AN ULTRASOUND INVESTIGATION INTO ARTICULATORY VARIATION IN AMERICAN /r/ AND /s/

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ABSTRACT

This ultrasound study investigates articulatory variability in American English /r/ and /s/ production in onset and coda position, and in the context of the vowels /a, i, o/. Variability both between and within participants is examined. Between speakers, our data support the position of Brunner et al.[2] that flatter palates are correlated with less articulatory variability. Within speaker, our data suggests that articulation of either /r/ or /s/ does not predict articulation of the other.

Keywords: Ultrasound, coronals, palate, variation

1. INTRODUCTION

This study considers the possible causes for patterns in articulatory variation within and across individuals. American English coronals in particular are known to vary. Here we focus on /r/ and /s/.

The English rhotic /r/ falls on a continuum. The two endpoints are retroflex, in which the tongue tip points up, and bunched where the primary constriction is formed by a raised tongue body. These two endpoints are referred to respectively as 'tip-up" and "tip down"[6]. Delattre and Freeman [5] identify eight different classifications along this continuum. The sibilant /s/ can similarly falls on a continuum from tip-up to tip-down. In an apical /s/, the tongue has a flat surface, and the tongue tip points up. In the laminal /s/, the tongue tip points down, and the tongue has a more domed contour [1, 3].

Many contexts may condition this variation of articulation. Mielke et al. [8] found that in the case of /r/, some speakers use one articulation in all contexts. Some patterns are syllable-based, such as retroflex in onset and bunched in coda. Speakers may vary their articulations based on phonotactics, favoring a bunched articulation in front vowel contexts but a retroflex articulation elsewhere. Social factors can also influence the variant and individual uses. Lawson et al. [6] found that for speakers of Scottish English, gender and social class were significant factors for predicting bunched versus retroflex /r/. Each study examined only a single consonant, which raises a hypothesis concerning whether speakers have a gestural phonology, such that the articulation of one consonant is related to the articulation of another.

Another possible factor contributing to speakers' ability to vary is anatomy. Individuals vary in palate size and shape [9]; Brunner et al. [2] have proposed that there is a relationship between palate shape and articulatory variability. In their electropalatographical study of front vowels, they found that individuals with flatter, less domed palates exhibit less articulatory variation because, all else being equal, tongue displacement should result in greater acoustic change. In other words, such a shape requires greater articulatory precision to reach the desired acoustic target than a domed palate.

This study asks whether the articulation of /r/ predicts the articulation of /s/ in the same speaker, and whether an individual's articulations are related to palate shape.

2. EXPERIMENTAL METHODS

2.1. Participants and Stimuli

Twelve native speakers of Californian English participated in this study (3 male) and received $15. Data from four (female) are analyzed so far.

Stimuli (see Figures 2 and 3) were English CV(C) words that contained /r/ or /s/ in onset or coda. The vowel environment was {a, i, o}. All words were presented in the carrier phrase "I'm a _____."

2.2. Methods and Analysis

Ultrasound was recorded using an Ultrasonix SonixTablet using a C9-5/10 microconvex transducer, operating at 107 fps. Audio was recorded with an AKG 535 EB microphone at a 48kHz sampling rate and digitized with a Steinberg UR22 USB audio interface. A synchronization file that served as a key between time in the audio and corresponding ultrasound frames was also created.

A stabilization helmet from Articulate Instruments Ltd was used to hold the ultrasound probe in place under the chin in the sagittal plane. A teleprompter displayed the test items, and the set of stimuli was randomized and repeated eight times. Participants also swallowed a small amount of water to generate a palate trace. Additionally a palate cast was taken. Participants held a dental tray filled with alginate against the palate and upper dentition. Dental stone was poured into the resulting impression to form a permanent model of the participant's palate.

For each utterance, a frame corresponding to the acoustic midpoint of the segment was determined, and subsequent analyses were performed on those frames. Edgetrak [7] was used to trace the tongue contours in the selected ultrasound frames. These traces were then visualized using the SSANOVA package [4] in R. These traces were used to make initial categorical observations visually, which were corroborated through principal components analysis (PCA). PCA is a dimensionality reduction analysis technique for data such as numbers or images that finds components along which variance in the data can be accounted for. ANOVAs were performed on individuals' PC1 and also on the group as a whole. We are considering PC1 here because it accounts for most of the variance across subjects. All reports of significance come from Tukey post-hoc tests at p < .05. Figure 2 shows how PC1 groups /r/ by vowel.

