	-0.2	0.3	2	-0.8	-1	-0.7	0	1.6	-0.2	150	0.04	0.94	0.5	0.42	1.02	0.12	150	0.04	0.94	150	0.04	0.94	474	2386	2996	401	2297	3014	1896	717
K1_KMU	n_ri	N	i	ret	nas	0	-1.2	0.6	-0.9	0	-0.1	2.2	0.8	-0.5	-3	-0.4	-1.4	1.2	0.6	-1.1	-1.3	-1.1	0.2	0.3	0.8	144	0.02	1.35	0.5	0.55	0.62	0.12	144	0.02	1.35	144	0.02	1.35	412	2528	3132	400	2383	3025	1983	642
K1_KMU	n_ro	N	o	ret	nas	-0.6	0.3	-0.6	-0.8	1.6	0.4	0.5	1.1	0.3	-0.2	0.2	-0.9	1.2	-1	-0.8	-0.6	-1	-0.2	0.8	0.8	143	0.02	1.22	0.5	0.23	1.04	0.13	143	0.02	1.22	143	0.02	1.22	467	1375	2403	487	1519	2697	1032	1178
K1_KMU	n_ru	N	u	ret	nas	-0.8	0.3	-0.4	-1.5	-0.4	0.8	-0.6	0.6	0	0.7	0.3	-1	0.5	1.7	-1.6	-0.4	-0.5	-0.2	0.7	-0.4	142	0.07	1.71	0.5	0.24	1.11	0.15	142	0.07	1.71	142	0.07	1.71	546	1658	3000	485	1471	2897	986	1426
K2_KD	n_ra	N	a	ret	nas	0.2	-0.9	0.1	-1	1.5	-0.9	-2.4	-1.4	-0.3	-1	-0.6	-0.2	0.2	-2.2	-2.2	-1	-1.8	-0.9	-1.5	0	130	0.04	2.59	0.5	0.62	0.6	0.28	130	0.04	2.59	130	0.04	2.59	753	2049	2402	623	2173	2439	1549	266
K2_KD	n_re	N	e	ret	nas	0.2	-0.9	0.6	-1.3	0.7	-0.7	-1.8	-0.9	-0.2	-0.9	-0.9	0.4	-0.3	-1.5	-1.5	-1	-1.8	-0.6	-1.1	0.4	134	0.04	2.1	0.5	0.76	0.6	0.32	134	0.04	2.1	134	0.04	2.1	597	2592	2968	600	2461	2938	1860	478
K2_KD	n_ri	N	i	ret	nas	0	-0.4	0.7	-1.2	-0.6	-1.1	-1	-1.4	-1	-1	-0.3	-0.6	-0.4	-1.6	-1.4	-1.2	-1.6	-0.2	-1.5	-0.2	131	0.05	2	0.5	0.72	0.6	0.23	131	0.05	2	131	0.05	2	411	2747	3101	503	2651	3057	2147	406
K2_KD	n_ro	N	o	ret	nas	-0.2	-0.7	-0.4	-1	-0.3	-0.3	-2.9	-0.9	0.1	-0.7	-0.2	-1.6	-0.2	-1	-0.7	-1.4	-1.4	-1	-0.5	0.6	130	0.03	1.71	0.5	0.52	0.71	0.22	130	0.03	1.71	130	0.03	1.71	687	1172	2625	785	1468	2362	683	894
K2_KD	n_ru	N	u	ret	nas	0.5	1.1	-0.4	-1.5	-0.3	-0.8	-0.8	-1.2	1.2	0.8	0.6	-0.1	0.1	-1.2	-1.4	-1	-1.6	0	-0.6	1.2	133	0.03	1.73	0.5	0.39	0.91	0.2	133	0.03	1.73	133	0.03	1.73	514	1184	2632	744	1404	2270	660	866
K1_KMU	la	l	a	dent	lat	-0.7	-1.4	0.7	0.7	-0.1	-0.3	-0.2	-0.5	-0.5	-0.2	0.1	-0.1	0.4	0.1	-0.3	0.6	0	0.6	-0.8	0.8	155	0.03	0.86	0.5	0.47	0.91	0.16	155	0.03	0.86	155	0.03	0.86	674	1881	3038	609	1862	3021	1253	1159
K1_KMU	le	l	e	dent	lat	-4.2	-0.7	0.3	0.6	0.3	1.1	0.2	1.4	-0.2	1.4	-0.8	0.1	1.9	-0.1	1.1	-0.4	1.3	0.7	0.8	0.4	155	0.03	1.33	0.5	0.51	0.92	0.34	155	0.03	1.33	155	0.03	1.33	502	2400	3083	519	2316	3145	1797	829
