Toward articulatory-acoustic models for liquid approximants based on MRI and EPG data. Part I. The laterals

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Magnetic resonance images of the vocal tract during the sustained phonation of /l/ (both dark and light allophones) by four native American English talkers are employed for measuring lengths, area functions, and cavity volumes and for the analysis of 3-D vocal tract and tongue shapes. Electropalatography contact profiles are used for studying inter- and intra-talker variabilities and as a source of converging evidence for the magnetic resonance imaging study. The general 3-D tongue body shapes for both allophones of /l/ are characterized by a linguo-alveolar contact together with inward lateral compression and convex cross sections of the posterior tongue body region. The lateral compression along the midsagittal plane enables the creation of flow channels along the sides of the tongue. The bilateral flow channels exhibit somewhat different areas, a characteristic which is talker-dependent. Dark /l/s show smaller pharyngeal areas than the light varieties due to tongue-root retraction and/or posterior tongue body raising. The acoustic implications of the observed geometries are discussed.
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INTRODUCTION

Accurate articulatory-to-acoustic modeling of speech production requires a detailed knowledge of the 3-D geometry of the human vocal tract. Magnetic resonance imaging (MRI) is a powerful tool in obtaining the vocal-tract geometry and does not involve any known radiation risks. The images have good signal-to-noise ratio (SNR) and are amenable to computerized 3-D modeling of the vocal tract. The low image sampling rate (i.e., high acquisition time), however, has restricted MRI use to the study of sustained speech sounds, corresponding to ''static'' tract shapes. In parts I and II of this paper, an analysis of the vocal-tract geometry obtained from magnetic resonance imaging in axial, coronal, and sagittal planes, of the liquid approximants in American English is reported. Due to similarities in certain phonetic and phonological properties, the lateral /l/ and the rhotic /ɹ/ are classified as ''liquids'' (Ladefoged, 1993). For example, both laterals and rhotics can be syllabic in word-final positions, and both are sonorous oral sounds. Part I focuses on the laterals, and part II on the rhotics. Linguopalatal contact profiles obtained through electropalatography (EPG) are used for the analysis of inter- and intra-speaker variabilities and to provide a source of converging evidence for the results of the MRI study.

I. PRODUCTION MECHANISMS OF LATERALS

Laterals are sounds which are typically produced with a lingual contact along the midsagittal line such that air flows along one or both sides of the tongue. The contact is made with the anterior tongue tip or blade in the anterior region of the roof of the oral cavity. In English, the lateral approximant[1] /l/ is voiced and has been broadly classified into two canonical allophones, namely the light and dark varieties, which will be referred to by the symbols [l] and [ɫ], respectively, in this paper. The light allophone [l] occurs in prevocalic contexts (for example, as in ''led'') and the dark allophone [ɫ] occurs in postvocalic and syllabic cases (for example, as in ''bell''). Acoustically, [ɫ] is characterized by a relatively lower F_2 and higher F_1 when compared to the F_2 and F_1 values of [l] (Lehiste, 1964; Espy-Wilson, 1992). The exact details of the vocal-tract geometry and the aerodynamics of these sounds are not well-known. Previous articulatory studies have indicated that there is a greater retraction of the anterior tongue body in the dark /l/ when compared to the light variety (Giles and Moll, 1975; Gartenberg, 1984). Although there has been some evidence for the raising of the posterior tongue body (dorsum) toward the velum (''velarization'') in [ɫ], such behavior has not been observed consistently (Sproat and Fujimura, 1993).

Articulatory and acoustic properties that are intermediate in nature to those associated with the canonical dark and light variants have been known to exist. In fact, it has been argued that the dark and light variants of /l/ are not distinct elements, either from a phonological or a physiological point of view, but rather are manifestations of phonetically predictable contextual characteristics (such as syllable-initial versus syllable-final) suggesting that an allophonic distinction in describing them may not be necessary (Sproat and Fujimura, 1993).

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Articulatory evidence from previous studies have shown differences in the production patterns of the laterals across different English dialects. For example, Giles and Moll (1975) report that lingual contact in the front region of the oral activity is often not observed in the dark variant of American English; results of Gartenberg (1984), on the other hand, indicate a significant front region linguopalatal contact for postvocalic /l/s in British English.

The primary objective of this study is to provide a characterization of the 3-D geometry of dark and light variants of /l/ so that better acoustic models for these sounds can be developed. Investigation of coarticulation and other dynamic properties are not within the scope of this study.

II. METHOD

A. Subjects

Four phonetically trained, native American English speakers [2 males (MI, SC) and 2 females (AK, PK)] served as subjects. Subjects AK and MI, both in their twenties at the time of the experiments, were raised in Northern California and have spent the 7 years preceding this study in Southern California. Subject SC, in his thirties, spent the first 10 years of his life in Indiana and has since been in California. Subject PK, in her early forties, lived in New Jersey and Ohio her first 3 years, and in the Boston area through her thirties. She has been living in the Los Angeles area for 14 years. All subjects have professional working knowledge of phonetics: PK for more than 20 years, and is an expert phonetician; SC and AK for more than 10 years through teaching and research; and MI for more than 5 years through phonetics classes and work experience. All have been subjects for various production and listening experiments.

B. Magnetic resonance imaging (MRI)

A detailed description of the acquisition and analysis procedures is provided in Narayanan *et al.* (1995). Magnetic resonance (MR) images were collected using a GE 1.5 T SIGNA machine with a fast SPGR (radio frequency spoiled GRASS) protocol in the coronal, axial, and sagittal planes. The image slice thickness was 3 mm with no interscan spacing. Each image was represented by a 256×256 pixel matrix, yielding a resolution of 0.0081 cm^2 per pixel for an FOV=24 cm. The subjects, in supine position, sustained dark or light /l/ for about 13–16 s enabling four to five image slices to be recorded in a particular plane (about 3.2 s/image). Dark and light /l/s were produced in a neutral vowel context, and the subjects repeated each sound six to nine times, with a pause of three to ten seconds between repetitions, to enable the entire vocal tract to be scanned. The data set comprised 28–35 images/sound/subject in the sagittal plane, and 40–45 images/sound/subject in the axial and coronal planes.

Scanning of each subject in any one particular plane (axial, for example), was completed within the same session. Scanning in each of the three orthogonal planes was carried out in different sessions. A special head-neck coil helped maintain the subjects' heads in a fixed position. Stability of the articulators could not be monitored during scanning. Instead, analysis results of EPG data, which were collected on a different day, suggest that our phonetically trained subjects maintained stable gestures while sustaining these sounds. In addition, a comparison of the EPG data for /l/s obtained from sustained utterances with those from in-context words (described in the Appendix) helped justify the use of sustained utterances for studying the articulatory geometry during the production of these sounds.

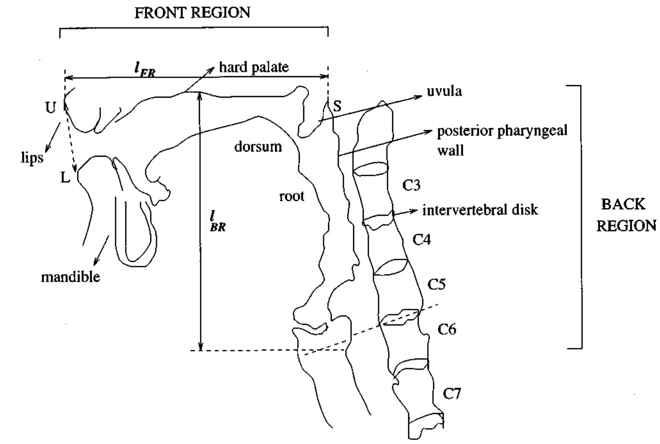

FIG. 1. Tracing of the midsagittal profile of the vocal tract during the production of the vowel /a/ (subject MI) highlighting terminologies and landmarks used for measurements.

In order to provide a convenient reference to key anatomical landmarks in the vocal tract, a tracing of a sample midsagittal MR image of the vocal tract for the vowel /a/ spoken by a male subject is shown in Fig. 1. The scanning region for the coronal and axial planes included the region between the lips and the posterior pharyngeal wall along the anteroposterior axis and the region between the top of the hard palate and just below the eighth vertebra along the inferosuperior axis. Coronal and axial scans were taken approximately perpendicular to the vocal-tract midlines, in the oral and pharyngeal regions, respectively, based on a midsagittal localizer image for each subject. Similarly, the scanning region for the sagittal plane was based on axial and/or coronal localizer images. In addition, reformatting of the raw images was used to obtain cross sections along any desired (oblique) plane. Since midsagittal profiles provide the most convenient reference for specifying grid locations for performing area calculations, sagittal scans were chosen for area calculations along the vocal-tract bend from reformatted images. Midsagittal data were also used for length measurements.

Automatic segmentation of the vocal-tract regions in the images was followed by careful manual verification of the selected regions in each image. Following segmentation, three-dimensional reconstructions of the entire vocal tract, or specific regions such as the sublingual cavities, could be made by computer-aided concatenation of the selected regions of interest. Length, area, and volume measurements could be made directly using a pixel counting algorithm.