3. RESULTS AND DISCUSSION

The following sections explore the articulatory variability within and across participants. Subjects differ from each other in terms of the phonological contexts in which their tongue shapes may be grouped. This does not apply only to subjects who have two different qualities of tongue shape (e.g. retroflex and bunched); even within one category distinct differences in tongue shape are observed. Tongue and palate tracings are shown by segment and participant in Figure 1.

3.1. Within-participant variation

3.1.1. 102

Participant 102 (as shown in Figure 1, first column) has a laminal /s/: the tongue body is domed and the tongue front slopes downward. Onset /s/ in the /a/ and /o/ environments have nearly identical tongue shapes but there is fronting and a more domed shape before /i/. This is true in coda position as well but with slightly less variation. Regardless of vowel context, the tongue blade is roughly the same distance from the palate, and the coronal region of the splines overlap at the point of constriction.

3.1.2. 103

The /s/ for participant 103 (Figure 1, second column) is on the apical side of the apical-laminal spectrum. In onset position, the tongue body varies in height, domedness, and retraction; it is more fronted and domed before /i/ than before /o/ and /a/. Similarly, in coda position the tongue body shows varying amounts of fronting by vowel context.

This is the only participant of the four analyzed so far with a retroflex /r/. The rhotic is always retroflex in onset position before /a/ and /o/, but bunched before /i/, a common pattern for retroflexers [8]. Coda /r/ is always bunched. (In the figure, SSANOVA extrapolates beyond the retroflexed tongue tip.) Although there is variation in tongue shape *type* (i.e. bunched or retroflex) by syllable position, within type there appears to be very little variation by vowel context, except for a following /i/, which is dissimilar from the other onset /r/s in the direction of the coda /r/.

3.1.3. 106

The participant's (Figure 1, third column) /s/ shows almost categorical differences by vowel context in both onset and coda, with a more apical articulation before and after /a/ but a more laminal articulation in the context of /i/ and /o/. While the bunched tongue shape is nearly identical in all environments for coda /r/, the amount of fronting differs in onset /r/.

3.1.4. 109

Participant 109 (Figure 1, fourth column) shows the least variation of all the subjects. The /s/ is apical, with nearly identical contours before /a/ and /o/ but some blade raising before /i/. The tongue tip splines lie directly on top of each other in all vowel contexts. There is minimal difference between onset and coda /s/; the tongue blade for /s/ following /o/ is slightly higher than for /s/ preceding /o/. The tongue shapes for /r/ are surprising in that, unlike onset /r/ for any other participant, they have very little variation in any context.

3.2. PCA

For each subject a six-way ANOVA was performed with dependent variable PC1 and factor "word." A significant main effect of word was found for all speakers (102, $F(5,38) = 8.171, p < 0.0001$; 103, $F(5,41) = 89.58, p < 0.0001$; 106, $F(5,42) =$

Figure 1: Average tongue shape by vowel and palate trace. From top: onset /s/, coda /s/, onset /r/, coda /r/.