K1_KMU	li	l	i	dent	lat	-0.4	-1	1.1	0.5	-0.2	1.3	-1.4	0.6	0.5	0.5	0.5	0.4	1	0.4	0.1	-0.2	0.3	0.8	0.8	0.2	156	0.03	1.46	0.5	0.48	0.93	0.18	156	0.03	1.46	156	0.03	1.46	391	2651	3230	461	2442	3157	1981	715
K1_KMU	lo	l	o	dent	lat	-0.5	0.6	-1	0.7	-0.3	0	-1.4	0	-1.3	0	-0.9	-0.5	0.4	-1.4	-0.5	0.6	-0.3	0	0	0.5	153	0.07	1.29	0.5	0.31	1.02	0.24	153	0.07	1.29	153	0.07	1.29	505	1473	2779	527	1713	2794	1185	1081
K1_KMU	lu	l	u	dent	lat	-1.7	0.5	-1	0.6	-0.6	0.6	-0.7	1.1	-0.2	-0.7	-1.1	-1.9	0.9	-0.1	-0.2	0.2	0.5	0.6	0.7	0	154	0.04	1.01	0.5	0.39	1.08	0.25	154	0.04	1.01	154	0.04	1.01	477	1429	2709	501	1279	2776	778	1497
K1_KMU	sa	s	a	dent	fric	0.3	0.1	0.8	0.5	-1.1	0.3	-0.6	-1	0.2	0.7	0.6	1.5	-1	0.3	-0.1	0.1	1.1	-0.2	0.3	0.1	159	0.14	1.44	0.5	0.45	1.04	0.23	159	0.14	1.44	159	0.14	1.44	725	1993	3134	599	2076	2953	1477	878
K1_KMU	se	s	e	dent	fric	0.3	-1.1	0.5	0.4	-1	0.2	-0.3	-1.1	0.3	-0.7	-1.7	1.4	-0.6	0.9	-0.3	-0.5	1.9	-0.7	0.5	-0.8	157	0.15	1.49	0.5	0.67	0.8	0.36	157	0.15	1.49	157	0.15	1.49	456	2334	3098	495	2084	2888	1589	804
K1_KMU	si	s	i	dent	fric	0.3	-0.5	0.8	0.7	-0.4	0.3	-0.4	-1	0	0.7	-0.1	1.5	-1.2	0.9	0	-0.2	1.2	-0.3	0.2	-0.7	160	0.17	1.57	0.5	0.52	0.93	0.28	160	0.17	1.57	160	0.17	1.57	328	2487	3186	473	2472	3106	2000	633
K1_KMU	so	s	o	dent	fric	0.3	1.8	-0.5	0.6	-1.1	-0.9	-0.4	-0.2	0.1	1.1	-0.8	1.3	-1.2	-0.9	-1	0	1.5	-1.3	-0.5	-0.3	157	0.17	1.37	0.5	0.37	1	0.37	157	0.17	1.37	157	0.17	1.37	481	1563	2786	498	1441	2807	943	1366
K1_KMU	su	s	u	dent	fric	0.1	1.6	-1.3	0	-2.2	-0.2	-0.5	-0.9	-0.2	0.9	-1.2	1.1	-1.1	-0.7	-0.9	0.4	1.7	-0.8	0.1	-1	156	0.15	1.23	0.5	0.29	1	0.41	156	0.15	1.23	156	0.15	1.23	448	1389	2872	471	1713	2933	1242	1220
K2_KD	la	l	a	dent	lat	-2	-0.5	0.3	0.5	0	-1.5	0.4	-1.4	-2.1	-1.4	-2.4	-1.8	-1	-1	-0.8	-1.4	0.6	2.1	-1.8	0.5	156	0.04	0.82	0.5	0.87	0.5	0.51	156	0.04	0.82	156	0.04	0.82	705	1864	2913	694	1856	2987	1162	1132
K2_KD	le	l	e	dent	lat	-0.9	-0.9	0.6	0.5	-1	-0.5	0.4	-0.8	-1.1	-1.2	-1.1	-1.7	-0.7	-0.5	-0.4	-0.4	-0.4	2.9	-0.9	-1	152	0.05	1.04	0.5	0.81	0.5	0.32	152	0.05	1.04	152	0.05	1.04	563	2524	3029	685	2237	3018	1552	781
