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RETROFLEX AND DENTAL CONSONANTS IN GUJARATI. A PALATOGRAPHIC AND ACOUSTIC STUDY

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Abstract: A palatographic investigation of dental and retroflex consonants of one Gujarati speaker shows the point of articulation of the retroflex consonants to be mostly prepalatal. The main result of the acoustic investigation which is based on one more informant is that retroflex consonants (compared to dental consonants) have a lowering effect on the transitions of F3 and F4 of the preceding vowel (though the effect on i and e is very small), whereas the influence on the following vowel is irregular, but clear for the vowel a. In addition, the burst of retroflex stops shows concentration of energy at a lower frequency than dental stops. The important contribution by Stevens and Blumstein is discussed in the final section.

1. Introduction[1]

1.1 The language

Gujarati is an Indic language belonging to the Indo-Iranian branch of the Indo-European language family. It is spoken by approximately 26 million people, most of whom live in the State of Gujarat in Western India, North of Bombay.

The present article is a somewhat abbreviated version of chapter IV of a doctoral thesis presented to the Graduate School of Cornell University.

The palatograms and spectrograms were taken at the Institute of Phonetics, University of Copenhagen. Most of the material has been recorded during my stay in Copenhagen 1967-68, but some supplementary material was recorded during a shorter stay in 1977. I am grateful for having been admitted at the Institute as a guest research worker. I am particularly indebted to pro-

1.2 The phonological system

Gujarati has 8 clear, oral vowels: /i e ɛ u o ɔ ə ɑ/ (in some dialects no distinction is made between /e/ and /ɛ/, /o/ and /ɔ/, and this is the case in the dialect spoken by the informant in the present investigation). There are further 8 (or 6) murmured vowels: /i̤ e̤ (ɛ̤) ṳ o̤ (ɔ̤) ə̤ ɑ̤/, and 6 nasalized vowels: /ĩ ũ ɛ̃ ɔ̃ ə̃ ɑ̃/. Phonologically, the murmured vowels may be interpreted as clear vowels + /h/, and the nasalized vowels as clear, oral vowels + /N/ (see Pandit 1957 and 1958, and Dave 1967a and 1967b).

It has the following consonantal phonemes:[2]

p	t	ṭ	c	k	
b	d	ḍ	ɟ	g	
ph	th	ṭh	ch	kh	
bh	dh	ḍh	ɟh	gh	
	s		ʃ		h
m	n	ṇ		N	
	r	ṛ			
	l	ḷ			
v			j		

(continued)
fessor Eli Fischer-Jørgensen for her encouragement and help during my studies. My research on Gujarati vowels and consonants has been made under her guidance and supervision, and I could not have completed this research without her active interest and extensive aid at all stages of my work. I am also grateful to Børge Frøkjær-Jensen and to Birgit Hutters for helping me with the palatograms, to Jente Andresen, Uffe Due, and Jørn Dyhr for taking and measuring part of the spectrograms, to Jeanette Gliming for making the graphs, and to Else Parkmann for typing a difficult manuscript. - I also want to express my gratitude to Professor K.N. Stevens, Research Institute of Electronics, MIT, who put his instrumentation for linear prediction analysis at my disposal and who kindly helped me taking the curves. Finally, I am thankful to Professor Linda Waugh, the chairperson of my special committee for the Ph.D. degree for her help and supervision.

2) In this paper a dot below the letter is used to indicate retroflex sounds.

The aspirated stops can be interpreted as stop + h (see Pandit 1957 and 1958). Retroflex [ṣ] is found only before another retroflex consonant and can be interpreted as a variant of /ʃ/. /N/ comprises the variants: [ɲ] (before palatal sounds), [ŋ] (before velar sounds), and nasalization of a preceding vowel (according to Pandit 1957 and 1958). The palatal nasal might be considered a variant of the dental or the retroflex nasal, but it is more natural to group it with the velar nasal. The latter cannot be considered a variant of either /n/ or of /ṇ/, since it is commutable with these before a velar stop. Retroflex /ḍ/ is often pronounced as a flap, thus like /ṛ/, except initially after a retroflex nasal and intervocalically, when the second vowel is followed by a retroflex consonant, but retroflex /ṛ/ is not pronounced as [ḍ]. Retroflex /ṛ/, /ḷ/ and /ṇ/ are not found initially.

2. The palatographic investigation

2.1 Preliminary remarks

Until now an instrumental investigation of Gujarati consonants has not been undertaken, and instrumental studies of retroflex consonants in other languages are rather scarce. N. Ramasubramanian and R.B. Thosar (1971) have undertaken a palatographic and spectrographic investigation of retroflex consonants of Tamil, and P. Nihalani (1974) has investigated Sindhi stops by means of palatography and X-ray. However, the point of articulation of retroflex consonants varies a good deal in different Indic languages, so that no direct conclusions can be drawn for Gujarati from these investigations. According to the traditional description of retroflex consonants they are pronounced with the apex of the tongue curled back to the palatal region; they may, however, also be post-alveolar. Firth (1950b) says that the retroflex consonants in Hindi are not pronounced with curled tongue, but he does not give any positive description. Ladefoged (1971b) considers retroflex sounds of some of the Indic languages to be post-alveolar and calls them retracted (cf., however, Bhat 1974).

It is also well known that American retroflex r may be pronounced in two different ways: either with the tip of the tongue curled back, or with the body of the tongue constricted and bunched up, with an almost identical acoustic effect, viz. a lowering of formant 3. The present writer therefore decided to make a palatographic and spectrographic investigation of the Gujarati retroflex consonants ṭ, ḍ, ṛ, ḷ, and ṇ and the corresponding dentals t, d, r, l, n. As for the stops, the material has been restricted to unaspirated types.

2.2 The method used

For the present investigation the dynamic palatographic method would have been adequate, particularly for the flapped retroflex sounds. But the present writer did not have access to this type of instrumentation. The method used was a more traditional, direct method: The tongue of the subject is painted with a mixture of charcoal, chocolate, water, and liquid glue, the subject taking care not to close his mouth before pronouncing the word to be investigated. Immediately after having pronounced the word he moves his head forward so that an oblique mirror mounted on a frame can be inserted into his mouth as far back as possible. The frame also contains a light source and some reflecting mirrors directing the light into his mouth, and a camera. A picture is taken by a helper. The picture may be slightly distorted if the mirror is not at right angles to the palate.

A normal means of presentation would have been to make paper copies of the photos. Instead, a somewhat different procedure was used: A photo was taken of a cast of the palate; it was then developed in natural size. A number of horizontal and vertical lines were drawn on this photo at a distance of 5 mm from each other. This type of reference lines was preferred to reference lines based on the teeth (see, e.g., Firth 1950b), because it is the absolute size of the cavity which is of importance for the acoustic output, and also because subjects may have defective dentition,and therefore reference lines based on the dentition are not so easily comparable from one subject to the other. The picture of the palate with the reference lines was then produced in a great number of copies, and the areas of contact were drawn on these copies by inserting the negative film in a projector and projecting the pictures onto the diagram of the palate. This drawing can be done with great precision and it combines the advantage of being cheaper than photographic copies with the advantage of having reference lines on each picture. No attempt was made to add the vertical dimension.

Fig. 1 shows this schematic drawing of the palate with the lines numbered from 0 to 10. The center of the alveolar ridge is just slightly above line number 2; the highest point of the palate is reached at line 5, which is considered to be the approximate dividing line between the pre- and the post-palatal regions. The boundary between the hard and the soft palate is approximately at line 10.

Fig. 1 is given here for a general reference to all the following palatograms. Note that the left side of the palate is to the right on the paper, and vice versa.

2.3 The informant

The investigation is based on one informant, RD, who was born in 1928 in Pad-Jari in Gujarat, spent the years 1965-68 in Copenhagen, and has been living in the United States since 1968. He is the author of the present paper. These recordings were made in 1967 and 1977.

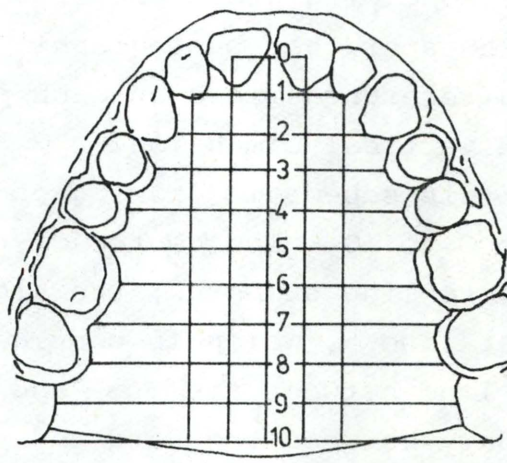

Figure 1

Schematic drawing of the palate with reference lines. Speaker RD.

2.4 The material

A preliminary list (list I) comprised 14 words with the dental and retroflex consonants r, n, l, ṛ, ṇ, ḷ finally after a and medially between a and o, or (for n and n) a and i, and d and ḍ between a and o. The initial consonant was p.

The main list (list II) contained 27 words with all dental and retroflex (unaspirated) consonants in initial, medial, and final position in combination with the vowel a, except for ṛ, ḷ, ṇ in initial position, since (as mentioned above) in Gujarati these consonants occur in medial and final positions only. In this list care has been taken to use words in which only the sound under investigation has contact between the tongue and the palate. For this purpose the vowel a was chosen both as preceding and following vowel. a is a central, low vowel in Gujarati, and it generally does not have contact with the palate; in any case, the contact is so far back that it does not interfere with dental and retroflex consonants. All consonants, except those to be investigated, were labials.

However, it may also be of interest to see whether the place of articulation is influenced by the surrounding vowels. For this purpose a list of words with all dental and retroflex (unaspirated) consonants medially between two i's was set up (list III). Moreover, a few words with u (list IIIa: bhoḍu, uḍũ and moṭũ, kuku) were used. As the vowels u and i have contact between tongue and palate at the sides but not in the middle, it is possible to see whether there is difference between consonants in a-, i- and u-surroundings around the mid line of the palate. A few words with velars before and after a (list IIa) and the words kiki and gəgi (list IIIa) were added for the purpose of comparing retroflex and velar consonants.

Generally 4 to 5 palatograms have been taken with the vowel a in all positions, i.e. before and after a, and intervocally between two a's. In the environment of the vowels o, i, and u-ũ the number is between 2 and 3.

2.5 Results

Figs. 2-54 show tracings of palatograms. The hatched area indicates a typical case, whereas the dotted lines indicate a different example, in principle a rather extreme case, which thus gives a rough idea of the degree of variation. In the following the typical case is referred to as a, the atypical one as b.

2.5.1 The dental and retroflex stops

Palatograms of the voiceless and voiced dental stops together with the retroflex stops are given in Figs. 2-21. Figs. 2-13 show stops in connection with the vowel a.

The contact area for the tongue is the dental region and the foremost part of the alveolar region. The front teeth are almost covered. The contact area generally goes back from line number zero to line number 2 and, in a few cases, to line number 3, which indicates the end of the alveolar region.

As the contact area is predominantly dental, t and d may be described in articulatory terms as apical, dental stops.

The palatograms of the retroflex consonants are presented adjacent to the palatograms of the dental stops, so that they can be easily compared. As mentioned in 3.1, the retroflex stops are traditionally defined as stops articulated with the apex of the tongue curled back and touching the hard palate. As both the upper and lower surface of the tongue had been painted and could have left marks on the palate, it cannot be decided directly on the basis of the palatograms whether the tongue was curled back or not, but the fact that sometimes the tongue has touched farther back in the middle than at the sides seems to indicate that it was curled back, and I have a very clear feeling that I do curl my tongue back. Observation in a mirror bears out this feeling, as do a few experiments in which only the lower surface of the tongue was painted.

The tongue contact is with the hard palate, generally between lines 3 to 6, or 3 to 6.5. Sometimes the contact goes as far back as lines 7 or 8 (see Figs. 3a, 5a, 9a).

The articulatory difference between the dental and the retroflex stops is clear. Their position of articulation is quite different. Similarly, the manner of their articulation is also different. Moreover, the retroflex stops cover more area of the palate than do the dental stops.

The area covered by the tongue in the articulation of *d* does not differ significantly from the area covered by *t*. On the average, however, *d* covers a slightly narrower area than *t*, but the difference is very small. Sometimes there is no difference at all. Compare, for instance, the palatograms of *vat* and *vad* (Figs. 6a and 12a). However, the tongue seems to have contact with a larger area of the palate in the articulation of intervocalic *ṭ* than in *ḍ*. See, for instance, *paṭa* (Fig. 5a) and *paḍa* (Fig. 11a). But in the initial position the difference is very small or non-existent.

The palatograms of *t* and *d* in the environment of the front and back vowels *i* and *u* show that the vocalic environment has no influence on the articulation of dental consonants (see Figs. 14-21).

The retroflex stops, unlike the dental stops, seem to be more or less influenced by the vocalic environment. *ṭ* and *ḍ* are slightly more fronted with the front vowel *i* than with the central vowel *a* or the back vowel *u*. Compare the palatograms of *piṭi* (Fig. 15) with *paṭa* (Fig. 5) and *moṭũ* (Fig. 19), and similarly *iḍər* (Fig. 17) with *paḍa* (Fig. 11) and *uḍũ* (Fig. 21), but retroflex and dental consonants are still clearly distinguished.

2.5.2 r and ṛ

The articulatory contact for dental *r* with the vowels *a* and *i* is generally in the alveolar region. The apex of the

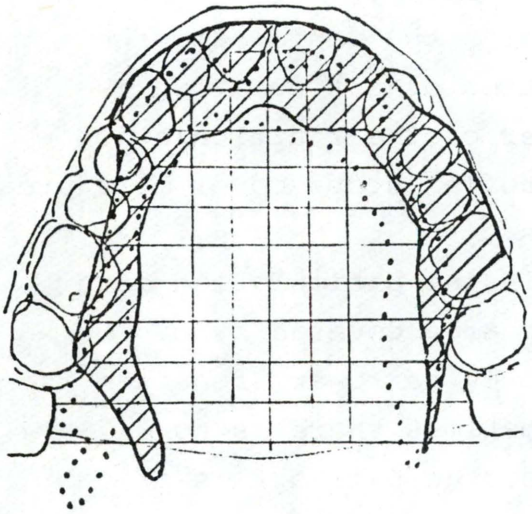

Figure 2ab

[tap]

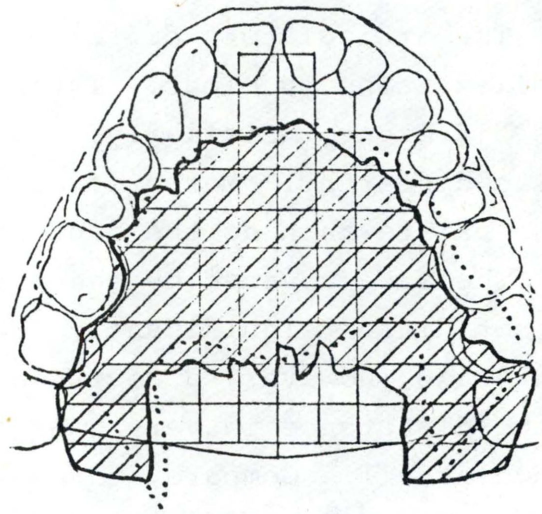

Figure 3ab

[ṭapu]

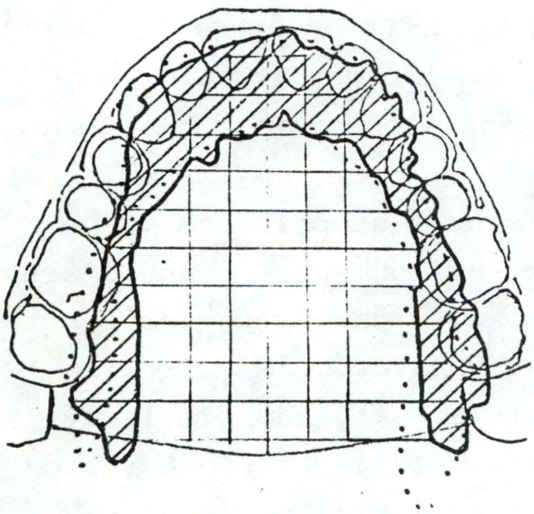

Figure 4ab

[mata]

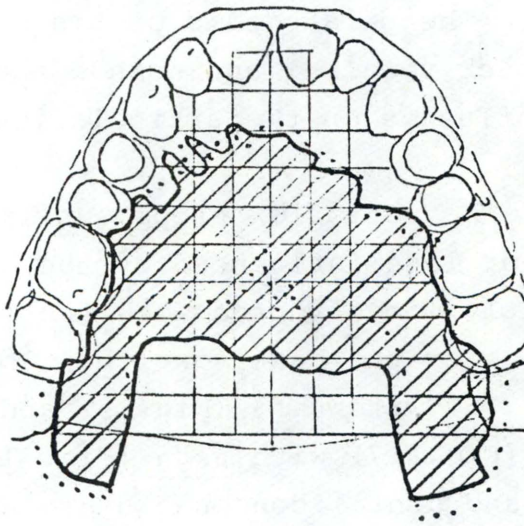

Figure 5ab

[paṭa]

Figures 2-5

Palatograms of speaker RD. The hatched area represents a typical case. The area enclosed by the dotted line represents a different, more extreme case.

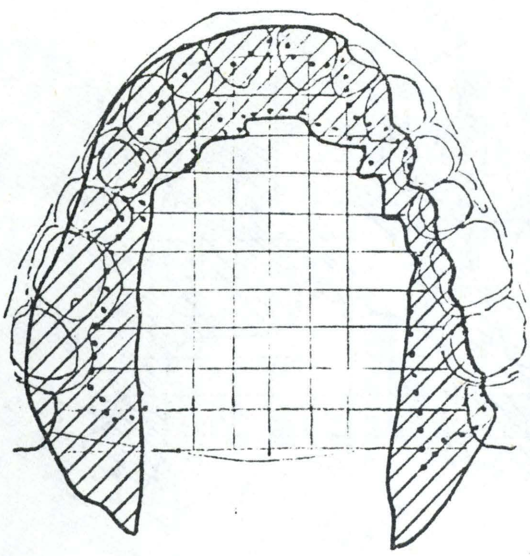

Figure 6ab

[vat]

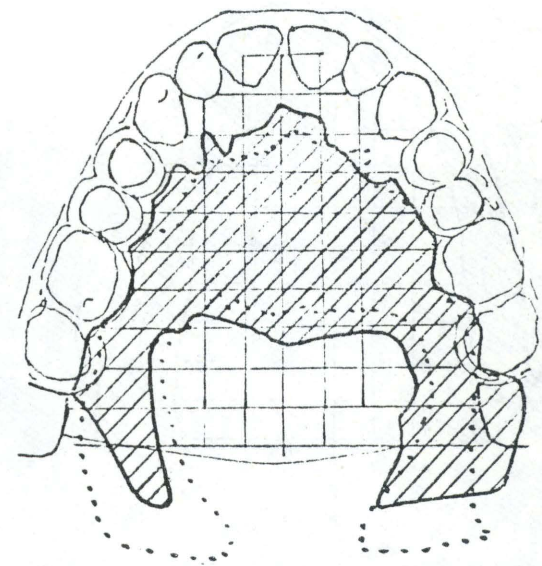

Figure 7ab

[aṭ]

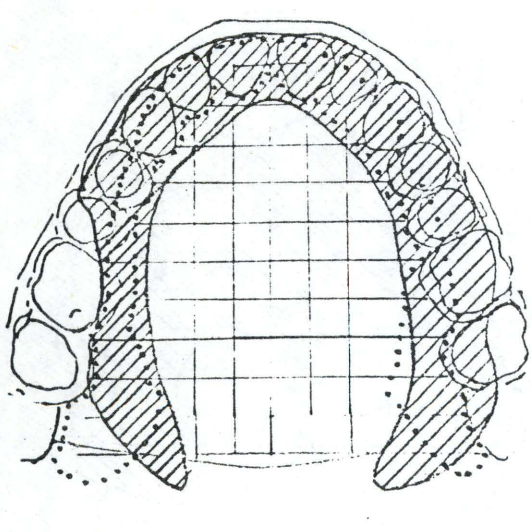

Figure 8ab

[dab]

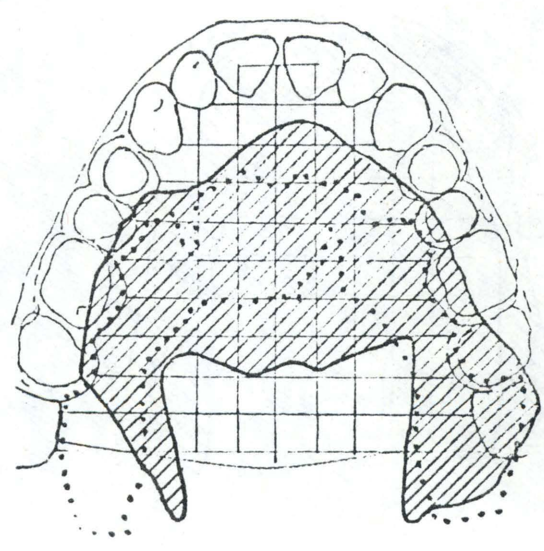

Figure 9ab

[ḍaba]

Figures 6-9

See legend of figs. 2-5.

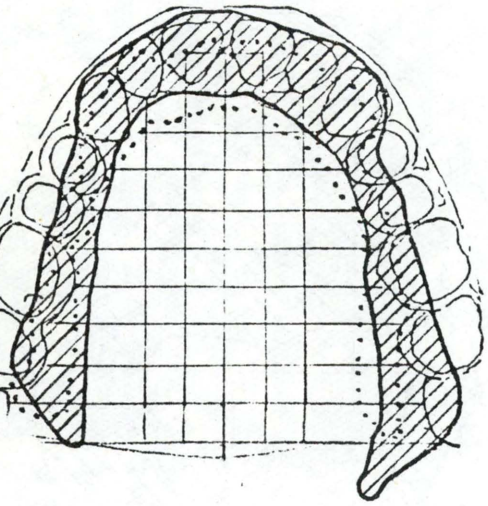

Figure 10ab

[mada]

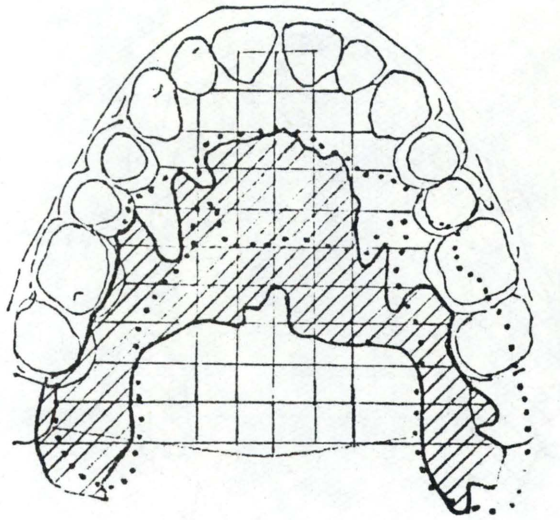

Figure 11ab

[paḍa]

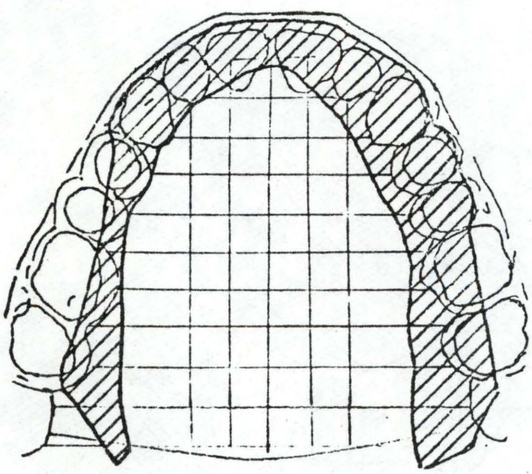

Figure 12a

[vad]

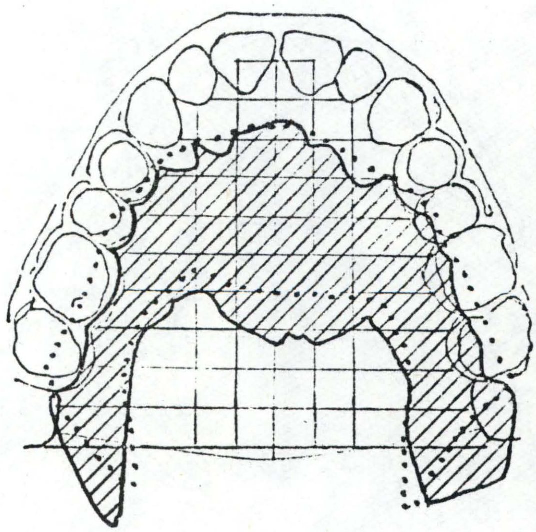

Figure 13ab

[aḍ]

Figures 10-13

See legend of figs. 2-5.

