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Tamil liquids: An investigation into the basis of the contrast among five liquids in a dialect of Tamil

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The Brahmin dialect of Tamil (Dravidian) has an unusual inventory of five distinctive liquid sounds: plain and retroflex rhotics, and plain and retroflex laterals, and a fifth liquid which has been variously described as a rhotic, a lateral, a glide and/or a fricative. This paper investigates the articulatory, acoustic, and perceptual properties of these liquids, and, in particular, the fifth liquid. Electropalatography (EPG) and static palatography were used to examine the articulatory properties of the liquids, the acoustic properties of the liquids were examined, and we tested the intelligibility of the EPG recordings in a perception experiment. Our intent is to propose a classification for the fifth liquid based on these studies. The fifth liquid is classified as a retroflex central approximant, with characteristics that make it distinct from the other liquids along three dimensions of contrast: static ~ dynamic, central ~ lateral and retroflex ~ non-retroflex.

1. Introduction

In the standard phonemic analysis, the Brahmin dialect of Tamil[1], a Dravidian language spoken in India, Sri Lanka, Malaysia and beyond, has an unusual inventory of five liquid sounds, two rhotics, a tap and a trill, two laterals, plain and retroflex, and a fifth liquid that has been described as both a rhotic and a lateral (Firth 1934, Arden 1942, Meile 1945, Fowler 1954, Ramasubramanian and Thosar 1970, Rajaram 1980, Christdas 1988). In many accounts of the language, the phonemic distinction between the tap and the trill has disappeared; the distinction is retained in the orthography alone (Firth 1934, Zvelebil 1970, Balasubramanian 1982a, Christdas 1988). In this case, there are four phonemic liquids: the rhotic /r/, two laterals /l/ and /ḷ/ and the fifth sound, which we will transcribe as /z/, following Firth and others (Firth 1934, Zvelebil 1970 and works cited within).

In this study we investigate five liquid contrasts. The set of consonantal reflexes in intervocalic position considered in this study is shown in table 1.

[1]Four orthographies are used in this paper: we use italic *t* for romanized Tamil orthography (in our own proposal and in citing others), /t/ for phonemic transcription, square brackets [r] for phonetic transcription, and cornered brackets <a_i> in section 5, also to indicate Tamil orthography. Transliterations from the Tamil were done by our primary consultant and checked with other speakers. We define 'Brahmin' as in Narayaran et. al. (1996), as the dialect of Tamil with this inventory of contrasts.

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Table 1. The five liquids of Tamil as characterized in this paper.

	retroflex	alveolar
rhotics: flap/tap	ɽ	ɾ
lateral: approximants	ɭ	l
rhotic: central approximant	ɻ	

These are a plain and retroflex lateral and a plain and retroflex rhotic and a fifth liquid that, we will argue, is best characterized as the retroflex central approximant [ɻ]. We examine these sounds along two planes of contrasts: rhotic versus lateral and plain versus retroflex. This paper is a preliminary investigation into some of the articulatory, acoustic and perceptual properties of these liquids, and, in particular, the fifth liquid.

This paper studies these Tamil liquids in a single prosodic position, the intervocalic (VCV) position. There are several reasons for limiting ourselves to this position. First, the phonotactics of Tamil bar retroflex sounds from initial position. Thus we chose to examine all the liquid sounds in intervocalic position where all the sounds occur. This decision, however, adds a further complication in that the consonantal reflexes in Tamil (and Dravidian in general) are conditioned by their prosodic position. For instance, in Proto-Dravidian, morphophonemic constraints state that fortis and lenis stops are in complementary distribution; initial stops are fortis, post-vocalic ones are lenis (Zvelebil 1970, Fowler 1970). This is referred to as Caldwell's Law. Fowler (1970) disputes Caldwell's Law, stating that the contrast has become phonemic in Tamil; in post-vocalic position both lenis and fortis stops contrast (p.366). However this intervocalic lenis ~ fortis distinction is enhanced by a length distinction; geminate versus singleton. The intervocalic fortis stops are geminate. We will take up the implications of these intervocalic contrasts more fully below. And finally, this paper is an extension of earlier instrumental studies by Ramasubramanian and Thosar (1970), Balasubramanian (1982a, 1982b) and Narayanan, et al. (1996), all of who examined Tamil liquids in post vocalic position.

In their study of the retroflex sounds in Tamil, Ramasubramanian & Thosar (1970) presented static palatograms of [ɭ] and [ɭɭ] in inter-vocalic and word final positions and acoustic vowel formant measurements comparing the 'steady-state' formants of [ɭ] and [l] intervocalically. The first author served as the sole speaker for this study. They found that the retroflex [ɭ] is pronounced with tongue/palate contact in the 'medio-palatal' region and that the contact area was larger for the doubled consonant than it was for the single consonant. The retroflex and non-retroflex laterals differed primarily in terms of F3 though they 'failed to synthesize a sound even remotely resembling [ɭ]' (p. 80) using symmetrical formant transitions before and after the consonant closure. Our data suggest that Ramasubramanian and Thosar's assumption, that [ɭ] has steady-state formants during the closure interval and symmetrical transitions around it, is incorrect.

Balasubramanian (1982a, 1982b) studied the two orthographic R's and geminate versus singleton nasals and laterals in Tamil using static palatography and electrokymography. The R's were studied in intervocalic and initial positions (where trill and flap productions seem to be in free variation) and the geminate/singleton comparison was made in intervocalic position. Four speakers participated in the study, though data from only one (the author) are shown. Balasubramanian concluded that the two orthographic R's of Tamil do not differ in pronunciation, both being realized as 'post-alveolar' taps intervocalically. The contact regions indicated in both of the palatograms of these sounds extended forward to the rugae on the alveolar ridge, though one appears to have been pronounced with contact extending slightly further back than the other. Concerning [ɭ] and [ɭɭ], Balasubramanian shows that the singleton was pronounced with tongue contact more forward in the mouth than the geminate (pre-palatal versus palatal) and more of the marking medium was removed by the articulation of the geminate perhaps indicating longer or tenser tongue palate contact in the geminate. Kymographic data also indicated that the geminate retroflex liquid was over twice as long as the singleton.

In a more recent study, Narayanan, et al. (1996) studied the pronunciation of the five Tamil liquid letters in intervocalic position in the speech of one speaker (the first author) using magnetic resonance imaging of sustained pronunciations, electromagnetic point tracking, and static palatography. Findings of this study will be discussed in more detail below as we discuss our data. Unlike previous authors, Narayanan et al. suggest that the two orthographic R's are pronounced differently, describing one as pre-alveolar and the other as post-alveolar. The sound that Narayanan et al. describe as pre-alveolar appears to be the sound which Balasubramanian's palatograms show with a slightly more posterior closure. This discrepancy between speakers and the overall very slight differences between the R's in Balasubramanian's and Narayanan's data suggest that the orthographic distinction does not reflect a phonological contrast.

We have chosen in this study to include a different set of liquid sounds than is usually indicated by the phonemic inventory of liquid and stop sounds in Tamil. As noted above, intervocalic position in (Proto-) Dravidian and in Tamil is considered a position of lenition, or 'weakened occlusion' and voicing. Many scholars consider the fundamental stop opposition to be tense ~ lax rather than voiced ~ voiceless both because of the intervocalic lenition and the development of the doubled consonants (Christdas 1988, Zvelebil 1970, and Kuiper 1958, Lisker 1958). Zvelebil's (1970: 82) study of Dravidian phonology states the Proto-Dravidian stop opposition as follows, " ...a *tense* voiceless articulation of the plosive in initial position in [complementary distribution] with a *lax* more or less voiced articulation with weakened occlusion intervocalically, in OPPOSITION to a consonant cluster developing into a tense long ("geminated") stop." (Emphasis is Zvelebil's.) He states, citing studies by Lisker (1958) and Kuiper (1958), that the tense / lax distinction holds of contemporary Tamil stops and not the voiced / voiceless one. See also Mohanan (1986) on Malayalam on this subject. L. Lisker (1958), cited in Zvelebil (1970: 82fn), states the opposition as such, "The contrasting sets which Tamil orthography renders by *p t ṭ k* and *pp tt ṭṭ kk* differ in closure duration, to be sure, but this may be considered a concomitant of the other phonetic dimensions which serve to separate the two sets: fricative versus stop and flap versus stop and voiced-lenis vs. voiceless-fortis". The occlusion of the stop is weakened to a flap or fricative in intervocalic position. Zvelebil (1970: 83) and Christdas (1988: 140) also claim that the intervocalic reflex of the alveolar /t/ is the flap /r/.