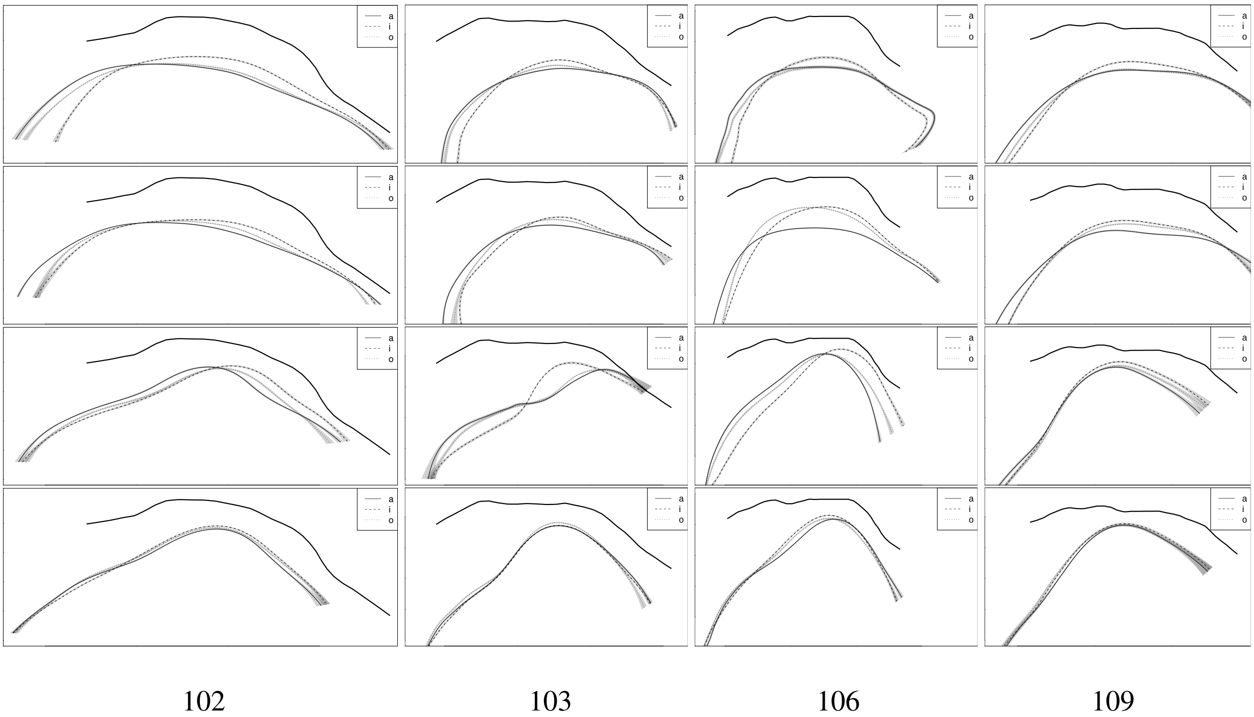
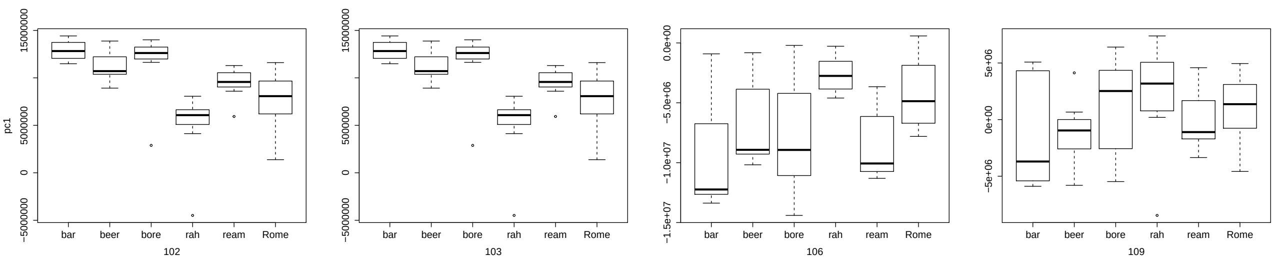


Figure 2: Values for PC1 given by subject and stimulus for /r/.



$3.98, p < 0.0048$) except 109 ($F(5,42) = 0.95, p = 0.4580$). This therefore suggests that for 109 no significant difference exists in the /r/ tongue shapes, corroborating our initial observations. For the remaining speakers we report differences based on Tukey HSD post hoc tests. Only significant p-values ($<.05$) are reported from the post hoc test.

For /r/, we observed that participant 103 had the most variation, then 102, 106, and finally 109 with the least. We expect this to translate into significant differences between phonological contexts for 103 and not for 109.

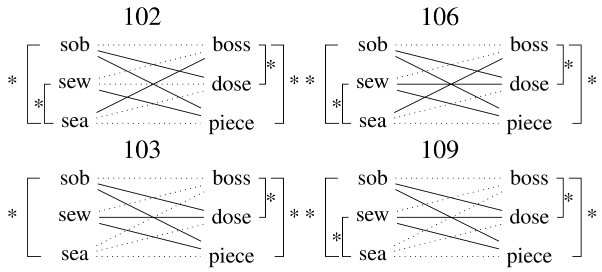
Along the first principal component (PC1) for 103, coda position /r/s formed a distinct group on their own. /r/ before /a/ and /o/ are not significantly different from each other, but they are different from coda /r/ as well as /r/ before /i/ (all $p < 0.0001$) as expected because 103's /r/ before /a/ and /o/ are retroflex, while her /r/s before /i/ are bunched. Despite the similarity in shape in bunched onset /r/ and coda /r/, the PCA demonstrates that they are significantly different ($p<0.0001$).