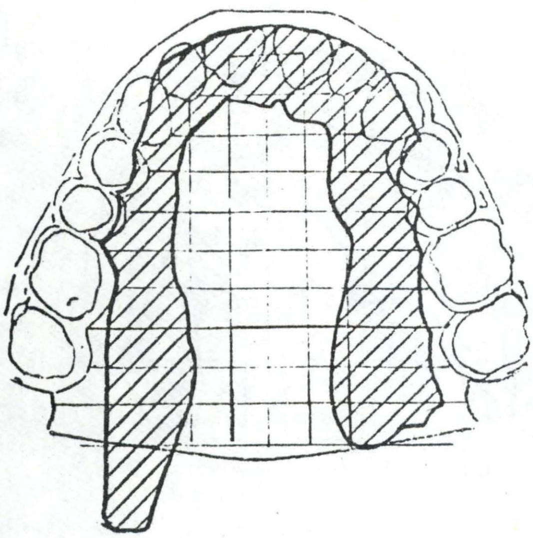

Figure 14

[iti]

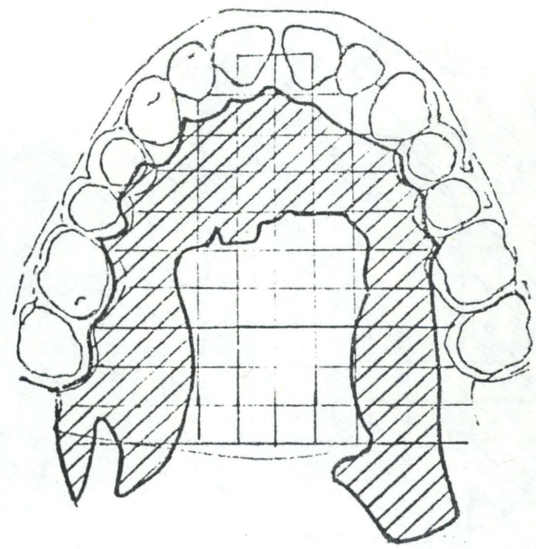

Figure 15

[piṭi]

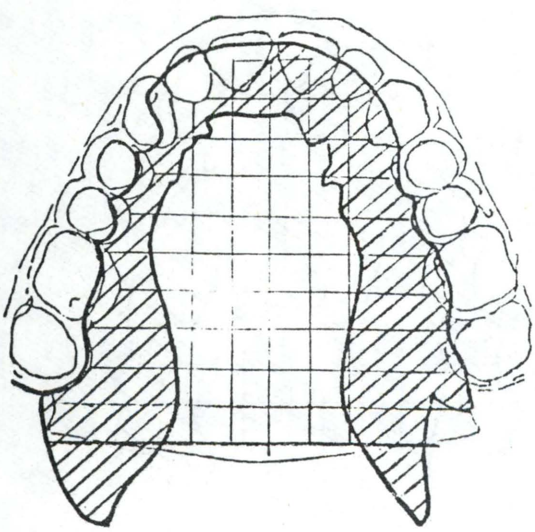

Figure 16

[sidi]

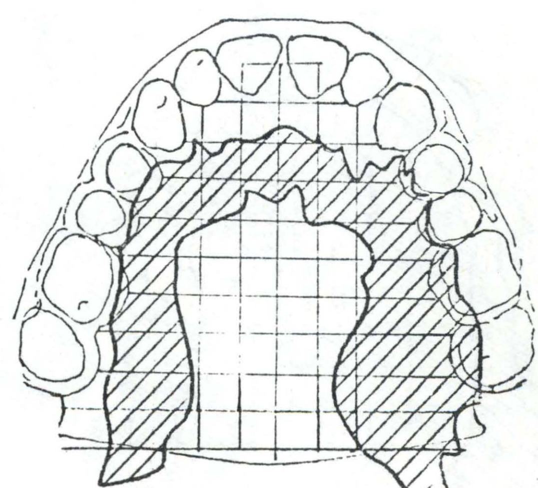

Figure 17

[iḍər]

Figures 14-17

See legend of figs. 2-5.

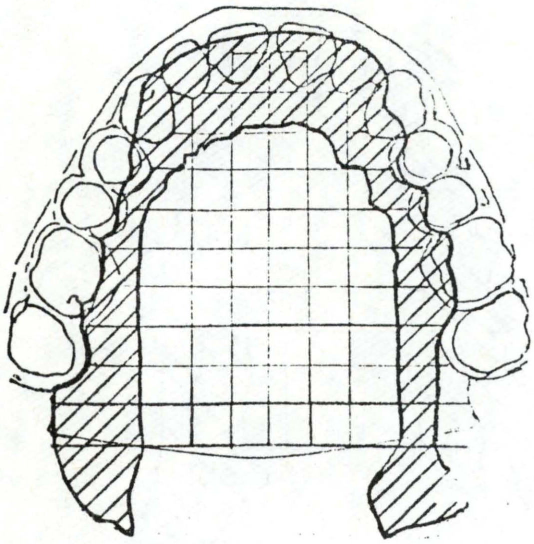

Figure 18

[hututu]

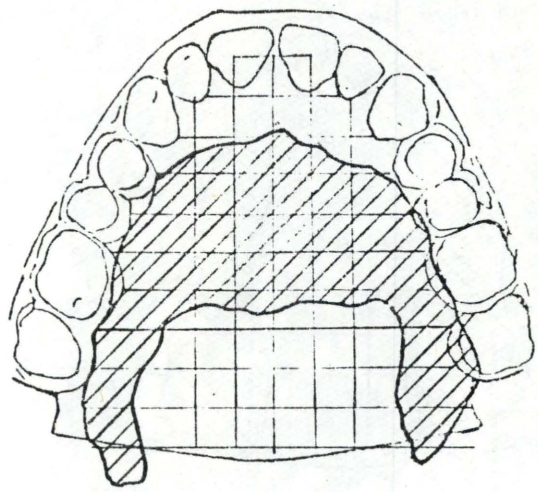

Figure 19

[moṭũ]

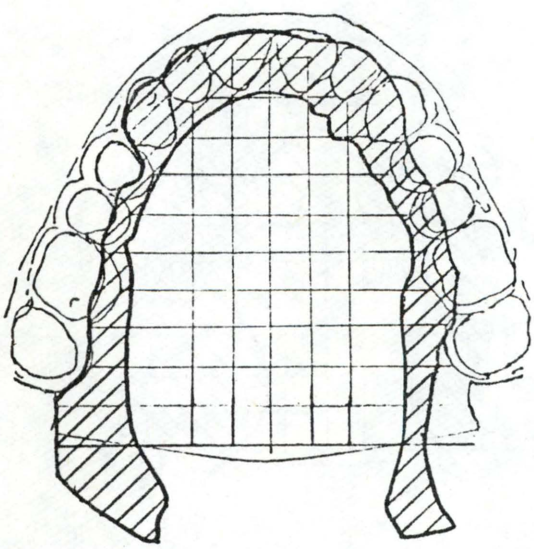

Figure 20

[bhodu]

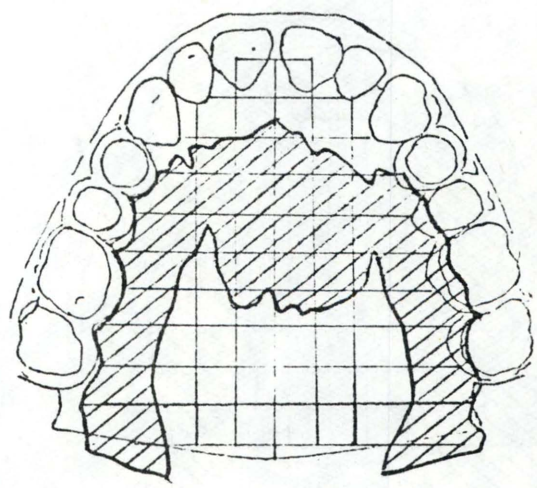

Figure 21

[uḍũ]

Figures 18-21

See legend of figs. 2-5.

tongue, however, covers a very narrow area of the alveolar ridge, approximately 5 millimetres (see Figs. 22a, 24a, 24b, 27a). The tongue contact is generally in the area of line number 2.

Some palatograms also show contact with the dental region. For instance, the word *rab* (Fig. 26a) shows marks of the tongue on the front teeth. Fig. 27b of the word *paro* shows a purely dental *r*.

There are also other variations of *r*. Sometimes no closure is seen in the palatograms (see Figs. 26b and 28 for *rab* and *əmiri*, respectively). The dental *r* and the *r* without closure should, however, be considered merely free alternants of the most frequent alveolar *r*. In other languages *r* is also generally alveolar. It seems to be difficult to produce a purely dental trill or flap.

The palatograms of *ṛ* with the vowels *a* and *i* have been placed on the same page as those of *r* for purposes of comparison (see Figs. 22-29). As stated above, *ṛ*, *ḷ*, and *ṇ* occur in medial and final positions only.

ṛ is flapped and the place of articulation for *ṛ* is the hard palate. The tongue seems to have been curled back obliquely at the left side of the hard palate. The contact area is generally found between the lines 2 to 5, and sometimes between the lines 2 to 6.

The palatogram of the word *biṛi* (Fig. 29) differs from the other palatograms in two ways: it does not show the oblique contact of the tongue, and there is no complete closure, but a lateral opening at the right side. Such cases are rare.

It should be noted that *ṛ* in *biṛi*, although having a small lateral opening, is quite different from the retroflex *ḷ* (see Figs. 31, 33, 35, 37). The palatograms do not show any effect of the front vowel *i* on *r* or *ṛ* (except for the fact that the contact at the left side seems to be slightly more advanced in *əmiri*). *r* and *ṛ* are quite distinct from each other in the palatograms.

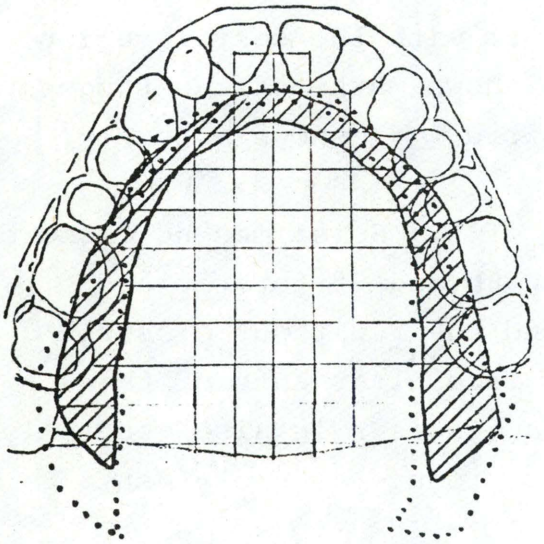

Figure 22ab

[mara]

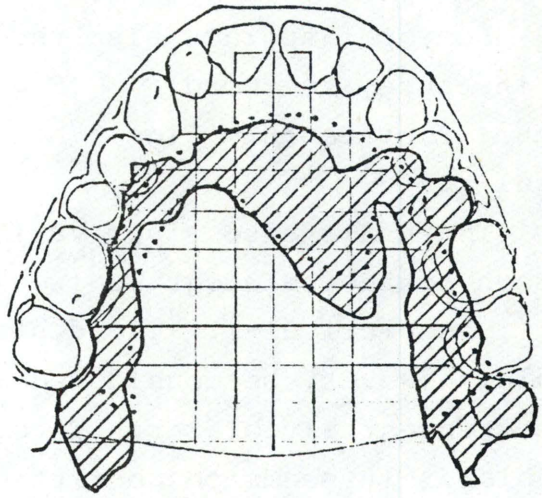

Figure 23ab

[phaṛa]

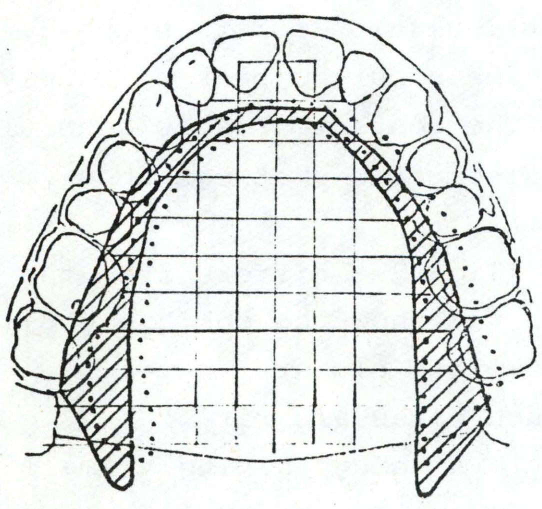

Figure 24ab

[par]

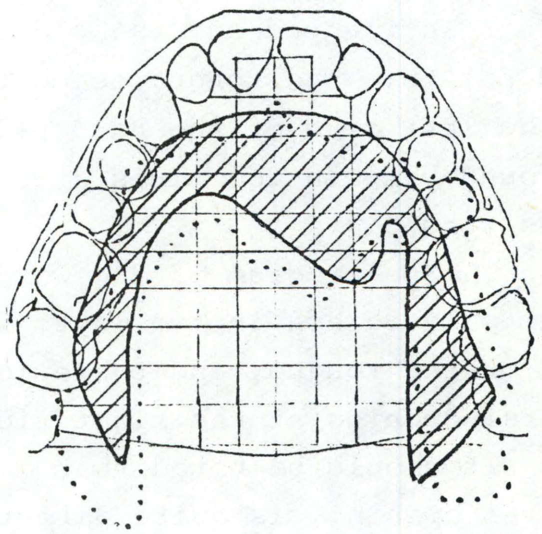

Figure 25ab

[phaṛ]

Figures 22-25

See legend of figs. 2-5.

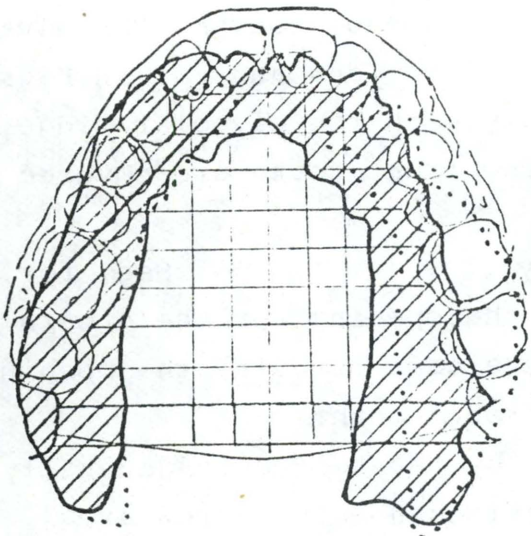

Figure 26ab

[rab]

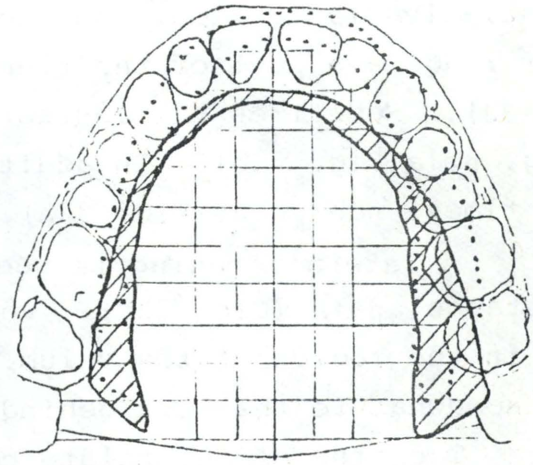

Figure 27ab

[paro]

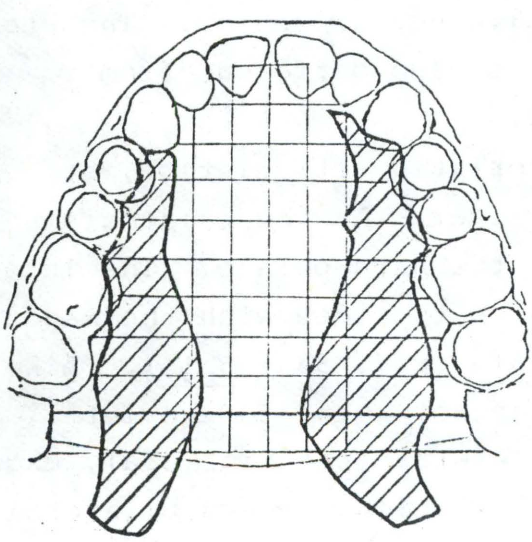

Figure 28

[əmiri]

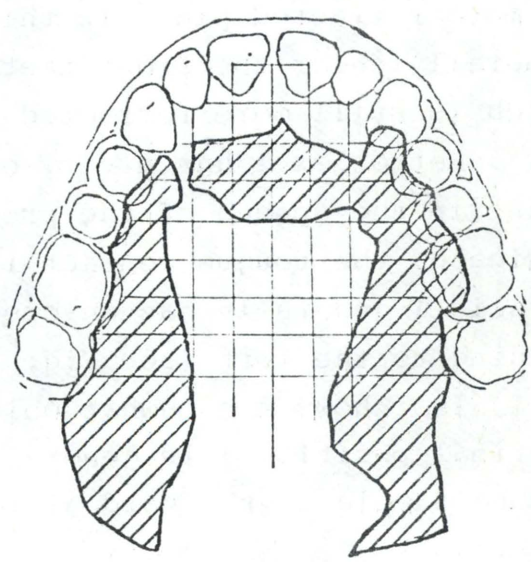

Figure 29

[biṛi]

Figures 26-29

See legend of figs. 2-5.

2.5.3 l and ḷ

The closure for the dental l is, in most cases, in the denti-alveolar region. The apex of the tongue touches the alveolar ridge and part of the front teeth (see labh and pal in Figs. 30-34). Sometimes the contact is only with the alveolar ridge, e.g. pala (Fig. 32b). In addition, the front teeth are covered at times: see pala (Fig. 32a).

A lateral opening is seen only in a few cases. See, for instance, pala (Fig. 32b). Perhaps the opening for the others is in the region of the velum. In the case of pala, the opening is somewhat to the left behind the front teeth.

The area of the palate covered by the tongue is generally between lines zero and one, but sometimes a very narrow area is covered around line number 1 (see pala, Fig. 32a).

l seems to be more fronted in the environment of the vowel i, see pili (Fig. 36). l differs from the dental stops mainly by its laterality, and also by its being articulated at a slightly more retracted place in the dental-alveolar region. The stops generally cover the front teeth. l is also different from r which is still more retracted than l.

Retroflex ḷ has a very characteristic articulation, at least in the speech of the present writer. As the palatograms indicate, the tongue contact is with the hard palate. The intervocalic ḷ generally has an opening at both sides with the major opening to the left (see Fig. 31a: baḷa, Fig. 33a: paḷo). Like ṛ, ḷ also shows a somewhat oblique contact going to the left. In final position ḷ is generally unilateral (see Fig. 35a), except in one sample of the word aḷ (Fig. 35b) which shows a bilateral opening.

The contact area for ḷ is between lines 2 and 7-8, and sometimes goes beyond line 8 (see Fig. 31a, baḷa). The final ḷ generally covers a smaller area, that is, between lines 2 and 5.

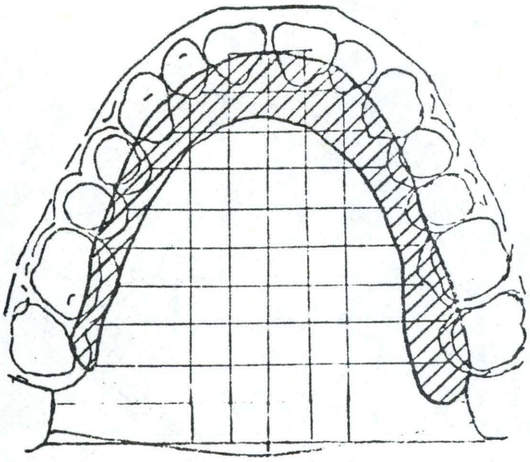

Figure 30

[labh]

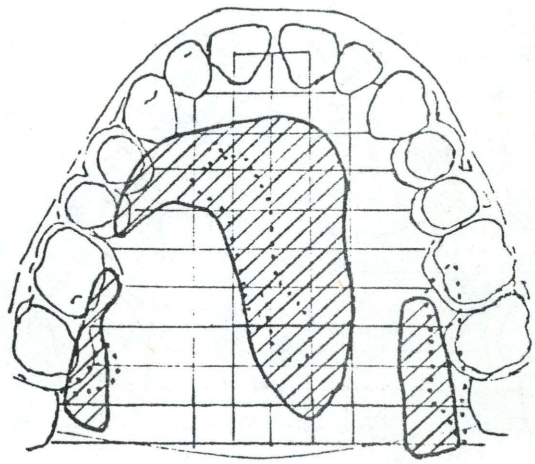

Figure 31ab

[baḷa]

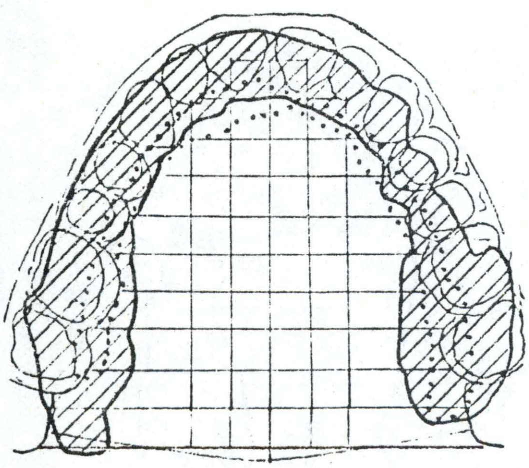

Figure 32ab

[pala]

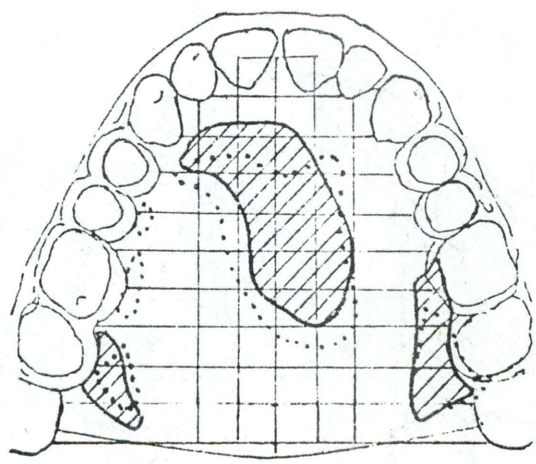

Figure 33ab

[paḷo]

Figures 30-33

See legend of figs. 2-5.

