Research Article

Quantifying Tongue Tip Shape in Apical and Laminal /s/: Contributions of Palate Shape

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Purpose: Anterior tongue shape during /s/ production is often described as “tip-up” or apical, versus “tip-down” or laminal. Typically, this is determined by observing the shape of the anterior midline tongue. The purpose of this study was to identify methods of curvature calculation that quantify the observed shape differences and to examine whether the shape differences were affected by palate shape. Previous work shows that palate height has some effect (Grimm et al., 2017).

Method: Four curvature-based measures were applied to a series of points selected along the tongue surface in midsagittal cine magnetic resonance images during speech. The measures were minimal curvature, averaged largest curvature (ALC), normalized ALC, and interpolated normalized ALC. These measures were compared to visual judgments of apical and laminal /s/. Anterior palate shape was measured from dental casts.

Results: The apical /s/ contained a flat or concave region in the anterior tongue, while the laminal /s/ had a convex shape along the entire tongue. Thus, the laminal shape was less complex than the apical. The last 2 metrics, based on averages of multiple normalized curvatures, captured this complexity difference. Subjects with a more steeply sloped anterior palate tended to use laminal /s/.

Conclusions: The tongue shape for the 2 /s/ types was best defined by complexity of the shape, rather than local anterior shape. Statistical quantities that measured curvature in multiple locations, and normalized across subjects, were best at distinguishing the 2 /s/ shapes. Interpolating additional points between the manually selected ones did not improve the method.

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The primary goal of this study is to create a simple, clinically useful method, based on curvature, to objectively quantify midsagittal tongue shape during apical and laminal /s/. The midsagittal tongue was chosen as the measurement site, because the midline vocal tract shape is the best single representative of the three-dimensional (3D) vocal tract contour and because two-dimensional midline data sets are available to researchers

more often than 3D data sets. The anterior tongue was measured because it executes the linguo-alveolar constriction used in /s/. Several curvature methods were tested to determine the one that best captures the shape features used by human observers (raters) when categorizing /s/ type from magnetic resonance imaging (MRI) images. In addition, we considered whether midline palate shape, that is, anterior slope and convexity, affects anterior tongue shape and choice of /s/ type.

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Apical and Laminal /s/

The tongue shape during /s/ is a funnel, wider at the back, which focuses and narrows the airstream into the alveolar constriction and onto the anterior teeth (cf. Stone & Lundberg, 1996). There are two types of /s/ production, apical and laminal (see Dart, 1991). For both types, the sides of the tongue contact the lateral palate and inner surface of the teeth, producing a tongue groove along the vocal tract midline to direct the air stream toward the incisors. The key difference between the two productions occurs

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in the anterior tongue. The apical /s/ creates the alveolar constriction with the tongue tip, while the laminal /s/ uses the tongue blade (Dart, 1991; see Figure 1). Apical and laminal tongue motions are usually categorized subjectively by direct observation of the tongue shape in a midsagittal tongue image (cf. Dart, 1998).

The use of apical or laminal /s/ type has been thought historically to be idiosyncratic and somewhat random across speakers. There is no audible acoustic or perceptual difference between the two /s/ types (Dart, 1991, 1998; Stoner, Gately, & Rivers, 1987). In addition, there is little evidence of languages preferring one type of /s/. Dart (1998) studied /s/ type in 20 English and 21 French speakers based on palatograms and linguagrams. She found 58% of American English speakers and 68% of French speakers used laminal /s/. Icht and Ben David (2018) used self-report to categorize /s/ type in 100 Hebrew speakers. They found about 60% used laminal /s/ with no effect of age, gender, or country of birth. Understanding the differences between /s/ types is useful when training speakers to produce a correct /s/, however. It is easier for a patient to correct their /s/ in the direction of their natural preference, apical or laminal.