Articulatory analysis and measurements were performed in several steps. Overall vocal tract and tongue shapes were first analyzed using raw images, and complete 3-D models were then reconstructed from appropriately segmented raw scans. All the 3-D reconstructions reported in this study were constructed using coronal scans. Interactive slicing of the 3-D objects, along any desired plane, facilitated the morphological analyses. Area measurements were made in two stages: in the first, cross-sectional areas were directly measured from the coronal and axial scans to provide information on the front (oral) and back (pharyngeal/laryngeal) regions, respectively; in the second, sagittal scans were reformatted to obtain areas along the planes perpendicular to the midline of the vocal-tract bend. To enable comparative graphical analyses across the various sounds and subjects, a simplified representation of the area function is considered. Areas up to the laryngeal inlet (glottal opening), defined by the section showing the complete separation of the piriform sinuses by the ary-epiglottic fold, were considered. Furthermore, the ''effective'' area of the airway was obtained by a simplification of the morphology: subtracting tissue areas, such as the uvula, and the various epiglottal folds, from the total pharyngeal cavity areas. Areas of the lateral channels, along the sides of the tongue, were measured using coronal scans. These areas were calculated using the airway segmentation technique aided by appropriate tracings of the teeth similar to that described in Narayanan *et al.* (1995).

C. Electropalatography (EPG)

1. Data acquisition

EPG data from the subjects were recorded on a later date using Kay Elemetrics Palatometer. Each subject has a custom-fitted acrylic palate with 96 sensing electrodes. The sweep rate of this system is 1.7 ms and the sampling period is 10 ms. The data for each subject were collected in a single session that lasted for about one and a half to two hours. The data were collected over a month (post-MRI experiments).

The speech material consisted of the lateral approximant (dark and light allophones) sustained for about 4 s/token. The sounds were produced preceded by the neutral vowel /ə/. The subjects assumed a supine position, similar to that assumed inside the MRI machine, while phonating the sustained utterances.[2] In addition, EPG data for dark and light /l/s from spoken words were collected for comparative analyses (described in the Appendix). Eight repetitions of each condition were obtained.

2. Data analysis

For the purposes of this study, the total region covered by the electrodes was broadly divided into front and back regions. A schematic of the region definitions is given in Fig. 2. The front region comprises the alveolar and prepalatal regions while the back region comprises the midpalatal and postpalatal regions. In addition, these regions could be further divided into left and right lateral zones, with respect to the midsagittal line, in order to study the symmetry in the linguopalatal contact profiles. The percentage of electrodes that are contacted in each of these regions served as a basis for our analysis.

The EPG data were used to study the stability of the articulatory gestures during sustained phonation and intertoken variabilities in each subject's production, and to compare

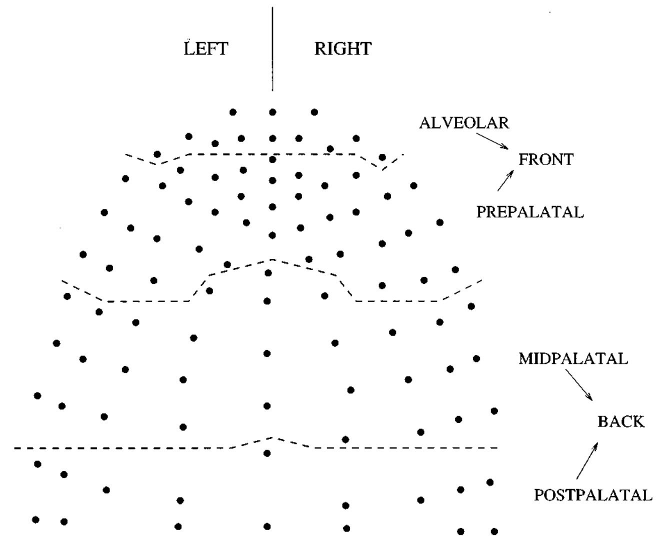

FIG. 2. Schematic of electrode placement on the pseudopalate used in electropalatography with region definitions.

sustained versus in-context phonations. The linguopalatal contact profiles provided by the EPG data were studied using repeated-measures multifactorial ANOVA (Analysis of VAriance) techniques (SYSTAT, 1992). Furthermore, wherever necessary, Tukey-HSD posthoc tests were used to isolate the potential sources of variations. Note that EPG only measures linguopalatal contacts, and is limited to the region between the teeth and the anterior part of the velum.

III. RESULTS

Articulatory analysis of the laterals is based on MRI and EPG data of sustained productions of the light [l] and dark [ɫ] allophones. Tracings obtained from midsagittal MR images of [l] and [ɫ] for the different subjects are shown in Fig. 3, and the corresponding area functions are shown in Fig. 4. Sample linguopalatal contact profiles for [l] and [ɫ] are shown in the Appendix.

Analysis of the midsagittal images reveals, for both [l] and [ɫ], that the tongue shapes are significantly different across the four subjects. Nevertheless, a detailed analysis of the cross-sectional shapes and the lingual contact patterns reveals several common characteristics. Moreover, for each subject, the tongue shapes for the dark and light allophones showed many similar characteristics, particularly in the oral region, but certain systematic differences were also found, such as in the degree of posterior tongue body raising in the velar region, and tongue-root retraction in the pharyngeal region.

A. The light [l]

1. The linguo-alveolar contact

For [l], all subjects revealed lingual contact along the midsagittal line, beginning in the region behind the front incisors and continuing over the majority of the alveolar region (starting at approximately 1 cm away from the lip opening and extending up to about 1.8, 1.8, 2.1, and 1.5 cm from the lip opening for AK, PK, MI, and SC, respectively). This linguo-alveolar contact was established either with a raised

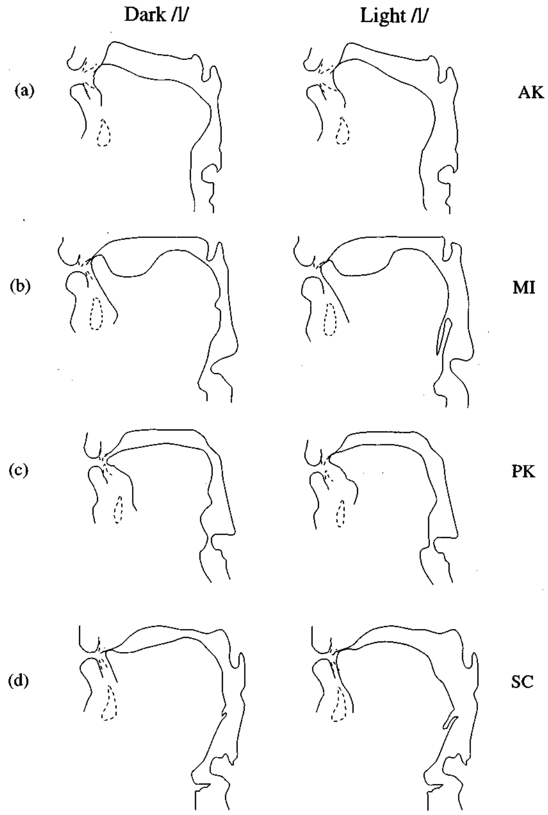

FIG. 3. Tracings of the midsagittal profiles of the vocal tract of the different subjects during the production of the lateral approximants [ɫ] (left side) and [l] (right side): (a) AK, (b) MI, (c) PK and, (d) SC. The front incisors and the jaw are shown in dashed lines.

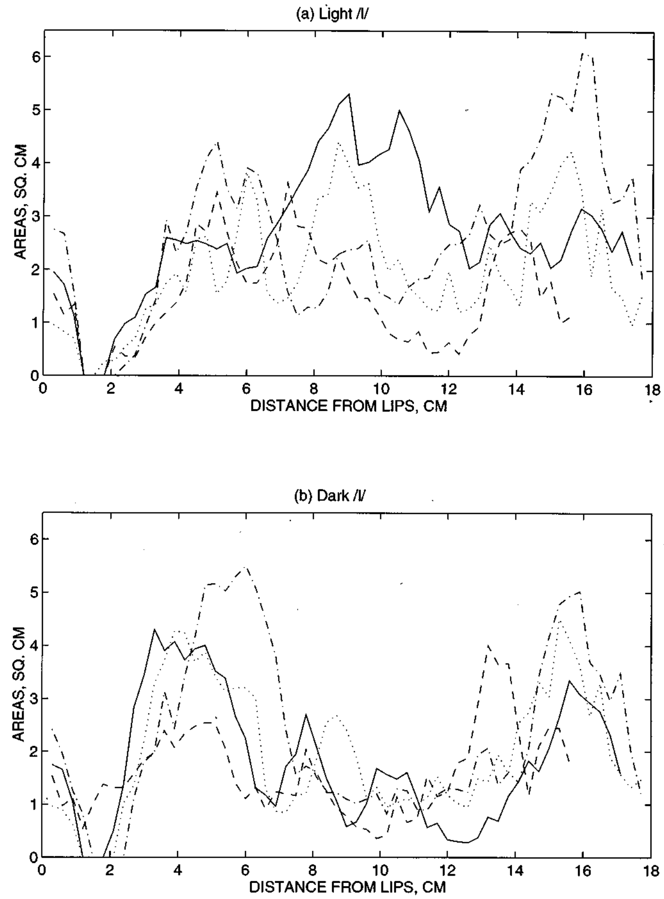

FIG. 4. Area functions, in cm^2, for the laterals of the different subjects: solid (AK), dashed (PK), dot-dashed (MI), dotted (SC). Top panel: [l], bottom panel: [ɫ]. Areas of the lateral openings around the alveolar contact are not included in these figures, but areas of the lateral openings behind the contact, if present, are included. The abscissa for the area functions are distances (in cm) from the outer lip opening. Approximately, the region about 1.5–2.5 cm from the lips is the alveolar region, 2.5–6 cm is the palatal region, 6–8.5 cm is the velar region, 8.5–13 cm is the uvular and upper-pharyngeal region, and 13–15 cm is the lower-pharyngeal region. For PK, 1–2 cm is the alveolar region, 2–5 cm is the palatal region, 5–7 cm is the velar region, 7–10 cm is the uvular and upper pharyngeal region, and 10–12.5 cm is the lower-pharyngeal region. The laryngeal region is posterior to the lower-pharyngeal region.

