An analysis of vocal tract shaping in English sibilant fricatives using real-time magnetic resonance imaging

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Abstract

This study uses real-time MRI to investigate shaping aspects of two English sibilant fricatives. The purpose of this article is to 1) develop linguistically meaningful quantitative measurements based on vocal tract features that robustly capture the shaping aspects of the two fricatives, and 2) provide qualitative analyses of fricative shaping. Data was recorded in both midsagittal and coronal planes. The proposed three quantitative measures of this study provide robust results in categorizing shape. The qualitative analyses describe tongue shape in terms of grooving and doming and they support previous research.

Index Terms: real-time MRI, fricatives, sibilants, tongue shape analysis

1. Introduction

Real-time magnetic resonance imaging (RT-MRI) promises a new means for visualizing and quantifying the spatio-temporal articulatory details of speech production. This study uses rt-MR imaging to study the shaping and dynamic aspects of two English sibilant fricatives /s/ and /S/. The RT-MRI data, which affords views of the entire moving vocal tract, and is accompanied by synchronized audio recordings, aims to build upon, and add to, the several excellent previous/ongoing studies that aim to fully capture the static and dynamic properties of fricatives. Acoustic studies are capable of illuminating the dynamical nature of fricatives, as changes in formant structure indicate changes in the vocal tract while producing speech sounds, (e.g., [1], [2]). However, acoustic studies are unable to characterize the exact shaping of the tongue (and perhaps other articulators) necessary for the production of fricatives. Other experimental methods for obtaining speech production information (e.g. EMA, static MRI, x-ray, etc.), lack information about change over time, or lack the spatial resolution necessary to properly characterize the complete shape of articulators during the production of fricatives. RT-MRI provides an ideal tool for measuring both the posture and temporal (dynamic) properties of fricatives and the effect of surrounding vowel context on the fricatives, as MRI provides us a (nearly) complete picture of the dynamics of the vocal tract. RT-MRI additionally provides valuable insights into the production of fricatives as it is able to examine the shaping of such fricatives in various planes. The current study employs this technique to obtain data from both midsagittal and coronal planes of the vocal tract.

Specifically, the aim of this paper two-fold. The primary objective is to investigate various derived measurements from MR images that are linguistically meaningful. These measurements are based on tongue shape and other properties of the vocal tract seen in the MR images, and they allow for analysis of the two fricatives under examination. The measurements described below allow for the explicit study of shaping differences between the tongue tip and tongue body gestures of /s/ and /S/. Sibilant fricatives are of particular interest because of the complexities displayed in their shape during production. This shaping of fricatives (e.g. the grooving of the tongue for sibilant fricatives) has shown to be crucial in yielding their acoustic properties necessary for perception [3]. Thus, defining measurements that allow for shape to be investigated as a variable is crucial for the validation of any hypothesis addressing the role of shape in the production of fricatives. Three derived measures are shown to yield linguistically meaningful results. They are 1) tongue-palate area behind fricative constriction (midsagittal), 2) tongue-palate area deformation (midsagittal), and 3) fricative groove-depth (coronal). These measurements are discussed in the methods section.

Secondly, the study aims to describe various strategies used by speakers to produce sibilant fricatives. Based on previous research on the shaping of English fricatives (e.g., [4]) it is expected that /s/ will show grooving of the tongue and /S/ will show doming of the tongue. This study also asks what effect surrounding vowel context will have on the shaping of the fricatives. The fricatives under examination were preceded and followed by the vowels /i/ and /a/. The vowel /i/ has been described as showing a convex dome-like shape, whereas /a/ is considered to be flat [5]. The study thus seeks to determine what happens when two contrasting shapes (such as flat /a/ and grooved /s/) are adjacent. Two possible hypotheses are considered: target shaping in the fricative will be more pronounced when contrasting shapes are adjacent, or target shaping in the fricative will be more pronounced when comparable shapes are present.