Quantification of Tongue Surface Shape

Tongue shape differences due to phoneme categories have been quantified from ultrasound images of the midsagittal tongue. Curvature signatures and polynomial functions quantify global tongue shapes in isolation, because ultrasound images do not capture other vocal tract features (Morrish, Stone, Shawker, & Sonies, 1985; Morrish, Stone, Sonies, Kurtz, & Shawker, 1984). A combination of curvature signatures and polynomial functions comprise the curvature index (CI; Stolar & Gick, 2013). The CI method applies a seventh-order fit to a tongue surface contour and then integrates the curvature of every point in the fit to create a single quantity representing tongue shape complexity. That study found that the /s/ and /z/ midsagittal tongue shapes are among the lowest in shape complexity for English phonemes; the study did not examine apical and laminal contrasts. In another study, Dawson, Tiede, and Whalen (2016) compared a modified CI to a Procrustes analysis (translation, rotation, scaling) and Fourier analysis (discrete Fourier transform) of ultrasound tongue shapes. The three methods

were all successful at labeling tongue shape complexity, with discrete Fourier transform being the best. Principal component analysis also provided good success in eliminating noise effects and facilitated quantification of tongue shapes from X-ray and ultrasound images (cf. Harshman, Ladefoged, & Goldstein, 1977; Hoole & Pouplier, 2017; Slud, Stone, Smith, & Goldstein, 2002).

This study is interested in subtle, local tongue shape differences between /s/ types, not the global effects of phonemic categories. The study uses MRI because it does a good job at imaging the anterior tongue, where the /s/ constriction and the apical/laminal differences are located. MRI has had more success in distinguishing apical and laminal /s/ than ultrasound. Narayanan, Alwan, and Haker (1995) used MRI to study /s/ type and found that apical fricatives showed deeper grooving behind the constriction than laminal ones. Our study aims to develop a quantity that captures subtle and local differences between laminal and apical /s/, which may include tongue shape complexity and which should be applicable to distinguishing other sounds that differ in only one region of the tongue.

Palate Effects

Our previous studies of /s/ type used MRI and dental casts to identify effects of palate height on /s/ type. Stone et al. (2013) and Grimm et al. (2017) compared palate vault height to /s/ type for single words in glossectomy patients and healthy controls. They showed that controls with low palates tended to use apical /s/, while those with high palates tended to use laminal /s/. It is possible that a low palate does not provide sufficient clearance for the tongue body elevation observed in laminal /s/. Alternatively, palate height could change the aerodynamics of the airflow into the constriction, thus affecting the nature of /s/ production.

Studies of palate doming offer another perspective on the effects of the hard palate on tongue behavior. Palate doming combines palate height and width, often by fitting a quadratic function to a coronal section of the palate. Three studies examined the effect of palate doming on /s/ variability. Brunner, Fuchs, and Perrier (2009) examined variability in Electropalatography contact patterns and found that speakers with low domed palates used little articulatory variability in target Electropalatography pattern for /s/, whereas some with high domes had large variability. Yunusova, Rosenthal, Rudy, Baljko, and Daskalogiannakis (2012) used Electromagnetic Articulography to measure variability in tongue height during consonants. They also found that subjects with low domed palates had less variability than those with high domed palates. Bakst (2016), in a principal component analysis of ultrasound images, also found that subjects with low domed palates had less articulatory variability in /s/ than those with high domed palates. These studies did not statistically analyze apical versus laminal effects. This study will consider only midline palate shape, that is, how the slope and convexity of the anterior midline palate influence the shape of the anterior tongue and the choice of apical versus laminal /s/.

Figure 1. Mid sagittal magnetic resonance imaging images of apical (left) and laminal (right) /s/.