tongue blade (i.e., a *laminal* articulation), as observed in AK and PK [Fig. 3(a) and (c)] or with a raised tongue tip (i.e., an *apical* articulation), as observed in MI and SC [Fig. 3(b) and (d)]. The MRI data also showed that the linguo-alveolar contact for the laminal [l]s of AK and PK extended laterally through the midpalatal region (up to about 5.4 cm and 4 cm from the lips, for AK and PK, respectively). The lateral extension of the alveolar contacts for apical [l]s of MI and SC, on the other hand, was smaller and confined to the prepalatal region (up to about 2.8 and 2.4 cm from the lips, for MI and SC, respectively). Note that *lateral* lingual contacts cannot be observed in midsagittal images (Fig. 3).

Analysis of the EPG data showed greater front-region linguopalatal contacts for the laminally articulated [l]s of AK and PK when compared to the more apical articulations of MI and SC (see for example, Fig. A1 in the Appendix). On average, about 75%–80% of the front-region electrodes were contacted in subjects AK and PK when compared to about 60% in MI and 40% in SC. ANOVA results showed that the front-region contacts of PK were significantly different ($p < 0.001$) from those of MI and SC. Similarly, the front-region contacts of AK were significantly different from those of SC.

Sample MRI coronal cross sections for subject MI are shown in Fig. 5. Linguo-alveolar contact can be seen in the three contiguous sections starting at the leftmost panel of the bottom row. Lateral linguopalatal contacts are observed in the panels following, and the loss of the linguopalatal contact is first observed in the 2nd rightmost panel in row 3 (from bottom). Around either side of the linguo-alveolar contact, small lateral openings were observed in the coronal scans until the lateral contacts ended. These lateral channels can be observed in a side perspective of MI's 3-D vocal tract shown in Fig. 6 in the region of the alveolar contact, behind the lips, and these channels extend to the oral region.

The cross-sectional areas of the lateral channels alongside the alveolar contact, for all subjects, are summarized in Table I. The areas vary between 0.1–0.5 cm^2 depending on the subject's oral morphology and how the lingual contact was formed, such as apically or laminally. Note that the left and right lateral channels have, in general, different areas.

2. Region behind the linguo-alveolar contact

The midsagittal tongue body contours for [l] were found to be quite different across the four subjects (Fig. 3). For example, the middle and posterior tongue body were gradu-

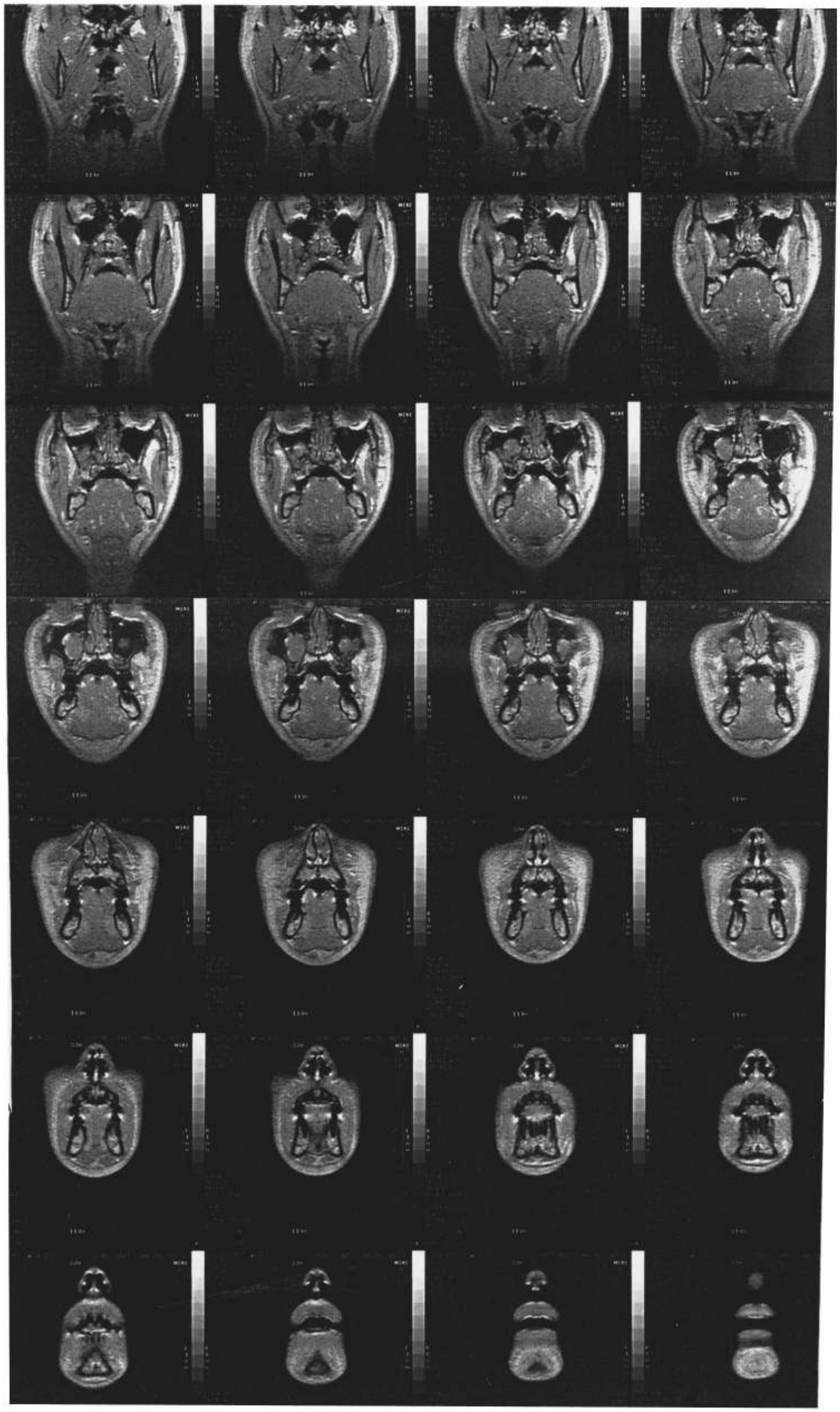

FIG. 5. Coronal profiles of the vocal tract during the production of [l] (subject MI) taken along contiguous sections in the oral cavity at every 3 mm starting from 3 mm from the outer lip opening and ending at the uvular region. The figure is arranged such that the cross section closest to the lips appears in the rightmost panel of the bottom row and successive cross sections, moving away from the lips, are placed right-to-left in each row. Linguo-alveolar contact can be seen in the three contiguous sections starting at the leftmost panel of the bottom row. Grooving along the midsagittal line is observed in the panels of rows 3 and 4 (from bottom), and the convex tongue surface is apparent in row 6 panels.

FIG. 6. A lateral (side) perspective of the 3-D vocal tract for subject MI's [l]. Small lateral channels can be seen in the region of the alveolar contact, just behind the lips. Also notice the presence of lateral channels in addition to the central airway in the oral region.

ally lowered toward the posterior pharyngeal wall for AK, while for PK, the entire tongue body behind the alveolar contact was maintained at the same height. For MI, on the other hand, the middle tongue body appears significantly lowered with respect to the anterior contact and the raised posterior tongue body. For SC, a slight raising of the middle tongue body was observed. In order to provide a clearer picture of the articulatory patterns, a detailed analysis of the cross-sectional shapes and the 3-D tongue and vocal-tract shapes becomes essential.

TABLE I. Areas (in cm^2) of the lateral channels in the alveolar contact region for [l] and [ɫ] (L:left channel, R:right channel) from coronal MR images. x_l is the distance from the lips in cm. Note that no lateral areas for PK's [ɫ] are reported due to difficulty in area measurements because of the absence of a complete alveolar contact.