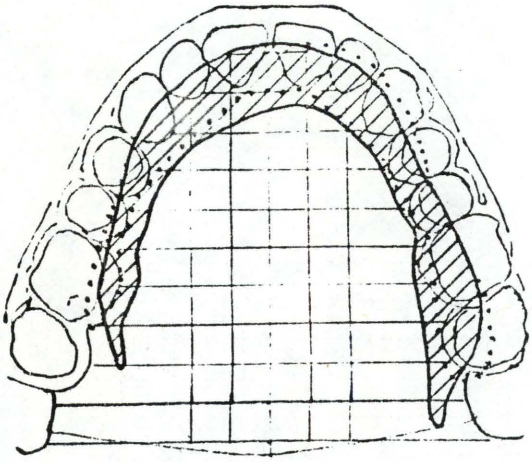

Figure 34ab

a. [pal]
b. [al]

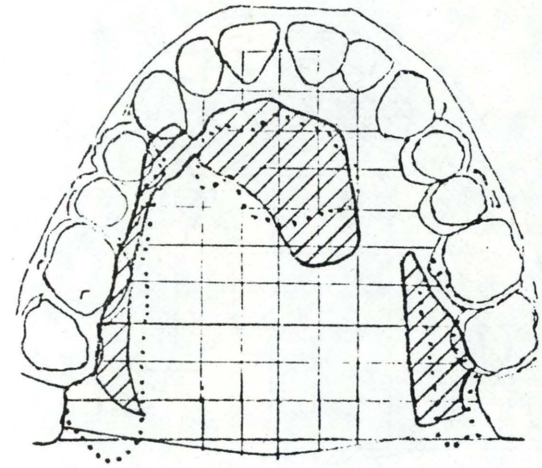

Figure 35ab

a. [paḷ]
b. [aḷ]

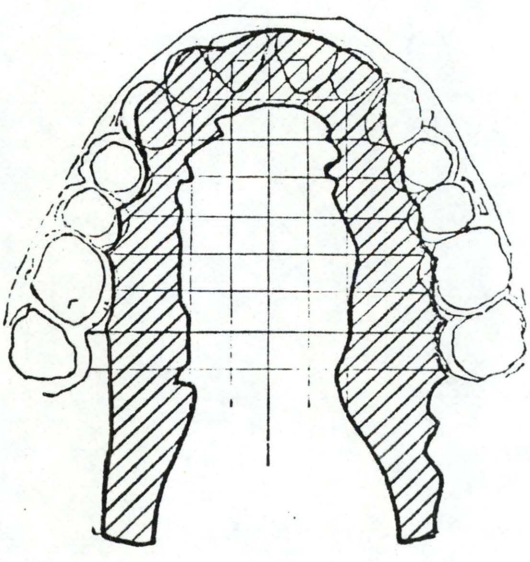

Figure 36

[pili]

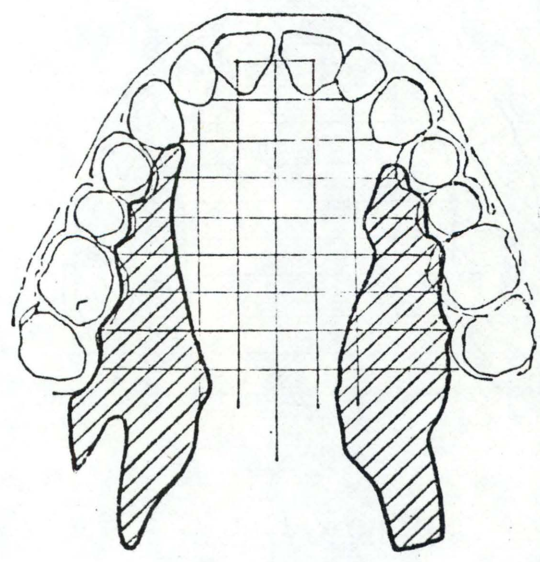

Figure 37

[piḷi]

Figures 34-37

See legend of figs. 2-5.

ḷ seems to be quite different in the palatogram of the word piḷi (Fig. 37). It shows only a slight contact with the pre-palatal region. (The contacts at the sides are due to the vowel.) The opening is at the right side. It is also rather fronted. My data is, however, not exhaustive.

Ramasubramaniam et al. (1971) describe the Tamil ṭ, ḍ, ṇ, and ḷ as medio-palatal retroflex consonants. The palatograms of Gujarati ṭ and ḍ look very similar to ṭ and ḍ of Tamil. However, the contact for ṭ and ḍ in Gujarati often extends beyond the mid-palatal region. Gujarati ḷ and ṇ are different from Tamil ḷ and ṇ in that they are flapped. In addition, their contact area generally extends beyond the mid-palatal region (see section 2.5.4 for the discussion of Gujarati ṇ).

2.5.4 n and ṇ

The palatograms of dental n show a rather large variation, with respect to both the place of articulation and the size of the contact area. The place of articulation may be dental, denti-alveolar, or alveolar, but is perhaps most often denti-alveolar. As nasality does not show up in palatograms, n may look very similar to the dental stops or to r and l. When alveolar, it resembles r, when denti-alveolar or dental, it looks more like l and the dental stops (see Figs. 38, 40, 42, 44).

Retroflex ṇ is flapped and the tongue contact is in the palatal region, approximately in the area between lines 2 and 8, sometimes from 2 to 6 (Fig. 43b: aṇ), or even 2 to 4 (Fig. 45: əphiṇi). Often the contact is far back at the hard palate beyond line number 7, and in some cases the ṇ has bilateral opening like ḷ (see paṇa, Fig. 39b and 41b). The retroflexed tip of the tongue comes back to its normal position very swiftly, passing through the palatal region, generally without touching the alveolar or dental zone. At times, however, it does touch the alveolar region, for instance paṇa, or baṇ (Figs. 41a, 43a).

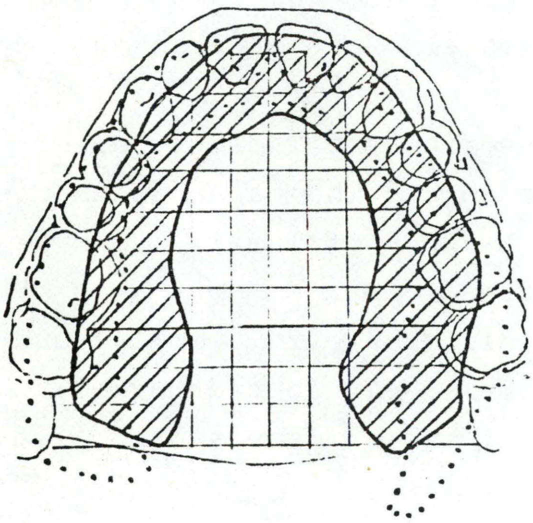

Figure 38ab

a. [nabhi]
b. [nam]

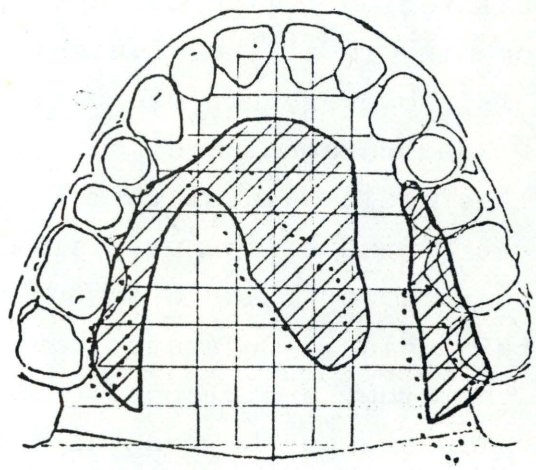

Figure 39ab

[paṇa]

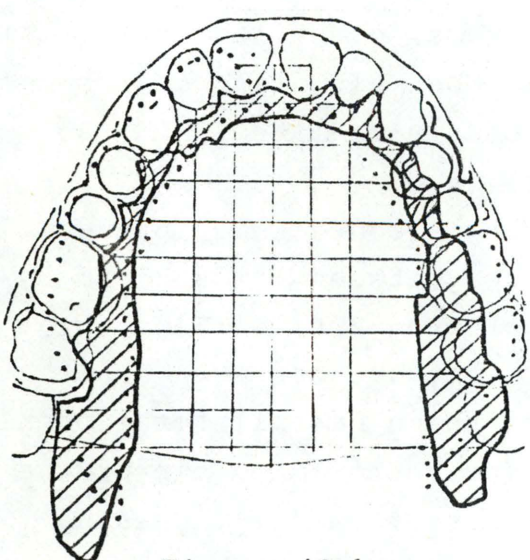

Figure 40ab

[mana]

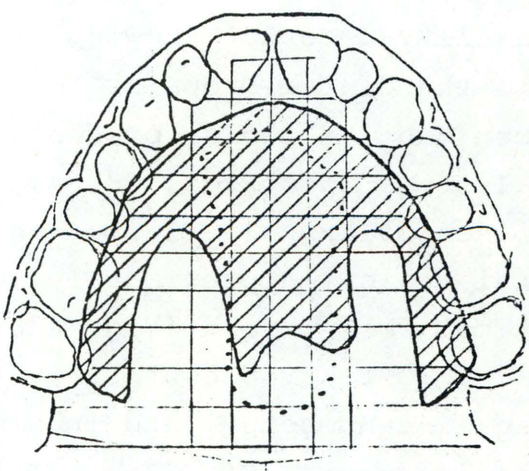

Figure 41ab

[paṇa]

Figures 38-41

See legend of figs. 2-5.

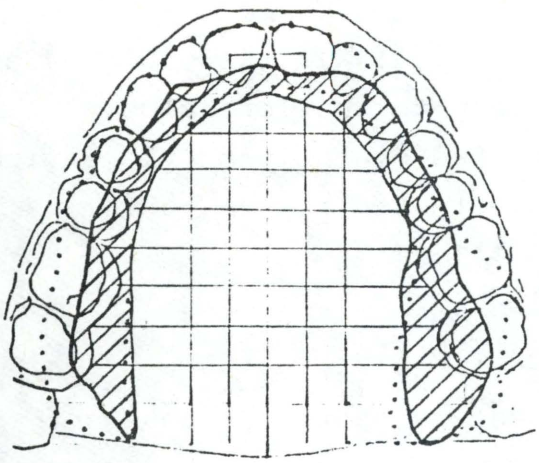

Figure 42ab

a. [an]
b. [ban]

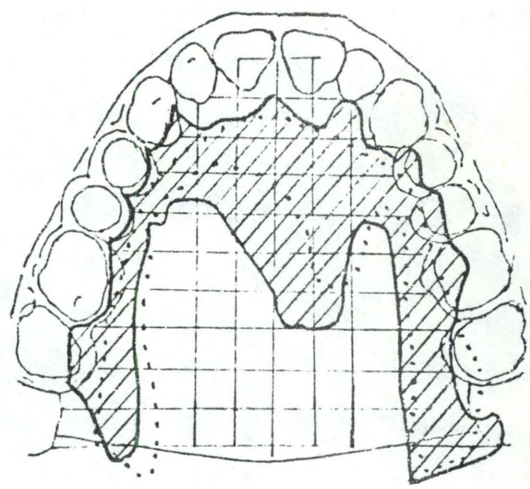

Figure 43ab

a. [baṇ]
b. [aṇ]

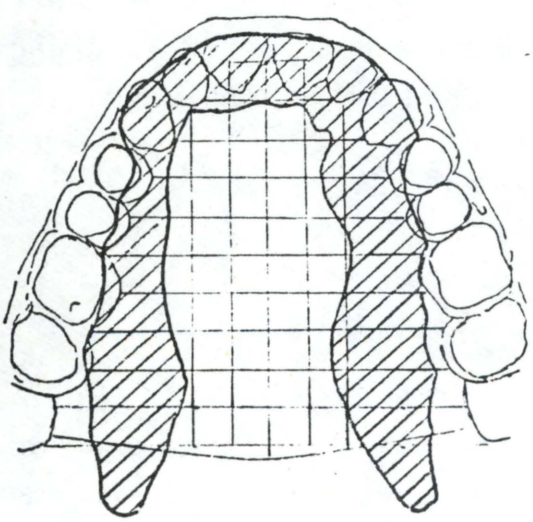

Figure 44

[mini]

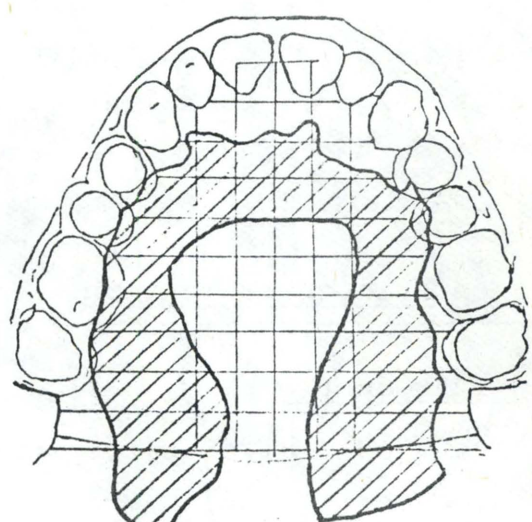

Figure 45

[əphiṇi]

Figures 42-45

See legend of figs. 2-5.

On the whole, the flapped consonants ṛ, ṇ, ḷ, and particularly ṇ and ḷ, seem to be produced with some constriction of the tongue and with a swift movement of the tongue tip, so that the contact is often rather weak.

In several palatograms (cf. paṇa, Fig. 41a, baṇ, Fig. 43a, aṇ, Fig. 43b), ṇ is asymmetric, slanting to the left side.

The articulation of ṇ is influenced by the phonetic environment. It is more fronted in the context with i (see əphiṇi, Fig. 45).

2.5.5 The velar stops (see Figs. 46a - 54)

Some velar stops have been investigated for purposes of comparison.

The contact area for the velar stops is in the velar region. Sometimes there is a slight contact in a small area in the region of the hard palate. Generally both k and g show contact beyond the area of line number 10. It will be clear from the palatograms that g is somewhat more fronted than k, and it also covers a somewhat larger area of the palate.

Both k and g are more fronted in the environment of the front vowel i, showing contact with the hard palate (see kiki and gəgi in Figs. 52-53). Nihalani (1974) notes a similar influence of the vowel i on the Sindhi velar stops.

3. Acoustic investigation

3.1 Introduction

A good deal of perceptual investigations of stops and nasals, and some on liquids, have been published during the last twenty years. Papers based on acoustic analysis of real speech have been fewer in number. We are, however, rather well informed about the acoustic properties of labial, alveolar (and dental) and velar

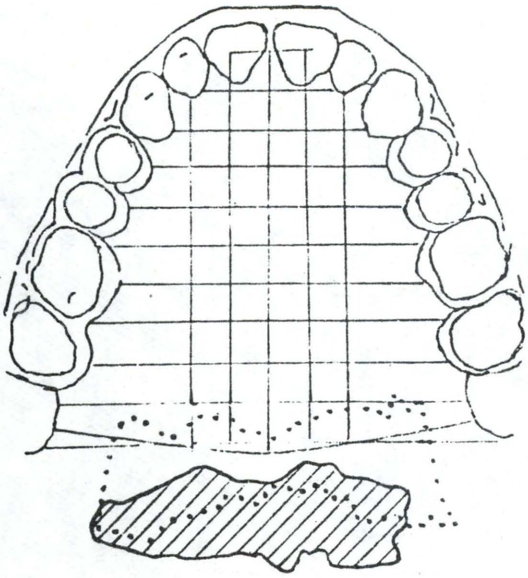

Figure 46ab

[kap]

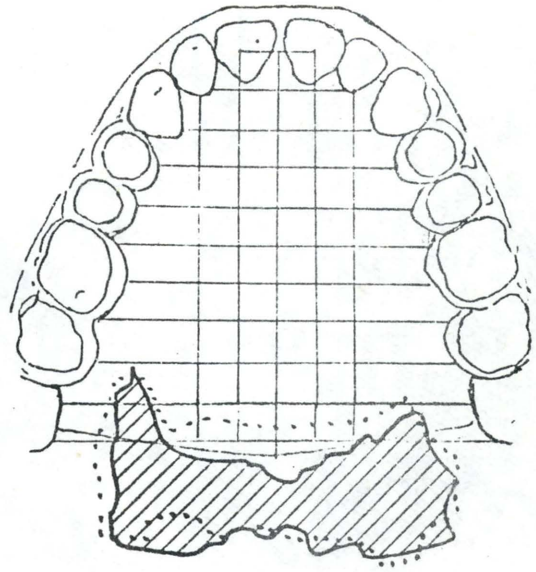

Figure 47ab

[gaw]

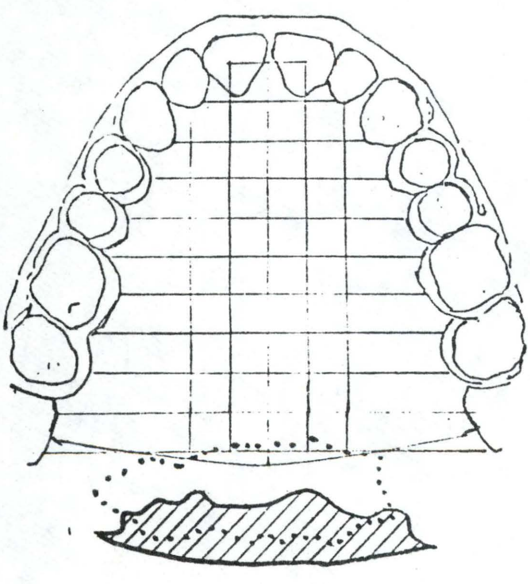

Figure 48ab

[paka]

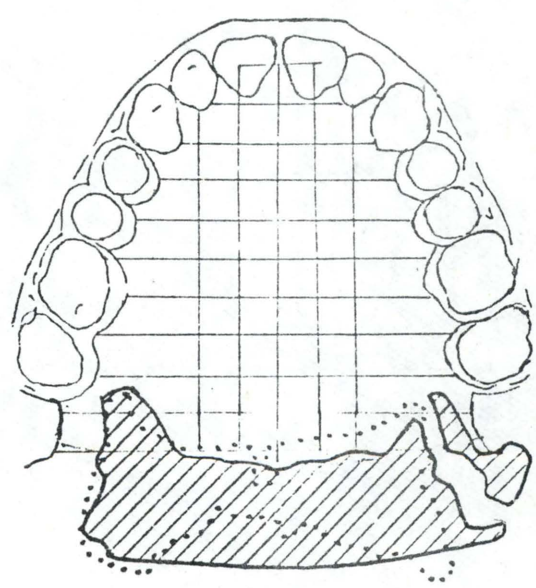

Figure 49ab

[gəga]

Figures 46-49

See legend of figs. 2-5.

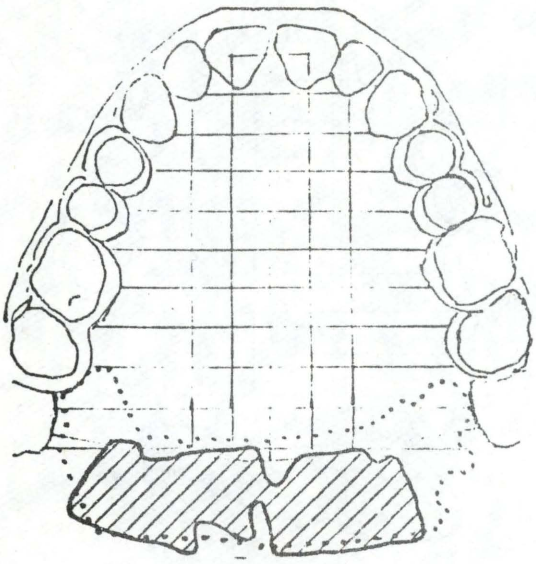

Figure 50ab

[pak]

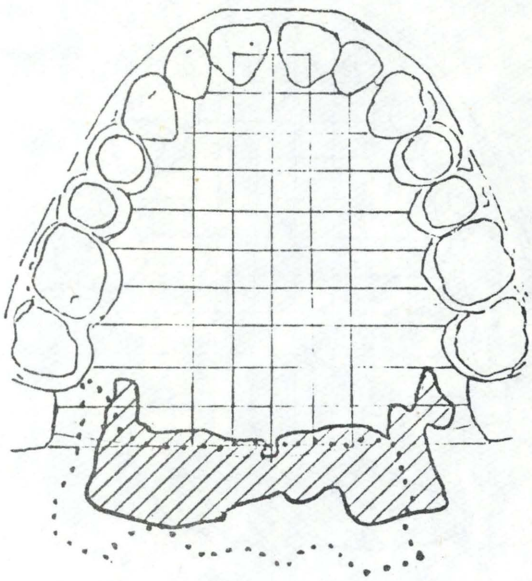

Figure 51ab

[bag]

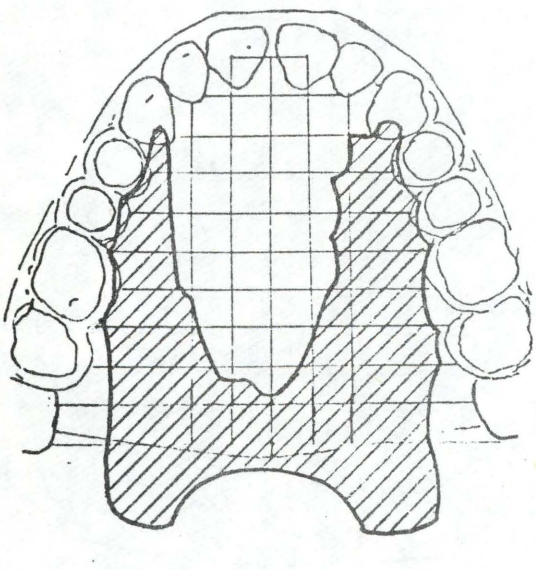

Figure 52

[kiki]

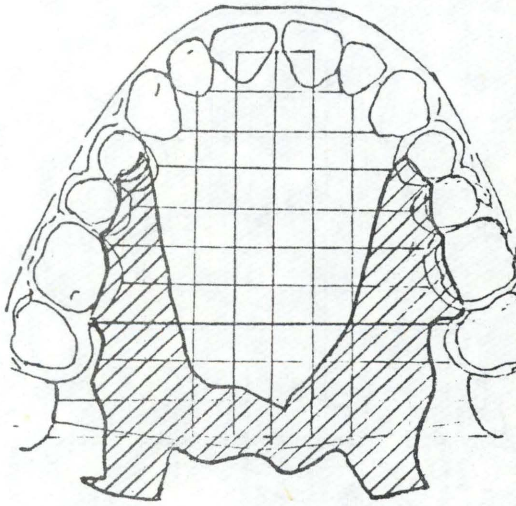

Figure 53

[gəgi]

Figures 50-53

See legend of figs. 2-5.

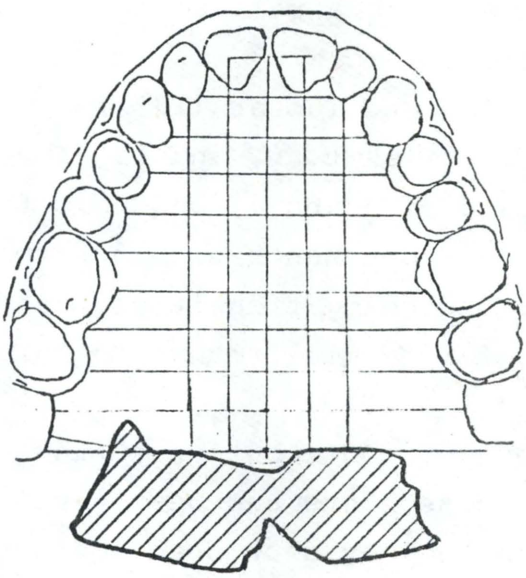

Figure 54
Palatogram of [kuku].

consonants, whereas little has been published on retroflex consonants, except for the retroflex American r and American vowels with retroflex modification, which are generally known to be characterized by a low F3.

Jakobson, Fant, Halle (1952, p. 49) reproduce a spectrogram of Bengali ṣ with the comment that "the retroflex consonant has energy in a lower frequency region and affects the third formant of the following vowel in a downward direction".

Fant (1968, p. 239) remarks very briefly that alveolar retroflex modification has the effect that F4 is lowered and comes close to F3, whereas with a palatal point of articulation F3 is lowered and comes close to F2.

Ramasubramanian and Thosar (1971) have analyzed a restricted number of Tamil retroflex ṭ, ṇ, and ḷ. They give formant values for the steady state of ṇ and ḷ, and have furthermore tried to synthesize retroflex consonants with 3 formants, in combination with i, u, and a, including transitions, and have arrived at some values for the loci. We will return to this investigation in more detail in section 4.1.

A very important contribution to the acoustic description of retroflex stop consonants has been given by K.N. Stevens and S. Blumstein (1975). They show spectrograms of the syllable aṭa spoken by three Hindi speakers. In addition, an extensive perceptual test has been made using stimuli changing, in 13 steps, from a dental consonant via a retroflex consonant to a velar consonant. A detailed discussion of this paper is taken up at the end of this article - in sections 4.1 and 4.2.

3.2 Informants

The informants of the present study were RD and RT, RD being the main informant. For his data, see 2.3. RT was born in 1941 in Bombay, and has been living in Copenhagen since 1965. His recordings were made in 1967.