Since the [ɾ] / [t], [d] distinction is awkward to represent phonologically but can be considered a closure duration feature (Steriade 1996), and since the intervocalic contrast is a contrast of lenition and not voicing, and since a tap/flap is never in clear contrast to a homorganic voiced stop and a rhotic (Banner-Inouye 1995), we will consider this intervocalic segment to be a rhotic flap/tap. Note also that the intervocalic reflex of the labial and velar stops are spirantized (Zvelebil 1970, Christdas 1988, Mohanan 1986) for Malayalam.) The alternative is to consider some stops to become voiced intervocalically (the coronals) and other (labial and velars) to become lenited. We prefer the former analysis.

In view of this, we included another liquid into the study, the intervocalic reflex of the retroflex stop /ṭ/. While this sound is often transcribed as /ḍ/, the intervocalic reflex of the retroflex stop /ṭ/ is the retroflex flap [ɽ], as a consequence of the lenition of intervocalic consonants in Tamil and analogous to the intervocalic neutralization of the coronal stop /t/ to /r/. Mohanan (1986: 64ff) claims that similar lenition effects for Malayalam, in particular the lenition of a retroflex stop to a retroflex flap. Thus for the purpose of this paper, stops in the intervocalic position are lenited, and the lenited reflexes of the coronal stops /t/ and /ṭ/ in Tamil are the flaps /r/ and /ṛ/. These, with the plain and retroflex lateral and the fifth liquid, are the five liquids under consideration.

There is confusion in the literature about the nature of this fifth liquid in Tamil, reflected in the many ways it has been transcribed. Christdas (1988) reports finding eight conflicting symbols for it (retroflex and alveolar, lateral and rhotic), including symbols for the fricatives [ʒ] and [ʐ]. Most seem to agree that this fifth liquid sound is retroflex and the characterizations can be broken into three groups: as a lateral (Rajaram 1980, Narayanan, et. al. 1996) or a rhotic (Firth 1934, Christdas 1988) or as "an obscure sound between r and l." (Arden 1942, cited in Christdas 1988). Firth (1934) called it a "frictionless continuant having an obscure unrounded back quality". Zvelebil (1970) summarizes '...most authors agree that is a retroflex or retracted voiced fricative...' (p. 148) and states that the "phonetic value of *J* in modern [Tamil] and [Malayalam] seems to range from retracted voiced fricative...to retroflex voiced vibrant [ṛ]..." (p.149). Rajaram (1980) characterized it as retroflex palatal lateral with fricative constriction: "...the tongue is curled back and the tip of the tongue is placed very near the roof of the mouth but not touching it. The airstream is allowed to pass through the sides of the tongue as well as in between the tip of the tongue and the roof of the mouth (p.33.)" Christdas (1988) calls the fifth liquid "the glide [ṛ]" (p.132), characterizing it as a retroflex glide. Part of our intent in this study is to propose a classification for the fifth liquid based on our instrumental studies. Our findings are consistent with Zvelebil and Christdas's descriptions; we classify the fifth liquid as a central approximant glide, with a retroflex tongue position. Frication, when it is present, is incidental to the contrast. These features are taken up in the discussion section.

In this study, we used electropalatography (EPG) and static palatography to examine the articulatory properties of the liquids in the speech of one speaker, we examined their acoustic properties in the speech of two additional speakers, and we tested the intelligibility of the EPG recordings and patterns of confusion in a perception experiment with four listeners. We discuss the method and results of this study below.

2. Methods used in the production studies

We used three techniques to examine productions of the Tamil sounds under study. These phonetic techniques taken together provide converging evidence for phonetic descriptions of the sounds. This section describes the methods used to collect the electropalatographic (EPG), static palatographic, and acoustic data. In the next section we will discuss the results of these studies for each of the sounds.

EPG

The word list for the EPG recordings is shown in Table 2. It consists of ten words, each of the five liquids in <a_a> and <a_i> contexts. Each word was repeated three times at three different speeds (normal / fast / slow) in a carrier phrase. This speaker was careful to maintain the liquid contrasts, including the sound [ɻ], at all rates of speech. The carrier phrase is [tʃol ___ enri] "say this ___". (This is a transcription of the pronunciation of the speaker and the transliteration given by us by our primary consultant.)

Table 2. Tamil word list (Brahmin dialect)

[pʌɾʌm]	param	'supreme being'
[pʌɻʌm]	pazam	'fruit'
[pʌlʌm]	palam	'small weight'
[vʌɭʌm]	vaḷam	'beauty / prosper'
[pʌɽʌm]	paḍam	'picture'
[pʌɾi]	pari	'horse'
[pʌɻi]	pazi	'blame'
[pʌli]	pali	'take effect'
[vʌɭi]	vaḷi	'wind' (lit.)
[pʌɾi]	paḍi	'read'

One female speaker of the Brahmin dialect of Tamil read the word list at the three self-selected rates (slow, normal, and fast). Tongue-palate contact patterns were registered using a custom-fitted pseudopalate implanted with 96 electrodes and Kay Elemetrics' electropalatography system. The electrodes on this palate are arranged symmetrically on the left and right sides of the palate. The most peripheral semicircle of electrodes are placed on the teeth, with the second semicircle on the gums. The electrodes are closer to each other in the alveolar and alveo-palatal regions, with more sparse placement on the hard and (anterior portion of) the soft palate. Locations of the electrodes projected onto the occlusal plane (in mm) are recorded in a 'user' file which we used to automatically measure constriction location, width, and length. The contact patterns were recorded at a sampling rate of 100 Hz with a simultaneous acoustic signal sampled at 10 kHz.

We examined both raw dynamic data (time series) and used a data reduction technique similar to that used by Flege et al. (1987), Hoole et al. (1989), and Fletcher & Newman (1991)[2]. A computer program measured the location, width, and length of midline constrictions for each frame in the consonant closure interval (see figure 1). In this EPG data reduction technique a constriction is defined as a point of narrowing around the midline of the palate. A midline closure is registered when a midline electrode is contacted and midline constriction is located at the smallest distance (in mm) between corresponding electrodes on the left and right sides of the midline of the palate. Constriction location is defined as the distance between the front incisors (the most anterior midline electrode on the pseudopalate) and the most anterior electrode in the constriction. This corresponds to Flege et al.'s (1987) anterior-posterior location of constriction and Hoole et al.'s (1989) position of maximum constriction. Groove width is 0 for closures and for constrictions is the distance between the contacted electrodes on the left and right sides of the constriction which are closest to the midline. Flege et al. also call this measurement groove width, and Hoole et al. call it constriction width. Constriction length is the distance between the most anterior and most posterior electrodes forming the constriction. In the case of closures this is measured on the midline and for constrictions is the maximal extent of the constriction on the left or right side of the palate. Hoole et al. found that 'it proved difficult to find a robust definition for this concept'. Fletcher (1992) defined 'contact length' for stop consonants only, and Flege, et al. (1987) measured the length of the constriction in fricatives by eye. Constriction lengths of closures at different constriction locations cannot be meaningfully compared in this study because the electrodes were not uniformly spaced on the pseudopalate. Therefore, we will only rely on constriction length comparisons for constrictions in the front part of the palate where the electrodes were more densely placed.

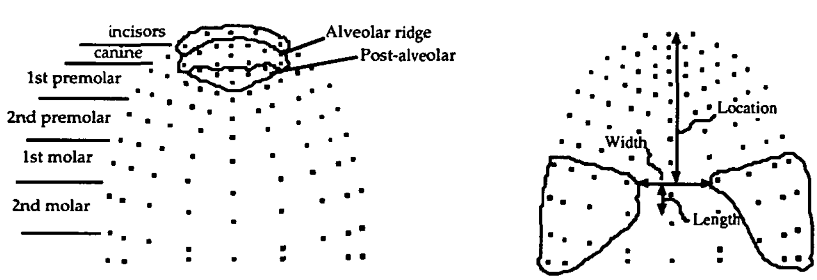

Figure 1. The arrangement of electrodes on the pseudopalate used in the EPG study.

[2] This technique of EPG data reduction is somewhat different from the methods discussed by Hardcastle, et al. (1991) and Recasens (1990, 1991).