K2_KD	li	l	i	dent	lat	-0.5	-0.7	1.2	0.6	-0.9	-0.2	0.3	-0.9	0.1	-1.6	-1.3	-0.9	-0.3	-0.8	-0.3	-0.1	-0.8	2.3	0.3	-0.3	149	0.03	0.75	0.5	0.94	0.3	0.36	149	0.03	0.75	149	0.03	0.75	453	2779	3088	496	2401	3061	1905	660
K2_KD	lo	l	o	dent	lat	-0.9	-0.2	0.3	0.5	-1.2	-0.2	-0.4	-0.5	-0.4	-0.3	-1.4	0.1	-0.2	-0.6	0.2	-0.2	-0.5	1.8	-0.6	0	154	0.02	0.99	0.5	0.78	0.6	0.4	154	0.02	0.99	154	0.02	0.99	637	1173	2914	629	1607	2884	978	1277
K2_KD	lu	l	u	dent	lat	-0.4	0.4	0.6	0.6	-0.6	-1	0.1	-0.9	-0.3	0.1	-0.7	0	-0.6	-0.9	-0.2	0.2	-0.4	1.5	-1	-0.6	154	0.03	0.58	0.5	0.75	0.7	0.32	154	0.03	0.58	154	0.03	0.58	485	1296	2871	510	1555	2886	1045	1331
K2_KD	sa	s	a	dent	fric	0.6	-0.6	0.4	0.8	0.6	-0.9	0.6	-0.2	-0.1	0.3	0.6	0.8	-1.9	0.4	-1.4	0.7	1.8	-1	-0.9	0.5	158	0.12	1.51	0.5	0.51	0.81	0.17	158	0.12	1.51	158	0.12	1.51	707	1767	3028	706	1810	3024	1104	1214
K2_KD	se	s	e	dent	fric	0.9	-1	1	1	0.1	0.2	1	2.3	-0.6	0.1	0.7	1.9	-0.8	1.5	-0.7	1.4	1.4	-1.1	1	-2.1	159	0.11	1.54	0.5	0.65	0.71	0.17	159	0.11	1.54	159	0.11	1.54	618	2417	3053	666	2260	2875	1594	615
K2_KD	si	s	i	dent	fric	0.8	-0.9	1	0.8	0.4	0.7	0.6	1.1	-0.3	-0.4	0.3	1.9	-0.7	2.1	-0.5	0.9	1.3	-0.3	1.4	-1.9	158	0.13	1.7	0.5	0.66	0.72	0.24	158	0.13	1.7	158	0.13	1.7	458	2868	3149	505	2436	3145	1931	709
K2_KD	so	s	o	dent	fric	0.8	1.5	-0.2	1	0.3	0.4	0.9	1	-3.1	1.4	0.6	1.1	-1.2	1.1	-1.1	0.6	1.8	-1	1	-1.8	157	0.2	1.65	0.5	0.4	0.91	0.24	157	0.2	1.65	157	0.2	1.65	564	1404	2991	669	1537	3012	868	1475
K2_KD	su	s	u	dent	fric	1.1	-0.1	-0.1	1	1	-0.5	0.7	2.1	-0.6	1.1	1	0.7	-0.9	1.1	-1.1	1.3	1.6	-1.3	0.4	-2.2	158	0.19	1.52	0.5	0.38	0.9	0.17	158	0.19	1.52	158	0.19	1.52	484	1397	3118	529	1678	3040	1149	1362
K1_KMU	l_ra	L	a	ret	lat	-1.7	-0.5	0.8	0.9	1.3	-1	-0.8	0.1	-1.7	0.9	0.2	-0.1	0	-1	-2.5	-0.6	-1.4	0.4	-1.5	0.5	128	0.04	1.69	0.5	0.45	1.01	0.14	128	0.04	1.69	128	0.04	1.69	589	2015	2506	574	1992	2383	1417	391
K1_KMU	l_re	L	e	ret	lat	-1.4	0	0.5	0.8	1.5	-1.5	1	1.4	-3	1.2	-1.7	0.9	0.9	-0.6	-2	-2.9	-1.5	-1.2	-1.7	1.4	130	0.04	2.28	0.5	0.66	0.92	0.4	130	0.04	2.28	130	0.04	2.28	485	2347	2805	494	2348	2676	1855	328
K1_KMU	l_ri	L	i	ret	lat	-0.8	-0.3	0.3	0.4	-0.3	-0.6	1.6	0.5	-2.4	0.2	-1.7	0.2	0.5	-0.3	-1.5	-1	-1	0.2	-0.8	0.2	146	0.03	1.23	0.5	0.63	1.01	0.36	146	0.03	1.23	146	0.03	1.23	410	2519	3034	440	2544	3178	2104	634