Several previous studies using MRI have shown shape as crucial parameter in the production of fricatives. Co-articulatory effects have been shown to be important in describing the shape of Swedish fricatives [6]. When examining English sibilant fricatives with MRI, various observations about tongue posture have been shown to be important. /S/ has been shown to be articulated with a raised tongue blade that is distributed across the alveolar ridge. /S/ also shows a sublingual cavity behind the constriction, whereas [s] shows an absence of a sublingual cavity [7]. The concave shaping of the tongue has also been shown to be crucial for the production of English sibilant fricatives; /s/ consistently shows concavity behind the constriction region, whereas /S/ does not [4]. The area posterior to the constriction has also been shown to be important: the area functions derived for /s/ tend to be less smooth than those for /S/. This difference has been shown to be due to a slight raising of the tongue for /s/ postures. This study further investigates the importance of the area behind the constriction during fricatives, examining area and area deformation behind the tongue. These two variables are shown to be important to quantitatively characterize the shaping differences in the two fricatives.

2. Methods

Three native speakers of American English were used as subjects, two female (A2, S2), and one male (A1). Subjects had no known speech or hearing deficits.

2.1. Simuli

The fricatives /s/ and /S/ under analysis occur between either the vowels /i/ or /a/ in a carrier phrase ("Go pVCVp okay", V={/a, i/}, C={/s, S/}). There are four different surrounding vowel contexts: symmetrical: /i_i/, /a_a/; asymmetrical: /i_a/, /a_i/. As

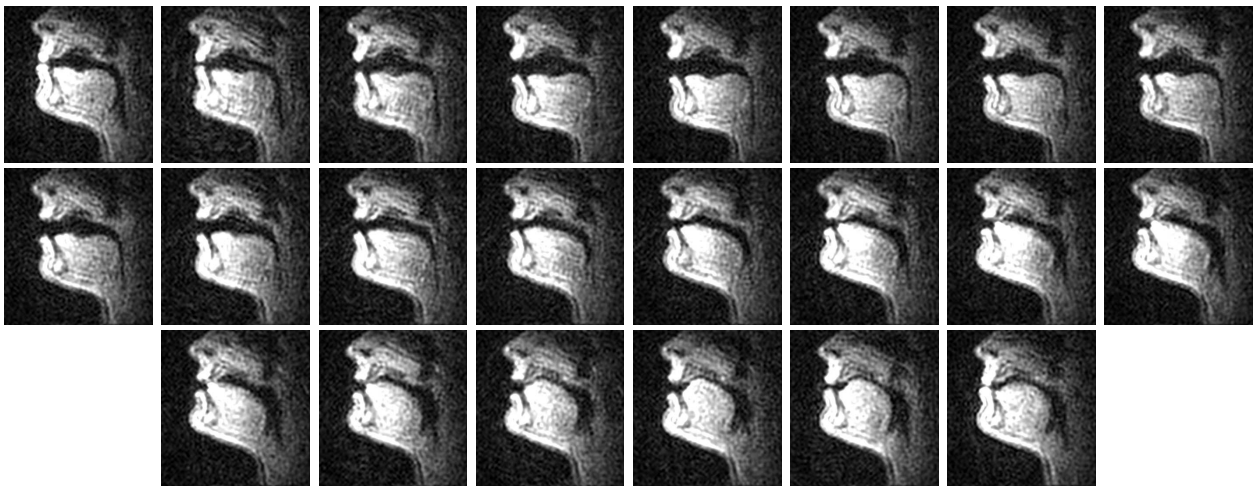


Figure 1: Production of “pa seep” by subject S1 in 22 midsagittal images (from left to right, top to bottom).

there are two different fricatives, this yields eight different stimuli.

The sentences were grouped into fourteen blocks, seven blocks for each fricative. Thus each stimulus was read seven times by each subject. Each block containing four sentences was randomized, and the order of the blocks was randomized, with the constraint that blocks alternated according to fricative (two /s/ blocks were never consecutive).