Like 103, 102's values for PC1 in coda /r/s were not significantly different, but unlike 103, PC1 for /r/ before /i/ patterned with them. This group was significantly different from /r/ before /a/ (for coda, $p < 0.002$; else $p = 0.04$) but *not* /r/ before /o/, even though /r/ before /a/ is not significantly different from /r/ before /o/. Thus /r/ before /a/ seems to represent one extreme value of PC1, /r/ before /o/ falls somewhere in the middle, and the rest form a group at the other end.

The tongue shapes for 106's /r/s were all bunched. The only significant differences found were between /r/ before /a/ and /r/ before /i/ (p = 0.036) and onset and coda in the context of /a/ (p = 0.008).

3.3. Across-participant articulatory variation

Figure 3: Solid lines and stars show significant differences in articulation of /s/ in word pairs; dotted lines are not significant.



Only one participant had retroflex /r/ in any context, so it is difficult to make a strong conclusion about the relationship between tip-up and tip-down articulations within participant. This participant also had tip-up /s/ in both onset and coda, but tip-up /r/ in onset position only. Additionally, other participants had bunched /r/ alongside apical /s/. The evidence does not support a correlation between tip-up and tip-down articulations.

Some degree of fronting was observed in nearly all front-vowel context productions, and most participants showed less variation in coda than onset positions. Although the principal components themselves for each segment can not necessarily be compared across subject, what they show is that each subject has a unique set of similar /r/ shapes in different vowel contexts.

Although the /s/ shapes themselves vary across participants, a nearly identical pattern of /s/ shapes is found for all subjects. The relationships of significance in phonological context is shown in Figure 3. The main conclusion to be drawn here is that there is an asymmetry with /o/. /s/ *before* /o/ tends to pattern more with /s/ in the context of /a/, but /s/ *after* /o/ tends to pattern with /s/ in the context of /i/.

What emerges from the PCA that could not be predicted from tracings alone is the fundamental difference in /r/ patterns and /s/ patterns. All four participants analyzed so far exhibit a unique pattern of /r/ shapes, whereas everyone had an almost identical pattern for /s/ shapes, with two minor exceptions. This suggests that the tongue shape for /s/ is likely to change due to co-articulatory pressures, whereas the shape of /r/, while likely influenced by adjacent vowel, is less continuously variable than /s/. The co-articulatory hypothesis is supported by the asymmetry observed in the behavior of /s/ in the context of /o/. The similarities in /s/ tongue shape appear correlated with which end of the /o/ the /s/ occurs on: the beginning of the diphthong is more open and thus has more in common with /a/, and /s/ before /a/ and /o/ are similar. Likewise, the end of /o/ is closer and possibly more fronted and thus has more in common with /i/, and /s/ after /i/ and /o/ are similar.

3.4. Palate shape

Variation in shape and size of palate may explain some of the articulatory variation observed in the data. Table 1 gives a measure of domedness (α) described in Brunner et al.[2]; this value is based on a ratio of height to width and is therefore inversely correlated with domedenss.

Table 1: Palate α values as in Brunner et al.

102	103	106	109
1.9	2.6	2.3	2.7

Participant 109 has the highest α and also shows by far the least variation in tongue configuration. Although 103 showed qualitative variation for /r/, within category little difference was observed. This extends to /r/ and /s/ the Brunner et al. [2] finding for vowels that a flatter palate provides less room for variation.

4. CONCLUSION

No reliable retroflex-apical/bunch-laminal correlation was found. The only retroflexer does have apical /s/ as would be predicted if such a correlation existed, but in the contexts where she has bunched /r/ she still has apical /s/. Further, Participant 109 has bunched /r/ in all contexts and a fairly apical /s/.

The participants here are different from one another not only in the qualitative articulations (retroflex/bunch, apical/laminal) they exhibit but also in the amount of articulatory variation within a single speaker. Participants 103 and 109 have the least domed palates, and within /r/ articulation quality they show little articulatory variation. Although each participant has an idiosyncratic set of similar /r/ segments, all participants have nearly identical patterns for /s/, indicating that the two consonants are fundamentally different in how their tongue shapes are influenced by coarticulation.

5. REFERENCES

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