K1_KMU	l_ro	L	o	ret	lat	-2.3	2.3	-0.3	0.5	0.2	-1.1	-0.1	1.8	-0.2	1.7	-0.4	0.5	0.6	0.7	-1.6	-0.6	-1.6	0.4	-1.6	1.6
K1_KMU	l_ru	L	u	ret	lat	-1.3	-0.3	-1	0.3	-0.3	-2.9	1.1	1.3	-2.1	-0.8	-1.7	-1	0	-2.1	-2.1	-1.6	-1.6	-0.5	-2.6	1.5
K1_KMU	SH_r	S	a	ret	fric	0.7	-1.2	1.1	0.4	-1	0.8	-1.3	-1.3	0.5	0	0.5	0.4	-1	1.9	-0.4	0.3	-0.1	1.5	0.7	-1.2
K1_KMU	SH_r	S	e	ret	fric	0.4	-0.1	0.6	0	-1.4	0.6	0.1	-0.4	1.4	0.7	-0.9	0.9	-0.1	0.4	-0.1	0.2	-0.3	1.3	0.7	-1.7
K1_KMU	SH_r	S	i	ret	fric	0.4	0.1	1.3	0.7	-0.4	0.4	-0.7	-1.3	0.3	0.5	-0.3	1	-1.1	0.3	-0.1	0	0.5	1.2	0	-1
K1_KMU	SH_r	S	o	ret	fric	-0.9	2.2	-1.1	0	-1.7	0.1	0.6	-0.7	-0.2	-0.3	-2.5	-0.8	-0.4	0	-0.5	1.4	0	1.3	0.2	-0.2
K1_KMU	SH_r	S	u	ret	fric	0	1.3	-1.1	-0.3	-2.4	0.5	-1	-0.7	0.8	0.6	-1.8	1	-0.9	-1.2	-0.2	0.5	-0.1	1.4	0.3	-1.1
K2_KD	l_ra	L	a	ret	lat	-0.7	-0.5	0.4	0.6	0.1	-1.9	-1.5	-1.7	-0.8	-0.9	-0.7	-0.5	-1.5	-1.4	-1.3	-0.7	-1.7	-0.7	-2.2	0.3
K2_KD	l_re	L	e	ret	lat	-0.7	0	1.1	0.4	-1.9	-1.1	0.5	-1.2	-1	-0.1	0.3	-1	-0.8	-0.9	-1.2	-0.6	-1.8	-0.1	-1.5	-0.7
K2_KD	l_ri	L	i	ret	lat	0.5	-0.3	1.2	0.6	-0.3	-1.2	-0.2	-1.1	-0.7	-0.1	0.8	0	-1.1	-1.3	-1.5	0.1	-1.9	-0.2	-1.3	-0.6
K2_KD	l_ro	L	o	ret	lat	-0.9	-0.5	-0.2	0.6	0	-2.1	1.2	-1.2	-1.3	-0.3	-1.3	-1.2	-0.6	-2.4	-1.4	-0.9	-2	-0.7	-2.5	-1.1
K2_KD	l_ru	L	u	ret	lat	0.1	0.6	0.2	0.7	1.2	-1.8	0.2	-1	-0.6	0.4	-0.3	0	-1	-0.9	-1	0	-1.9	-1	-2	-0.9
K2_KD	SH_r	S	a	ret	fric	1.4	0	0.5	0.9	-0.3	-0.1	-0.3	0.3	0.8	0.7	-0.6	0.8	0.1	1.5	-0.3	0.6	-0.2	1.7	0.1	-0.6
K2_KD	SH_r	S	e	ret	fric	1.1	0.8	0.7	0.8	0.5	1.2	0.8	1.4	-2.7	1.1	-0.3	1.5	0.2	0.4	0.2	-0.2	0.4	1	0.4	-2.2
K2_KD	SH_r	S	i	ret	fric	0.9	-0.1	1	0.6	-1.1	0.8	0.4	0.7	-0.1	0	-1.1	0.6	-0.6	1.2	0.1	0	0.7	1.1	1	-1.6
K2_KD	SH_r	S	o	ret	fric	1.4	3	0.4	0.6	0.9	0.6	1.1	0.8	0.5	2.7	0.2	1.6	-0.4	0.7	0.2	0.2	0.4	1	1.7	-1.5
K2_KD	SH_r	S	u	ret	fric	1	2.4	0.1	1	0.3	0.1	1.1	1.8	-0.4	1.6	-0.1	0.2	-0.7	0.8	-0.4	0.7	0.5	1.7	0.4	-1.3