3.3 The material

The material is partly the same as that used for the palatographic investigation, i.e. the preliminary list I, and the main list II containing 27 words with all dental and retroflex (unaspirated) consonants in initial, medial and final position in combination with the vowel a (with the exception of ṛ, ḷ, ṇ in initial position). In addition, for this investigation words with medial and final t, ṭ, d, ḍ, l, ḷ, r, ṛ, and n, ṇ in combination with the vowels i e ə o u (i.e. five lists of 10 words each, called lists III-VII) were analysed. Of these only list III (with the vowel i) was used in the palatographic investigation. In almost all cases the medial consonant has the same vowel on either side. The exceptions were iḍər in list III, eḍi in list IV, and udar, phuṭe, uḍe, sura, and unəp in list VII. It was difficult to find words with u-u. Therefore, list VIIa with the words bhodu, moṭũ, and uḍũ was added. (VIIa was used in the palatographic investigation.) The words with velars (lists IIa and IIIa and the word kuku) were used in the acoustic investigation as well as in the palatographic investigation. Finally, two lists of nonsense syllables were added, namely List VIII comprising 26 CV nonsense syllables with t, ṭ, d, ḍ, k, g before the vowels i, a, u and t, ṭ, d, ḍ before e and o, and List IX comprising 60 CV nonsense syllables containing all unaspirated stop consonants before the vowels i, e, u, o, ə, a.

Lists I-VII were spoken by both informants in Copenhagen in 1967. Lists II, III, and VII were spoken again by RD in Copenhagen in 1977, lists IIa, IIIa, VIIa, and IX were added in Copenhagen in 1977 and spoken by RD only. List VIII was recorded at Cornell University by RD. A list with VCV syllables was also spoken by RD in Copenhagen in 1977, but only a few words from this list were utilized. Lists VIII and IX (which were added in 1977) contain initial stop consonants only. There is thus a larger number of examples with initial stops than with stops in other positions, and the number of examples with nasals and liquids is rather restricted. The reason is that since it was difficult to see a clear difference between dental and retroflex stops in initial position, more such examples were considered necessary. List VIII was recorded specifically for the investigation of bursts.

3.4 Method of analysis

The material was recorded on a professional tape recorder in a sound treated room, and was analysed by means of a Kay Electric Sonagraph. For RD spectrograms were taken of one reading of each list (for lists II, III and VII both the 1967 and the 1977 readings were analysed). For RT a somewhat smaller number of spectrograms were taken, and only stops in initial position were measured, but spectrograms of stops in other positions and of nasals and liquids were inspected visually and compared with the results for RD.

As a rule both a wide band and a narrow band spectrogram were taken of each word. Very often two or three wide band spectrograms with different intensity and different degrees of compression were taken in order to get a clear picture of both formants and bursts in stop consonants.

The spectrograms were used for the measurement of formant transitions. In order to specify the transitions both the frequency of the steady state vowel formants and the end points of the transitions were measured together with the duration of the transition. The measurement of formant 4 was rather difficult because there are cases of split formants or weakened formants. Generally RD has a formant 4 around 3700 Hz and a formant 5 around 4200 Hz, and in some cases of <u>a</u> and <u>o</u> also a (weaker) formant around 3100 Hz. In some cases F5 is too weak to show up in the spectrograms, in other cases this is true of F4, and it is sometimes difficult to decide which one it is, particularly since they may all be lowered in rounded vowels, or be very weak, or missing in these vowels. Moreover, it is not always evident from where the formant transition designated as "F4-transition" starts. There are, therefore, certainly some inconsistencies in the measurements. In some other cases it has also been difficult to decide about the formant number and to exclude possible spurious formants. There have been many points of doubt, but the cases have been carefully considered.

The measurement of the duration of the transition is not exact since the boundary line between transition and steady state is rather arbitrary in many cases; the measurements have been used for the statement of clear differences in transition length (e.g. the rather brief transition of F4), and for the drawing of schematic spectrograms.

A rough analysis of the bursts was also undertaken on the basis of wide band spectrograms. A more precise analysis might have been undertaken by means of sections, but such an analysis would have required segmentation of burst and vowel (electrically or by tape cutting), which would have taken a great deal of time. Instead, an acoustic analysis of the bursts and the start of the vowel was undertaken in the Research Institute of Electronics at MIT, based on a computer directed linear prediction analysis.

A detailed technical description of the computer program is given in V.W. Zue (1976). It is based on a speech production model containing a source and an all-pole filter representing the combined effect of the glottal source, the vocal tract resonances, and radiation losses. The filter is excited either by a periodic impulse train for voiced speech or random noise for unvoiced speech. The zeros found in nasal consonants can be approximated by means of poles. By means of linear prediction (in this case using a form of autocorrelation analysis) a best fit is found between the incoming signal and the smoothed curves generated by the computer. The frequency band analysed is restricted to 5000 Hz, because most of the interesting characteristics of the speech wave are found below 5000 Hz, and because a filter including higher frequencies would lead to a number of complications. The time window was 25.6 ms wide. It is symmetric and has a smooth bell-like shape, which means that signals found at the sides are recorded with decreasing intensity. Because of this shape the effective width of the window is somewhat narrower. See Fig. 55, which is a sketch drawn by professor Stevens.

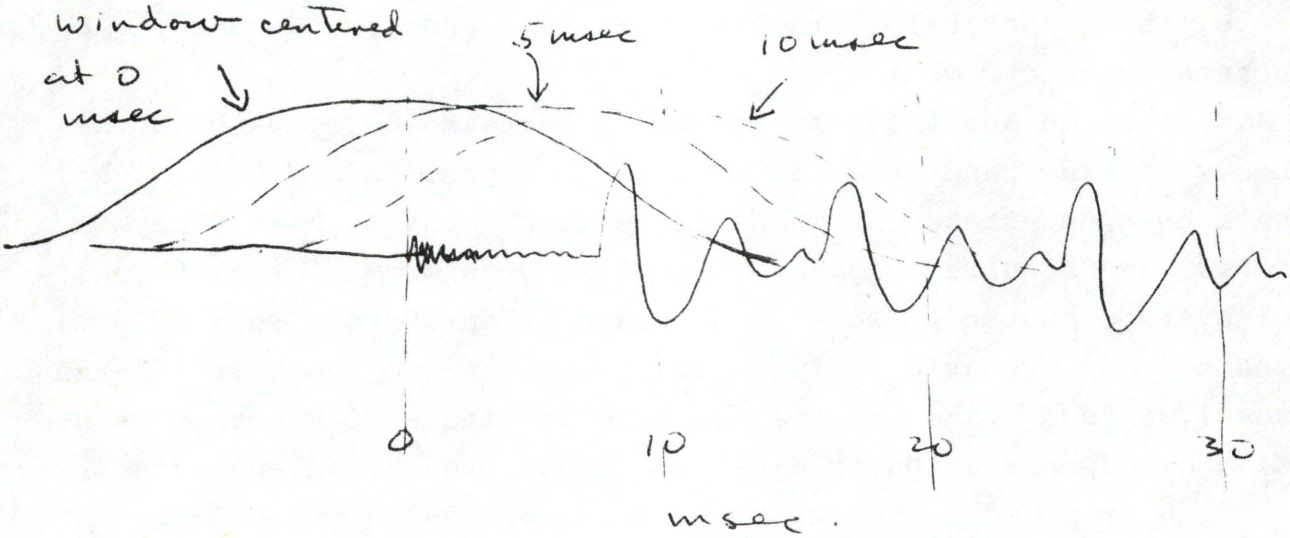

Fig. 55

Sketch of the windows used in the linear prediction analysis (K. Stevens).

The window can be moved in steps of 5 ms. The first point, designated as zero, is placed in such a way that the top of the window is at the start of the burst.

If the distance from burst to vowel is less than half the window, i.e. 12.8 ms, as in this picture, the spectrum will also be somewhat influenced by the start of the vowel formants, and the spectra taken at the following two points (5 and 10 ms) will also be influenced by both burst and vowel, but increasingly by the vowel formants. If the distance is more than 12.8 ms, it is possible to get a separate spectrum of the burst. A hard copy reproduction of the curves can be made, either one curve at a time (as in Fig. 56a), or curves from a number of consecutive points together, as in Fig. 56b. In Fig. 56b (the syllable to) it can be seen that the first two curves (taken at points 0 and 5) have a maximum around 1300 Hz due to the burst, whereas the last (point 10) has a maximum at 550 Hz, corresponding to the first formant of o.

By this method a number of consonants in initial position have been analysed, namely the stops of lists II-VII spoken by RD and RT, and list VIII spoken by RD. In most cases points 0, 5, and 10 have been recorded together. The main purpose was to find the relevant differences between the bursts in dental and retroflex stops. However, due to the length of the time window the zero curve will indicate the burst alone in voiceless stops only where the distance between burst and vowel is sufficiently large. (In some cases of retroflex stops there will be a slight influence from the vowel formants even in voiceless stops, because the distance is somewhat shorter in these stops than in dental stops, see 3.5.2A.) As for the voiced stops, the curve at point zero will always comprise both burst and vowel start. Therefore only the curves of voiceless stops have been utilized for this purpose.

Moreover, the curves taken at point 10 (or sometimes 15) have been compared with the spectrographic measurements of the start of the transition. The agreement is quite good except for the first formant of the high vowels i and u, for which the linear prediction analysis often gives much higher frequencies. For

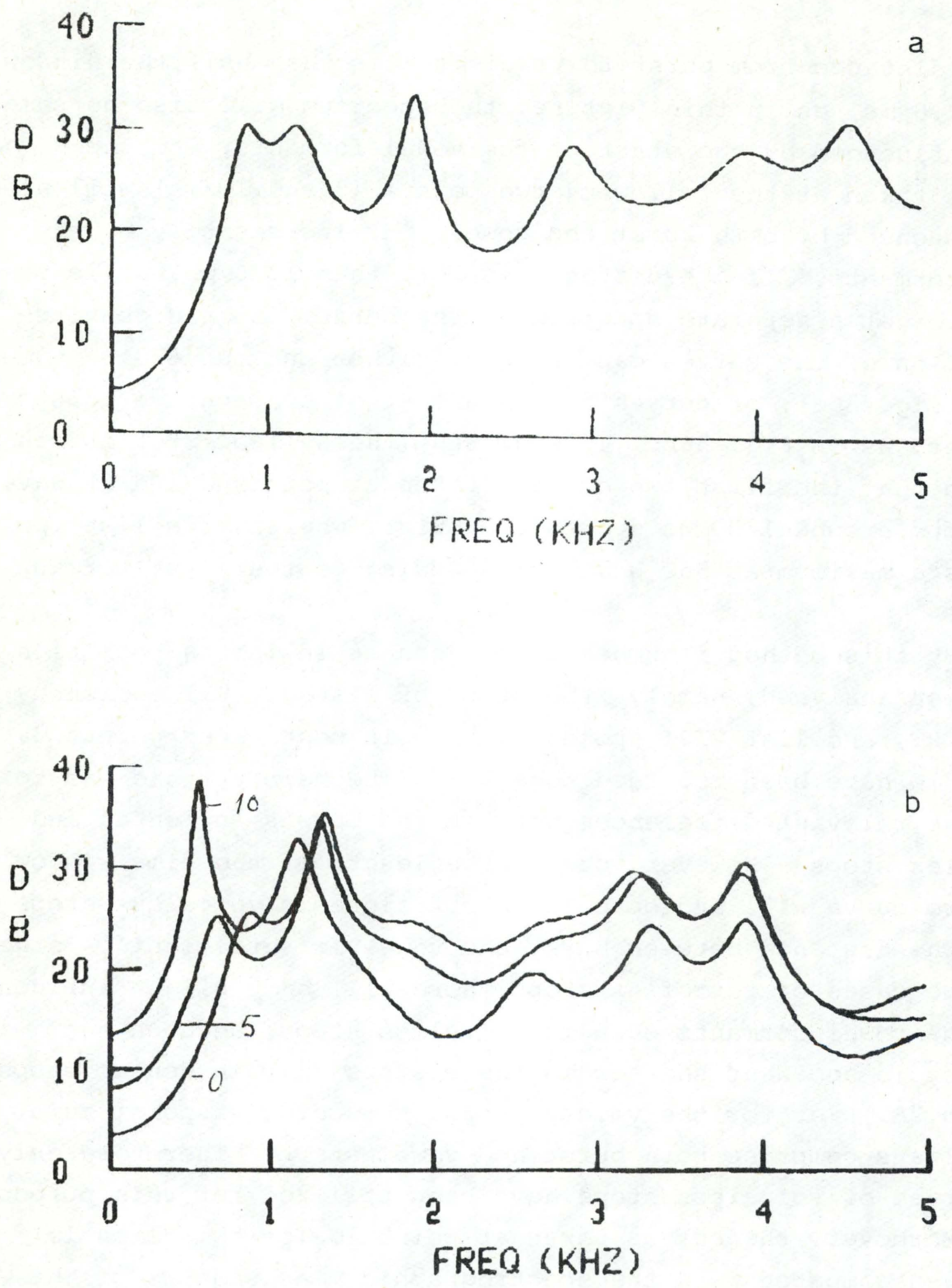

Figure 56

Spectral envelopes obtained by means of the linear prediction technique. a) shows the spectrum corresponding to one position of the time window; b) shows spectra taken at three different (consecutive) positions of the time window.

instance, by the spectrographic analysis the first formant of these vowels was found to have a frequency around 300 Hz, whereas the frequency according to the linear prediction analysis is often 400 Hz. This may partly be due to the fact that spectrographic measurements are based on peaks in the acoustic curve, whereas the linear prediction analysis is based on a theory of poles in the vocal tract. This may give some differences in the results for very low formants. There may, perhaps, also be mistakes in the linear prediction curves, for an F1 of 400 Hz for i seems to be too close to the F1 of e, which is generally 450-500 Hz, corresponding to the results of the spectrographic analysis. There are also some differences in formant 4 and the higher peaks of the bursts. Generally the values obtained by the spectrographic method are somewhat higher.

A binomial pair test has been used to test the significance of the differences between dental and retroflex consonants (see Sidney Siegel, Nonparametric Statistics for the Behavioral Sciences, 1956, table p. 250).

3.5 Results

3.5.1 Liquids and nasals

As mentioned in 1.2, the retroflex liquids and nasals (ṛ, ḷ, and ṇ) are not found initially, so that the contrast to the dentals is restricted to the medial and final positions. - Only RD's consonants have been measured.

3.5.1.1 r and ṛ

A. The consonantal section

Initial r is a one-tap r. There are only two examples in the material (two readings of rab); they have the average formants 550, 1537, and 2450 Hz.

In final position both r and ṛ have a single tap or flap. There are three examples of each, all with a preceding There is a consistent difference in the formants, the second formant of ṛ being slightly higher, and its third formant lower than the corresponding formants of r. The averages are for r: 600, 1442, and 2425; for r: 515, 1572, and 2188. The differences in F1 are not consistent.

Medial r and ṛ are both flaps with a very short closure phase. The average duration is 21 ms for r, and 13 ms for ṛ. During the closure no formants are seen in the spectrograms except for a low resonance around 250 Hz. There are, however, two exceptions: boṛo, which has a second formant of 1250 Hz, and one reading of əmiṛi, with formants at 300(?), 2100, 2630, and 3750 Hz.

B. Formant transitions in adjacent vowels

In the case of medial r and ṛ, the transitions of the adjacent vowels are the only features that are visible in the spectrograms, apart from the short pause. The transitions following initial r (rab) differ from those following medial r by having a very long and extensive transition of F3 (1850-2263, of 120 ms duration). F2 shows a transition of 55 ms duration (1425-1363).

With respect to the transitions preceding the final consonants, there is no difference between them and those preceding the medial consonants: the averages have therefore been combined. Table 1 of the Appendix gives the frequencies of start and end point of the transitions and the extent of the rise or fall (+ and - indicate "positive" and "negative" transitions).

Schematic drawings of the transitions are given in Figs. 57-59, and some specimens of spectrograms in Fig. 60. The averages of vowel transitions of preceding and following *a* are based on 7 and 6 examples, respectively. For the other vowels there are only 1-2 examples.

It appears from the figures that there are no consistent differences between vowel transitions after *r* and after *ṛ*. Both have in most cases a clearly negative F3, and in some cases a negative F4.

The transitions of the preceding vowels are, however, clearly different. Both F3 and F4 are strongly negative before retroflex *ṛ*. F2 is positive both before *r* and before *ṛ*, but it goes somewhat higher up before *ṛ*. The most relevant measure is probably the frequencies of the end points of the transitions. They differ for all three of the formants 2, 3, and 4, the end points of vowel transitions before retroflex consonants having a higher frequency of formant 2, and a lower frequency of formants 3 and 4 than those before the dental consonants. These differences are very consistent. For F3 and F4 there are no exceptions when the single words are compared in pairs (there are 11 and 12 comparable pairs); for F2 the difference is found in 10 out of 13 comparable pairs. The differences are significant at the 1% level. The frequency of F4 of the steady state part of the vowel preceding retroflex *ṛ* is also often lower than the steady state part of the vowel preceding dental *r*, whereas F3 varies. The transitions of F4 in vowels preceding a retroflex *ṛ* are often very steep and start slightly later than those of F3. In *e* and *i* the F3 transition takes place in the middle of the vowel, the F4 transition at the end (see Fig. 60).

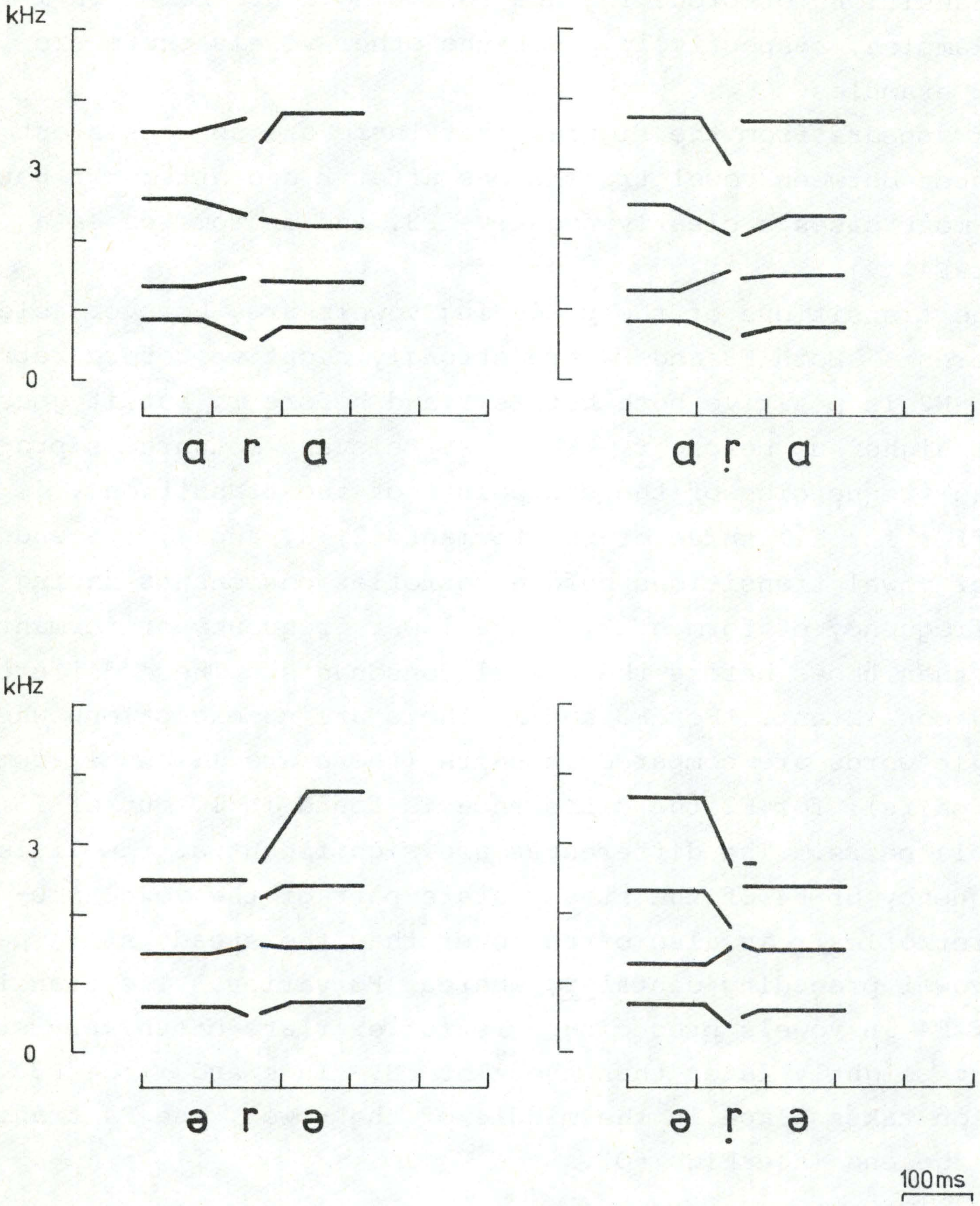

Figure 57

Schematized spectrograms. Speaker RD.

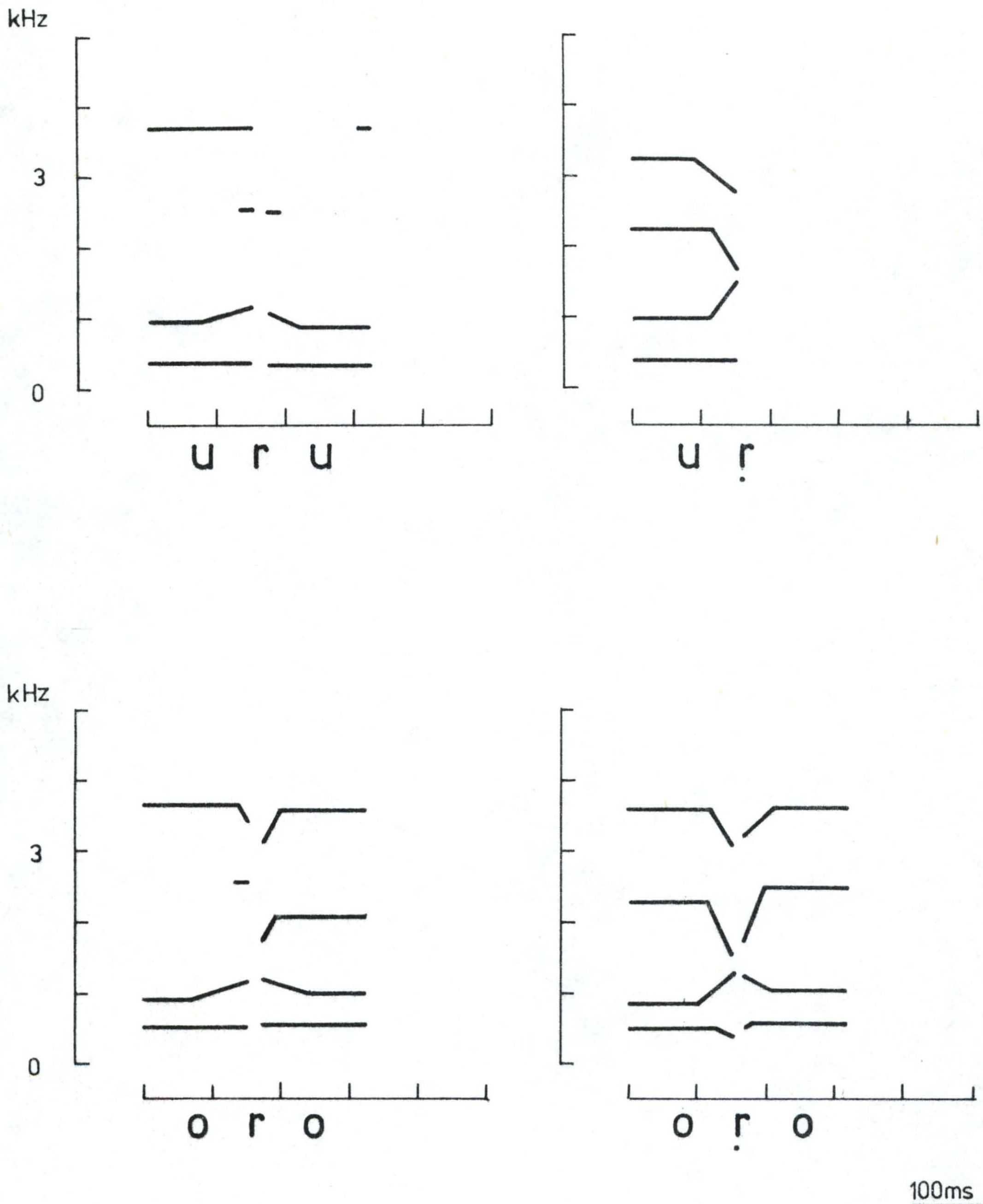

Figure 58
Schematized spectrograms. Speaker RD.