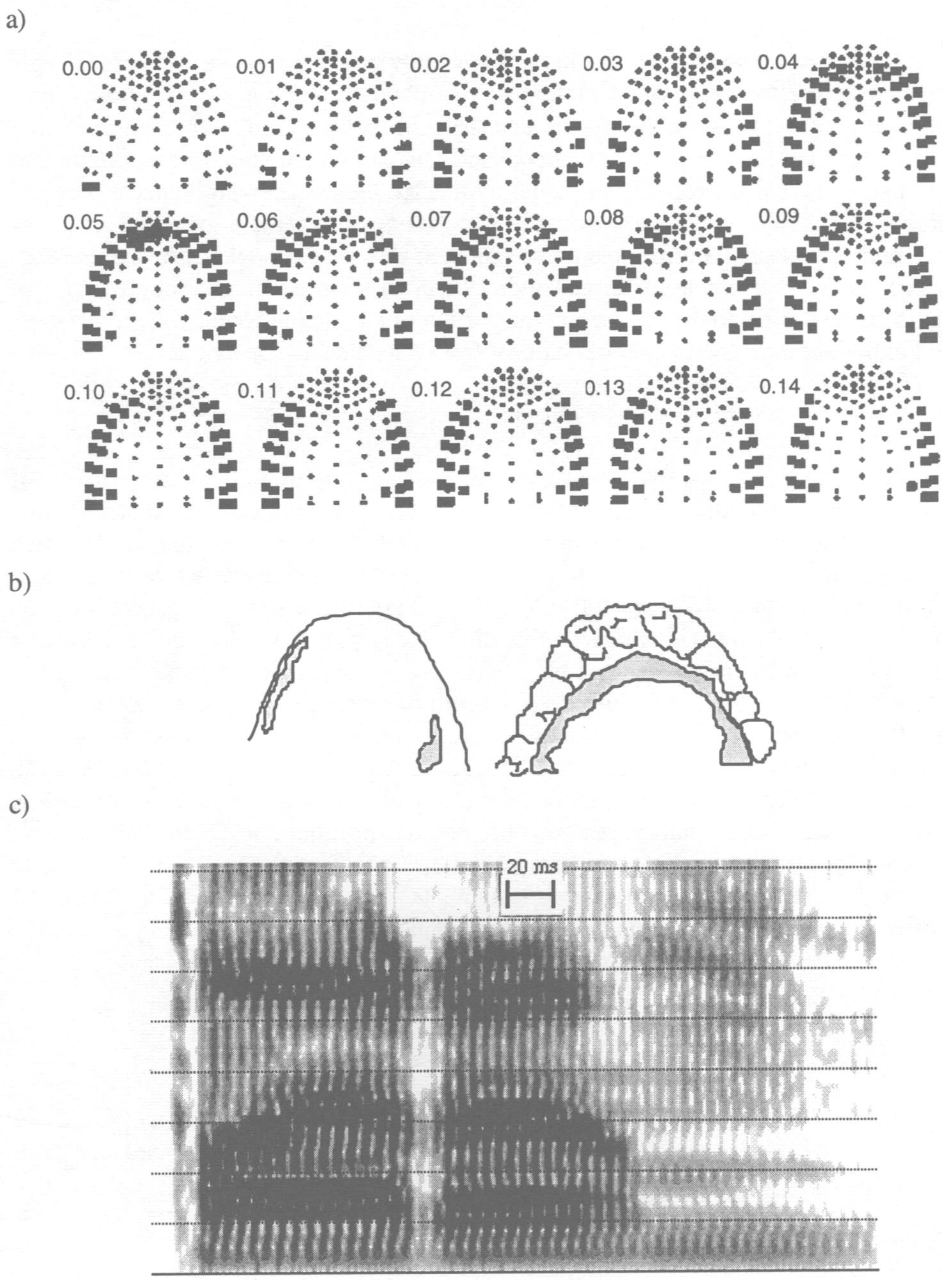

Figure 2. a) A typical EPG time series of a production of the Tamil alveolar flap [ɾ] in the <a_a> context. b) Linguographic and palatographic records. c) A spectrogram of a typical production again in the <a_a> context.

Static Palatography

The same speaker who participated in the EPG study produced the <a_a> words (Table 2) once for static palatography study. Static palatography (Abercrombie, 1957; Ladefoged, 1957) registers contact between the tongue and the roof of the mouth. We used the wipe-on method (Dart, 1991). A mixture of charcoal and olive oil was applied to the tongue (for palatograms) or the palate (for linguograms) and, after the speaker produced a word, a photograph was taken of the palate or tongue. We used a video camera to record an image of a small tear-drop shaped mirror held in the mouth at a 45 degree angle to the camera lens (Ladefoged, 1997). Place of articulation is indicated in wipe-on palatograms by transfer of charcoal from the tongue to the palate, and the portion of the tongue contacting the palate is indicated in linguograms by transfer of charcoal from the palate to the tongue.

Recordings and Acoustic Measurements

Recordings were made of two speakers (male and female) of the Brahmin dialect of Tamil. The speakers who did not speak this dialect either could not produce this sound or considered this sound to belong to another dialect than the one they spoke. The two speakers in the acoustic study were between the ages of 25 and 35, were native speakers of Tamil from Madras, and they were self-selected speakers of the Brahmin dialect with the fifth liquid. Both speakers (neither of whom participated in palatographic studies) read four repetitions of each word in the list in table 2 in the same carrier phrase used in the EPG study at a self-selected normal rate of speech. Recordings were made in a sound-attenuated booth (IAC Double-walled Chamber) using a head-mounted microphone (Shure SM10A) and a portable cassette recorder (Marantz PMD 320). The recordings were digitized (22 kHz, 16 bits) with digital decimation anti-alias filtering at 9 kHz and measurements of the first three formants in the analysis frames just before and after the acoustic consonant closure were taken from digital spectrograms which had a frequency range from 0 to 4 kHz (Melenkovic and Read 1992). Formant measurements were taken from LPC estimates of formant frequencies (24 coefficients, pre-emphasis, and automatic peak-picking). The LPC estimates were visually verified by overlaying the formant tracks on wide-band (300 Hz bandwidth) spectrograms.

3. Production Results

Typical productions of the sounds are shown in figures 2-6, and quantitative results are shown in figure 7. The results for each sound will be discussed individually with comparisons to previous findings reported in the literature.

The alveolar flap [ɾ]

Figure 2 shows a typical EPG time series, the linguogram and palatogram, and a typical spectrogram of the alveolar flap [ɾ] in the <a_a> context. The EPG time series and spectrogram both show that this sound has a closure interval of about 15 ms (see figure 7c). The tongue contacts the roof of the mouth behind the upper incisors. This is most apparent in the static palatogram where it can be seen that the most anterior point in the contact region in the midline of the vocal tract lies behind the gingiva. This observation is confirmed by the EPG token in which the most anterior two electrodes in the midline remain uncontacted during the production of the word.

Narayanan et al. (1996) suggest that midline closure is not achieved during [ɾ] and inspection of the linguogram in figure 2b suggests that in some productions in our study this may indeed have been the case (recall that different productions are represented in the linguogram and static palatogram in figure 2b). Further evidence which may be taken to support Narayanan et al.'s conclusion may be seen in figure 7b which shows average groove width across all EPG tokens. Recall that complete closure is indicated by a groove width of 0. So the fact that groove width at the acoustic onset and offset of [ɾ] is not 0 is consistent with their suggestion. Evidence that complete midline closure does occur during [ɾ] in our data comes from productions such as the one shown in the EPG time series in figure 2a and from our acoustic analysis in which an apparent occlusion such as the one seen in figure 2c was present in every spectrogram of [ɾ] that we inspected. With a quick ballistic movement such as a flap there is the possibility that our EPG system which has a relatively slow sampling rate (100 Hz) may have missed the short moment of occlusion. This account may explain the occasional lack of complete closure indicated in figure 7b and the failure of the charcoal transfer in the linguogram in figure 2b. Balasubramanian (1982a) found using the wipe-off method of static palatography 'just a suggestion of a wipe-off' in this sound. We suspect that the wipe-on method which we used (and which Narayanan et al. used) may be less sensitive to light quick contacts than is the wipe-off method. At least there is nowhere in any study of Tamil [ɾ] any indication that a wide, asymmetrical opening such as that indicated by figure 2b occurs for this sound). Narayanan et al. also base their conclusion on the assumption that the tongue-tip transducer in EMMA can be used to determine the presence or absence of a vocal tract occlusion. We feel that this assumption is somewhat suspect because the "tongue-tip" transducer is not mounted at the very tip of the tongue (Perkell et al. 1992) and so offers no direct evidence regarding tongue-tip occlusions. Similarly, we question the value of MRI images of static vocal tract "hold" positions in the study of inherently dynamic articulations. In summary, we believe an inference that there is no midline occlusion on the flap [ɾ] to be in error because (a) every spectrogram of the flap showed an occlusion (even when one was not seen in the EPG), (b) no prior study of Tamil has suggested this conclusion - in fact Balasubramanian shows static palatographic evidence against this, (c) the difficulty in acquiring an accurate description of a quick ballistic movement using palatography (static or dynamic) means that it is possible to miss the occlusion of a flap, (d) the "tongue-tip" electrode in EMMA was not actually at the tongue-tip, and (e) MR images of static vocal tract "hold" positions for inherently dynamic articulations can only be suggestive at best. We conclude the Tamil flap [ɾ] is the commonly described articulatory gesture in which the active articulator hits the passive articulator in passing.