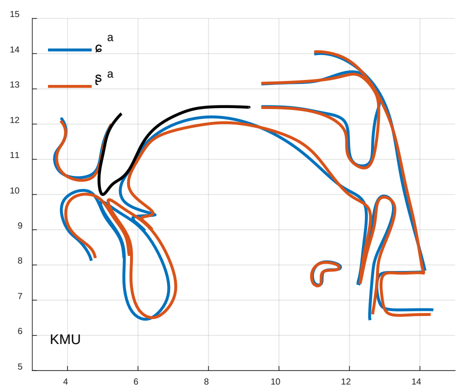
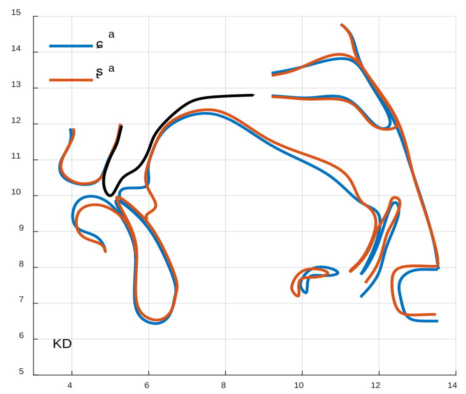
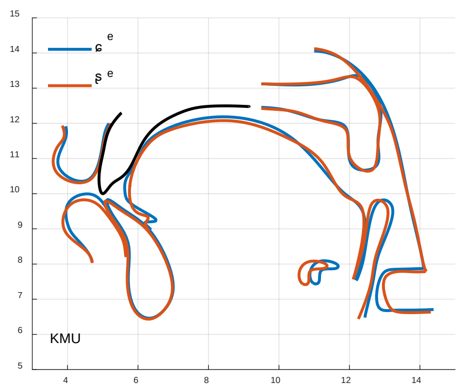
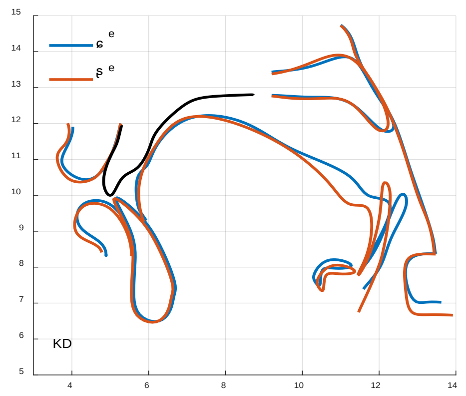
K1_KMU	l_ro	L	o	131	0.04	1.67	0.5	0.36	1.11	0.33	131	0.04	1.67	131	0.04	1.67	450	1287	2081	457	1227	2146	770	919
K1_KMU	l_ru	L	u	135	0.02	1.98	0.5	0.44	0.92	0.32	135	0.02	1.98	135	0.02	1.98	499	1545	2443	460	1439	2648	980	1208
K1_KMU	SH_r	S	a	148	0.12	1.97	0.5	0.49	0.91	0.15	148	0.12	1.97	148	0.12	1.97	765	2021	2965	580	1855	2581	1275	727
K1_KMU	SH_r	S	e	146	0.16	2.78	0.5	0.59	0.91	0.33	146	0.16	2.78	146	0.16	2.78	481	2414	3169	459	2430	3103	1971	673
K1_KMU	SH_r	S	i	145	0.18	2.83	0.5	0.63	0.92	0.27	145	0.18	2.83	145	0.18	2.83	352	2634	3246	405	2593	3255	2188	662
K1_KMU	SH_r	S	o	149	0.12	1.26	0.5	0.54	0.92	0.46	149	0.12	1.26	149	0.12	1.26	568	1771	2757	451	1575	2856	1124	1281
K1_KMU	SH_r	S	u	152	0.1	1.34	0.5	0.42	1.01	0.42	152	0.1	1.34	152	0.1	1.34	328	1784	2985	463	1312	2713	849	1401
K2_KD	l_ra	L	a	126	0.04	2.05	0.5	0.7	0.6	0.3	126	0.04	2.05	126	0.04	2.05	726	1924	2652	559	2112	2883	1552	771
K2_KD	l_re	L	e	128	0.03	1.83	0.5	0.73	0.7	0.21	128	0.03	1.83	128	0.03	1.83	528	2455	2896	577	2320	2892	1743	573
K2_KD	l_ri	L	i	127	0.03	1.39	0.5	0.66	0.6	0.12	127	0.03	1.39	127	0.03	1.39	451	2585	2874	496	2376	2700	1880	324
K2_KD	l_ro	L	o	122	0.03	2.22	0.5	0.68	0.7	0.41	122	0.03	2.22	122	0.03	2.22	652	1124	2638	624	1494	2606	870	1112
K2_KD	l_ru	L	u	127	0.05	2.25	0.5	0.62	0.8	0.28	127	0.05	2.25	127	0.05	2.25	455	1213	2554	543	1740	2371	1197	631
K2_KD	SH_r	S	a	135	0.14	3.13	0.5	0.69	0.81	0.33	135	0.14	3.13	135	0.14	3.13	707	1761	2922	732	1879	2751	1147	873
K2_KD	SH_r	S	e	145	0.14	2.22	0.5	0.71	0.7	0.32	145	0.14	2.22	145	0.14	2.22	550	2506	3007	652	2374	3083	1722	709
K2_KD	SH_r	S	i	144	0.15	1.89	0.5	0.85	0.5	0.37	144	0.15	1.89	144	0.15	1.89	487	2750	3075	504	2584	3058	2080	474
K2_KD	SH_r	S	o	144	0.18	3	0.5	0.59	0.9	0.28	144	0.18	3	144	0.18	3	601	1383	2758	626	1552	2718	926	1166
K2_KD	SH_r	S	u	146	0.16	1.98	0.5	0.62	0.91	0.32	146	0.16	1.98	146	0.16	1.98	463	1480	2938	536	1756	2893	1219	1137