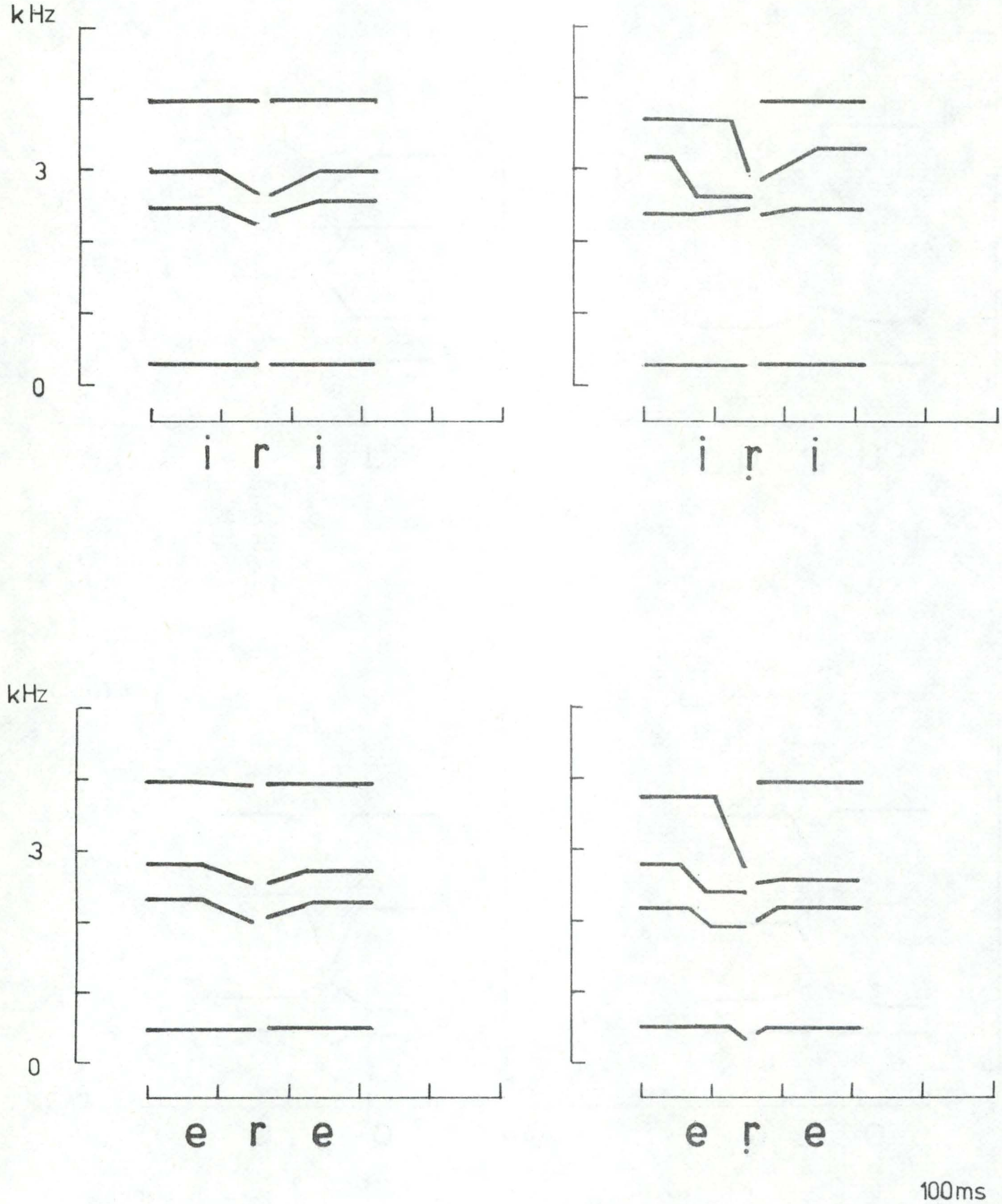

Figure 59

Schematized spectrograms. Speaker RD.

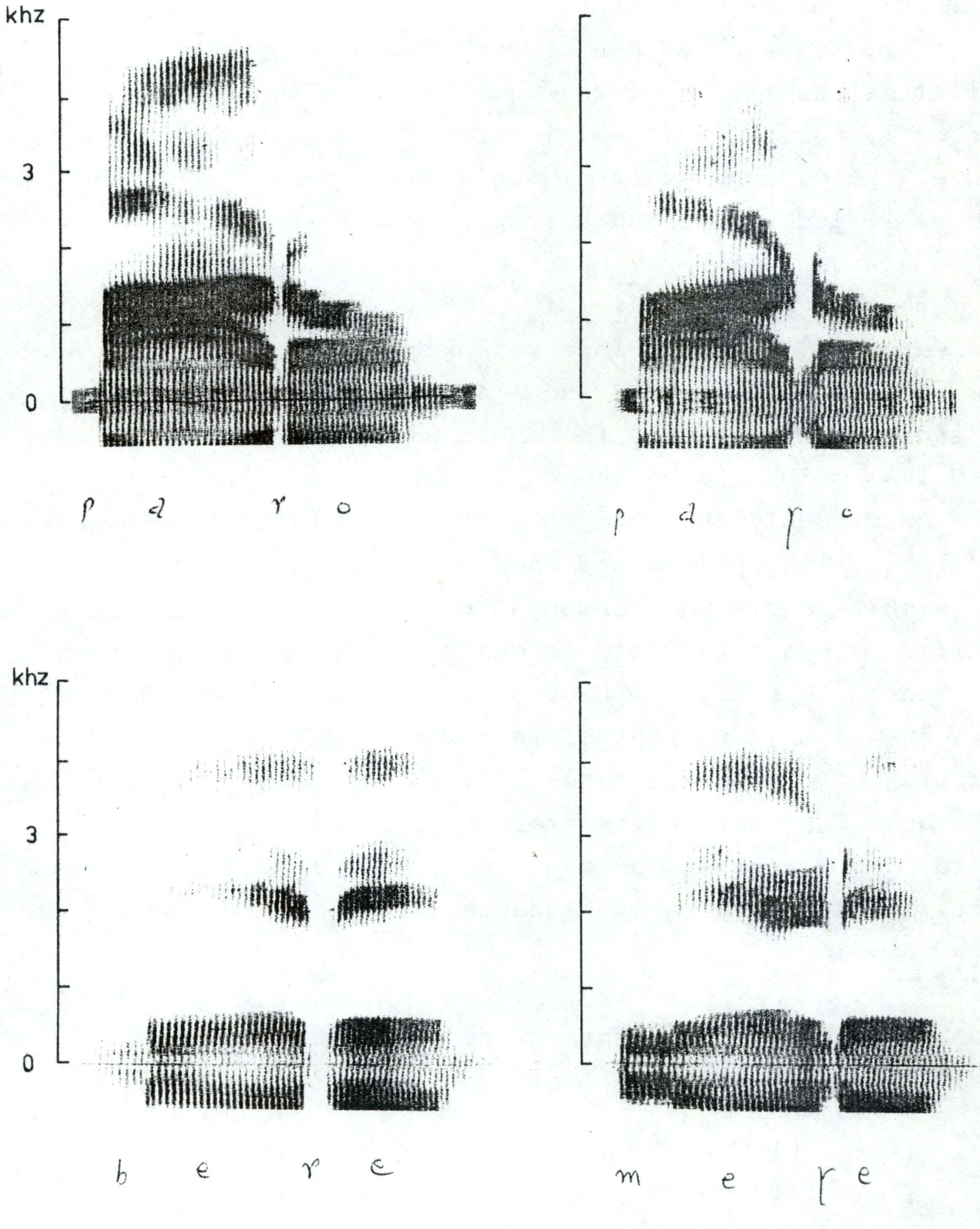

Figure 60

Sample spectrograms. Speaker RD.

3.5.1.2 l and ḷ

A. The consonantal section

The delimitation of retroflex ḷ from the preceding vowel is often problematic, as can be seen from the spectrograms in Fig. 63 (the examples baḷa and eḷe). If, in the examples with retroflex ḷ, the beginning of ḷ were considered to start when the vowel transitions start, ḷ would have approximately the same length as l, and the preceding vowels would also be of the same length. However, if these spectrograms are compared to the spectrograms of retroflex ṛ (Fig. 60) and to spectrograms of retroflex stops, it seems more reasonable to consider the downward movement of formants 3 and 4 as belonging to the preceding vowel and to consider only the short period of closure of the flapped ḷ as belonging to the consonant section proper. What happens is probably that the tongue moves relatively slowly up to the roof of the palate and then, after a very short touch, moves quickly down. The consonant proper has therefore been considered as starting where formants 3 and 4 have come down. Calculated in this way the closure time of dental l will be on the average 86 ms, and that of retroflex ḷ only 27 ms, with no overlapping of the single cases. (l in ullu (185) is a geminate and has been left out in the averages.)

In contradistinction to r and ṛ, both l and ḷ show clear formant values during the consonantal section, as shown in the table below:

Formants of dental l

Adjacent vowels	a	ə	u	o	i	e
N	(8)	(1)	(1)	(1)	(2)	(2)
F_4	3669	3725	3500	3600	3850	3750
F_3	2697	?	2650	2650	2713?	2600
F_2	1281	1300	1350	1150	2563?	1600
F_1	319	350	250	275	275	275

Formants of retroflex ḻ

Adjacent vowels	a	ə	u	o	i	e
N	(2)	(1)	(1)	(1)	(2)	(1)
F_4	3330	3300	3100?	3550	3550	3425
F_3	2280	2500	?	1925	2425	2400
F_2	1400	1425	1100	1050	2000	1800
F_1	710	700	400	550	350	525

There are very clear differences in the formant frequencies between the two types of l: retroflex ḻ has a higher F1, and in the environment of a and ə also a higher F2, moreover, in all cases a lower F3 and a lower F4. The differences in F1, F3, and F4 are found in all comparable, single pairs and are significant at the 1% level, and the difference in F2 is consistent for ə and a.

B. Formant transitions of adjacent vowels

The frequencies of start and end of the vowel transitions are shown in table 2 of the Appendix, and schematic drawings are given in Figs. 61-62.

The averages for the vowel a are based on 6 examples before l and ḻ: 4 examples after l, and 2 after ḻ. For the other vowels there are only 1-2 examples. As there were no consistent differences between the transitions after initial and medial consonants, nor before final and medial consonants, these examples have been combined into one average.

It appears from the tables and from the schematic drawings in Figs. 61-62 that differences in formant transitions between the dental l and the retroflex ḻ are found in both the preceding and in the following vowel, but most consistently in the preceding vowel. In a and ə F1 ends at a higher frequency before ḻ than before l (and this is true of all 6 examples of a), but for the other vowels and in vowels after l and ḻ there is no consistent difference.

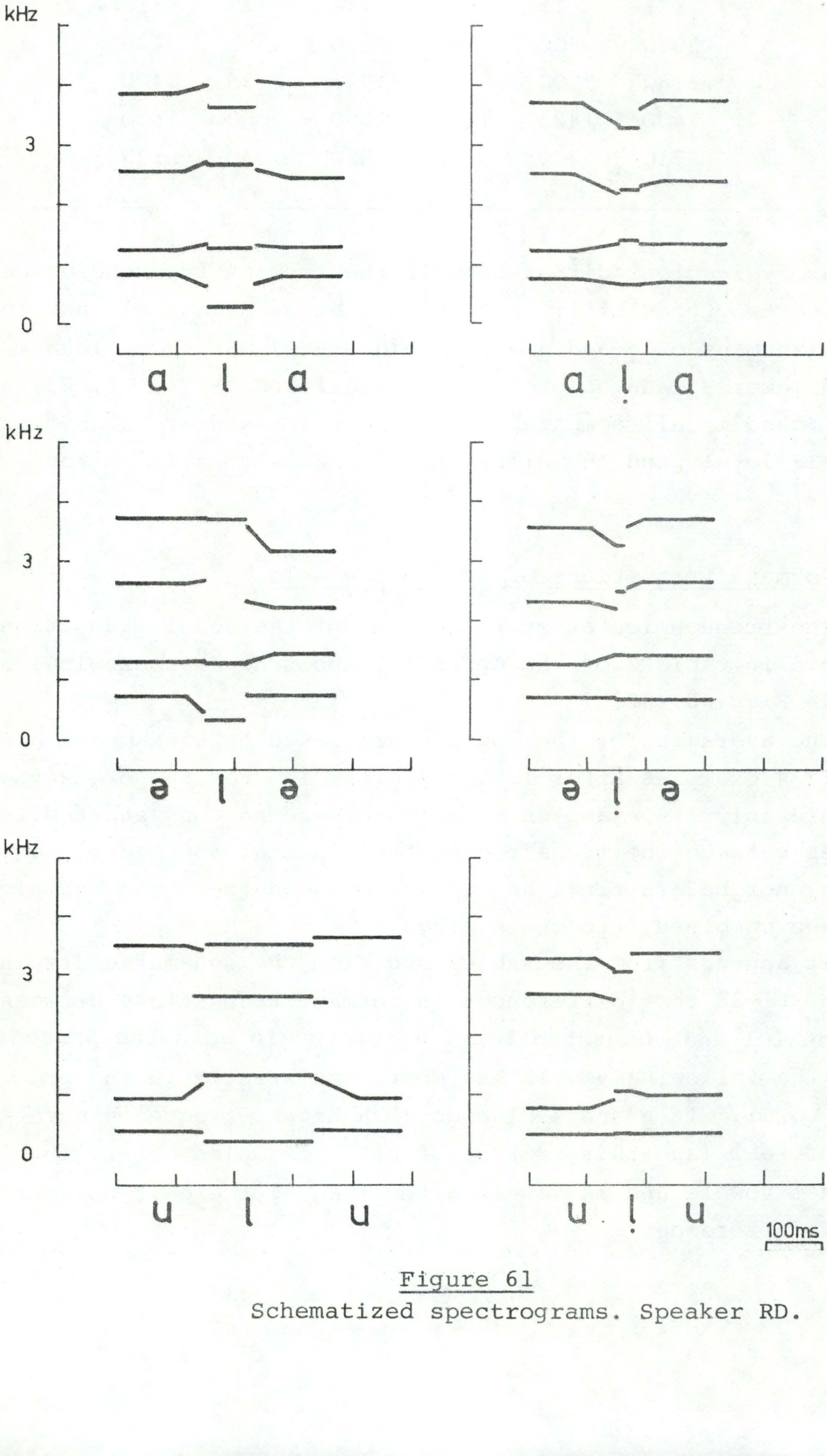

Figure 61
Schematized spectrograms. Speaker RD.

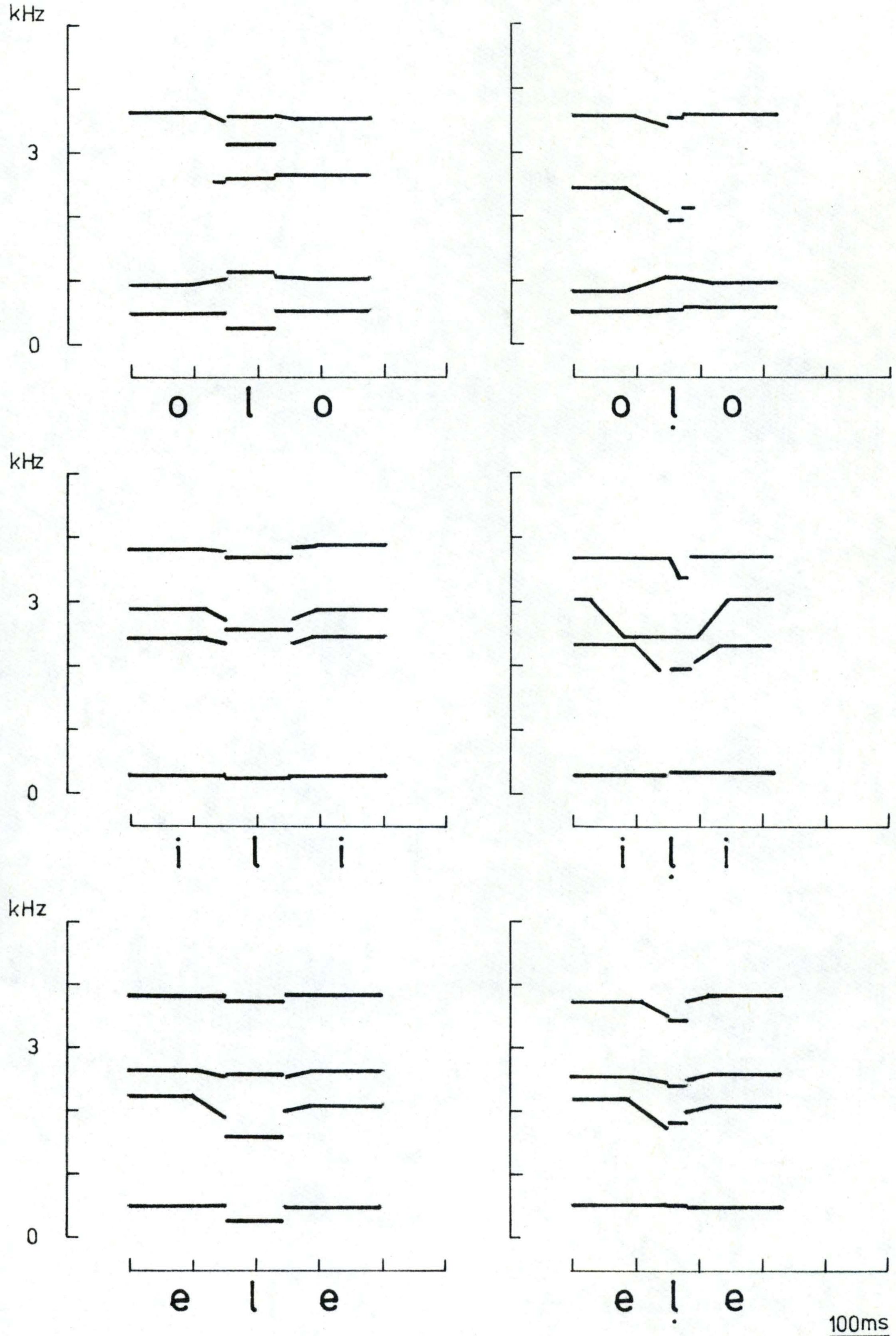

Figure 62
Schematized spectrograms. Speaker RD.

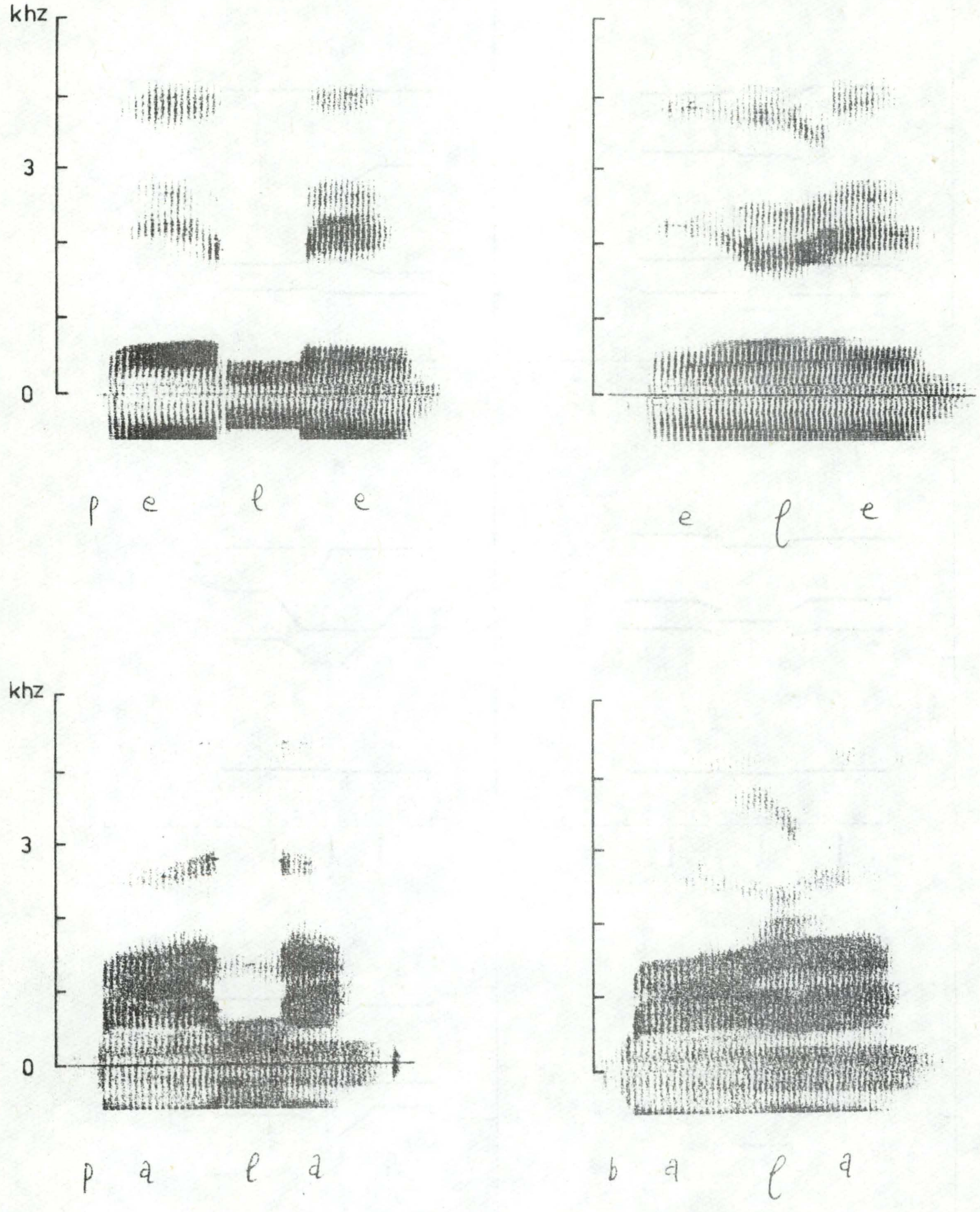

Figure 63

Sample spectrograms. Speaker RD.

The differences in F2 are not consistent. F3 and F4 show much more consistent differences. Particularly the vowel before l̤ shows a more strongly negative transition than the vowel before l, and the end points of F3 and F4 are lower before l̤ than before l in all cases (12 comparable pairs), the difference being significant at the 1% level. Similarly, F3 and F4 of the following vowel have a tendency to start at lower frequencies after l̤ than after l, but the difference is only found in 6 out of 8 comparable word pairs. The vowel a sometimes has an extra formant around 3000-3300 Hz, particularly before dental l. F4 is also consistently lower in the steady state part of a vowel preceding retroflex l̤ than in one preceding dental l, whereas F3 varies.

3.5.1.3 n and ṇ

A. The consonantal section

Retroflex ṇ is a flapped consonant like l̤ and ṛ, and the delimitation is not easy, although it is not as difficult as in the case of l̤. The transitions have been considered to belong to the vowels, and ṇ is thus of very brief duration (see the spectrograms Fig. 66). The average duration of n is 88 ms, and that of ṇ 31 ms, and there is no overlapping (n in unnu has been left out of the average, because it is a geminate (170 ms)).

The formants of nasal consonants are not easy to measure. They are rather irregular, and some may be too weak to appear on spectrograms. Particularly the higher formants are dubious, and the averages for n before i are rather problematic.

Nevertheless, some consistent differences appear from the tables:

Formants of dental n

Adjacent vowels	a	ə	u	o	i	e
N	(6)	(1)	(1)	(1)	(3)	(1)
F_4	4275 (3075)	4400	3700 (2900)		3775	
F_3	2563	2415	2600	2525 }	2680	2575
F_2	1450	1325	1425	1200 }		
F_1	313	275	300	300	300	300

Formants of retroflex ṇ

Adjacent vowels	a	ə	u	o	i	e
N	(6)	(1)	(1)	(1)	(3)	(1)
F_4	3400			3450	3870	
F_x	2625	2800	2800	2900	2867?	2800
F_3	2125	2300	1850	1900	2400	?
F_2	1408	1450	1225	1100	2063?	1900
F_1	250	250	300	225	350	300

There are no consistent differences between F1 or F2 of dental and retroflex nasals. F3 is, however, consistently lower in ṇ than in n. This is true of 12 comparable pairs, and the difference is significant at the 1% level.

Moreover, ṇ has in all positions a formant around 2800 Hz.