Our data are inconclusive as to whether the active articulator for this sound is the tongue tip or blade. Previous researchers (Narayanan et al., 1996) have characterized this sound as apical.

The denti-alveolar lateral [l]

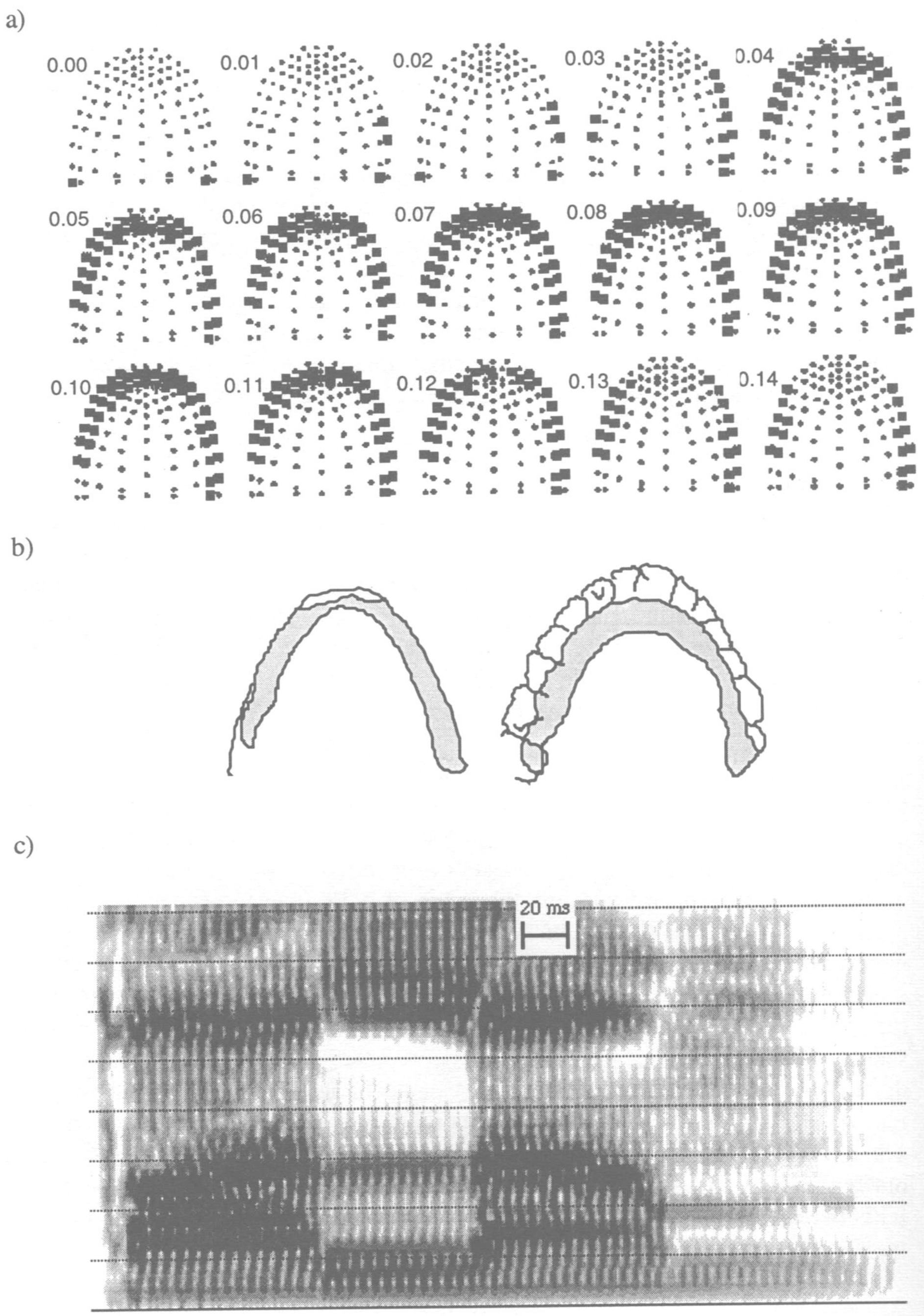

Figure 3. a) A typical EPG time series of a production of the Tamil alveolar lateral [l] in the <a_a> context. b) Linguographic and palatographic records. c) A spectrogram of a typical production again in the <a_a> context.

Figure 3 shows a typical EPG time series, the linguogram and palatogram, and a typical spectrogram of the denti-alveolar lateral [l] in the <a_a> context. The EPG time series shows a consonant closure which lasts about 80 ms and the spectrogram also shows a relatively long consonant closure interval (see figure 7c). The place of articulation is slightly more forward than was the case for [ɾ]. This is indicated in the EPG data by the fact that the second most anterior midline electrode, which was located at the margin of the gums and teeth, was contacted (where the third midline electrode was the most anterior one in [ɾ]). The static palatogram also shows that the tongue contact extends forward to the gingiva. Unlike the MRI image published by Narayanan et al. (1996) we see no evidence of tongue tip protrusion in our data. This is in agreement with their static palatographic data and summary description of [l], and with the static palatograms published by Balasubramanian (1982b). The spectrogram clearly shows that this consonant is voiced and sonorant and the lateral opening can be seen in the EPG and in both the static palatogram and linguogram. Judging by the linguogram in figure 3b we would suggest that the active articulator for this sound is the blade of the tongue because there was no charcoal at the tongue apex, though there is not extensive blade contact as might be expected for a laminal denti-alveolar (Ladefoged and Maddieson, 1996, p. 22).

Data on the closure length were consistent with the characterization of [l] as laminal, assuming that longer, more distributed closures at the dental/alveolar portion of the roof of the mouth are characteristic of laminal tongue contact. Describing Tamil [l] as a laminal denti-alveolar agrees with Dart's (1991) observation that dental sounds tend to be laminal while alveolar sounds tend to be apical. However, Narayanan et al. (1996) report that their linguograms (none of which are shown) indicate that [l] in Tamil is apical and it must be admitted that our evidence for the laminality of [l] is based on rather limited data (one linguogram) and a speculative interpretation of a larger dataset (closure length). Nonetheless, given the range of individual differences in the use of the tongue apex and blade within languages (Dart, 1991) it would not be surprising to find some variation among speakers of Tamil as well.

The retroflex flap [ɽ]

The retroflex flap is the intervocalic reflex of /ṭ/. Figure 4 shows a typical EPG time series, the linguogram and palatogram, and a typical spectrogram of the retroflex flap [ɽ] in the <a_a> context. The closure interval for this sound was about half the duration of the closure interval for [l] and [ɻ] and was somewhat shorter than [ɭ] as well (see figure 7c). Though this sound had a longer duration than [ɾ] it is classified here as a flap on the basis of our auditory impression of the sound and because it is shorter than the three sustained liquids in this study.