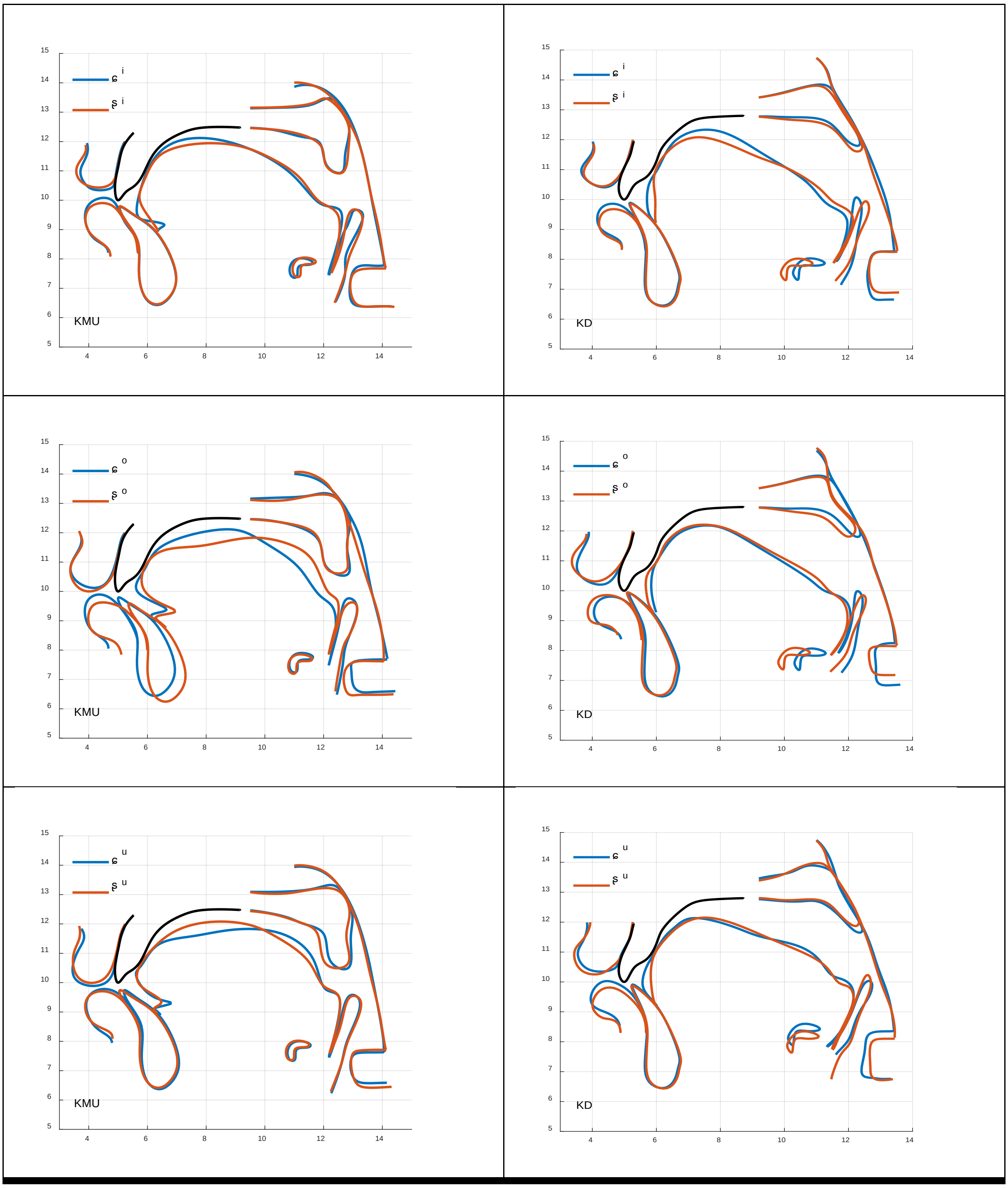
Kochetov *et al.* (submitted) An MRI-based articulatory analysis of the Kannada dental-retroflex contrast. The Journal of the International Phonetic Association.