B. Formant transitions in adjacent vowels

The frequencies of start and end of the transitions are given in table 3 of the Appendix, and schematic drawings of the transitions are shown in Figs. 64-65. There are no con-

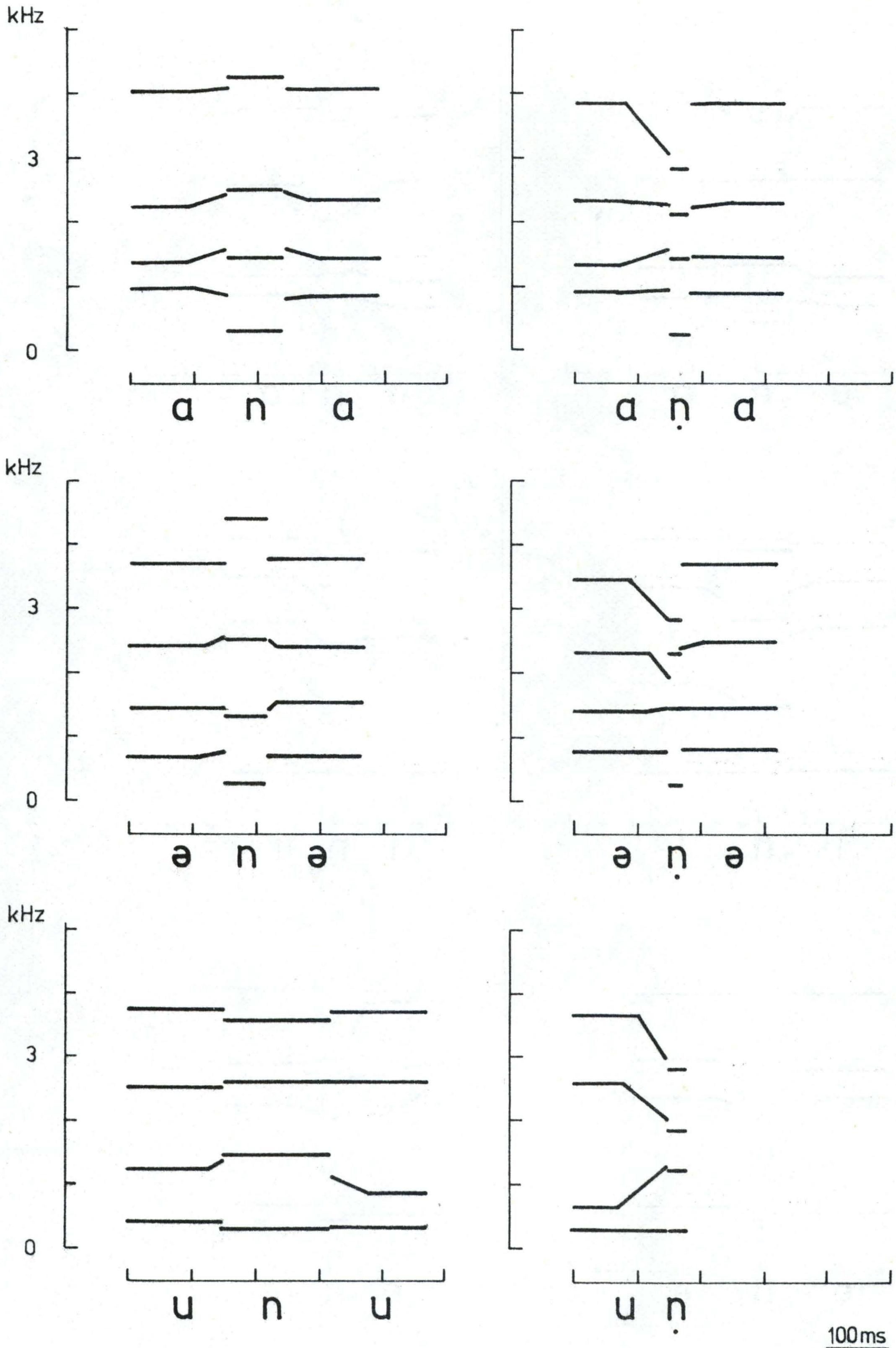

Figure 64

Schematized spectrograms. Speaker RD.

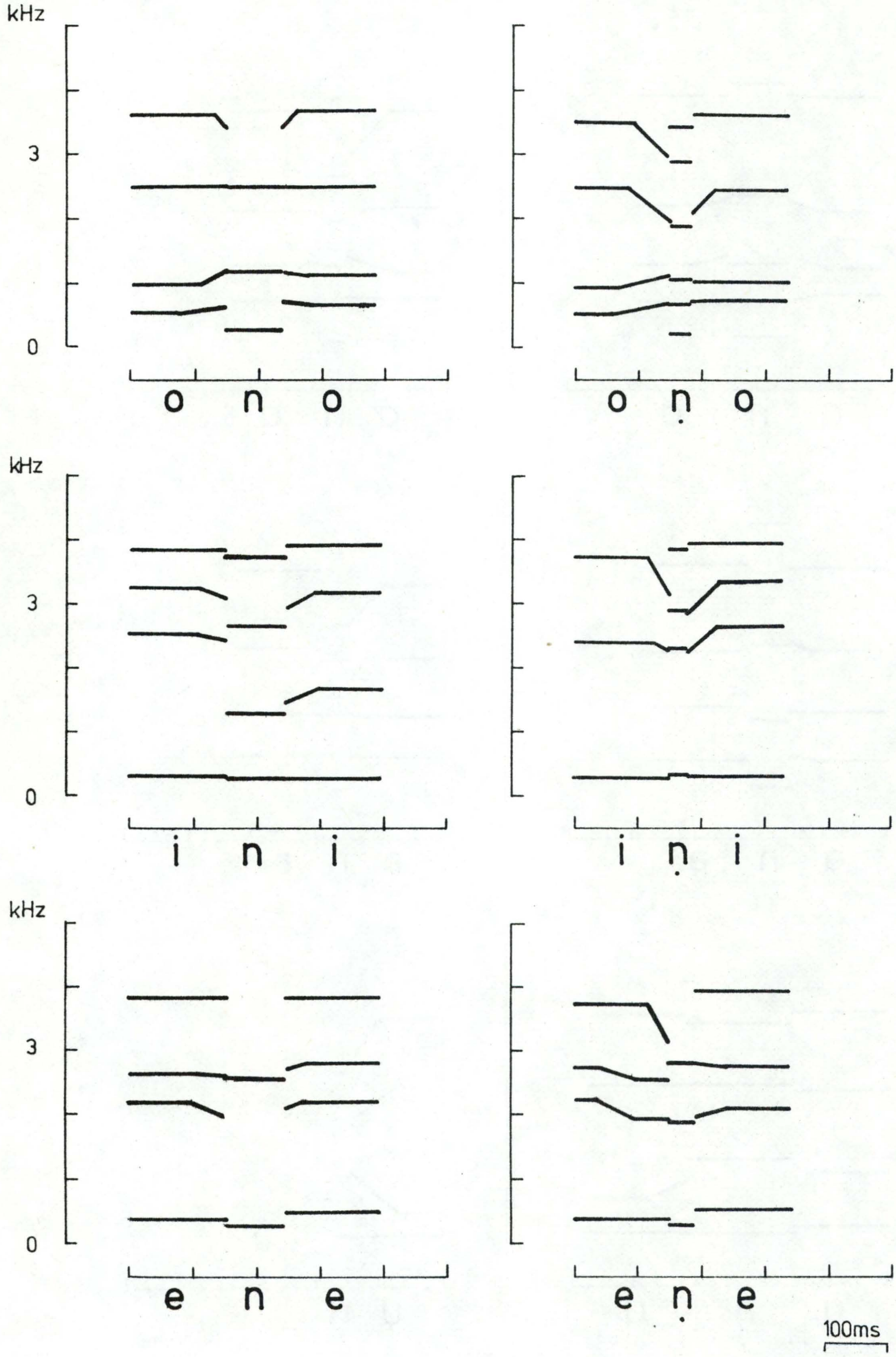

Figure 65
Schematized spectrograms. Speaker RD.

sistent differences between vowel transitions in connection with dental and retroflex consonants in F1 and F2, but there are clear differences in F3 and F4. Vowels before retroflex ṇ have a more pronounced negative transition of F3 and F4 than vowels before dental consonants, and in most cases there is also a difference in the F3 transition after the consonant. F4 has a lower end point of the transition before retroflex ṇ in all 12 comparable pairs, and F3 in all of 10 comparable pairs. In the position after the consonants the same tendency is found, but not consistently (6 out of 8 comparable pairs). F4 in the steady state part of a vowel preceding retroflex ṇ is also consistently lower than in one preceding dental n̲, whereas F3 is variable.

A further difference between RD's dental and retroflex nasals is that the retroflex consonants tend to nasalize the preceding vowel to a higher degree, cf. Fig. 66. The vowel before ṇ has a higher and weaker F1 and a stronger subformant than the vowel before n̲.

The common feature for retroflex ṛ, ṇ, and ḷ is thus a lowering of the third and fourth formants of the preceding vowel, and the lowering is also seen in the spectra of the consonantal section of ḷ and ṇ.

3.5.1.4 RT's retroflex liquids and nasals.

The spectrograms of RT show, on the whole, the same differences between dental and retroflex consonants as those found in RD's spectrograms. The lowering of F3 before retroflex consonants is particularly clear. He also has the tendency to higher frequency of F2 before ṛ. As for F4, he has some cases of clearly negative transition before retroflex consonants, but the fall is generally slower than in RD's curves and very often missing. Two pairs of spectrograms reproduced in Fig. 67 from RD and RT show this difference.

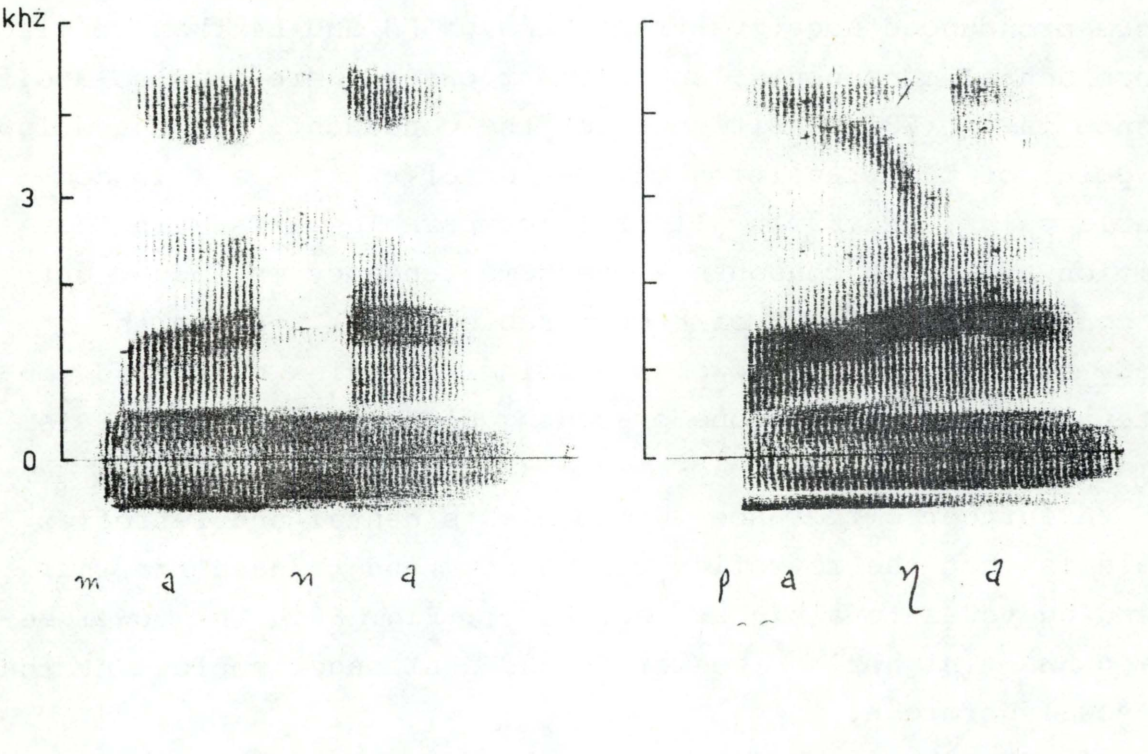

Figure 66
Sample spectrograms. Speaker RD.

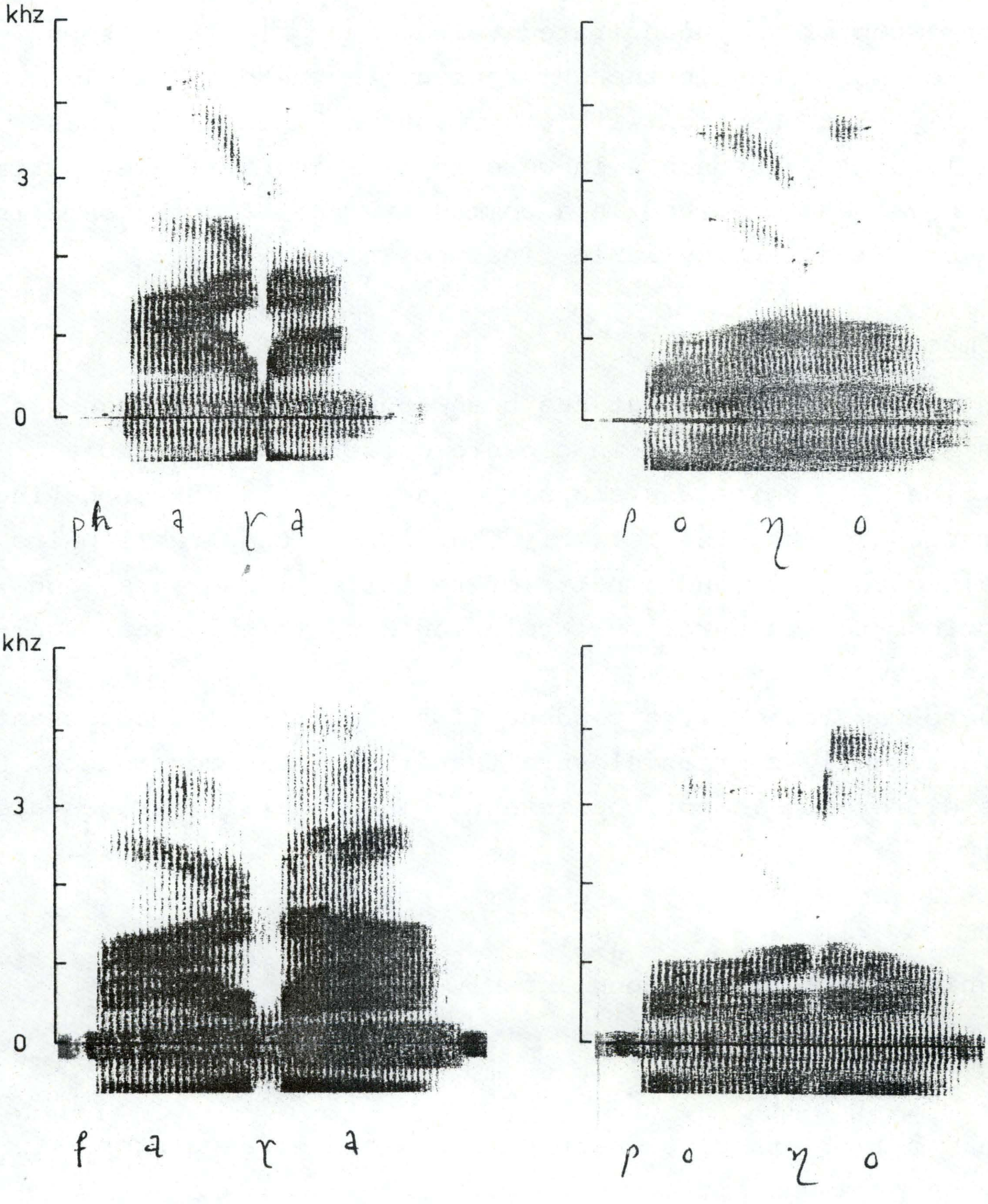

Figure 67

Spectrograms of the two speakers' [ṛ] and [ṇ];
RD above, RT below.

3.5.2 Stops

Both dental and retroflex stops are found in all positions of the word: initially, medially, and finally. Spectrograms have been taken of the unaspirated voiced and voiceless stops in all three positions in the environment a-a, and initially and medially in connection with other vowels. As was the case with the liquids, consonants in word-initial and syllable-initial position have been combined in a common average, and the same is true of word-final and syllable-final position.

A. Temporal relations

In accordance with what has been found in other languages there is a clear difference in closure duration between RD's medial voiced and voiceless stops t ṭ and d ḍ, the former having a longer closure than the latter. There are 8 comparable pairs of dental consonants, and 8 pairs of retroflex consonants, and no exceptions to the durational relationship, which gives significance at the 1% level.

There is, moreover, a tendency for the retroflex consonants to have a slightly shorter closure than the dental consonants, but this difference is not consistent. The general averages are:

t 124 ms, ṭ 114 ms, d 83 ms, ḍ 71 ms.

RT has quite similar relations, namely

t 106 ms, ṭ 103 ms, d 68 ms, ḍ 51 ms.

But he has only 3 examples where ḍ is pronounced as a stop. Normally he pronounces it as a flap.

More important is the difference in distance between burst and vowel start, found in RD's spectrograms. This distance has sometimes been called "open interval" (e.g. by Fant and by Eli Fischer-Jørgensen 1954), but is now commonly called "voice onset time", abbreviated VOT, a term introduced by Lisker and Abramson (1964).

In RD's spectrograms the VOT value is smaller for retroflex consonants than for dental consonants. For the voiced stops the VOT is in any case very short and sometimes difficult to measure, but there is at least a tendency for ḍ to have a few ms shorter VOT than d̪. For the voiceless stops the difference is quite clear. The averages (in ms) are:

	a	ə	u	o	i	e
t̪	15	15	16	15	24	20
ṭ	9	9	13	10	10	9

There are 27 examples of t̪ and 25 of ṭ, and of 24 comparable pairs the dental consonant has a longer VOT in 21. This is significant at the 1% level.

However, the other informant (RT) has no such difference between dental and retroflex stops. The VOT of his dental stops is on the average 15 ms, and that of his retroflex stops 16 ms.

B. Burst frequency

The burst frequency has been analysed by the linear prediction method, mentioned in 3.4. When the point for analysis is chosen at point zero, so that the time window has its peak at the start of the burst, the spectrum of the bursts of voiceless stops will, in most cases, be based on the burst alone, except for some cases of retroflex stops where there may be a slight influence from the vowel start.

Figs. 68-73 show such spectra of the bursts of RD. Dental stops are shown at the top and retroflex stops at the bottom of each figure. In most of the drawings 2-3 examples of stops at

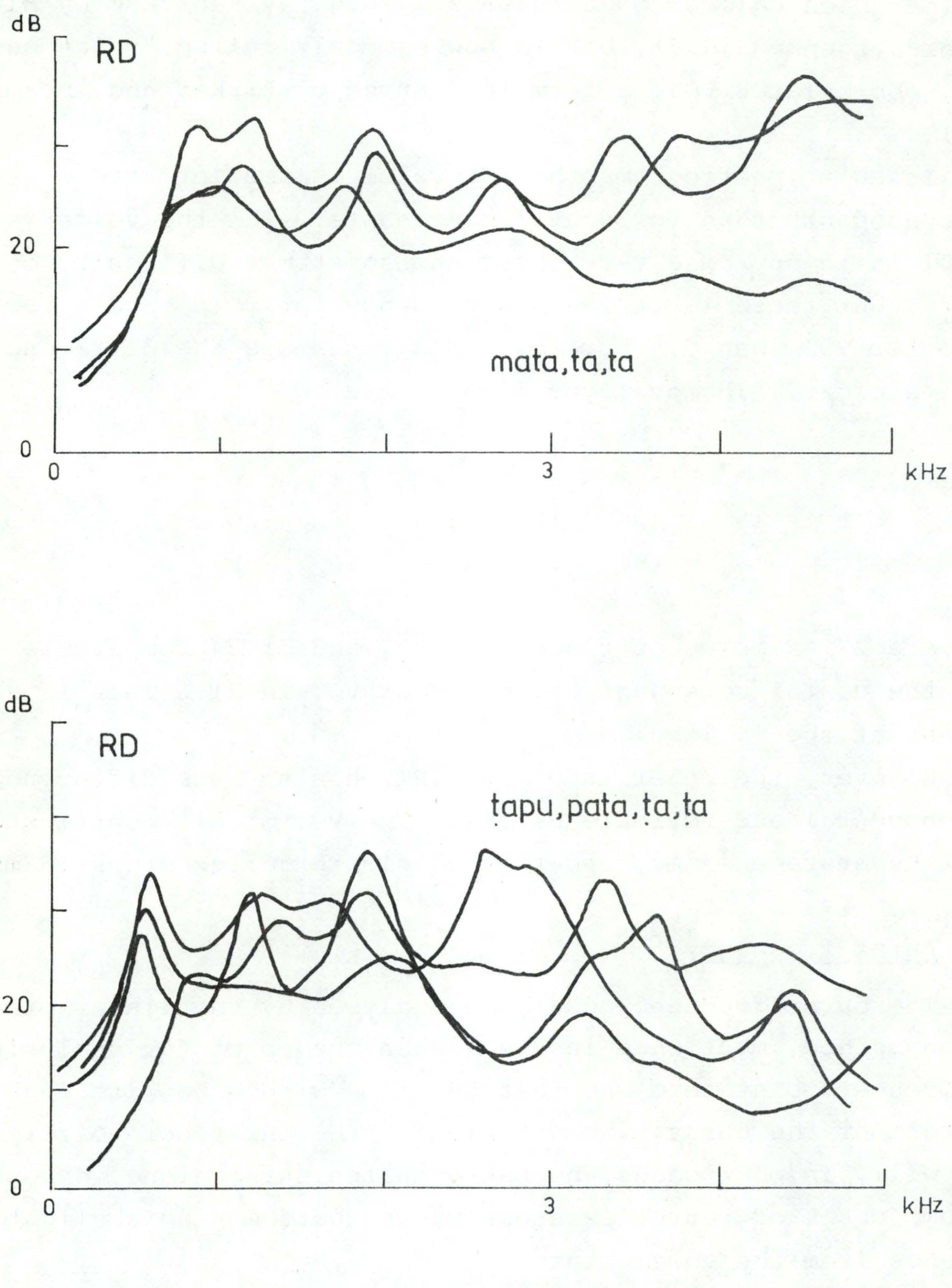

Figure 68

Burst spectra. Speaker RD. The position of the time window was at zero, i.e. the window was placed symmetrically around the burst.