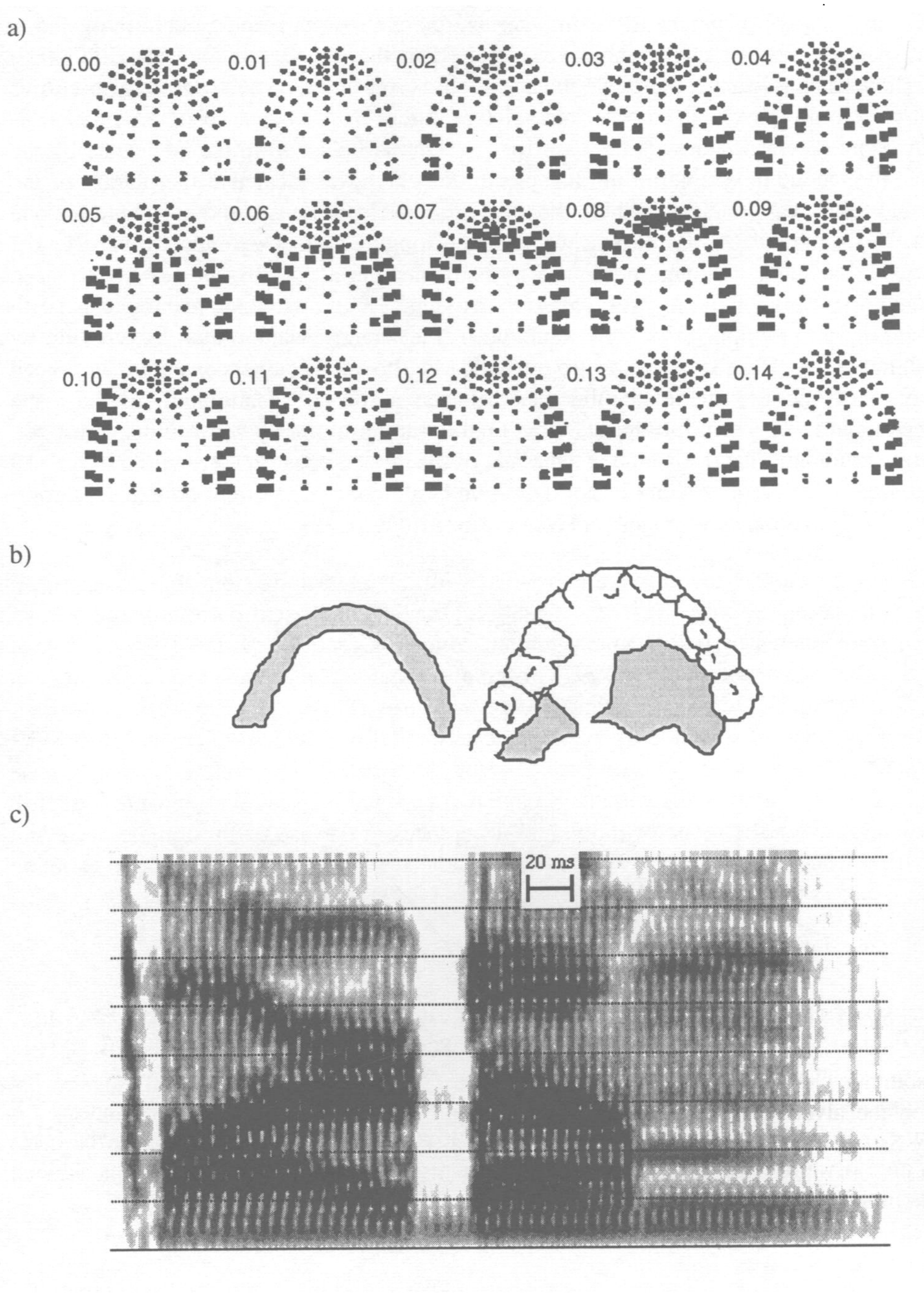

Figure 4. a) A typical EPG time series of a production of the Tamil retroflex flap [ɽ] in the <a_a> context. b) Linguographic and palatographic records. c) A spectrogram of a typical production again in the <a_a> context.

The EPG series shows that the location of tongue contact moved during the closure from the hard palate at the beginning to just behind the alveolar ridge at the end of the consonant. Ramasubramanian & Thosar (1971) presented static palatograms of this sound in which contact extends from between the 1st and 2nd premolars to the canine teeth. The speaker in our study appears to pronounce [ɽ] somewhat further back in the mouth (1st molar) with movement during the sound extending to the canine teeth in the EPG data or 1st premolar in the static palatogram. The average data shown in figure 7a shows that this pattern is typical of productions at other rates of speech and in the <a_i> context as well. In figure 7a the location of the anterior margin of the midline closure at the onset of the consonant is shown with an open circle and the location of the closure at the end of the consonant is shown with a filled circle. The static palatogram and linguogram are consistent with this description and provide additional information about the active articulator for this sound (figure 4b). The palatogram shows contact over a wide region extending from the hard palate forward to the posterior portion of the alveolar ridge (though evidently the transfer of charcoal was incomplete in this production). The linguogram shows a very slim contact region on the tongue which includes the tongue tip. Additional data indicated that the underside of the tongue also contacts the palate in this sound. This pattern of data indicate that the tip of the tongue was curled back to touch the hard palate and then moved across the palate during the pronunciation of the sound. Further evidence for this motion during the consonant closure can be seen in the spectrogram (figure 4c). Here we see a large difference in the frequency of F3 before and after the consonant closure. The data shown in figure 7d indicate that this spectrogram is typical of the pattern we found across rates and vowel environments. Palatal constriction occurs near a velocity node of the third formant resonance causing the resonant frequency to drop (Johnson, 1997; Hagiwara, 1996). Note in the spectrogram in figure 4c that the lowering of F3 begins in the first half of the vowel prior to [ɽ], well in advance of the consonant closure giving the vowel a rhotic quality (to the American English ear at least). The spectrogram also shows that by the end of the consonant the third formant frequency is quite high indicating that the vocal tract is no longer constricted at the hard palate.

The retroflex lateral [ɭ]

Figure 5 shows a typical EPG time series, the linguogram and palatogram, and a typical spectrogram of the retroflex lateral [ɭ] in the <a_a> context. Like the retroflex flap this sound is characterized by movement of the midline closure from the hard palate to just behind the alveolar ridge during the consonant. This can be seen in the EPG series in figure 5a (the average data in figure 7a indicate that this pattern is typical) and in the static palatogram and linguogram (figure 5b), and in the movement of F3 in the spectrogram (figure 5c). Closure duration in this EPG record of [ɭ] is longer than it is in the retroflex flap (about 80 ms) and our acoustic closure duration data (figure 7c) indicate that [ɭ] is on average somewhat shorter than [l] and [ɻ] and longer than the flaps. A lateral opening behind the closure can be seen in the EPG series, with consequent sonority indicated in the spectrogram. Ramasubramanian and Thosar's (1971) static palatograms of intervocalic [ɭ] show a pattern which is somewhat different from the pattern we see in these data. Their speaker (the first author) appears to have pronounced the sound with less movement during the closure, resulting in smaller contact area in the palatogram, and as with [ɽ] without contact as far back as the 1st molar. Balasubramanian's (1982b) palatogram of intervocalic [ɭ] shows midline contact in the post-alveolar and pre-palatal zones (at the level of the 1st and 2nd premolars). Both Ramasubramanian and Thosar, and Balasubramanian show backer and more extensive wipe-off in doubled retroflex consonants. The fact that we see backer and more extensive contact regions in our palatographic data than they found for singletons suggests that our speaker was producing hyper-articulated, careful speech[3]. The comparison of palatographic data from Ramasubramanian and Thosar (1971) and Balasubramanian (1982b) with our own data on retroflexes in Tamil involves a comparison of male and female speakers, because our palatographic data are the first data from a female speaker of Tamil. Therefore, the observed differences may not be merely idiosyncratic but related to gender (see Hagiwara, 1995). Narayanan et al. (1996) published point movement trajectories for [ɭ] which have a sweeping back to front motion of the tongue-tip consistent with the pattern of movement seen in our EPG data. Their description of this motion as 'flapping' is also consistent with the shorter closure duration of [ɭ] that we see in figure 7c.

There are some interesting small differences in the retroflexion gestures for [ɭ] and [ɽ] in our data. First note that the linguogram for [ɭ] did not show palatal contact with the top part of the tip of the tongue while the linguogram for [ɽ] did. Narayanan et al. (1996) show an MRI picture of the articulation of this sound in which the tongue is curled back so that contact with the palate is made with the underside of the tongue. (Presumably the sound was held for the MRI at the onset of the consonant closure). The pattern of charcoal transfer that we see in the linguogram in figure 5b is consistent with this manner of production and additional photographs of the underside of the tongue indicated that our speaker also used a sublingual articulation in [ɭ]. Comparing [ɭ] and [ɽ] in figure 7a (closure location average data) we see that the closure for [ɭ] starts with a more posterior constriction than does [ɽ]. This is reflected in figure 7d by the lower F3 onset value for [ɭ] as compared with [ɽ], indicating that the pattern we discuss is consistent with the productions of the two speakers who spoke for the acoustic study as well as the speaker who provided the EPG and static palatography data. Finally, we note that the anticipation of the retroflexion gesture in the vowel preceding [ɭ], indicated by a drop of F3 during the vowel in figure 5c, occurs somewhat later than it did for [ɽ] though we have not measured this in all productions. Taken together these differences indicate that though [ɭ] and [ɽ] can both be described as 'retroflex' the phonetic realization of retroflexion differs slightly in the two. A theoretical account of this difference is beyond the scope of this paper, but following Narayanan et al. (1996) we would look to possible systemic consequences of differences in lingua-palatal bracing for an explanation.

[3] The comparison of palatographic data from Ramasubramanian and Thosar (1971) and Balasubramanian (1982b) with our own data on retroflexes in Tamil involves a comparison of male and female speakers, because our palatographic data are the first data from a female speaker of Tamil. Therefore, the observed differences may not be merely idiosyncratic but related to gender (see Hagiwara, 1995).