MRI

MRI uses a strong magnetic field and radio-frequency excitations to image various properties of the hydrogen atoms in tissue (cf. Brown, Haacke, Cheng, Thompson, & Venkatesan, 2014). Soft tissue has a high water content, so MRI is a highly useful and minimally invasive technique to study soft tissue anatomy (cf. Stone et al., 2018). Cine MRI (as in cinema) can be used to capture the dynamic movements of subjects' tongues while performing speech tasks, enabling morphological characterization at the instant the /s/ sound is generated. Cine MRI captures image information over several minutes while the subject repeats the task, and this information is pieced together to create a movie that represents a single execution of the task. Cine MRI yields lower spatial resolution than that of anatomical MRI, which is captured while the subject lies still for several minutes. However, movies generated by cine MRI have sufficient spatial resolution to allow clear visualization and measurement of the midline tongue surface (see Figure 1).

Curvature

Most studies categorize /s/ production using visual inspection of data. Human raters attempt to distinguish between the two /s/ types by observing the midsagittal tongue profile (see Figure 1). This study aimed to validate this type of categorization with a more objective measure of /s/ type, namely, the curvature of the anterior midline tongue. Human ratings of /s/ type were used to test four curvature-based metrics that represent local and global tongue shape properties.

The curvature value, κ , represents the degree of deviation from a straight line at a point within a series of points (Cassey, 1996). Here, the local curvature can be positive (i.e., arched or convex), zero (i.e., flat), or negative (i.e., depressed or concave). The midsagittal tongue profile in its entirety is naturally arched, or convex, at rest reflecting the curve of the vocal tract. Elevation of the tongue tip will reduce that convexity locally, more than elevation of the blade. Therefore, this study expected laminal /s/ to have a convex anterior tongue profile, because the blade is elevated by the body toward the alveolar ridge. For apical /s/, the anterior tongue profile was expected to be flatter or even concave, because the tongue tip is elevated to a greater extent than the tongue body.

Two hypotheses were proposed. First, curvatures for apical /s/ were expected to be higher dimensional than those for laminal /s/ due to a local flatness or concavity in the anterior tongue for apical /s/. Second, we expected that steeper palate slopes and a more protruded (convex) alveolar ridge region would result in apical tongue shapes, with a less high tongue body, to properly funnel the air into the constriction.

Materials and Method

Subjects

Participants for this study were 20 healthy, native speakers of American English, who spoke with a Maryland

regional accent. They were chosen from a larger database containing MRI and dental data, and many have been used in previous studies, such as Stone et al. (2013) and Grimm et al. (2017). The subjects had normal hearing test results, including acuity, word recognition tests, and speech reception thresholds. The subjects had an average age of 35.8 years ($SD = 12$) and included nine males and 11 females ($n = 20$).

Speech Task

The speech task was /əsuk/ ("a souk"). This task was chosen for several reasons. First, it begins with a fairly neutral tongue position (schwa), and after the forward movement into /s/, the tongue motion is in a straightforward backward/upward direction. Second, the high vowel minimizes jaw motion, maximizing the deformation of the tongue when creating the sounds. Finally, the cine image acquisition was limited to 1 s to allow comparison between these data and tagged data collected in the same session (not used in this study). For these subjects, there was a distribution of /s/ types, with 12 apical and eight laminal speakers (see Figure 2). Categorization of apical or laminal /s/ for each subject was done independently by a speech scientist and two dentists trained by the speech scientist. The time frame in which the tongue-palate constriction first appeared for /s/ was chosen for measurement. The three raters used visual inspection criteria consistent with Dart (1991, p. 12), who used the terms to refer to the part of the tongue used to make the constriction. Apical refers to the tip; and laminal, to the blade. Disagreement by one rater was addressed by consultation among all three.