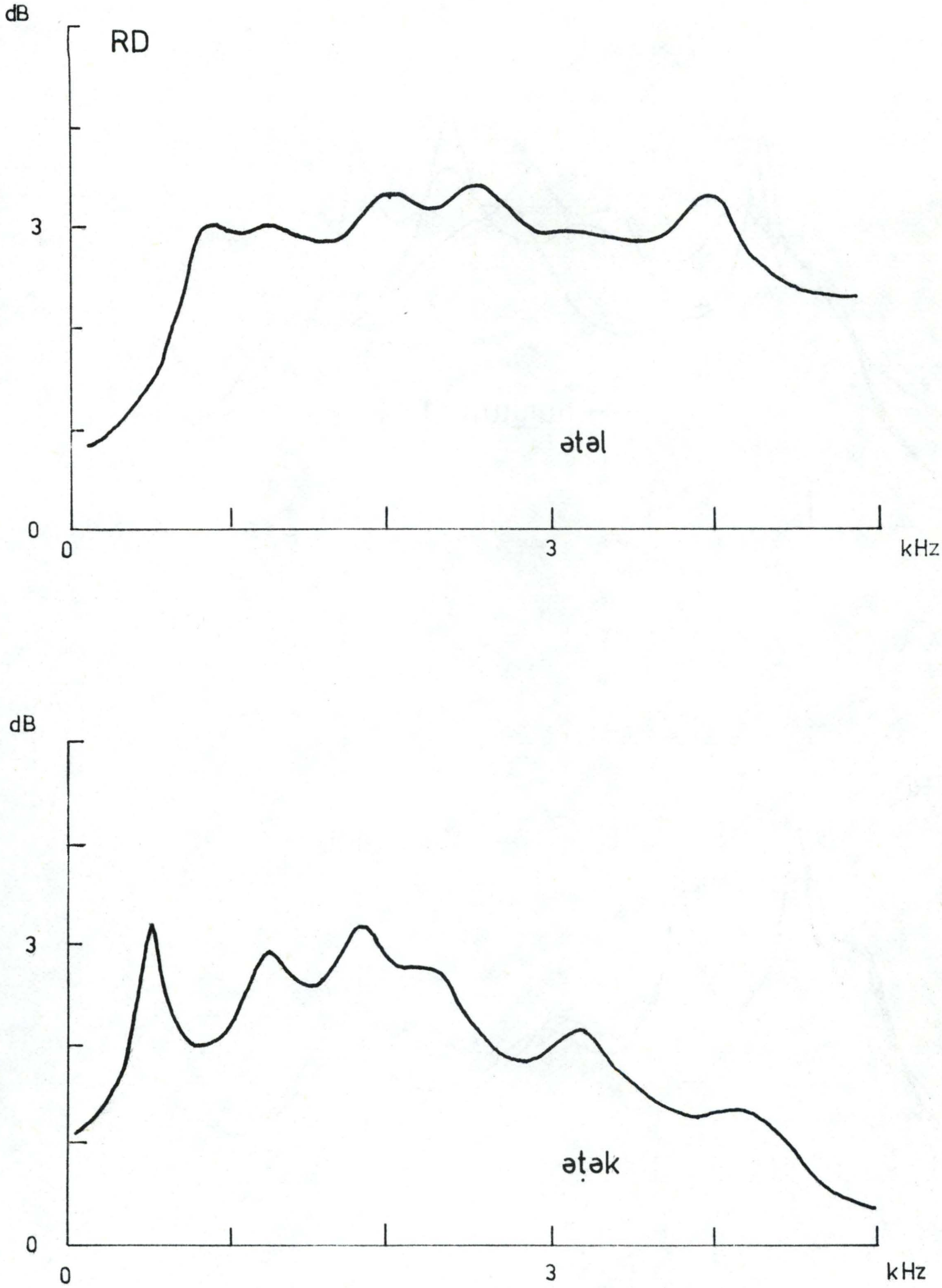

Figure 69

See legend to fig. 68.

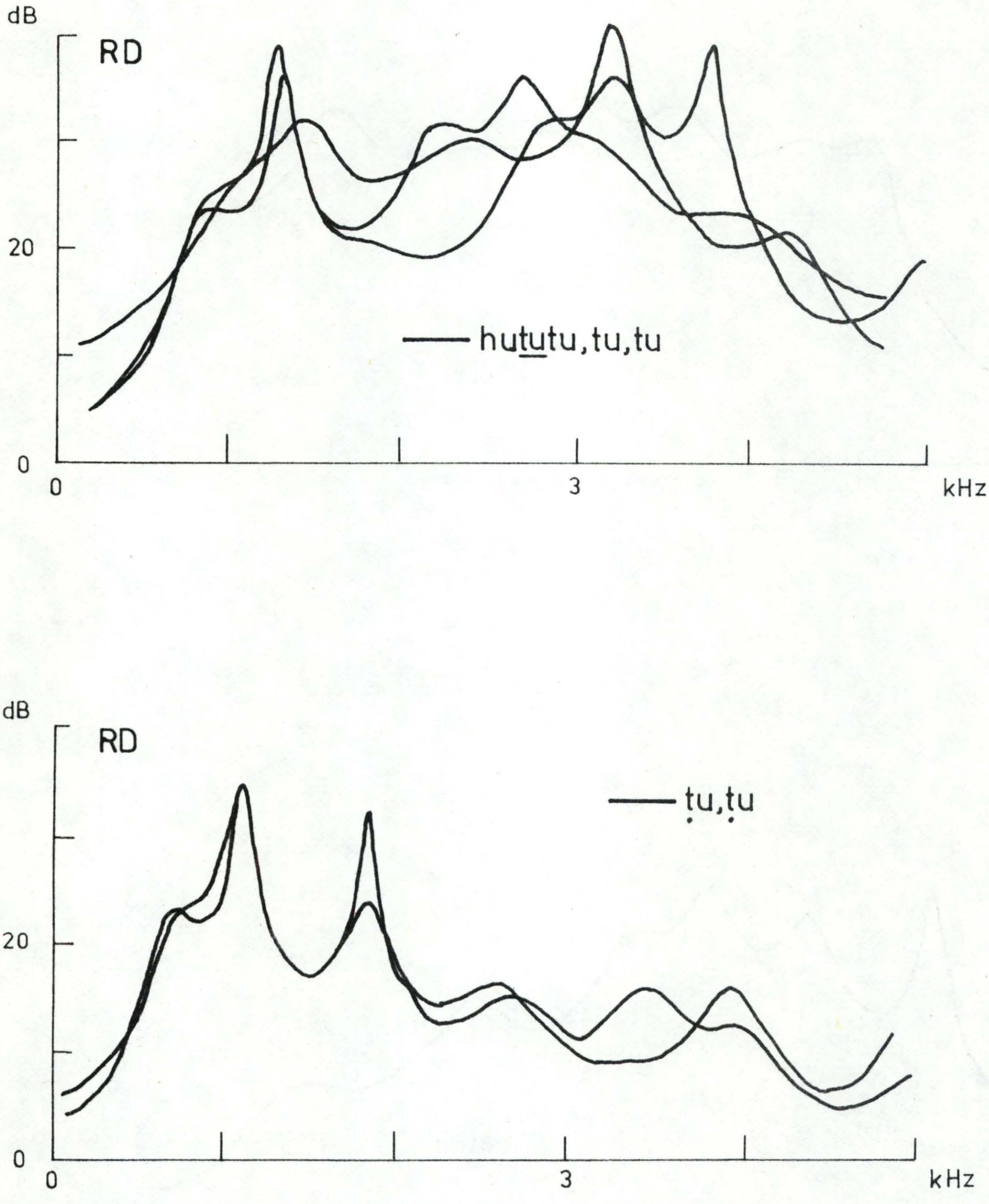

Figure 70

See legend to fig. 68.

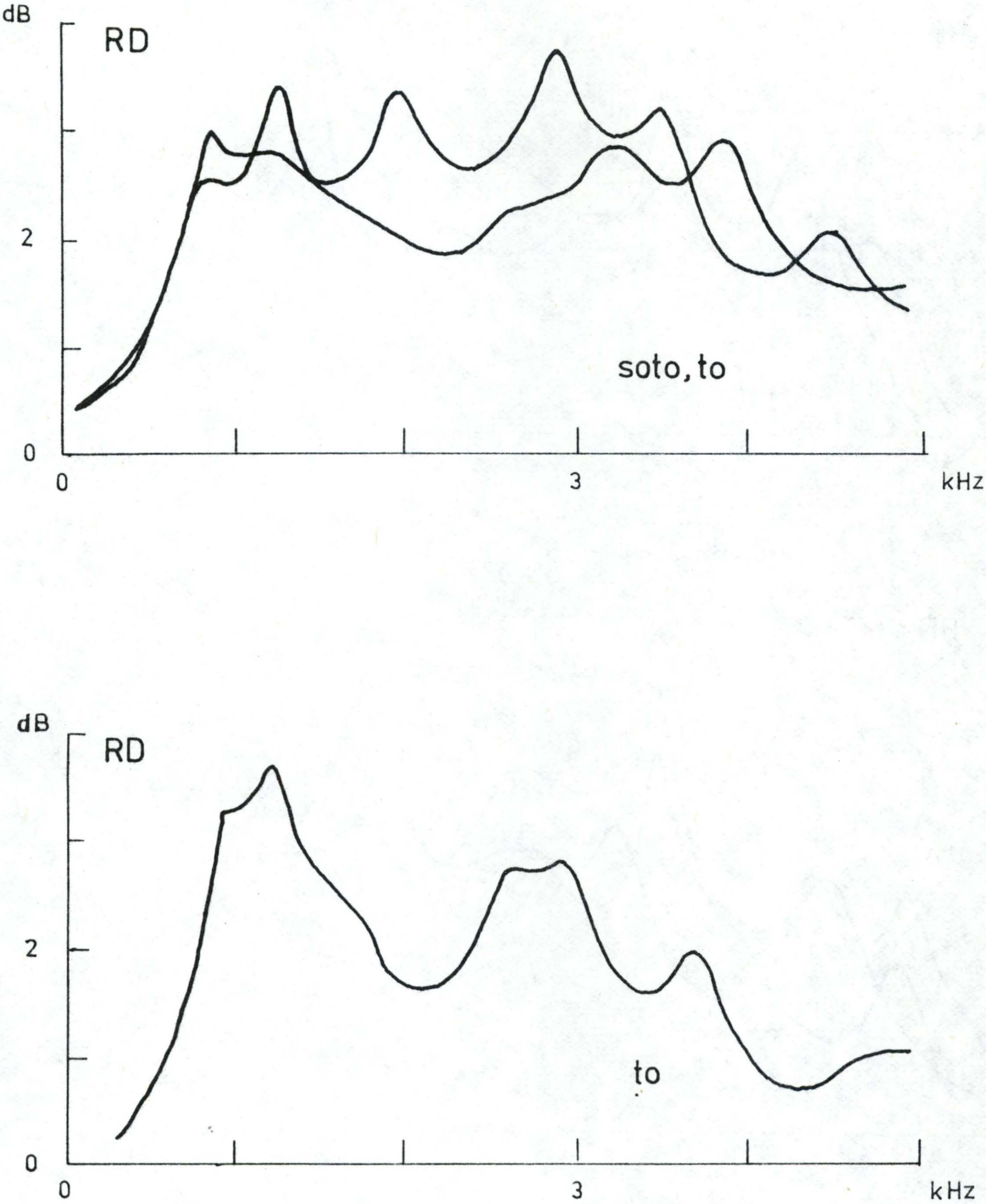

Figure 71

See legend to fig. 68.

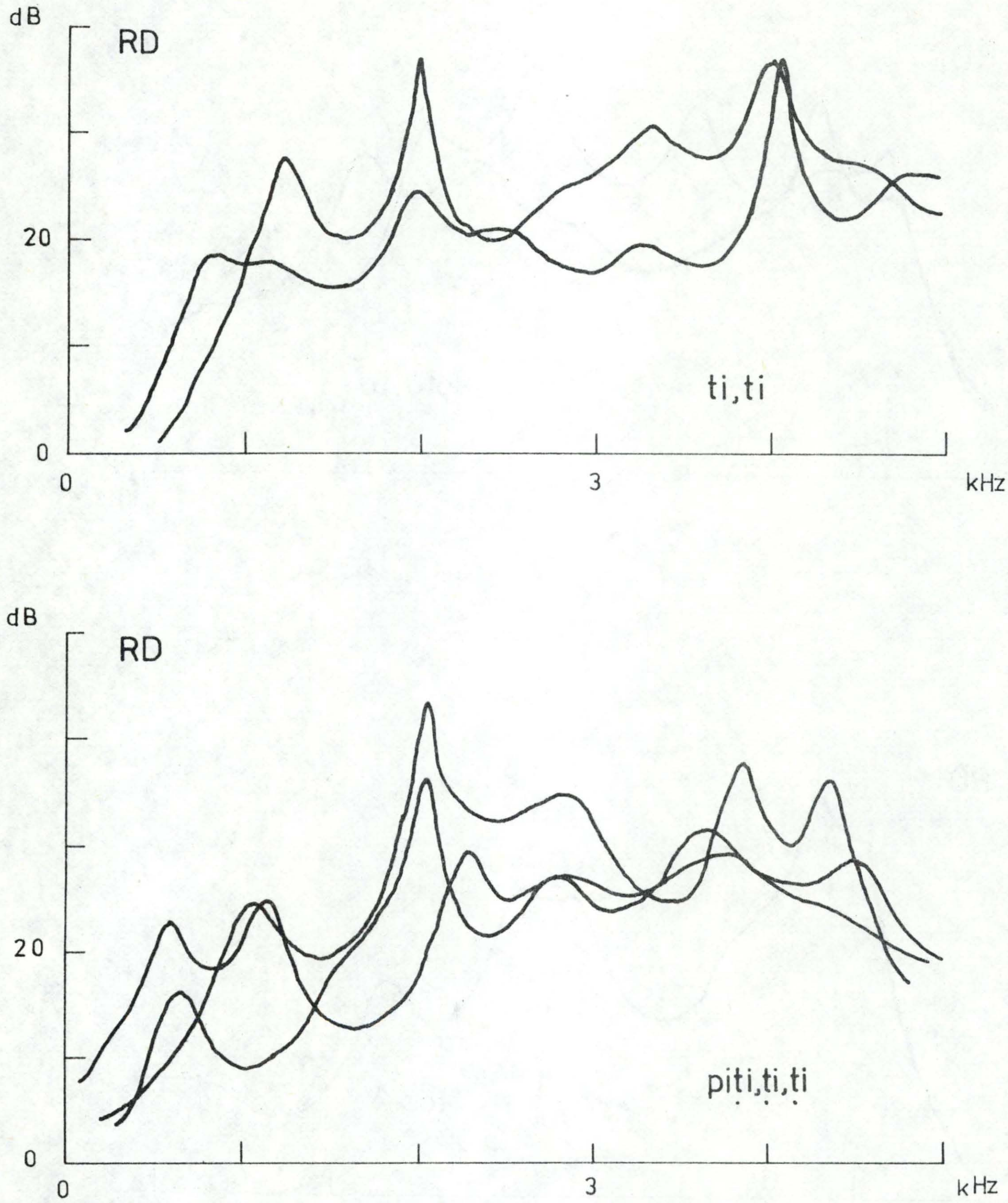

Figure 72

See legend to fig. 68.

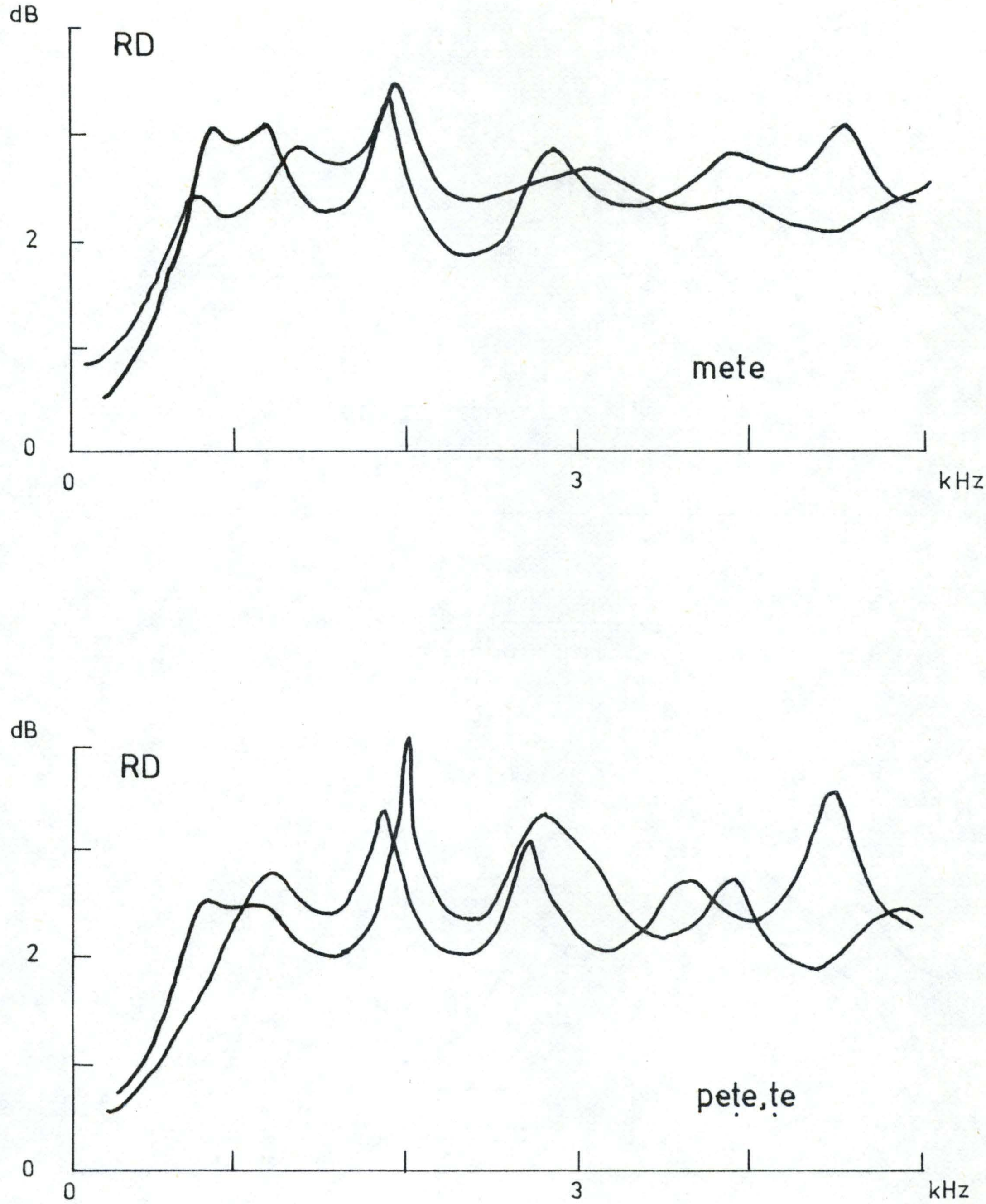

Figure 73
See legend to fig. 68.

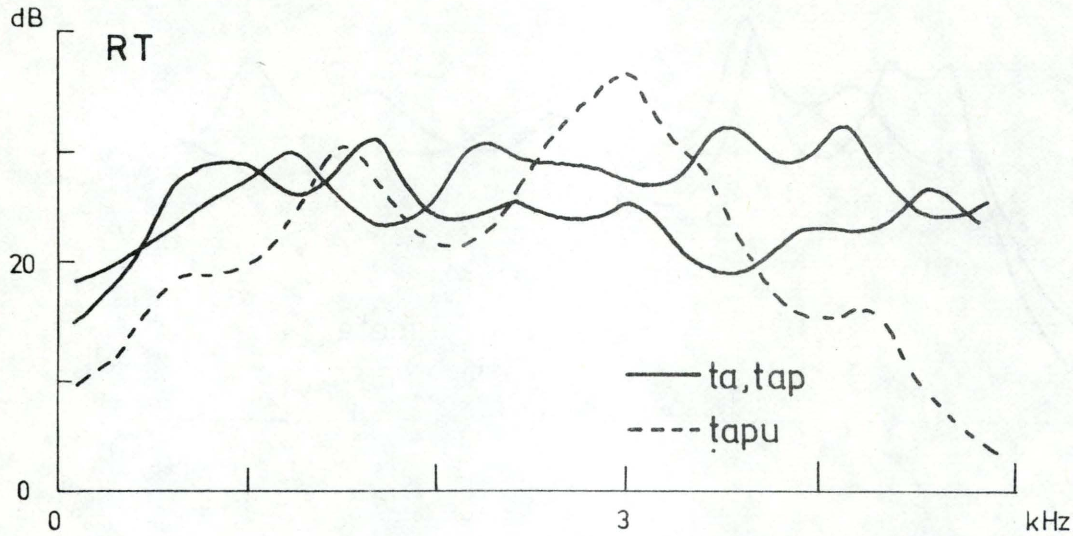

Figure 74
Burst spectra. Speaker RT.

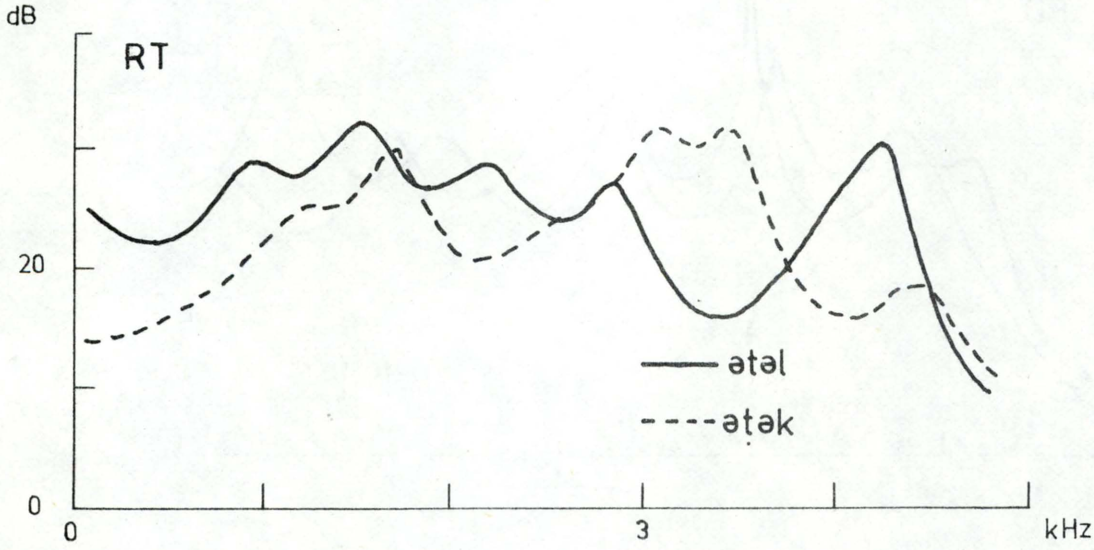

Figure 75
Burst spectra. Speaker RT.

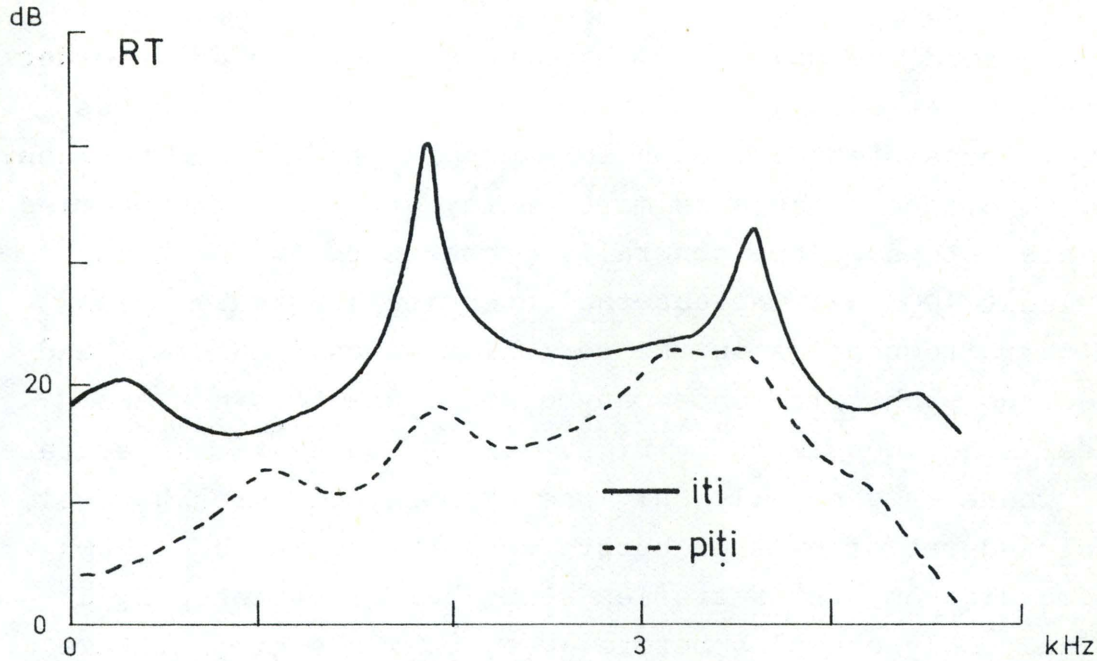

Figure 76
Burst spectra. Speaker RT.