2.2. Real-time MRI and synchronized audio aquisition

MR images were acquired on a GE Signa 1.5 Tesla scanner using a fast gradient echo pulse sequence with a 13-interleaf spiral readout [8] within the RTHawk framework [9]. A four-channel targeted phased-array receiver coil was employed. Images were formed from the data of two coils located in front of the subject’s face and neck through root sum of squares combining. The repetition time TR was 6.376ms. The MRI resconstruction was carried out using a standard gridding and sliding-window technique [10] with a window offset of 7 acquisitions. The resulting in a frame rate for processing and analysis was 22 frames per second. The slice thickness was 3mm.

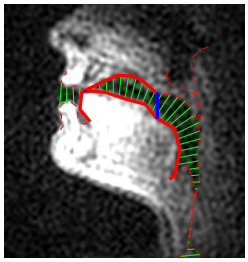
Images were acquired in the midsagittal plane and in a coronal plane. The midsagittal field-of-view (FOV) was chosen to capture the entire vocal tract from glottis to lips. The image rotation was chosen so that the pharyngeal wall is approximately vertical. A sample midsagittal image sequence of the utterance “pa seep” is shown in Figure 1. The coronal scan plane was selected prependicular to the midsagittal scan plane at the position of maximal doming of the hard palate. The FOV was identical in size with respect to the midsagittal value. A sample coronal image is shown in Figure 4.

Simultaneous synchronized speech audio was collected during the MRI scans. Subsequently, a noise cancellation procedure was applied to the audio signal to remove the MRI gradient noise [11]. Sample videos are available at http://sail.usc.edu/span/interspeech2008/index.php.

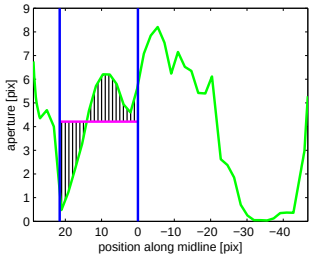
2.3. Image analysis

In the midsagittal MR images the vocal tract contours were traced using the procedure described in [12]. Figure 2(a) shows an example midsagittal MR image of the fricative /s/ during its maximum constriction. Here the red lines deliniate the outline of the vocal tract, and the green lines are the aperture lines which were computed using the methods described in [13].

In order to quantify the spatio-temporal shaping characteristics of the speech sounds of interest appropriate geometrical features have to be derived from each image. For the fricative sounds /s/ and /S/ one candidate feature is the midsagittal aperture at, and posterior to, the critical vocal tract constriction, which in these cases is formed using the tongue tip and the alveolar ridge/front palate. We hence proceed by defining a region of



(a) *Midsagittal real-ime MR image with vocal tract contours (red), aperture lines (green), and tongue-palate region boundaries (blue).*

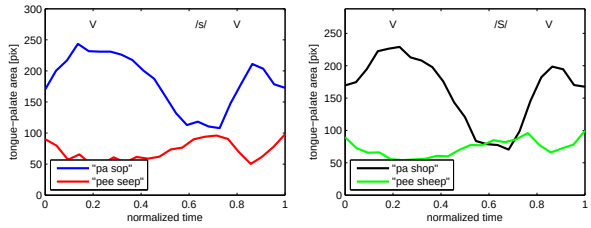


(b) *Aperture function (green), tongue-palate region boundaries (blue), mean aperture in tongue-palate region (magenta), and aperture deformation area (black).*