Data Collection and Measurements

Cine MRI

MRI data were acquired on a 3-T Tim Trio scanner (Siemens Healthcare), with a 12-channel head coil and a four-channel neck coil. Cine MRI was acquired using a segmented gradient echo sequence at an in-plane resolution of 1.875 mm/pixel, a field of view of 240 mm × 240 mm slice, a thickness of 6mm. The echo time between the RF excitation pulse and the start of MRI recording was 1.33 ms. The repetition time, which is the cycle duration between two sequential RF excitation pulses, was 2 seconds. Five speech repetitions were used to complete data acquisition for each single slice including 26 time frames of 38 ms each. Cine MRI creates a single movie by ensemble summation of multiple repetitions of the speech task. Each time frame (1–26) is averaged with the same time frame from all five repetitions to boost signal strength because the signal emitted by the hydrogen protons in the short time frame is quite weak. The cine-MRI recordings were made during a 1-s recording period within a 2-s repeat cycle. Data were collected at multiple slices and in three orientations (sagittal, coronal, and axial). The midsagittal slice was identified based on all three data sets and used for the tongue analysis in this study. Subjects were trained to speak the words to a

Figure 2. Twenty midline tongue profiles showing apical and laminal shapes.

four-beat metronome to increase the precision of repetitions, using the methods of Masaki et al. (1999).

High-resolution MRI volumes for each subject were collected in the same session as the cine-MRI data and in the same orientation, so that the two data sets could be overlaid (cf. Stone et al., 2013). These volumes were used to identify the location of the anterior edge (alveolar) of the first molar tooth roots, which along with the midpalate point at the same location, formed a plane perpendicular to the occlusal plane. This plane served as a landmark for placing the fifth midsagittal tongue surface point during the /s/.

Dental Cast

Dental casts were available for all subjects collected from alginate impressions and poured in dental stone. Subjects were not included if they were missing first molars or had a significant palatal torus or if the cast had major imperfections that made palatal measurements inaccurate. The acceptable casts were scanned using a 3D optical scanner (Ortho Insight 3D Scanner; Motion View Software Chattanooga, TN). Three landmarks were measured on both the stone and digital dental casts (see Figure 3a). These three material points and the occlusal plane were used to calculate the convexity angle (CA) and the slope of the

anterior palate. The stone casts were measured by hand using dial calipers. The digital casts were measured using MeshLab V1.3.3 (Cignoni et al., 2008). Those digital and stone cast values that did not agree were remeasured. Once the digital points were accurately identified, the 3D coordinates were exported to an Excel spreadsheet (Microsoft) file for analysis. The two palate angles were calculated as follows:

1. CA: This angle quantifies the prominence of the alveolar ridge of the hard palate. The CA is the angle formed by Points 1–3 in Figures 3a and 3b. These points represent the central incisor interdental papilla (Point 1), the base of the incisive papilla (Point 2), and the palate high point adjacent to the first molars (Point 3), shown as black dotted lines (see Figure 3b). The incisive papilla is a small oval protuberance that sits on the incisive foramen directly behind the central incisor teeth. As it is a protuberance, the CA is always slightly convex. The subjects were divided into two groups based on the range of their CAs, which was 147°–177°. Higher numbers indicate flatter, less convex shapes, because 180° is flat (colinear points). Low CAs were defined as $\leq 173^\circ$, which was the median value.

Figure 3. Measurement points selected on (a) the palate cast, (b) the midsagittal palate profile, and (c) the tongue surface. Palate points are (1) the interdental papilla between incisors, (2) the base of the incisive papilla, and (3) the deepest point of the palate adjacent to the first molars. The eight tongue points include two landmarks: (1) the tongue tip and (5) the anterior edge of the first molars. Tongue points are equidistant.

2. Anterior angle (AA): The AA is at Point 0 and is formed by the projection of a line (dashed green) drawn between the base of the incisive papilla (Point 2) and the interdental papilla (Point 1) at the intersection with the occlusal plane (Point 0). The perpendicular from the occlusal plane to the base of the incisive papilla (see Figure 3b, vertical green line) completes the triangle. The AA represents the slope of the anterior midline palate. Subjects were sorted into two AA groups, where low angles were $\leq 37.0^\circ$, which was the median angle of our larger database.