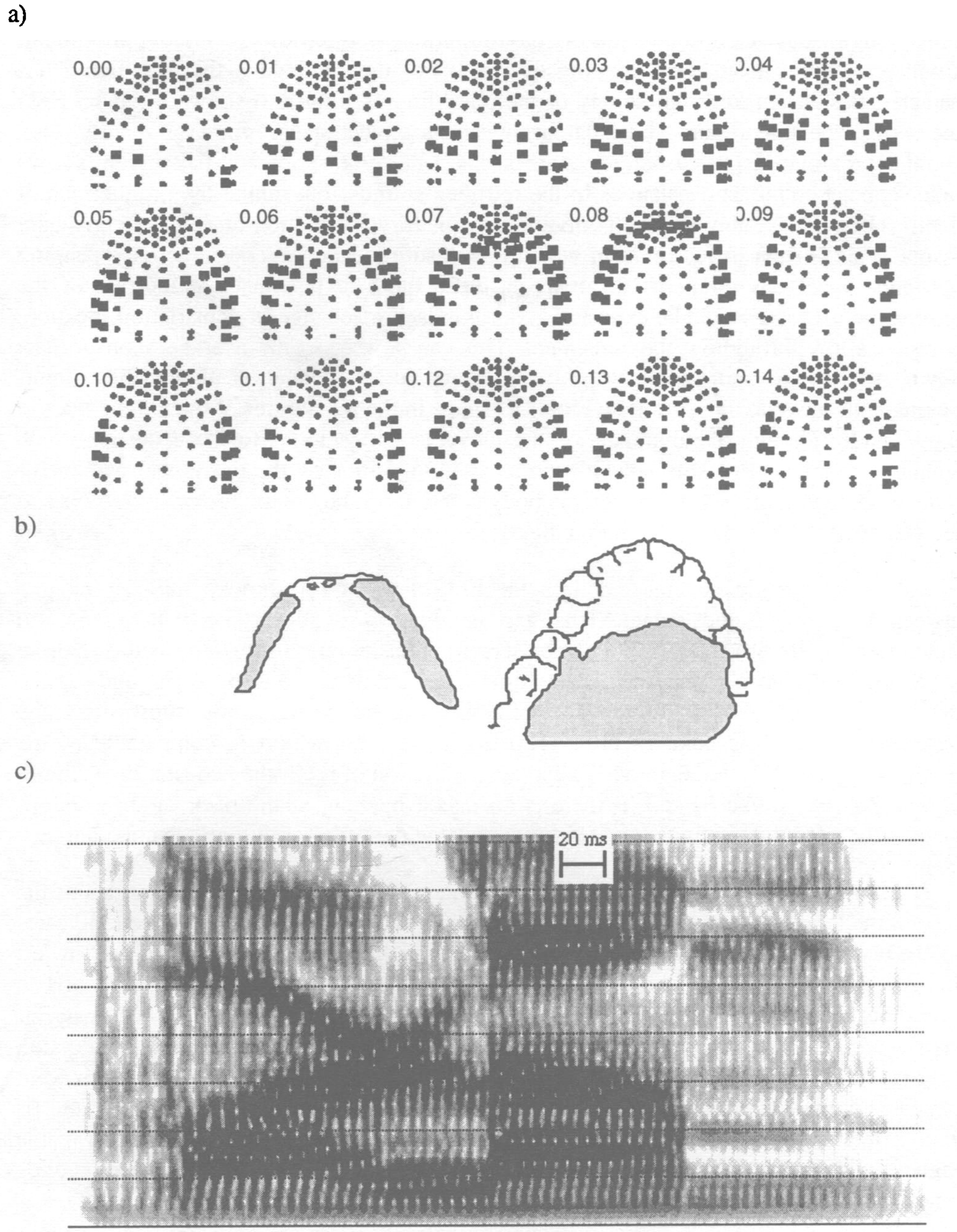

Figure 5. a) A typical EPG time series of a production of the Tamil retroflex lateral [ɭ] in the <a_a> context. b) Linguographic and palatographic records. c) A spectrogram of a typical production again in the <a_a> context.

The retroflex central approximant [ɻ]

Although we have chosen to classify the fifth liquid as a retroflex central approximant, as will be obvious from the following discussion of the EPG data, the fifth liquid has characteristics that make it unlike any of the other liquids. Figure 6 shows a typical EPG time series, the linguogram and palatogram, and a typical spectrogram of the retroflex central approximant [ɻ] in the <a_a> context. The EPG time series and palatogram shows tongue contact on the hard palate as in the retroflex sounds, but unlike the productions of [ɭ] and [ɽ] examined above there is no evidence of forward motion during the consonant closure. This is seen in figure 7a in which the closure location averaged across speaking rates and vowel environments is about the same both at the onset and offset of the consonant closure as would be expected given this lack of change in constriction location. F3 remains low throughout the consonant. This can be seen in the average acoustic data shown in figure 7d and the spectrogram in figure 6c. Narayanan et al.'s (1996) point-tracking data show an interesting inverted 'V' shape in the trajectories of the tongue tip and tongue blade. Though the alignment of the movement trajectories to the acoustic speech signal is not indicated in their data (as well as their MRI image), the movement pattern for [ɻ] suggests that in this sound the tongue body is retracted and the tongue tip curled up and then jabbed vertically toward the hard palate.

Unlike the retroflex lateral and flap, the EPG data for [ɻ] show a mid-sagittal gap between the tongue and palate. This gap is apparent in the static palatogram and linguogram (figure 6b) as well, and can be seen in the palatogram shown by Narayanan, et al. (1996). Average closure width data (figure 7b) show that a substantial mid-sagittal opening is typical of this sound. The EPG time series in figure 6a shows that the constriction in [ɻ] was held for about 100 ms; a duration which is comparable to the durations of [ɭ] and [l] noted above. The average duration of [ɻ] in the acoustic data (figure 7c) was 84 ms. Unlike [ɭ] and [l] there is no lateral opening at the back of the pseudo-palate in the EPG data in figure 6a. This suggests that the fifth Tamil liquid is not a lateral.

The linguogram in figure 6b shows tongue/palate contact with the lateral margins of the blade of the tongue. Narayanan et al. (1996) present an MRI image of [ɻ] which indicates that the body of the tongue is held quite low in the mouth with the tongue curled up toward the hard palate. They also show that the middle of the tongue body is laterally braced during this sound, creating a pit-like cavity. The lack of charcoal transfer on the posterior lateral margins of the tongue in the linguogram in figure 6b suggests that in this production the tongue body was held low enough in the mouth to brace against the teeth (which were not coated with charcoal) rather than the sides of the palate. The linguograms for [ɭ] and [l] (figures 3b and 5b) showed tongue/palate contact with the posterior lateral margins of the tongue indicating a somewhat higher position of the tongue body in these sounds compared with [ɻ].