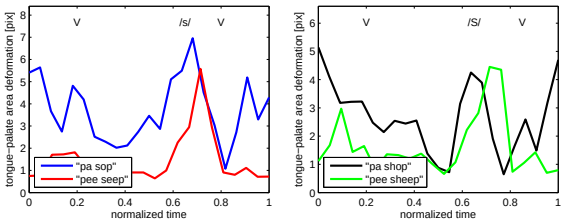
Figure 2: *Midsagittal sample image and geometrical features during the fricative production in “pa seep.”*

interest in the midsagittal profile of vocal tract bordered by the minimum opening between tongue and hard palate on the left (left blue line in Figure 2(a)) and a vertical line dropping from the hinge point of the velum (right blue line in Figure 2(a)). The selection of these boundaries is motivated by the relatively reliable detection of these anatomical landmarks. Figure 3(a) shows the time evolution of the size of this tongue-palate area for single tokens of the utterances “pee seep” and “pa sop.” During the interval of the fricative production, which was identified for all tokens using the spectrogram of the synchronized audio recording, we observe a local minimum in the time function for the /a_a/ context and a local maximum for the /i_i/ context. The same holds for the /S/ sound as shown in Figure 3(b).

However, in order to better discriminate between the shaping difference of /s/ and /S/ it is also desired to devise a shape feature that is largely independent of the morphology of the subject’s hard palate. To be more specific, we would like a measure of how parallel the palate and the tongue contours are in the region of interest in order to be able to deduce information on the nature of the airway channel. We hence propose the use of a tongue-palate area *deformation* measure, which is illustrated in Figure 2(b). Here, the aperture function is shown (green) in addition to the location of the boundaries of the tongue-palate area of interest (vertical blue lines). As the deformation measure we use the variation (black shaded area) of the aperture about its mean value (magenta line) in the region of interest. This scalar *deformation* value will be near zero if the tongue is largely parallel to the hard palate, irrespective of the actual shape, and it will be large for non-parallel configurations. Figures 3(c) and 3(d) show sample time functions for the *deformation* feature for /s/ and /S/,



(a) *Tongue-palate area for /VsV/.* (b) *Tongue-palate area for /VSV/.*



(c) *Tongue-palate area deformation for /VsV/.* (d) *Tongue-palate area deformation for /VSV/.*

Figure 3: *Midsagittal features sample time functions.*

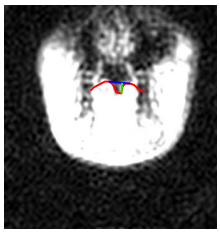


Figure 4: *Coronal sample image, tongue contour (red), groove tangent (blue), grove depth feature (green) during the fricative production in "pa seep."*

respectively, for the /a_a/ and /i_i/ context, and we observe a local non-parallelity maximum during the interval of the fricative production. We assume that at the maximum point the constriction target was achieved the preparation of the production of the following vowel will set it.

Our subsequent investigations will utilize the averaged maximum *deformation* over all tokens of a particular type, as well as the averaged area size at the time of maximum *deformation*. However, at this point we also want to point out a limitation of the proposed feature extraction process. As can be seen in Figure 1 the region of the hard palate is generally subject to rather larger image noise. This likely due to the fact that it consists of bone which is covered with a rather thin layer of soft-tissue. Since bone has a very low hydrogen content it produces a weak signal to noise ratio leading to faint MRI contrast. Hence the hard palate contour location, if left unconstrained during the automatic tracing process, can be adversely affected more than other sections of the vocal tract contours.

2.4. Coronal plane images

For the coronal images, the tongue contour was traced using a semi-automatic method [13]. Contours were initialized and corrected manually. Figure 4 shows an example coronal image with the traced tongue contour (red).

As the analysis feature of interest we chose the coronal tongue groove depth. It is derived from the coronal tongue surface contour by finding the tangent (blue) onto the surface which forms the triangle with a maximum height (green). This is accomplished through an exhaustive search over all triangle combination of contour points for a given frame.

It should be noted that while the choice of the scan plane here was motivated to capture the nature of shaping in the region behind tongue front constriction (based on [4]), since it was anchored to an anatomical landmark, the images are not expected to align to any key shaping landmark such as maximal grooving for /s/ or doming for /S/, but instead provide an indication of the general shaping in that region.