Tongue Curvature Measures

Tongue profile point sequence. The midline tongue profile was identified in the time frame identified as the maximum constriction for /s/. Eight roughly equidistant tissue points were selected as *xy* coordinates. Five were between the tongue tip and the first molar, and three were posterior to the first molar. In order to normalize points across subjects, the following method was used. Point 1 was the most anterior point on the upper profile of the tongue. Point 5 was selected at the plane cut by the M1 roots onto the profile of the midsagittal tongue (see Figure 3c). To make this projection, a vertical plane was defined at M1 by selecting three points—one at each M1 alveolus and a third point at the midpoint of the palate at the M1 alveolus. These three points defined a plane, perpendicular to the occlusal plane, which cuts through the tongue coronally at the first molar (Grimm et al., 2017). Points 2–4 were selected manually to be equidistant visually between Points 1 and 5. The first five points covered the region of the tongue

tip and blade. Since human observers may use more than just the tip and blade in making their decision, Points 6–8 were selected posterior to Point 5 using the same manual selection of spacing as the first five points. This allowed a larger shape region to be considered objectively.

Basic curvature calculation. The resulting sequence of eight points was considered to be part of a curve on which κ (curvature) was calculated by fitting a circle to every three consecutive points (κ was not defined at the end points). We approximated local values of κ by fitting a circle of radius r passing through three adjacent Cartesian points in the sequence described above (Cassey, 1996). For three such points (say, p_1 , p_2 , and p_3), $\kappa = r^{-1}$ at the center point can be extracted from

$$r = \frac{1}{2} \frac{||v_{12}|| ||v_{13}|| ||v_{32}||}{||v_{axis}||}, \quad (1)$$

where v_{12} , v_{13} , and v_{23} are vectors between the points and $v_{axis} = v_{12} \times v_{32}$ is normal to the plane in which the circle is defined. Curvature calculations were implemented in a script written in MATLAB v2015a (see Supplemental Materials S1–S5). Curvature values were assigned a sign to represent whether the local shape acted with or against the global convexity of all points along the tongue profile. Figure 4 shows the global curvature represented as a dotted circle with radius R , which has been fitted to the points in the eight-point sequence using least squares (Gander, Golub, & Strebel, 1994). The direction of the global convexity is represented by the vector from each point in the sequence toward the center of the circle (C) associated with R . Likewise, the local curve shape is represented by the vector from each point

Figure 4. Curvature calculation and sign assignment in discrete points. The global circle (dotted line) fits to all eight points, has a radius R , and is centered at C . Local curvature values are extracted by fitting a circle on three neighboring points. The local circle has a radius r and is centered at c . The global fit is used to determine the sign of the local curvature values. A negative sign is assigned when the internal angle in the segment cpC is larger than 90° (blue) and positive if the angle is smaller than 90° (red).

to the center of the local circle (c) associated with r (solid blue or solid red). Thus, κ was negative if the angle between the vectors (C, P, c) was greater than 90° (see Figure 4, Point 3) and positive if the angle was less than 90° (Point 7).

Profile shape classification. As a reference, apical and laminal /s/ were identified from the images by visual inspection, as described above. For quantification, four data-driven approaches were also used to classify the shapes based on the eight-point sequence. Because the data points are coarse, several millimeters apart, some of the methods below include normalization of subject size and refinement by adding more points.

1. **Minimum curvature (MC):** This method uses the minimum local curvature value among the measured points, be it a small convex or a large concave curve. Negative values of κ represent a local concavity in the overall curvature. Using this approach, the lowest curvature values during /s/ typically occurred at Points 3, 4, or 5, so the lowest of these three values was selected to represent the anterior tongue shape for the /s/ of that subject. (The concept is illustrated in Figure 5, Row 1.) This is the only one of the methods that used the sign of the curvature and is fairly intuitive in reflecting concave versus convex minima.
2. **Averaged largest curvatures (ALCs).** The ALC method consists of classifying profile shapes based on the largest curvature values (or smallest r circles), to capture deviations from the smooth arc formed by the anterior tongue profile (as shown in Figure 5, Row 2). It is not sign sensitive. The two largest curvature values were averaged together because the addition of a second anatomical region increases sensitivity to the complexity of the profile curve. The largest curvature values are examined irrespective of sign and thus do not contain zero values. This prevents flat surfaces of the tongue from dominating the

classification results. Flat surface regions can occur locally in both apical and laminal /s/ shapes.