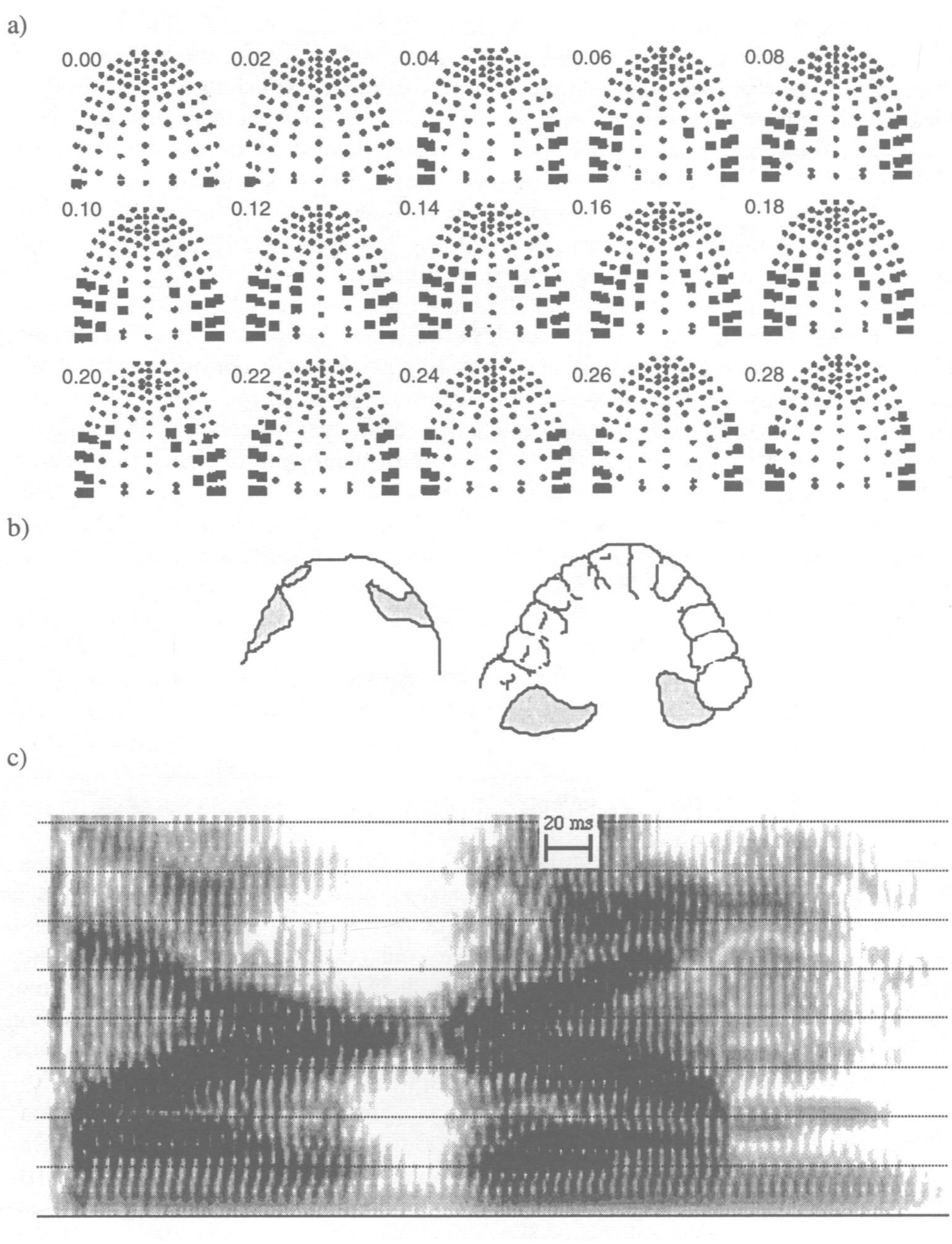

Figure 6. a) A typical EPG time series of a production of the Tamil central retroflex approximant [ɻ] in the <a_a> context. b) Linguographic and palatographic records. c) A spectrogram of a typical production again in the <a_a> context.

It has sometimes been claimed (e.g. Rajaram, 1980) that the fifth Tamil liquid is simultaneously lateral and central. As we have suggested above, we find no evidence to support this claim. However, one interpretation of the linguogram shown in figure 6b is that it shows both lateral and central opening. In this connection we note an apparent lateral asymmetry in Narayanan et al.'s MRI 3D tongue shape reconstruction for this sound. It may also be that our interpretation of the linguogram in figure 6b as evidence for a lowered tongue body during [ɻ] is not inconsistent with the presence of lateral opening below the level of the gums. Further study, perhaps employing aerodynamic techniques to estimate channel area, is needed before this question can be settled.

Our data do not clearly indicate whether this sound should be described as apical rather than sub-apical, though the linguogram in figure 6b is similar to the linguogram of a sub-apical fricative published by Ladefoged and Maddieson (1996, p. 160). Also, Narayanan et al. (1996) describe the Tamil [ɻ] as sub-apical. However, their data leave some room for doubt. In Narayanan et al.'s MRI image of [ɭ] the tip of the tongue is clearly more curled back than it is in their image of [ɻ]. We speculate that a true sub-apical posture is more likely when the tip of the tongue can be braced against the roof of the mouth. Thus, it is preferable to describe the Tamil [ɻ] as an apical retroflex central approximant.

4. Perception Test

One concern with EPG data is that speech produced with a dental appliance and cables protruding from the mouth may not accurately reflect normal pronunciation (Hamlet & Stone, 1978). To test the validity of the EPG data reported in section 2, we presented the speech signals which were recorded simultaneously with the tongue/palate contact patterns to four Tamil speakers for perceptual identification.

Two of these listeners (male and female) speak the Brahmin dialect of Tamil (and also spoke for the recordings analyzed in section 4) and two (male) did not. All the listeners came to the USA as adults, all were doing postgraduate work at Ohio State University. They were recruited through an advertisement on a local Tamil chat group on the Internet. All of the listeners were native speakers of Tamil in their late 20's or early 30's. Three of the listeners are from Madras. The last listener, a non-Brahmin speaker, is from a region south of Madras. Perceptual data from the two non-Brahmin listeners shed light on the confusion which has surrounded the phonetic description of the fifth Tamil liquid

Methods

We edited the speech signals which had been recorded simultaneously with the EPG data using a digital signal analysis system (Kay, Computerized Speech Lab). Three productions (fast, normal, and slow) of each of the ten words shown in table 2 were digitally spliced from the carrier phrases in which they were produced. Because the initial consonant was not the same for all of the words, we cut the initial consonant transitions off all the tokens. The tokens were then recorded to audio tape in four blocks of thirty with the order of the tokens randomized separately in each block. Four speakers of Tamil participated in this study, two were speakers of the Brahmin dialect and two were not.

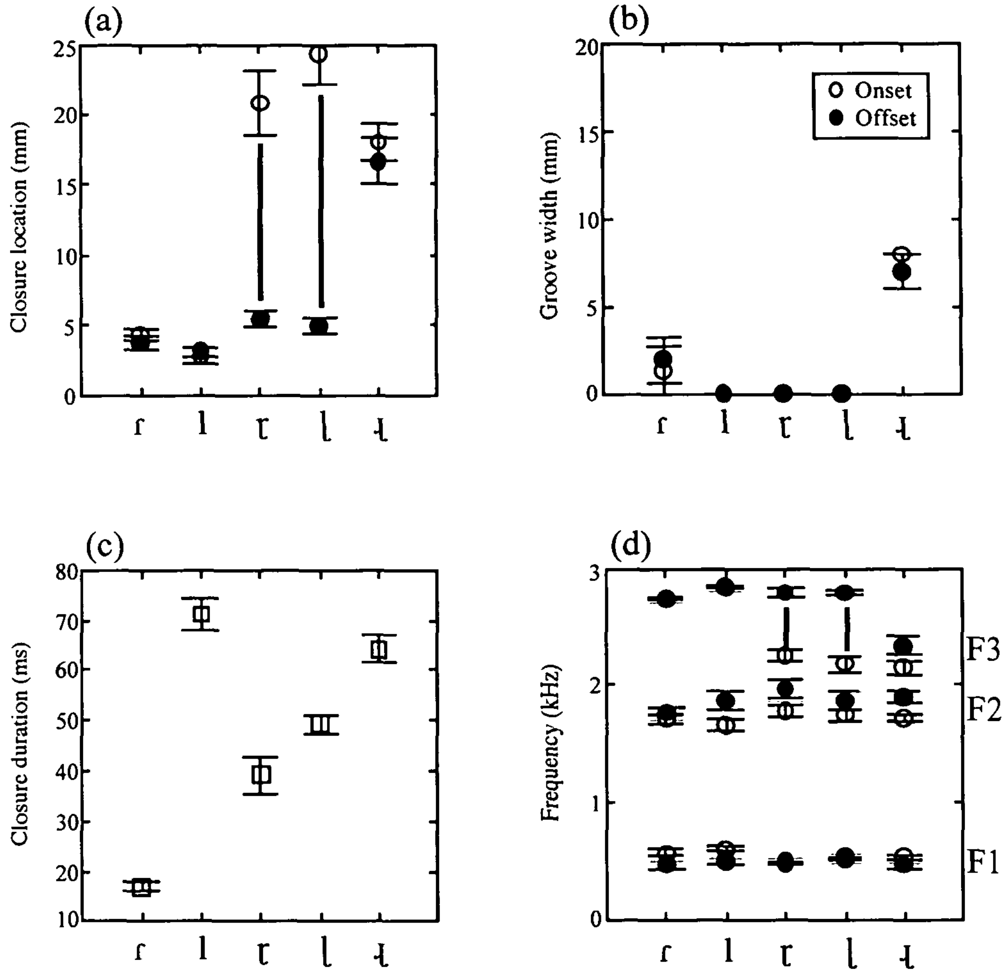

Figure 7. Quantitative EPG and acoustic results. Each point in the EPG data (panels a & b) is an average of six tokens, three in <a_a> context and three in <a_i> context. Each point in the acoustic data (panels c & d) is an average of sixteen tokens, four in <a_a> context and four in <a_i> context for two speakers. Measurements were taken at the start (open circles) and the end (filled circles) of the closure interval. a) The location of the front edge of the midline closure. b) Groove width. c) Average acoustic vowel duration. d) Average formant values. The error bars plot the standard errors of the measurements.

Listeners were asked to identify the token by circling one of five possible words on an answer sheet (the contexts 'a_am' or 'a_i' were indicated on the answer sheets).

Results

Two listeners identified the stimuli correctly in 96% of the trials. As the confusion matrix in table 3 shows, only [l] was occasionally misidentified by these speakers of the Brahmin dialect of Tamil.

Table 3. Confusions among the five Tamil liquids for two speakers of the Brahmin dialect. Columns are labelled according to which of the liquids was presented and rows indicate the listener's response. Data are percent response averaged over listener and vocalic environment.

	ɾ	l	ɽ	ɭ	ɻ
ɾ	100	2	0	0	0
l	0	85	2	0	0
ɽ	0	0	98	0	0
ɭ	0	10	0	98	0
ɻ	0	2	0	2	100

These speakers made more mistakes with the <a_a> context than with the <a_i> context, and the plain lateral [l] was heard as a retroflex lateral [ɭ] in the low vowel context 4 times by one of the speakers.