3. Results

3.1. Descriptive analysis

Differences in the grooving and doming of the two sibilant fricatives and shape of the surrounding vowel were examined. Table 1 describes tongue shaping aspects based on both the coronal and midsagittal planes. Here, "D," "G" and "F" stand for "domed," "grooved," and "flat," respectively. The sequence in each cell is the sequence of the segments: the preceding vowel, the fricative, and the following vowel.

Table 1: *Qualitative analysis of tongue shaping in the three subjects ("D," "G" and "F" stand for"domed," "grooved," and "flat," respectively).*

subject	fricative	/i_i/	/a_a/	/i_a/	/a_i/
A1	/s/	DGD	GGG	DGG	GGD
A1	/S/	DDD	FDF	DDG	GDD
A2	/s/	DGD	FGF	DGF	FGD
A2	/S/	DDD	FDF	DDF	FDD
S1	/s/	DGD	FGF	DGF	FGD
S1	/S/	DDD	FDF	DGF	FDD

Based on previous studies of sibilant fricative shaping (e.g., [4]), /s/ is expected to show concave grooving of the front tongue, whereas /S/ is expected to show convex doming. The vowels are also expected to show specific shapes: /i/ has a domed tongue shape, and /a/ is expected to be flat (or sometimes, slightly concave).

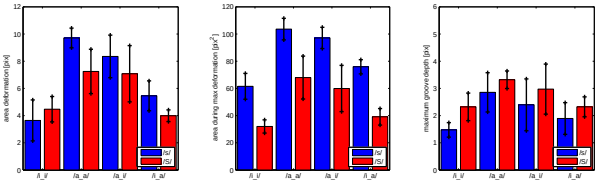
The expectations are largely seen in the speakers' productions in this study. Speaker A2 behaved the most canonically with respect to the above expectations. /i/ and /S/ both showed doming, whereas /s/ showed grooving and the /a/ vowel was flat. Speakers A1 and S1 also behaved as expected; in fact, speaker A1 showed a slight grooving (concavity) of /a/ when this vowel was adjacent to both fricatives.

One hypothesis that is evaluated in the current study deals with the effect of the surrounding vowels on the shaping of the fricative: whether contrasting tongue shapes in the surrounding vowels will cause the shaping of the fricatives to be more pronounced, or whether tongue shape follows "inertia," and the shaping of the fricative is more pronounced with comparable shapes of adjacent vowels. The trends seen in the data support the latter hypothesis. For example, the grooving of /s/ is more profound in the /a_a/ context than in the /i_i/ context. The derived measurements discussed above reveal quantitative support for this finding. These are further discussed below.

Observational differences found in this study also point to wide inter-speaker variability. One such parameter of inter-speaker variability is seen in the symmetry of groove/dome formation in the coronal plane. Subject S1 generally had very symmetrical tongue shapes during the formation of the groove of /s/ and the dome of /S/. This symmetry was not generally seen for speaker A1. A1 had an asymmetrical tongue shape during groove/dome formation; one side of the tongue, to the observer's left of the observed groove in /s/, was often higher than the other side. This asymmetry was likewise observed for /S/: one side of the tongue was higher than the other during the formation of the dome.

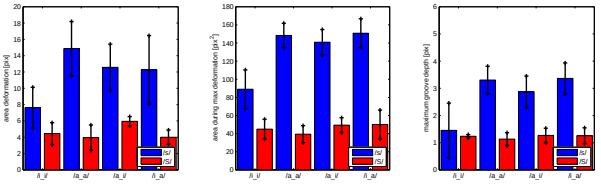
Another dimension of much inter-speaker variability was the tongue front apicality or laminality in producing the fricatives studied. English sibilant fricatives have been described as produced either apically or laminally. The three speakers examined in this study showed wide variability with respect to this aspect. Subject A2 showed an apical /s/ and a laminal /S/. Subject S2 had apical articulation for both /s/ and /S/, whereas speaker A1 had a laminal articulation for both of the fricatives.