[l]					
x_l	AK (L)	AK (R)	x_l	PK (L)	PK (R)
1.2	0.214	0.256	1.2	0.223	0.180
1.5	0.197	0.209	1.5	0.107	0.280
1.8	0.246	0.238	1.8	0.085	0.432
x_l	MI (L)	MI (R)	x_l	SC (I)	SC (R)
1.2	0.514	0.177	1.2	0.153	0.111
1.5	0.197	0.159	1.5	0.357	0.307
1.8	0.116	0.145	⋯	⋯	⋯
2.1	0.137	0.136	⋯	⋯	⋯
[ɫ]					
x_l	AK (L)	AK (R)	x_l	PK (L)	PK (R)
1.2	0.165	0.226	⋯	⋯	⋯
1.5	0.182	0.128	⋯	⋯	⋯
1.8	0.212	0.279	⋯	⋯	⋯
x_l	MI (L)	MI (R)	x_l	SC (L)	SC (R)
1.5	0.150	0.136	1.2	0.131	0.200
1.8	0.119	0.057	1.5	0.249	0.398
2.1	0.235	0.111	1.8	0.100	0.122
2.4	0.409	0.382	2.1	0.131	0.171

For MI, the coronal cross sections (Fig. 5) in the region immediately posterior to the contact revealed a flat tongue shape and grooving along the midsagittal line which extended over the majority of the palatal region (approximately 2.4–4.5 cm from the lip opening). Grooving can be observed in the panels of rows 3 and 4, from bottom, in the figure.

The 3-D tongue body shape revealed a tongue which was drawn *laterally* inwards, directed toward the midsagittal plane, and this inward movement was particularly prominent in the posterior tongue-body region where the lateral linguopalatal contact ended. This lateral tongue compression facilitates air flow along the sides of the tongue behind the alveolar contact. The overall tongue-body shape exhibits a convex[3] contour especially in the posterior tongue body region. The convex shape, clearly observed in row 6 panels in Fig. 5, perhaps aid the lateral flow along the tongue sides in this region. This results in an airway opening that is more or less ''crescent'' shaped, at least until lateral lingual contacts are reestablished with the roof of the oral cavity in the velar region. Similar observations were made by Stone and Vatikiotis-Bateson (1995). The linguovelar contact can be observed in the leftmost panel in row 6, and above.

The overall tongue-shape behavior for the other subjects was similar to that of MI:

(1) For SC, grooving in the region immediately behind the alveolar contact was not marked and extended over only a short region (about 0.5 cm). The overall 3-D tongue body behind the contact exhibited a convex contour, and was drawn laterally inwards (toward the midsagittal plane). Asymmetry was observed in the lateral flow channel with more opening on the left side than on the right. Lateral channels extended till the linguovelar contact was established.

(2) For PK, the cross-sectional tongue surface which appeared flat, but nonconcave, until about 5 cm from the lip opening turned distinctly convex in the middle part of the tongue body. Behind the alveolar contact, lateral channels were not evident until lateral linguopalatal contact ended at about 4 cm from the lip opening. Asymmetry in the tongue shape and airway areas was noticed in the posterior region (4.2–5.7 cm). Lateral channels disappeared again in the region where lateral lingual bracing against the roof of the oral cavity was reestablished in the velar region, at about 5.7 cm away from the lips.

(3) For AK, the tongue surface, in general, was distinctly convex. Like PK, the appearance of lateral flow channels in the region behind the contact coincided with the disappearance of the lateral linguopalatal contact (at about 5.4 cm from the lip opening). The lateral contribution started decreasing in the velar region with the establishment of lingual bracing with the roof of the oral cavity. Furthermore, coronal scans illustrated a medial notch on the posterior tongue surface once the linguopalatal contact disappeared. This, perhaps, is a consequence of the inward lateral com-

pression of the tongue body toward the midsagittal plane and lateral linguovelar bracing.

The area functions were similar in their patterns across the four subjects, particularly up to about 4 cm from the lips [Fig. 4(a)]. Lateral openings alongside the tongue, created by inward lateral compression of the tongue body, contributes to increased airway areas in that region. For subjects SC and MI, grooving along the midsagittal line immediately behind the alveolar contact contributes to the increased areas as well. Subjects showed some area decrease in the velar region which is attributed to the disappearance of the lateral channels due to lingual bracing against the roof of the oral cavity. Decreased areas in the uvular and upper-pharyngeal region [at about 10–11 cm in Fig. 4(a)] for MI and SC result from a slightly raised and retracted posterior tongue body, perhaps a consequence of their apical articulation. The decreased areas in the upper- to lower-pharyngeal region for PK [8–12 cm in Fig. 4(a)], and for AK (approximately, 12–15 cm), on the other hand, is due to a slight tongue-root retraction; a probable consequence of their laminal articulation. Note the large areas in the velar- to upper-pharyngeal region for AK [7–12 cm in Fig. 4(a)]; this is probably due to her lowering the middle and posterior tongue body.

Analysis of the EPG data showed that the total (percentage) contacts were smaller for MI and SC when compared to PK and AK (on average, 60% in AK and PK compared to 40% in MI and 25% in SC). ANOVA results showed that differences in the back region contacts of AK and PK were significant ($p<0.001$) when compared to those of MI and SC implying that indeed the lateral contacts of AK and PK extend further back. Systematic asymmetry in linguopalatal contacts was only found for subject PK with the right side more favored than the left.

B. The dark [ɫ]

1. The linguo-alveolar contact

The [ɫ] articulations of subjects AK and PK were laminal while those of MI and SC were apical (Fig. 3). The MRI data showed no lingual contact in the anterior (dental/alveolar) region for subject PK, while for AK medial lingual contact was seen in the anterior alveolar region (extending between 1.2–1.8 cm from the lip opening). Analysis of the EPG data of subjects AK and PK showed little or no front-region linguopalatal contact in [ɫ] with only about 10%–25% of the front-region electrodes contacted on an average (see for example Fig. A1 in the Appendix). The linguo-alveolar contact along the midsagittal line for MI's and SC's [ɫ], on the other hand, extended between 1.5–2.4 cm and between 1.2–2.1 cm from the lip opening, respectively. EPG data showed that MI and SC consistently showed linguo-alveolar bracing with 50%–75% front-region contacts on an average. Except for SC, the linguo-alveolar contact did not extend laterally through the palatal region.

Coronal profiles of the vocal tract during the production of [ɫ] (subject MI) are shown in Fig. 7. Medial linguo-alveolar contact is observed in the panels of the second row from the bottom. Areas of the lateral channels, found on either side of the linguo-alveolar contact, for all subjects are given in Table I.

2. Region behind the linguo-alveolar contact

For subject MI, prominent convex tongue body shapes are observed at and behind the linguo-alveolar contact (from about 1.8–3.3 cm from the lips.) Although the medial surface of the tongue body shows a slight flattening in the postpalatal region (row 4 panels and the 2 rightmost panels in row 5 in Fig. 7) the tongue body shape turned convex again in the vicinity of the velar region (2 leftmost panels in row 5, from bottom, and above). Grooving along the midsagittal line (observed in the 3 leftmost panels in row 4 from bottom) is not as prominent as that observed in [l]. Lateral bracing with the roof of the oral cavity in the velar region, at about 7.5 cm away from the lips, can be seen in rightmost panel of row 7.

The cross-sectional tongue shapes of the other speakers were as follows:

(1) For SC, there was a slight concave cross section of the tongue behind the linguo-alveolar contact, from about 2.1–2.4 cm, which changed into convex at the end of the lateral linguopalatal contact. The medial tongue surface, in general, was flat with the sides relatively rounded. A small notch on the tongue surface (along the midsagittal line) was observed in the vicinity of the postpalatal region, although it was found not to alter the overall convex shaping of the tongue body. Lateral lingual bracing with the roof of the oral cavity was established in the velar region.

(2) For PK, the cross-sectional surface of the anterior tongue body was convex. A slight flattening of the surface was found behind the alveolar contact (between 2.7–4.5 cm from the lip opening), although the surface turned significantly convex again, in the middle and posterior tongue body regions. No linguovelar bracing was observed.

(3) For AK, the tongue body showed distinct convex shapes in the anterior region (1.2–2.4 cm) with a tendency toward decreased convexity (flattening of the surface) in the middle part of the tongue body (2.7–3.6 cm from the lips). The overall cross-sectional shapes of the posterior tongue body were also convex with slight grooving along the midsagittal line, and significant asymmetry which resulted in greater right-side openings in the airway. No linguovelar bracing was observed.

The overall 3-D tongue shapes and linguopalatal contact patterns suggest that the grooving found sometimes in the region immediately behind the alveolar contact (in MI's /l/s, SC's [l], and AK's [ɫ]) is, most likely, a secondary effect of the anterior lingual contact and the lateral compression of the tongue body, rather than a primary characteristic to satisfy an aerodynamic requirement. Grooving along the midsagittal line did not appear to be actively controlled during production, and, hence, is susceptible to intra- and inter-subject variabilities. Groove dimensions (width and depth) were small and did not exceed 5 mm for any of the subjects.