3. **Normalized ALC (NALC):** To account for size differences between subjects, the ALC method was normalized using the global curvature. The ALC was inverted to approximate a radius, which was then divided by the size normalization factor R (see Figure 5, Row 3). As with ALC, this approach captures the complexity of the curve and includes normalization as well as averaging.
4. **NALC with interpolation (NALCi):** This method consisted of recalculating NALC after refining the point sequence by interpolating 10 additional points between each original point via a cubic spline. This method determines whether point distance is important when calculating curvature. The use of 78 points instead of eight enables a better approximation of local curvatures. The length scale differs for each subject based on the size and spacing of their teeth; Tissue Point 5 is located at the first molar. To maintain sensitivity to the length scale, the top 20 local curvatures or one fourth of the curvature measurements were averaged instead of the Top 2 as in NALC.

The presented approaches are intended to balance efficacy and conceptual accessibility based on our experience. However, the list of methods described above is by no means exhaustive, and there are multiple plausible shape classification schemes. For instance, it is possible to approximate the properties of a continuous curve (including rotation, axial torsion, and cumulative curvature through a line integral) as has been demonstrated to classify shape differences in the spine (Donzelli et al., 2015) or to measure diversity of curvature via the standard deviation of local curvature values.

Statistical Analyses

Mystat 12 (Systat Software) was used to calculate statistics on these data. Because of the small amount of data, nonparametric statistics were used. First, a Spearman rho correlation (Myers & Well, 2003) was performed between AA and CA to determine whether the two palate measurements were independent of each other (see Figure 6). They were found to be uncorrelated ($\rho = 0.005$). A ρ of 2.11 was needed for significance at $p = .05$ given the number of subjects in the study. Therefore, the two palate angles were treated independently in subsequent analyses. Curvature was grouped separately by /s/ type, AA, and CA, and the median differences were tested with two-tailed Mann-Whitney U tests.

Results

We hypothesized that the curvature-based metrics would classify the anterior tongue profile into categories of apical and laminal /s/ consistent with the subjective classification of three raters. To test this, the four curvature quantities,

Figure 5. Strategies for numerical distinction between apical and laminal profile shapes. Top row: The minimum curvature (MC) method places emphasis on curvatures with relatively large negative values (left) and values close to zero (right). Second row: The average largest curvature (ALC) method averages the two largest curvature values (dotted, solid) in the tongue profile. Smaller circles yield larger averaged curvature values and typically reflect apical shapes (left). Third row: The normalized ALC (NALC) method is the ratio of the ALC divided by the global curvature (aqua), which normalizes for size differences among subjects. Laminal tongue profiles have ratios closer to 1 (right). Bottom row: The NALC with interpolated points (NALCi) method is applied to a more continuous (interpolated) curve to assess the effects of closer points. Note that, in NALCi, the interpolated points are close together and give the impression of a continuous line. avg. = average.

namely, MC, ALC, NALC, and NALCi, were compared to the apical and laminal subjectively rated groups.

The metric classification results appear in Table 1 and are visualized in Figures 7 and 8. The MC method did not show a significant difference between the apical and laminal shape categories ($U = 26$, $p = .09$; see Figures 7 and 8). However, the ALC analysis without normalization also did not show a significant difference between the

apical and laminal shape categories ($U = 55$, $p = .589$; see Figures 7 and 8).