The general shaping of the tongue also varied across speakers. Generally, speakers A2 and S1 showed a narrow constriction region for /s/ and a wide constriction region for /S/. Coarticulatory effects of the surrounding vowels also played an important role on the shaping of the fricatives. The constriction for /S/ is made further back before the back vowel /a/ than the front



(a) *Maximum tongue-palate area deformation.* (b) *Tongue-palate area at time of maximum deformation.* (c) *Maximum tongue groove depth.*

Figure 5: *Subject A1 results.*



(a) *Maximum tongue-palate area deformation.* (b) *Tongue-palate area at time of maximum deformation.* (c) *Maximum tongue groove depth.*

Figure 6: *Subject A2 results.*

vowel /i/. It is also seen that the grooving of /s/ is more profound when this consonant is between /a/ than /i/.

3.2. Quantitative analysis

Using the measures discussed above, clear differences between the two English fricatives /s/ and /S/ can be seen. Figures 5, 6, and 7 show the measurements for subjects A1, A2, and S1.

The tongue-palate area at the time of maximum constriction shows robust differences between /s/ and /S/ for all three subjects. The fricative /s/ has a greater tongue-palate area at time of maximum constriction across all vowel contexts.

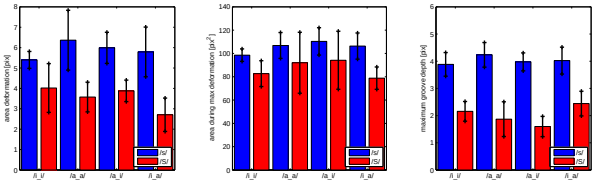
The differences in the measures were most robust for speaker A2. For tongue-palate area deformation and for tongue-palate area, clear differences are seen for the two fricatives. The maximum tongue-palate area deformation for speaker A2 was much greater for /s/ than it is for /S/ across all vowel contexts. The groove depth measurement for the coronal slice shown in Figure 6(c) also yields robust measurements. The grooving for /s/ was consistently seen in all subjects; the groove depth measured from the coronal slice was significantly greater under /a_a/ context than the /i_i/ context, with the other other two vocalic conditions considered showing intermediate values. The coronal plane choice for /S/ was further back in the oral cavity to capture the doming; rather, it provided a slice through the posterior tongue region that shows a cupping formation to support a raised doming in the anterior region [4]. In fact, the derived measures for /S/ do not show any significant variations indicating that this tongue back is not directly manipulated in the constriction formation.

The derived measures proposed in this paper are thus able to robustly account for the differences in articulation between /s/ and /S/.

4. Discussion

The measurements of MR images of the vocal tract discussed here provide useful techniques for studying the differences between the two English fricatives /s/ and /S/. The measurements of area and variance (midsagittal) and groove depth (coronal) are able to provide a way to distinguish between the two fricatives, which is not always a transparent and simple task.

Deriving concrete measurements of the articulatory properties of fricatives is necessary for further studies examining the shaping properties of fricatives. The real-time MRI techniques described here provide for fruitful analyses of the co-articulation effects between vowels and consonants. Examining the concavity of the fricatives with respect to the convexity of /i/ and the flatness of /a/ allows for several linguistic hypotheses to be addressed. The level of explicit control of tongue shape during



(a) *Maximum tongue-palate area deformation.* (b) *Tongue-palate area at time of maximum deformation.* (c) *Maximum tongue groove depth.*

Figure 7: *Subject S1 results.*

fricative production is one such research question that will be considered using the data set discussed above.

Another possible avenue of research involves examining the variability across speakers. In our data, A1 uses a different part of the tongue tip to produce the sibilant fricatives than the other two subjects. Palatal morphology or other physiological differences could play a role. The MR data and measures developed here provide for clear ways of answering this question and others.

5. Acknowledgements

This work was supported by NIH grant R01 DC007124-01. The authors would like to thank the USC Imaging Science Center.

6. References

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