Table 4 is a confusion matrix for a speaker of a dialect of Tamil that has four liquids. This speaker does not have the retroflex approximant [ɻ] as a contrastive liquid. His four way contrast is apparent in the table. He quite consistently heard the retroflex approximant [ɻ] as a retroflex lateral [ɭ] and vice versa. Meile (1945) notes that southern dialects of Tamil tend to make this substitution. This confusion is reflected in his own speech - he pronounced the retroflex approximant [ɻ] as if it were a retroflex lateral [ɭ].

The fourth speaker (table 5) is a bilingual English-Tamil speaker who lives in the United States and uses Tamil only occasionally. He could distinguish the retroflex rhotic [ɽ], the plain lateral [l], and the flap [ɾ] and retroflex approximant [ɻ] when they were in the <a_a> context. In the <a_i> context, however, he mistook the alveolar flap [ɾ] for the retroflex rhotic [ɽ] 11 times. The reverse was true of the laterals. He could not identify the retroflex lateral [ɭ] in 80% of the cases, none in the <a_a> context, but he did consistently hear it as a lateral, or as the retroflex approximant [ɻ] in 3 cases. From this, we conclude that his main contrast in this series was between the retroflex rhotic and the alveolar lateral. These were qualities of his English speech. He identified the retroflex approximant [ɻ] in the <a_i> context as a retroflex lateral [ɭ], the unfamiliar sound.

Table 4. Confusions among the five Tamil liquids for one speaker of a non-Brahmin Tamil dialect. Columns are labelled according to which of the liquids was presented and rows indicate the listener's response. Data are percent response averaged over vocalic environment.

	ɾ	l	ɽ	ɭ	ɻ
ɾ	100	4	0	0	0
l	0	96	0	0	0
ɽ	0	0	100	0	0
ɭ	0	0	0	50	25
ɻ	0	2	0	50	75

The Brahmin speakers had no difficulties in perceiving the intended sounds, so we conclude that the EPG data reported earlier are representative of normal speech. Non-Brahmin speakers tended to confuse [ɻ] and [ɭ], depending on their dominant language.

Table 5. Confusions among the five Tamil liquids for one English-dominant Tamil listener. Columns are labelled according to which of the liquids was presented and rows indicate the listener's response. Data are percent response averaged over vocalic environment.

	ɾ	l	ɽ	ɭ	ɻ
ɾ	50	0	0	0	0
l	4	88	0	58	13
ɽ	46	0	100	0	0
ɭ	0	4	0	13	33
ɻ	0	8	0	29	50

This confusion seems reasonable in light of the fact that of the Tamil liquids [ɭ] is most similar to [ɻ] as a relatively long sonorous retroflex liquid. These facts may be related to various reports about the articulation of the fifth liquid.

5. Summary and discussion of the data

Taken as a whole, these results confirm that there are five liquid consonants in the Brahmin dialect of Tamil: two alveolar consonants, a lateral [l] and a flap [ɾ], two retroflex consonants a lateral [ɭ] and a flap [ɽ] and a fifth liquid, a retroflex central approximant [ɻ]. The alveolar and flàp retroflex sounds involve movement of the tongue forward during articulation of the consonant.

Regarding the fifth liquid, our EPG data confirm that [ɻ] is retroflex, but also indicate that [ɻ], unlike the other retroflex liquids, is not a contour segment. We also found no evidence of lateral opening in this sound. The static palatograms and linguograms confirm the EPG data, and indicate that the retroflex sounds is sublingual. Acoustic data show that the retroflex consonants are characterized by a low F3 locus at the offset of the preceding vowel. But unlike the other retroflex liquids, [ɻ] has a low F3 both before and after the consonant closure.

The perceptual data confirm that the five way contrast among the Tamil liquids produced in the EPG study was intelligible to speakers of this dialect. Speakers of dialects of Tamil that do not have the fifth liquid tended to confuse it with the retroflex lateral, possibly because of its longer duration and retroflexion. A fourth speaker, in keeping with his own liquid contrasts in English (retroflex rhotics and plain laterals), tended to categorize the liquid sounds according to whether or not they were retroflex, regardless of their laterality.

From this data we conclude that the fifth liquid is a central retroflex approximant whose outstanding articulatory characteristics are apical retroflex approximation and lack of movement during the consonant closure. We predict that any laterality in this sound is incidental and possibly speaker dependent, due in part to the physiological constraints on retroflex constriction. It is also the case that the fifth liquid sometimes sounds more fricated than the others, reflected in that fact that this sound has been considered by some grammarians to be a fricative. Given Zvelebil's (1970) description of the variation in the articulation of this sound, this frication may be a result of a secondary or enhancing cue for the sound, incidental to the parameters of contrast.

The fact that [ɻ] has been variously described as /l/-like and/or /r/-like is reminiscent of languages with no <r/l> distinction - like Japanese (Mochizuki 1981). In Japanese, we might assume that the lack of distinction is accompanied by significant variation in an uncrowded phonetic space. But in Tamil this cannot be so: there are four other contrasting liquids. And there is no evidence for significant variation, standard deviations in this study were very small.

An aim of this study has been to investigate the phonetic dimensions of phonological contrast among liquids by studying a language with an unusually rich set of liquid contrasts. Liquids sounds are a difficult class of sounds to categorize; there are no clear articulatory parameters that these sounds share. Cross linguistically, laterals and rhotics often pattern together in alternations and show similar kinds of distributional effects

(Maddieson 1982, Ladefoged and Maddieson 1996). Pike (1943) spreads the classification of laterals and rhotics over two secondary categories derived from his main classes (vocoids and contoids): non-syllabic vocoids (glides and some rhotics such as the English /r/) and syllabic contoids (laterals and some rhotics such as a trilled rhotic in Serbian). In phonological theory, liquids are sonorant consonants with the features [+cons] [+son] [+voc], making them distinct major class category (Chomsky and Halle 1968). The difficulty in classification is not only a problem of finding similarities between laterals and rhotics, but it is a problem within the class of rhotics itself. For instance, trills and taps have been classified as subclasses of stops (Abercrombie 1967, Laver 1994). The relationship between these rhotics and the rhotics in English, which have vowel-like properties, is hard to capture. Ladefoged (1995) and Lindau (1978) proposed that rhotics are generally characterized by a low F3 despite considerable variation in place (uvular or alveolar) and manner (flap, approximant, etc.). Later work (Lindau, 1985; Ladefoged & Maddieson, 1997) found that this characterization is not completely adequate cross-linguistically and that rhotics are better characterized according to family resemblances among sounds which are historically related and written with the letter 'r'. Nonetheless, for many languages (and we would include Tamil with English in this group) rhotics can be described primarily as sounds in which the F3 is low. Insofar as this is true, the relation of taps/flaps and trills to stops is a subset relation only along articulatory dimensions. In many views, such as Nolan (1996) and also Ladefoged (1997), the parameters of distinction among vowels (vocalic sonorants) are best characterized in the acoustic domain, versus the arguably strong articulatory basis of consonantal (stop and fricative) contrasts (Chomsky and Halle 1968, Clements 1985).

Stevens (1989) and Maeda (1991) have provided an explanatory hypothesis; they propose that there is less stability in articulatory parameters than in acoustic parameters. Because of the presence of areas of stability in the acoustic domain, it is possible to make small articulatory changes in a region of acoustic stability with little acoustic effect. Given this asymmetry between the acoustic and articulatory domains, the basis of the contrasts among vowels is best found in the acoustic dimension (Jones 1956, Lindau 1978, Odden 1991, Johnson, Ladefoged and Lindau 1993). We have observed that the liquid contrasts in Tamil are built from three sets of oppositions (with secondary characteristics): static/dynamic, central/lateral and retroflex/non-retroflex. These oppositions have prominent acoustic correlates, as suggested by Ramasubramanian and Thosar (1970). For instance, static versus dynamic can be defined in terms of F3 contour during consonant closure (as we have seen above), lateral/central as the presence or absence of acoustic zeros, retroflex/non-retroflex in terms of low versus high F3. Cross linguistic studies of the acoustic and articulatory properties of laterals and rhotics are uncommon. This study lends validity to a research strategy that investigates the acoustic as well as articulatory dimensions of liquid contrasts. We adduce that what has been suggested for vowels and for rhotics can be extended to the case of Tamil liquids: the distinctions may be best characterized in the acoustic domain. For the Tamil data we can hypothesize that Tamil represents a case where the set of liquid contrasts are best defined by the F3 contours. Further cross-linguistic research into the nature of rhotic and lateral sounds will be necessary to establish the role of the acoustic dimension in defining the unifying properties of these sounds.

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