Supplementary material S6: Comparisons of retroflex and alveopalatals sibilants

Articulation

Figure 1 displays the superposition of the retroflex sibilants (in blue) and alveopalatals sibilants (in red) in the five separate vowel contexts for the two speakers (first five rows) and averaged over the five contexts (last row). These comparisons show that both sibilants are produced nearly in the same way as alveopalatals, with the entire tongue fronted and raised towards the hard palate. One apparent exception is the context next to /o/, where /ʂ/ is produced by KMU with a somewhat flatter tongue shape and a lower jaw, relative to /ɕ/. Next to /u/, however, it is /ɕ/ that shows a somewhat flatter tongue shape. These few differences may not be therefore representative of distinct articulations, but reflect token-to-token variation.

Speaker KMU	Speaker KD
	
	


ɕ i
ʂ i
KMU
ɕ i
ʂ i
KD
ɕ o
ʂ o
KMU
ɕ o
ʂ o
KD
ɕ u
ʂ u
KMU
ɕ u
ʂ u
KD

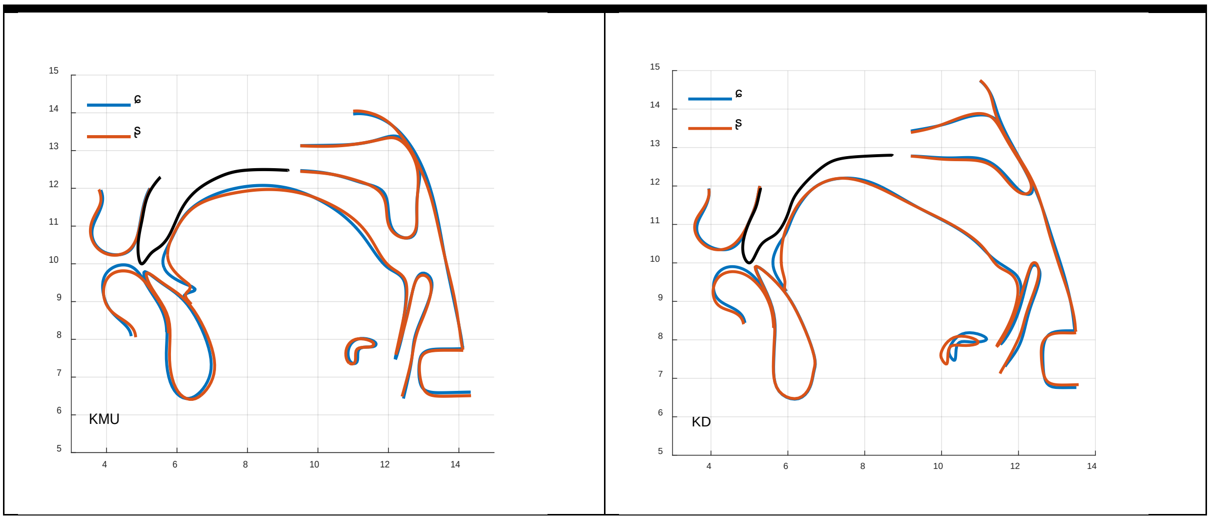
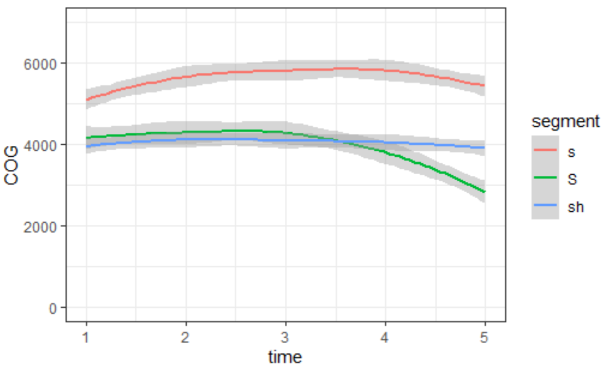


Figure 1. MRI tracings of /ʂ/ and /ɕ/ by speakers KMU and KD, separately by vowel context (first five rows) and averaged across vowels (last row).