Analysis of the area functions, shown in Fig. 4(b), indicates similarities in the overall patterns across all subjects except for PK. For the other three subjects there was an

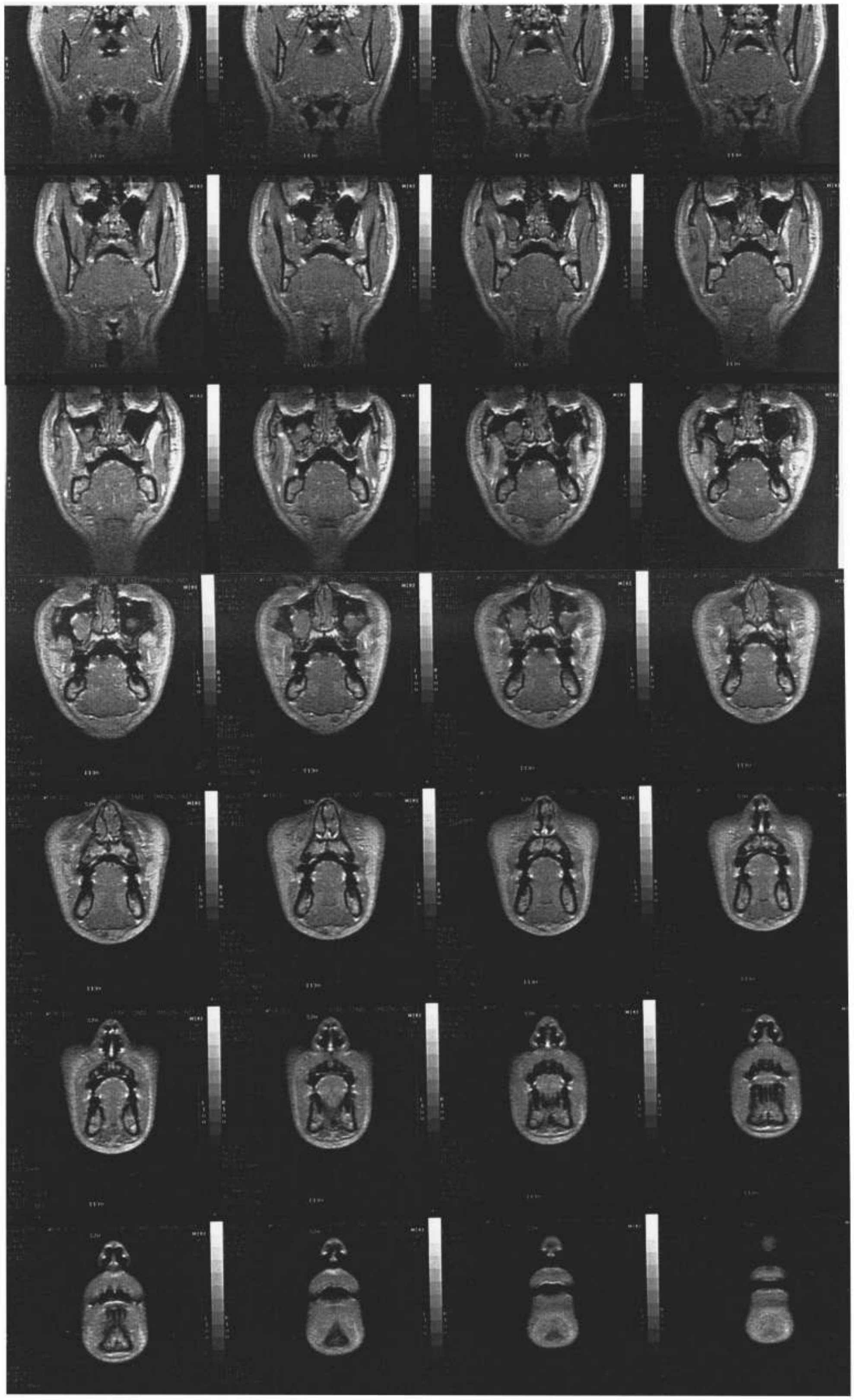

FIG. 7. Coronal profiles of the vocal tract during the production of [ɫ] (subject MI) taken along contiguous sections in the oral cavity at every 3 mm starting from 3 mm from the outer lip opening. The figure is arranged such that the cross section closest to the lips appears in the rightmost panel of the bottom row and successive oral-cavity cross sections, moving away from the lips, are placed right-to-left in each row. Linguo-alveolar contact is observed in the panels of the second row from the bottom of the page. Prominent convex tongue body shapes can be seen at and behind the linguo-alveolar contact. Grooving along midsagittal line (see panels in row 4 from the bottom) is not as prominent as that observed in [l] (Fig. 5). Lateral lingual bracing with the roof of the oral cavity is seen in the rightmost panel of row 7 (from the bottom).

abrupt increase in the areas in the region immediately posterior to the alveolar contact, and large areas in the palatal region due to the contribution of lateral openings alongside the tongue (created by the inward tongue compression). For PK, the area change was more gradual than the other subjects due to the absence of a linguo-alveolar contact in the MRI data. The EPG data, however, showed that PK's [ɫ] may or may not be produced with a complete linguo-alveolar contact.

All subjects reveal a distinct narrowing of the airway in the uvular and upper-pharyngeal region. For subjects MI and SC, the decreased areas, which extend to the velar region for MI, are due to a significantly raised tongue body in the velar region. For PK and AK, on the other hand, the decreased areas are a consequence of a retracted posterior tongue body. The area functions also reveal decreased pharyngeal areas which result from tongue-root retraction. The extent of the pharyngeal region affected by the tongue-root retraction varied across subjects. The upper- and lower-pharyngeal regions [9–14 cm in Fig. 4(b)] showed small areas in the [ɫ]s of AK and MI. For SC and PK, the area reduction is mostly confined to the uvular and upper-pharyngeal region [10–12 cm, and 9–10 cm, respectively, in Fig. 4(b)], especially when compared to their [ɫ]s.

Analysis of the area functions shows that narrowing of the vocal tract at the uvular and upper-pharyngeal region is a consistent correlate of [ɫ]. This narrowing may not necessarily be due to velarization [defined as the raising of the posterior tongue body (dorsum) in the velar region], since only subjects MI and SC showed velarization. It may be that velarization only occurs for apically produced [ɫ]s.

Analysis results of the EPG data were consistent with those of the MRI study. ANOVA results showed the mean contact patterns of subjects AK and PK were significantly different from those of MI and SC.

C. Comparing light [l] and dark [ɫ]

The midsagittal tongue contours for [l] and [ɫ] were similar in the front region but showed noticeable differences in the back region. The front region EPG contact for [l] and [ɫ], on the other hand, showed different behavior across subjects: laminal light [l]s (AK and PK) exhibited significantly more front-region contacts than the laminal dark variety, while these contacts were comparable for the apically-produced [l]s and [ɫ]s (MI and SC). ANOVA results confirmed the statistical significance of this observation. Moreover, [l] exhibited greater lateral contacts in the palatal region for all subjects. These results imply variabilities in strategies used by different speakers to achieve similar tongue shapes.

The inter- and intra-speaker variabilities observed in the total electrode contacts appeared to be greater in [ɫ] than in [l]. For example, PK produced [ɫ] either without any contact in the alveolar region (in 3 out of the 8 tokens) or with linguo-alveolar contact (in the remaining tokens). The other subjects, on the other hand, consistently exhibited linguo-alveolar contact. The total linguopalatal contacts for the dark allophone of subjects AK and PK were much smaller than those of MI and SC while the reverse was true for the light allophones. ANOVA results showed significant differences in the front, back, and total linguopalatal contacts of the dark and light allophones of both AK and PK.

The overall 3-D tongue body *shape*—alveolar contact (constriction), lateral compression, and convex tongue body—for [l] and [ɫ] were similar although the tongue body *position* in the velar and pharyngeal regions were different. The area functions of [ɫ] contrast with those of [l] in two ways: (1) [ɫ]s show somewhat larger areas in the palatal region immediately behind the alveolar contact due to a greater inward lateral compression of the tongue body and less lateral contacts; the greater compression is also evidenced by somewhat larger sizes of postcontact lateral openings in [ɫ], and (2) [ɫ] exhibit significantly decreased areas in the uvular and upper-pharyngeal region, with effects extending either as far as the velar region and/or the lower-pharyngeal region depending on the part of the tongue body used in forming the pharyngeal ''constriction.'' Involvement of the upper part of the tongue root and/or posterior tongue body results in decreased velar to upper-pharyngeal areas while retraction of the whole tongue root influences most of the pharyngeal region. Figure 8 contrasts 3-D tongue shapes for MI's [l] and [ɫ]; both posterior and anterior views of the tongue are shown. Note the greater lateral compression for MI's [ɫ] when compared to [l] [parts (a) and (c)] and the convex shape of the posterior tongue body for both sounds [parts (b) and (d)].

D. Length measurements

The vocal-tract length (l_{VT}) and the vertical lip-opening (l_{VO}) measurements are summarized in Table II. Dark [ɫ]s have somewhat greater l_{VT} values when compared to light [l]s due to tongue-root retraction and/or posterior tongue body raising. Recall that the length of the vocal tract is measured along the midline and, hence, raising or backing of the tongue increases the effective length of the back region, and hence increases the overall length. The l_{VO} values appear to be subject dependent, and no contrastive differences are noticed among these values for the different sounds.