The third measure, the NALC, resulted in a statistically significant differentiation between /s/ types ($U = 16$, $p = .028$). The NALC, which measures the ratio between the ALCs and the global curvature, found that the laminal curvatures were more similar to the global curvatures than were the apical ones; that is, the ratio was closer to 1. The

Figure 6. Scatter plot of the convexity angle and the anterior angle of the palate.

laminal profiles had a median ratio of 0.368 ± 0.14 , and the apical median was 0.225 ± 0.10 (see Figures 7 and 8). This means that the apical tongue had a less convex shape, often containing an anterior local concavity. Thus, this metric captured somewhat more complexity in the apical than laminal /s/.

The final metric, NALCi, was also statistically different between groups ($U = 15$, $p = .028$). The laminal profiles had a median value of 0.260 ± 0.10 , and the apical profile shapes averaged 0.158 ± 0.07 (see Figures 7 and 8). A correlation showed that NALC and NALCi were highly correlated ($R = .99$).

In addition to the /s/-type effect, this study examined the effect of palate shape and slope on curvature. Mann–Whitney U tests found that palate CA had no significant effect on curvature. The AA, however, did have a significant effect on tongue shape for NALC ($U = 16$, $p = .019$). Less steep anterior palate slopes were more likely to produce an apical /s/. AA was close to significant, with identical U and p values, for MC ($U = 21$, $p = .052$) and NALCi ($U = 21$, $p = .052$).

Discussion

Apical–Laminal Effect on Curvature

The main goal of this study was to use curvature to capture quantitatively apical and laminal /s/ shapes in the

Table 1. Median values of curvature in apical and laminal groups.

Method	Apical	Laminal	p value
MC	-0.020 ± 0.02	-0.010 ± 0.02	.090
ALC	0.062 ± 0.02	0.057 ± 0.01	.589
NALC	0.225 ± 0.10	0.368 ± 0.14	.028*
NALCi	0.158 ± 0.07	0.260 ± 0.10	.028*

Note. MC = minimum curvature; ALC = average largest curvature; NALC = normalized average largest curvature; NALCi = normalized average largest curvature with interpolated points.

*Indicates a significant difference between apical and laminal /s/ tongue shape.

midsagittal tongue. Within even a single tongue profile, there is variability in curvature between the tip and the region beyond the first molar, as measured in this study. In addition, vocal tract size differs across subjects, so scaling becomes an issue in quantification of shape. Visual inspection suggested that a laminal /s/ was associated with a convex-to-flat tongue profile shape, while apical /s/ was associated with a flat-to-concave shape. Only the MC used signs when calculating curvature; the other three methods examined only curvature magnitude. Results showed that, the normalized curvature quantities, NALC and NALCi, predicted the subjective categories of apical and laminal /s/ very well (see Figure 5 and Table 1). The apical /s/ shape was slightly more complex than the laminal /s/, with more zero crossings. Every time the curvature value passes through zero and switches sign, an inflection point occurs. More inflection points create more curvature minima. If the curvatures of the apical and laminal tongues had been mirror images, this method would not work; however, they were not. Thus, one outcome of this study was the observation that apical tongue contours have more shape complexity than laminal ones.

Metric Representation of Tongue Curvature

The second goal of this study was to optimize the curvature metric used to represent the midsagittal tongue profile. The simplest metric was the MC value as it identified the local tongue tip shape. However, an MC value near zero occurred in half of the subjects and in both apical and laminal /s/ shapes (see Figure 6). A value of zero arises when points are colinear, which can be a feature of the profile or from the digital nature of the images in cases where three consecutive points lay in the same (or close to the same) voxel row, resulting in a radius of curvature approaching infinity. For these subjects especially, it was clear that a larger region of the tongue needed to be used in quantifying its shape. The second metric, ALC, indicated that the radius of the smallest circles (largest local curvature) in the laminal /s/ profiles could be close in magnitude to the circle encompassing all points in the sequence (see Figures 4 and 5). This was generally not the case for the shape of apical /s/ profiles, because the local circle fits were generally smaller than the global circle fit. However, this metric also failed to distinguish the shape categories. The third metric, NALC, included a normalization factor (the global radius of curvature), which prevented tongue size differences from affecting curvature values. Cases such as that shown in Figure 5 also suggest that apical profiles may have a larger radius of global curvature; thus, the numerator would decrease while the denominator increases, magnifying the sensitivity of the metric. The NALC clearly distinguished between the two groups of tongue shapes in a manner consistent with the raters' categorizations. The similarity of results between the NALC and the fourth metric, NALCi, indicated that the addition of interpolated points was less important than normalizing the length scale used in the