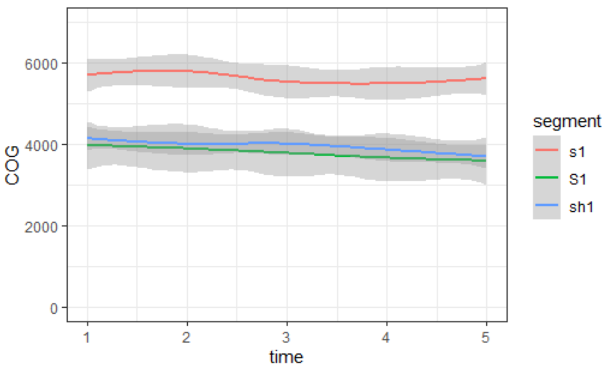
Acoustics

Figure 2 shows measurements of Centre of Gravity (COG) of fricative noise[1] for the sibilant fricatives /ʂ/, /ɕ/, and /s/ (as a control) measured over time in normal (left) and sustained (right) productions by the speakers KMU (top) and KD (bottom). It can be seen that the COG trajectories for the two posterior sibilants are near-identical and are much lower than the trajectory for the anterior fricative. The only difference we can observe between /ʂ/ and /ɕ/ is towards the end of the frication interval for KMU (a). This is because this speaker tended to produce /ʂ/ with some aspiration.

Speaker KMU

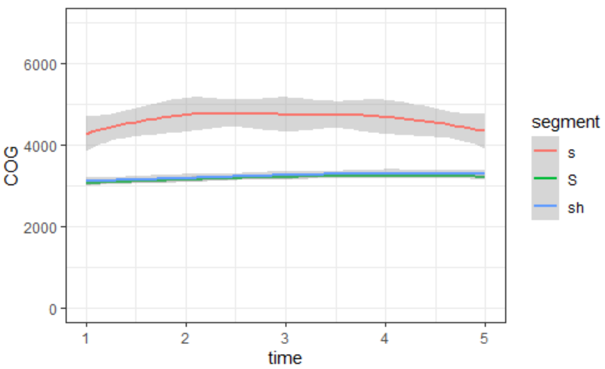


a.

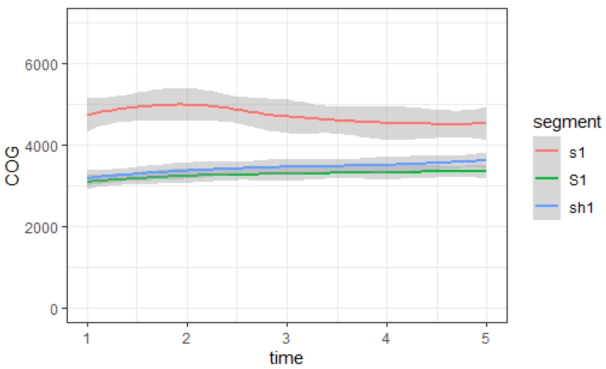


b.

Speaker KD



c.



d.

Figure 2. Measurements of Center of Gravity of fricative noise taken at five equidistant points during the frication interval for /ʂ/ ('S'), /ɕ/ ('sh'), and /s/ produced across five vowel contexts in normal productions (a, c) and at the beginning of the sustained productions (b, d) by speakers KMU (a, b) and KD (b, d); the trajectories were plotted using the `geom_smooth()` function and the 'loess' method in ggplot2 (Wickham (2009)).

[1] The annotation of fricatives and COG measurements were performed in Praat (Boersma & Weenink (2021)).

Conclusion

To conclude, both articulatory and acoustic measurements point to a lack of contrast between /ʂ/ and /ɕ/ as produced by our speakers (with the exception of post-aspiration possibly distinguishing the two consonants by KMU). The contrast appears to be neutralized towards the alveolopalatal.

References

Boersma, P. & Weenink, D. (2021). *Praat: doing phonetics by computer [Computer program]. Version 6.1.40, retrieved 27 February 2021 from http://www.praat.org/*.

Wickham, H. (2009). *ggplot2: Elegant graphics for data analysis*. New York: Springer-Verlag.