E. Summary of the results

MR images for both the light allophone [l] and the dark allophone [ɫ] indicate that the midsagittal tongue contours can be different across subjects. Common characteristics, however, were revealed in cross-sectional and 3-D tongue shapes, area functions, and linguopalatal contact profiles. These sounds were characterized by a complete linguo-alveolar contact or, just a constriction as observed in some cases of the [ɫ] of subject PK. The contact location was about 1–1.5 cm away from the lip opening and the contact length, 0.6–1.5 cm in the alveolar region with relatively small openings around both sides of the contact. These ''*lateral channels*'' alongside the tongue appeared in the alveolar contact, or constriction, region and, in general, continued posteriorly until the lateral linguovelar contact was established. The right and left channels were, in general, unequal and their areas started increasing behind the alveolar contact (due to

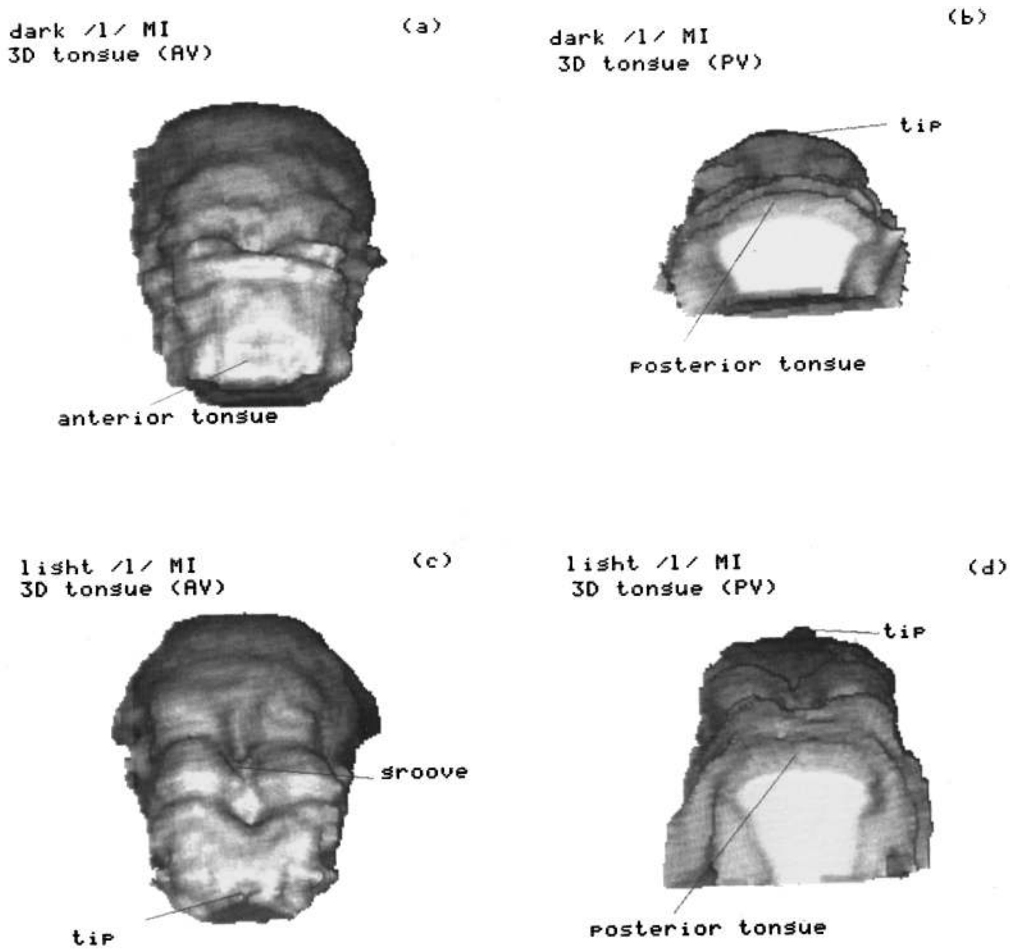

FIG. 8. The 3-D tongue shapes for the MI's dark and light lateral approximants. (a), (b) Anterior (AV) and posterior views (PV) for [ɫ]. (c), (d) Anterior and posterior views for [l].

inward lateral compression of the tongue body), and started decreasing again as the region of the lateral linguo-velar contact, if present, was approached.

The merging of the lateral channels with the central opening along the palatal region resulted in crescent-shaped cross sections and relatively large areas. The extent of the lateral flow channel in the palatal region behind the linguo-alveolar contact was limited by the extent of the lateral linguopalatal contact: [l] typically revealed more lateral contact than [ɫ], thus explaining, in part, the smaller areas consistently observed in the palatal region of [l].

The posterior tongue body, as observed in 3-D tongue shapes, showed *inward lateral compression* which was directed toward the midsagittal plane. This lateral compression enables the creation of the lateral flow channels along the curved sides of the tongue. This observation is perhaps related to the tongue blade narrowing which is hypothesized to be a feature for the laterals (Sproat and Fujimura, 1993). The overall 3-D tongue shape behind the contact tended to be convex. For some subjects, the cross-sectional coronal tongue shapes immediately behind the linguo-alveolar contact appeared flat due to lateral linguopalatal bracing. In addition, some subjects showed grooving along the midsagittal line. Grooving along the midsagittal line or tongue-surface flattening, which appear sometimes, may be viewed as a ''superposition'' on the otherwise basic convex tongue body shape. The anterior grooving is less prominent than that observed in alveolar sibilants such as /s/ (Narayanan *et al.*, 1995). Unlike alveolar fricatives, the grooving, if present, does not continue through the posterior tongue region as a concave surface, suggesting that it is not a key component of a medial airflow channel. Hence, the modification of the tongue body contour, in terms of surface flattening and/or grooving, observed in some portions of the tongue surface for some subjects, is not a primary articulatory characteristic satisfying an aerodynamic constraint, but merely represents secondary effects of the linguopalatal bracing and the lateral inward compression of the posterior tongue body.

It is important to note here that midsagittal tongue shapes can be misleading in characterizing /l/. Similar 3-D tongue shapes (convex surface, lateral compression, and alveolar contact) with somewhat different groove characteris-

TABLE II. Vocal-tract length (l_{VT}) and vertical lip opening (l_{VO}) measurements (in mm).

	Subject AK		Subject MI		Subject PK		Subject SC	
Sound	l_{VT}	l_{VC}	l_{VT}	l_{VO}	l_{VT}	l_{VO}	l_{VT}	l_{VO}
Light [l]	170.7	22.7	178.1	22.9	153.7	7.5	178.4	14.1
Dark [ɫ]	173.2	26.1	184.9	23.5	156.7	6.8	179.6	13.3

tics along the midsagittal line may look vastly dissimilar in midsagittal slices. Conversely, similar groove lengths and depths in two somewhat different 3-D tongue body shapes may appear similar in the midsagittal plane.

The back region areas for [l] showed significant intersubject variability. In the case of [ɫ]s, on the other hand, all subjects revealed decreased areas in the uvular and upper-pharyngeal regions due to significant retraction of the tongue root and/or raising of the posterior tongue body. In addition, the effect of this pharyngeal ''constriction'' was found to extend either as far as the velar region and/or through the lower-pharyngeal region depending on the particular part of the tongue body actively involved in the constriction formation. These results indicate that velarization, which is typically associated with [ɫ], is not necessarily a consistent characteristic across speakers although decreased uvular and upper-pharyngeal areas, when compared to those of [l], is a consistent feature for all subjects.

IV. DISCUSSION

It appears that the primary tongue-shaping mechanisms for laterals are responsible for the alveolar contact, inward-lateral compression, and convex shaping of the middle and posterior tongue body. These features seem to be invariant across subjects. Flattening or grooving of the tongue body immediately behind the alveolar contact, appear to be *secondary* features. We speculate that these secondary features are influenced by the extent and force of front-region linguopalatal contact and the muscular activity of the middle and posterior tongue body. For example, a tendency toward a greater grooving in the middle tongue body was observed in the apically articulated [l]s that showed smaller lateral linguopalatal contacts than laminally articulated [l]s; laminal [l]s were characterized by a somewhat flat middle tongue body shape.

Although there were differences in the tongue body *position* of the dark and light /l/s in the back region, the overall 3-D tongue body *shapes* comprising the alveolar contact and convex middle and posterior tongue body with inward-lateral compression, were, in general, similar. These tongue body shapes were, however, quite distinct from those of the vowels /a,i,u/ (Narayanan *et al.*, in preparation). Hence, the similarity in the midsagittal tongue contours of the laterals and vowels observed by Giles and Moll (1975) does not, most likely, translate to similarity in the corresponding overall tongue shapes. Further corroborating evidence for this observation regarding the tongue shapes of the vowels and laterals is provided by ultrasound data (Stone, 1991; Stone *et al.*, 1992).