Figure 7. Group comparison per different shape classification metrics. Minimum curvature (MC) and average largest curvature (ALC) are curvature measurements with units as noted; normalized ALC (NALC) and NALC with interpolated points (NALCi) are both normalized curvature radii ratios (the mark “(-)” denotes a dimensionless quantity). Significance is indicated with an asterisk, which indicates $p < .05$.

analysis (see Figures 4 and 5). Thus, the automated, data-driven metrics showed that the human /s/ shape categories appeared to follow curvature differences in the anterior tongue, in which apical /s/ had a more complex shape with a local flat or convex region.

It can be observed that Subject 18 (S-18) was unusual. In Figure 6, S-18 was the outlier who had the least upwardly sloped and the most convexly shaped palate of all the subjects. S-18 also was physically a large person, with a large oral cavity and tongue. Although S-18 was judged to have a laminal tongue shape (see Figure 2, Subject 18), the tip region was very flat and not inconsistent with the apical shapes. The MC and ALC methods put 18 in the middle reflecting the ambiguous shape. By dividing the largest curvatures by the global curvature, the NALC and NALCi eliminated the effects of the large tongue size by using a ratio, but that also removed the shape ambiguity in the quantity. Instead, the large normalized circles used to comprise NALC and NALCi placed S-18 numerically in the apical region.

Palate Effects on Curvature

This article hypothesized that anterior palate shape might affect anterior tongue profile shape. The effect of CA on tongue shape was nonsignificant for all four metrics. However, the AA had a significant effect on NALC ($p = .019$) and approached significance for MC ($p = .052$) and NALCi ($p = .052$). Flatter anterior palate slopes were more likely to produce an apical /s/, and steeper ones led to laminal /s/. This was of interest as our previous research

(Grimm et al., 2017) showed that palate height affected the /s/-type categorization made by human raters. These two results are consistent, because even though palate height does not correlate with AA, there is a tendency for a steep AA to accompany a higher palate (Grimm et al., 2017).

Conclusions

This study found objective curvature measures of the midsagittal tongue, when scaled across subjects, supported the classical, visually determined categories of apical and laminal /s/. More convex tongue shapes were associated with the laminal /s/ and occurred with steeper palate slopes. The flatter anterior palates, associated with the apical /s/, sometimes produced concave regions in the anterior tongue and occasionally more complex profile shapes (more zero crossings). It is tempting to think that differences between these two /s/ types are entirely due to morphology of the palate. However, glossectomy patients tend to use laminal /s/ irrespective of palate features, due to difficulty controlling the tongue tip (Grimm et al., 2017). Thus, palatal constraints are not obligatory.

In our experience, the best metric was the NALC. Both NALC and NALCi included a normalization factor, which allowed them to distinguish between the two /s/ types and also show the relationship between tongue shape and palate angle. However, NALC is more convenient and cost effective than NALCi because it does not require interpolation of additional points. The NALC prevented tongue size differences from affecting curvature values and obscuring subject differences.

Figure 8. Ranked shape classification metrics. The metric value for each participant was ranked in ascending order along the x-axis. MC = minimum curvature; ALC = average largest curvature; NALC = normalized average largest curvature; NALCi = normalized average largest curvature with interpolated points.

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