Acoustic implications: Some preliminary speculations regarding the acoustic characteristics of the laterals can be made based on these articulatory data. The observed supraglottal ''constriction'' areas (lateral channel areas and/or areas along the midsagittal line) together with the relatively low flow rates, typically 100–200 cm^3/s (Stevens, to be published), suggest no significant pressure drop in the supraglottal constriction region, and hence, negligible chances for frication. The absence of a significant supraglottal pressure drop also implies a sustained, and almost uniform, transglottal flow through the entire duration of the sound. Most of the spectral energy of the laterals is below 5 kHz, with the low-frequency behavior greatly influenced by the cavity posterior to the primary supraglottal constriction (back cavity). The first formant frequency (F_1), which typically occurs between 250–500 Hz, can be associated with the Helmholtz resonance between the relatively large back-cavity volume and the oral-constriction space. The losses at the oral constriction contribute to relatively high bandwidth for F_1 which in turn tends to reduce the amplitude of the spectrum. Furthermore, the anterior tongue body shape suggests that changes in F_1 at the consonant's release (for example, into a following vowel) can be expected to be somewhat abrupt in /l/ due to abrupt changes in the corresponding area functions. The second formant frequency (F_2) can be associated with the half-wavelength resonance of the back cavity (for example, lengths of 12–14 cm would approximately correspond to resonances in the range 1250–1460 Hz). Retracting or raising the posterior tongue body observed in the case of [ɫ] result in an increase in the effective length of the back cavity, and hence, a lowering of the F_2 values.

The acoustic characteristics of the lateral channels in /l/ have not yet been studied in detail. The pole-zero cluster observed in the acoustic spectra of /l/s (around 3–5 kHz) most likely results from both back-cavity and lateral channel effects. A simple approximate analysis suggests that the two lateral channels, which, in general, have different areas, would contribute a pole–zero–pole cluster in the frequencies below 5 kHz (Stevens, to be published). Variability, however, is expected in the structure of the high-frequency cluster due to intra- and inter-subject differences in the shapes and sizes of the back cavity and the lateral channels. Effects of coarticulation and speech rate may further influence these variabilities (Giles and Moll, 1975).

In this paper, a detailed account of the 3-D vocal tract and tongue shapes for the laterals in American English was presented. The results of this investigation may be used as a baseline for studying articulatory-to-acoustic relations of these sounds and will be reported in the future.

ACKNOWLEDGMENTS

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APPENDIX: VARIABILITY ANALYSES THROUGH EPG STUDIES

In this Appendix, we describe the results of an EPG study which is aimed at investigating:

(1) Intra-token articulatory (temporal) stability during sustained phonation of light and dark /l/s.

(2) Inter-token articulatory variabilities of these sounds.
(3) Differences and similarities between these sounds produced in sustained utterances with respect to the sounds produced in naturally spoken words. Both inter-subject differences in the articulatory patterns for each sound and differences and similarities between light versus dark /l/ are investigated. Our focus here is to study the variabilities of sustained sounds with respect to those occurring in natural contexts, and not to investigate specific coarticulatory effects.
(4) Inter-subject differences in the articulatory patterns for each sound.

1. Data analysis

EPG data from the sustained utterances (eight repetitions) were collected from the subjects in a supine posture (simulating the position assumed inside the MRI scanner). EPG data were also collected for the words {*elitist, freely, Robert E. Lee*} for light /l/, and the words {*paul, peel, pool*} for dark /l/, all of which were spoken embedded in the carrier phrase ''Say—again''. These utterances were spoken by the subjects in their normal upright posture.

The total percentage of electrodes contacted in the front and back regions (refer to Fig. 2 for region definitions) were calculated and used for variability analyses. Temporal averaging of the contact measures was done over the middle 3.8 s of each sustained data segment.

It should be noted that, given differences in individual oral morphologies (such as palate structure), the intersubject comparisons using EPG contacts can be justified since: (a) region definitions for each subject were selected based on their individual palate structure instead of an arbitrary assignment of electrodes to particular regions, (b) comparisons were based on normalized ''percentage'' contacts in each region, and (c) intersubject comparisons are intended to give, at a gross level, differences in the tongue-palate interactions (e.g., whether light /l/ is characterized with greater contact in one subject compared to another). Due to the data ''normalization,'' such comparisons should reflect differences in gestural rather than anatomical differences.

Sample EPG contact profiles are shown in Fig. A1. For the sustained utterances, the mean and standard deviation of the *total* (i.e.,=front+back) linguopalatal contact were calculated. For [l], the total linguopalatal contact (expressed in percentage relative to the total number of electrodes) across tokens was 60% in AK and PK when compared to 40% in MI and 25% in SC. Token-to-token variability was less than 5%, and within-token variations were within 4%, assuring both within- and across-token consistency. For [ɫ], the total contact was 20%, 40%, and 25% for AK, MI, and SC, respectively. Token-to-token variability was less than 7%, and within-token variations were within 3.7%. Subject PK produced [ɫ] with no lingual contact (in 3 tokens) or with minimal contact (5%–10% total contact in 5 tokens). Recall that the ''sampling time'' for EPG is 10 ms. Hence, about 400 EPG profile samples were averaged in each token.

These results indicate that our phonetically trained subjects produced the sustained sounds in a consistent manner assuring a degree of articulatory stability during the MRI experiments. Further detailed analysis of intra- and inter-token variabilities was done using repeated measures ANOVA with total linguopalatal contact as the dependent variable.

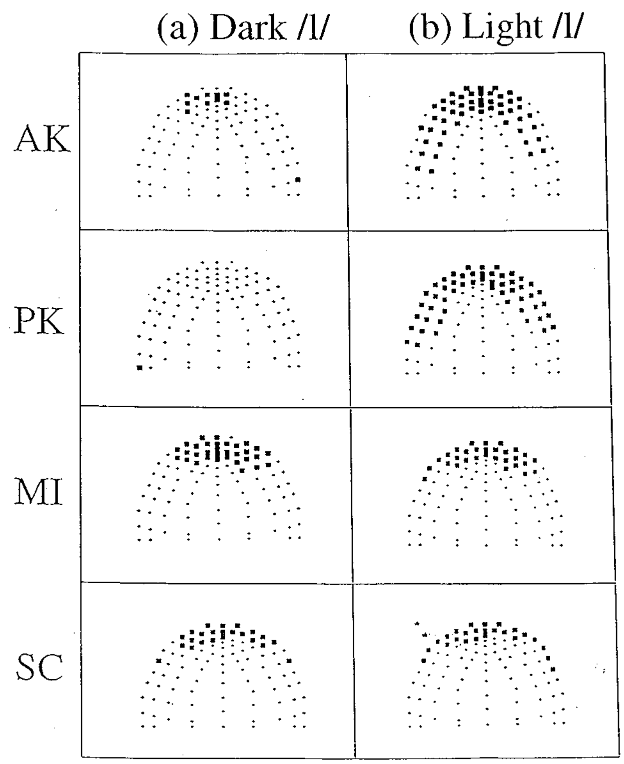

FIG. A1. Sample linguopalatal contact profiles for the dark and light lateral allophones of the different subjects.

The first set of these tests used sustained utterances. Results showed no significant intra-token variations in the total contact values for both dark and light /l/ ($F=0.183$, $p=0.903$) for all the subjects.

ANOVA results (one-way repeated measures using allophone type as factor and total linguopalatal contact as the dependent variable) for between-subjects variation in the total contact of the sustained light versus dark /l/ may be considered somewhat statistically significant ($F=4.092$, $p=0.092$). The absence of a high significance in these variabilities is not surprising since the contact patterns for the dark and light /l/ of subject MI, and to a lesser degree, of subject SC, are comparable. This may have resulted due to either the tongue shaping and bracing associated with the apical nature of the /l/s produced by these subjects, and/or a greater tongue bracing in the artificial scenario of sustaining the lateral sounds (the latter hypothesis may be verified by comparing sustained and in-context EPG data). The analysis also showed variations in the total contacts of dark versus light cases for each subject with similar statistical significance levels ($F=1.984$, $p=0.080$). There was an equally significant interaction with the sound-type factor ($F=2.198$, 0.054) which may be due to the fact that not all subjects showed the same contrast in tongue-palate contact patterns between [l] and [ɫ].

In the second of these tests, EPG data corresponding to the laterals extracted from naturally spoken words were com-

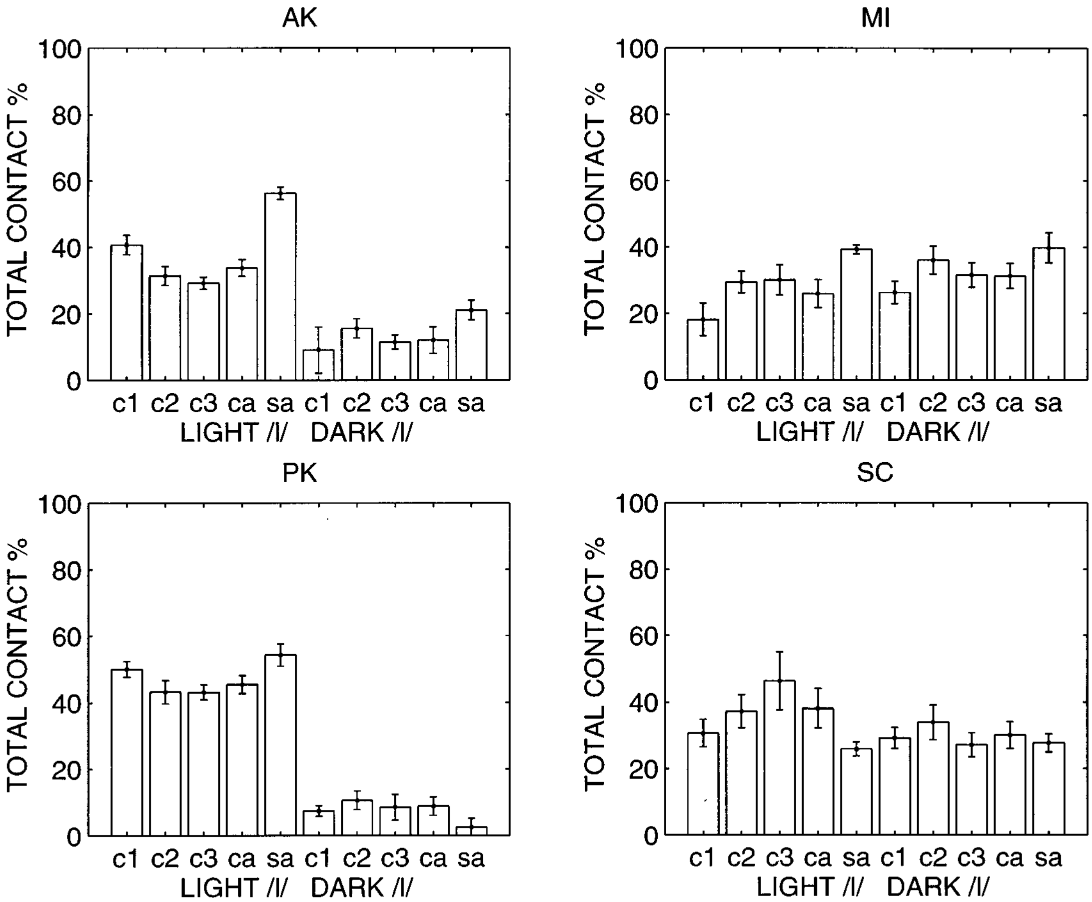

FIG. A2. Total linguopalatal contact expressed in percent relative to the total number of electrodes for light and dark /l/ obtained from both naturally spoken words and sustained utterances, averaged across eight repetitions for each subject. The first five bins in each panel correspond to light /l/ while the last five correspond to dark /l/. For light /l/,c1,c2,c3 represent contact values extracted from the words {*elitist, freely, Robert E. Lee*}, respectively, while for dark /l/, they represent contact values extracted from the words {*paul, peel, pool*}. ca and sa represent the pooled average values for the in-context and the sustained utterances, respectively. The error bars represent the variations in linguopalatal contact across repetitions. Further data analysis was based on ANOVA techniques (see text for details).

pared against the sustained ones. Segmentation from each word was done manually using time-aligned displays of the acoustic waveform, spectrograms, and EPG data. The total contact for each token was then obtained by (temporal) averaging over the segmented duration and used for variance analyses. The variabilities within the eight repetitions of each token were found to be statistically insignificant, and the results reported in this paper are based on averages of the total contacts across the eight repetitions. The average total linguopalatal contact values for each of the in-context cases, along with their pooled average and the average value for the sustained utterances, are shown in Fig. A2. ANOVA on total average contact (dependent variable) for [l] with respect to context showed no significant variation ($F=0.554$, $p=0.655$). Similar tests for [ɫ] with respect to context (words vs sustained) also showed no significant variation between the various cases ($F=2.098$, 0.154). Matrices of comparison probabilities computed following Tukey *post hoc* tests (Tables AI and AII, for [l] and [ɫ], respectively) showed that, although statistically not significant, relatively greater variability was found when the in-context cases were compared with the sustained cases. The reason for this may be the somewhat greater (but not significant) tongue bracing seen in the sustained utterances of all subjects, except subject SC.

The final set of tests were comparisons (two-way ANOVA followed by Tukey *post hoc* tests) based on pooled averages across the various in-context cases with respect to averages for sustained cases. The resulting matrix of com-

TABLE AI. Matrix of pairwise comparison probabilities from Tukey *post hoc* tests following ANOVA of average total linguopalatal contact for [l] across various contexts and sustained utterances ($F=0.554$, $p=0.655$).

	*e*__l__*itist*	*free*__l__*y*	*Robert E.* __L__*ee*	sustained
*e*__l__*itist*	1.000			
*free*__l__*y*	1.000	1.000		
Robert E. __L__*ee*	0.991	0.995	1.000	
sustained	0.675	0.707	0.831	1.000

TABLE AII. Matrix of pairwise comparison probabilities from Tukey *post hoc* tests following ANOVA in average total linguopalatal contact for [ɫ] across various contexts and sustained utterances ($F=2.098$, $p=0.154$).

	*pau*__l__	*pee*__l__	*poo*__l__	sustained
*pau*__l__	1.000			
*pee*__l__	0.864	1.000		
*poo*__l__	0.987	0.693	1.000	
sustained	0.250	0.638	0.151	1.000

TABLE AIII. Matrix of pairwise comparison probabilities from Tukey post hoc tests following a two-way ANOVA in average total linguopalatal contact for [ɫ] and [l] across various contexts (pooled averages) and sustained utterances. ANOVA results: For, the factor *allophone*={[ɫ],[l]}, ($F=34.108$, $p=0.000$); for the factor *type*={in-context, sustained}, ($F=6.243$, $p=0.019$); for the interaction between allophone and type, ($F=0.174$, $p=0.680$).

		[ɫ] context	[ɫ] sustained	[l] context	[l] sustained
ɫ	context	1.000			
ɫ	sustained	0.190	1.000		
l	context	0.000	0.108	1.000	
l	sustained	0.000	0.020	0.467	1.000

parison probabilities (Table AIII) helps us to further isolate some of the variabilities. No significant differences were found between the sustained and in-context cases for both [l] and [ɫ]. The differences in the total linguopalatal contact were significantly different between [l] and [ɫ] in both sustained and in-context cases ($p<0.005$). A two-way ANOVA with respect to the different subjects and sound type (dark, light) showed significant differences ($p<0.01$) between [l] and [ɫ] for subjects AK, PK, and SC (Table AIV).

In summary, the EPG analyses indicate significant intra- and inter-token articulatory stability in the production of [l] and [ɫ] by our phonetically trained subjects. Furthermore, no significant differences were found in the linguopalatal contact patterns of the artificially sustained utterances of /l/ and those that occurred in natural contexts. These results give credibility to our using MR images of sustained laterals to capture ''canonical'' tongue shapes for these sounds. The caveats of our study, however, should be reiterated. The coarticulatory influences in the production of liquid consonants are well-known, and EPG data provides only limited articulatory information. Our study, however, is an attempt to provide insights into the three-dimensional vocal tract and tongue shapes during speech production and to gather quantitative data that can be useful for articulatory-to-acoustic modeling.

TABLE AIV. Matrix of pairwise comparison probabilities from Tukey *post hoc* tests following a two-way ANOVA in average total linguopalatal contact (pooled across various contexts) for [ɫ] and [l] across various subjects. ANOVA results: For, the factor *allophone*={[ɫ],[l]} ($F=44.231$, $p=0.000$); for the factor *subject*={AK,MI,PK,SC} ($F=1.044$, $p=0.391$); for the interaction between allophone and subject ($F=1.358$, $p=0.279$).

		[ɫ] AK	[ɫ] MI	[ɫ] PK	[ɫ] SC	[l] AK	[l] MI	[l] PK	[l] SC
[ɫ]	AK	1.000							
[ɫ]	MI	1.000	1.000						
[ɫ]	PK	1.000	1.000	1.000					
[ɫ]	MI	1.000	1.000	1.000	1.000				
l	AK	0.031	0.035	0.024	0.033	1.000			
l	MI	0.437	0.470	0.374	0.454	0.836	1.000		
l	PK	0.002	0.002	0.002	0.002	0.933	0.206	1.000	
l	SC	0.111	0.124	0.089	0.118	0.998	0.991	0.638	1.000

[1]An approximant is a sound that is characterized by the approach of one articulator toward another but without the tract being narrowed to such an extent that a turbulent air stream is produced (Ladefoged, 1993).

[2]Data from sustained utterances were also collected from the subjects in upright position, but no significant differences in the linguopalatal contact patterns of these sounds produced in the two postures were found. Some of the minor differences found for [l] include: for PK, a tendency toward relatively larger linguo-alveolar contacts in the upright articulations when compared to the supine ones; for AK, slightly greater lateral linguopalatal contacts were observed in supine position; and for SC, lateral contact in the postpalatal region, which is probably due to the anterior extension of the linguo-velar bracing, were found in supine position.

[3]A convex shape refers to doming of the tongue surface as viewed from the palate, whereas concave refers to curving of the surface inwards as viewed from the palate.

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