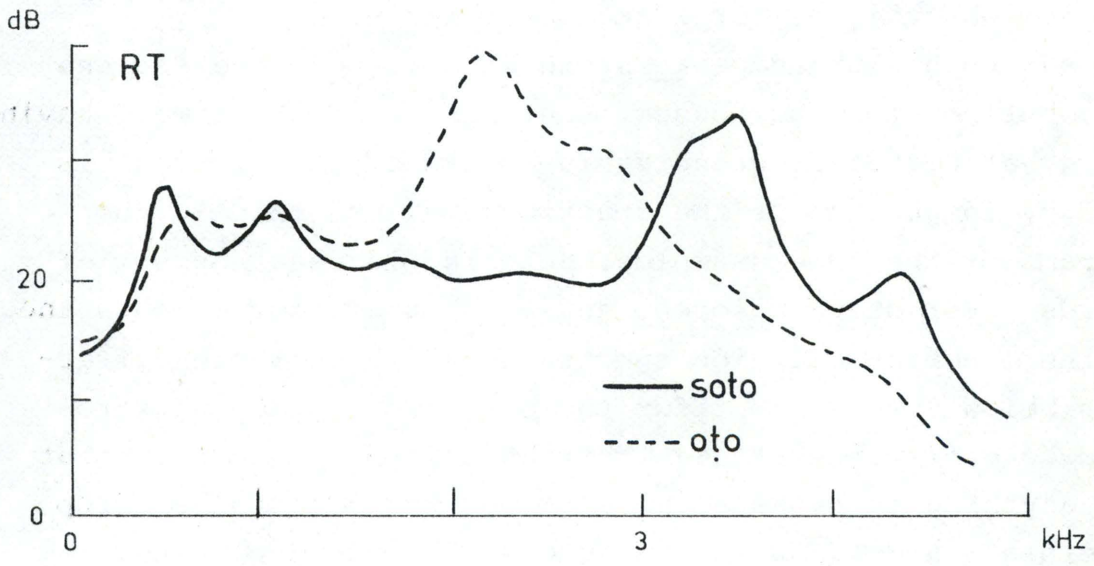

Figure 77
Burst spectra. Speaker RT.

point zero before the same vowel have been superimposed in order to show the variation. The differences between the two types are not very consistent although some general trends can be seen. Before a, u, o, and ə there is more energy at higher frequencies in the dental stops. They generally preserve their intensity up to at least 4000 Hz, whereas the intensity gradually falls off at higher frequencies in the retroflex stops. Before i and e, however, no such difference can be seen, and before a the difference is not consistent. Figs. 74-77 show similar spectra from RT. There is generally only one example before each vowel, and dental and retroflex stop bursts have therefore been shown in the same diagram, the retroflex stops being indicated by a dashed line. Only examples before a, ə, o, i are given (there was no pair before u, and before e it was not possible to distinguish the zero-curve from the other curves on the original picture). RT has a more consistent difference: the bursts of the retroflex consonants seem to have a rather broad peak around 3000 Hz, somewhat higher for i and lower for u.

RD has such a broad peak in one example before a and one before ə, but not in other cases. But RD's tendency toward having more energy at higher frequencies in bursts of dental stops is confirmed by inspection of the spectrograms, not only in the spectrograms of the same examples, but also in spectrograms of other words. For stops before o and u the spectrograms show the same as the linear prediction spectra because the whole difference lies below 5000 Hz, but for the other vowels the spectrograms show a difference at higher frequencies.[1] It is rare that there is anything to be seen above 4-5000 Hz in retroflex stop bursts before a and ə, but dental stops show energy around 5-6500 Hz and sometimes higher (see Fig. 78 showing the differences before ə). As for stops before the front vowels e and i, both may show some energy above 5000 Hz, but the retroflex stops have a concentration of energy from 2500-4500 Hz, whereas the

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1) This is not seen in the linear prediction spectra.

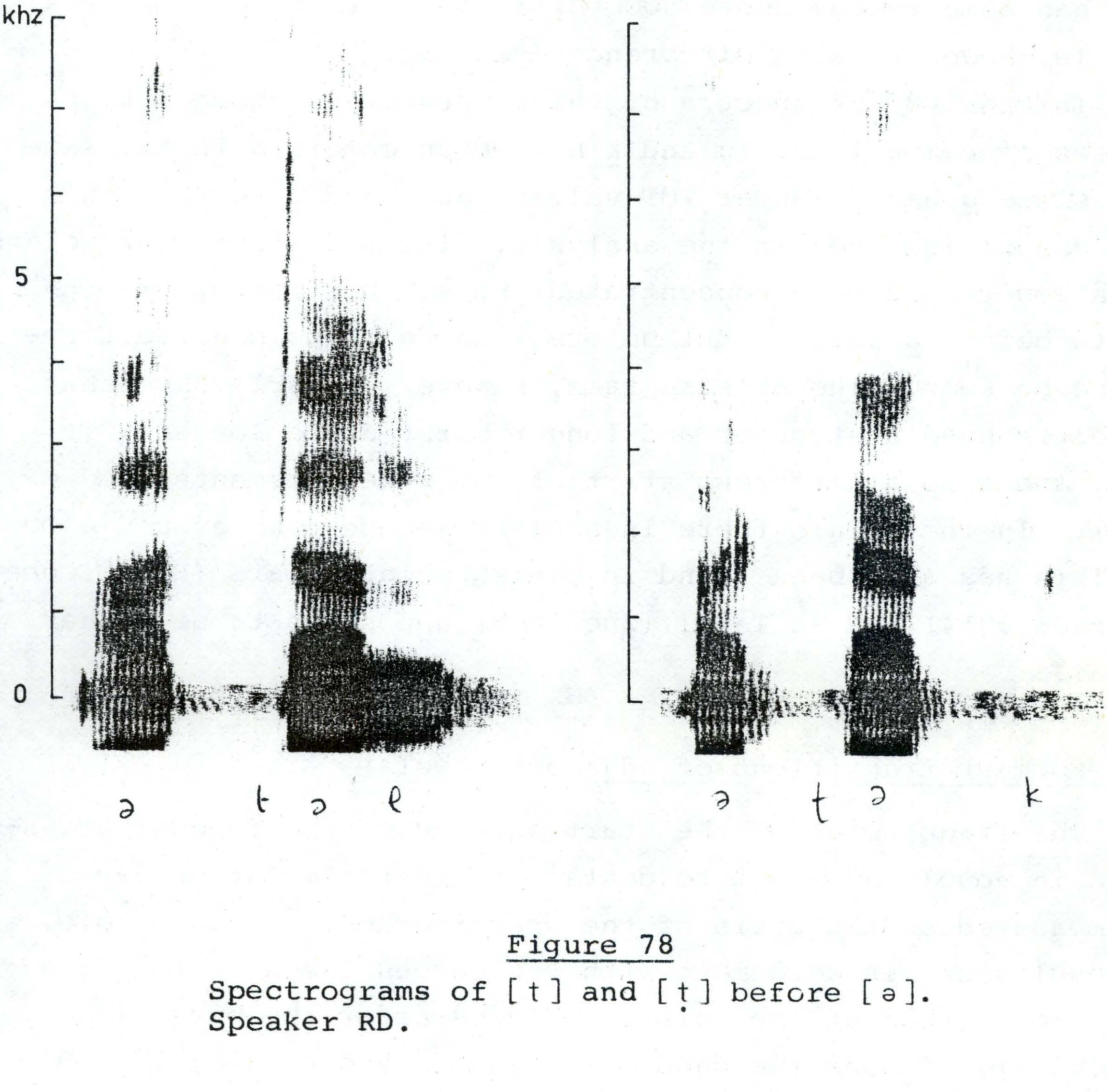


Figure 78

Spectrograms of [t] and [ṭ] before [ə].
Speaker RD.

dental stops have more energy at higher frequencies. This is very evident for e (Fig. 79). Before i both have high frequency noise but ti has less energy at the frequencies at which ṭi shows concentration of energy. These differences are rather consistent (see Fig. 80).

In RT's spectrograms the distinction is less clear; he often has some energy above 5000 Hz in the bursts in all cases; there is, however, some difference (see Fig. 81).

In Figs. 82-84 spectra of velar bursts are shown for purposes of comparison. g and k have been combined in the same graph since g has a longer VOT-value than b and d so that the burst can be isolated in the analysis. It is evident that velars have a lower (and more concentrated) burst than retroflex consonants before a and u. But before i there is no clear difference to be seen. The spectrograms, however, clearly show that the velars have a stronger and longer burst and a longer VOT value, and also a different start of the vowel formants (see below). In the velars there is a clear second peak around 4500 Hz. This has also been found in Danish palatovelars (Eli Fischer-Jørgensen 1954) and in Tamil (Zue 1976) and seems to be rather general.

C. Formant transitions of adjacent vowels

The frequencies of the start and end of the formant transitions in vowels adjacent to dental and retroflex stops have been measured on the basis of the spectrograms. On the whole, the results are in agreement with the curves taken by the linear prediction method at the points 10-15 ms after the burst (see above, 3.4). As was the case with liquids and nasals, only RD's spectrograms have been measured, but they have been compared with RT's spectrograms of list I-VII by visual inspection.

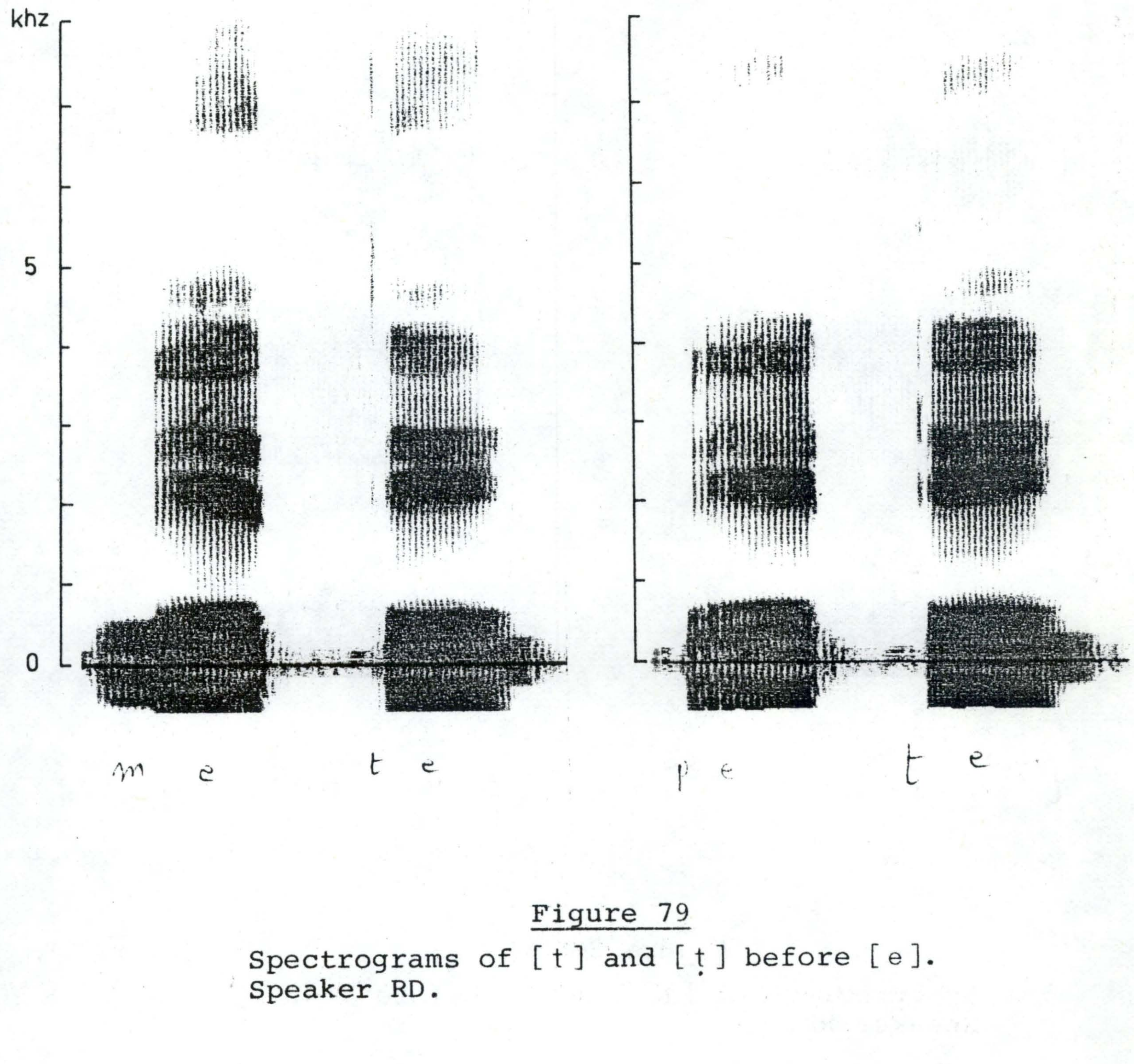


Figure 79

Spectrograms of [t] and [ṭ] before [e].
Speaker RD.

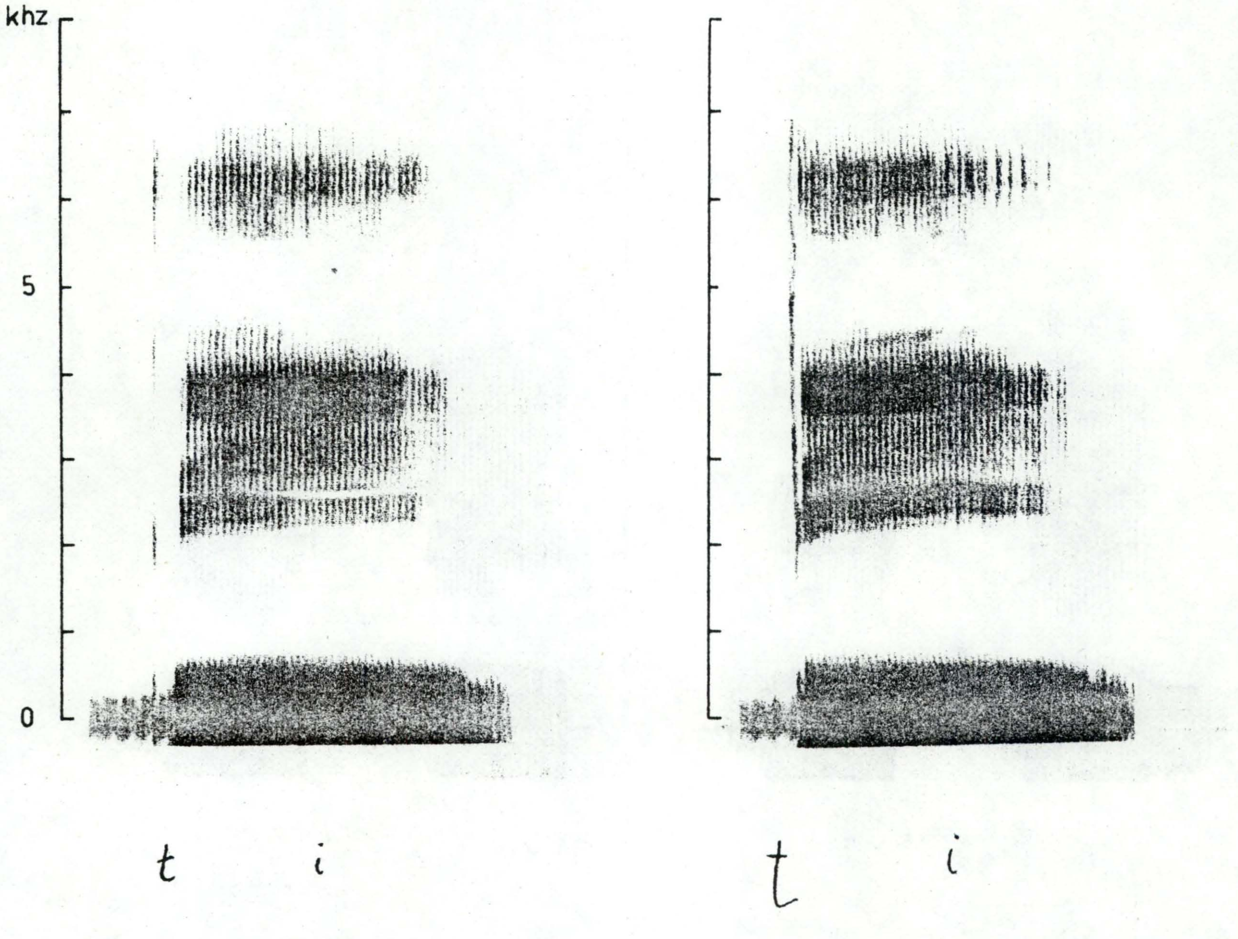


Figure 80

Spectrograms of [t] and [ṭ] before [i].
Speaker RD.

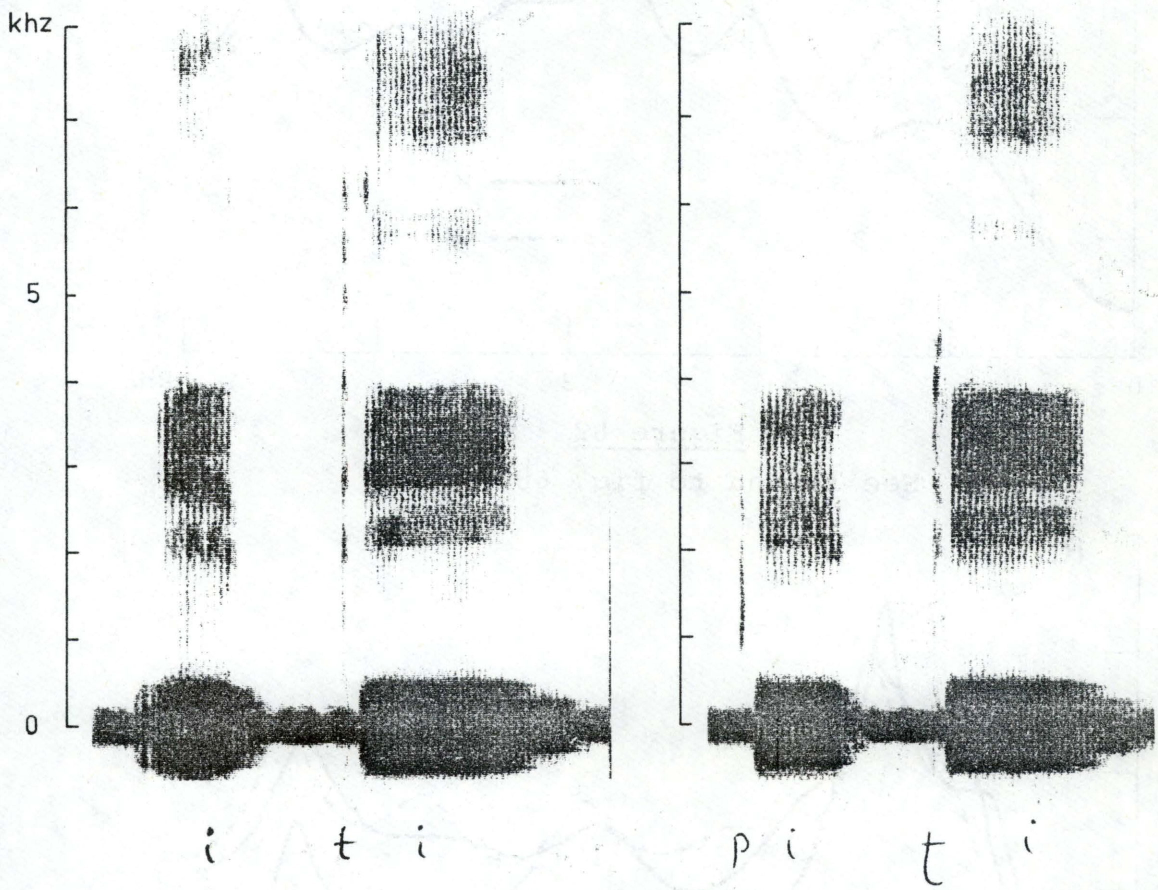


Figure 81
Spectrograms of [t] and [ṭ] before [i].
Speaker RT.

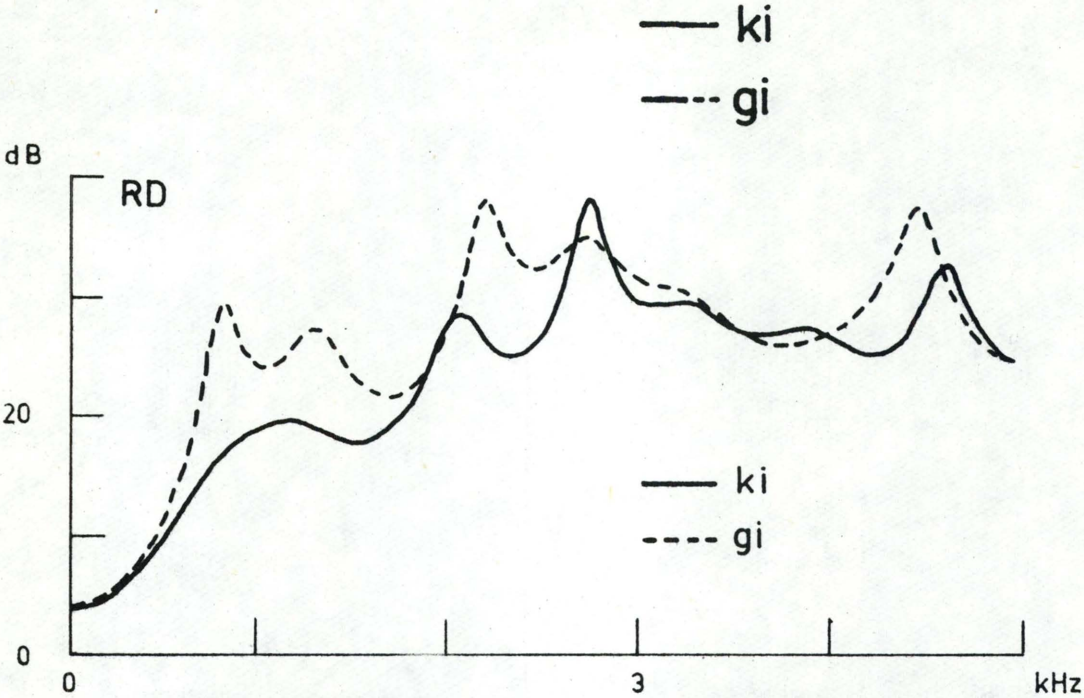


Figure 82

See legend to fig. 68.

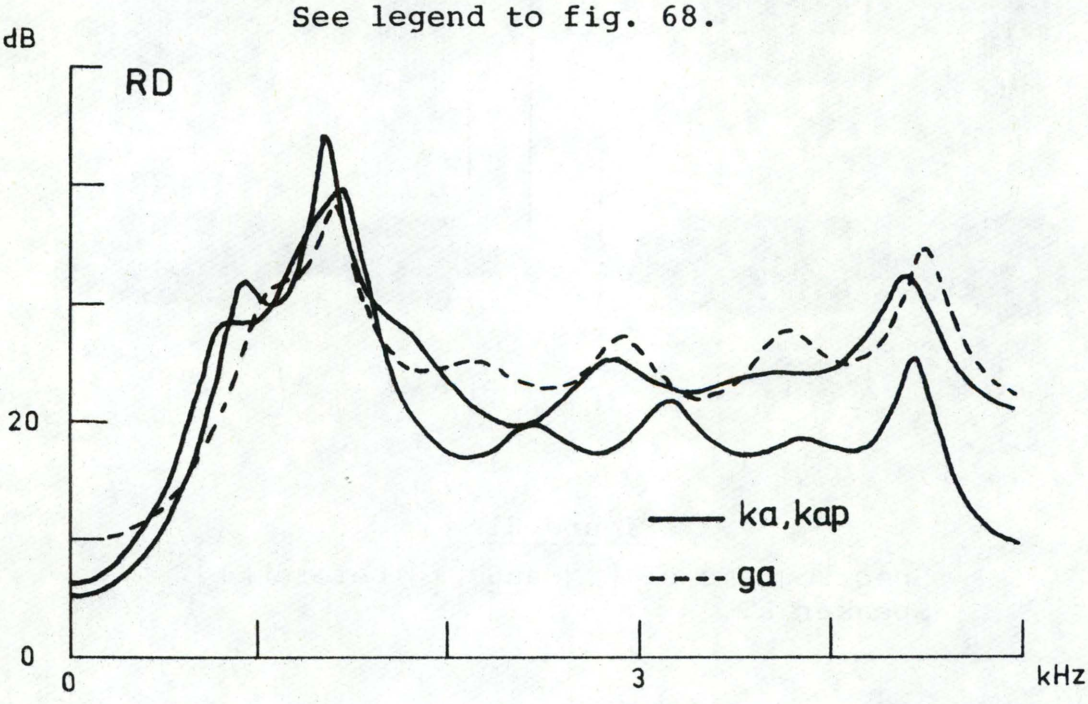


Figure 83

See legend to fig. 68.

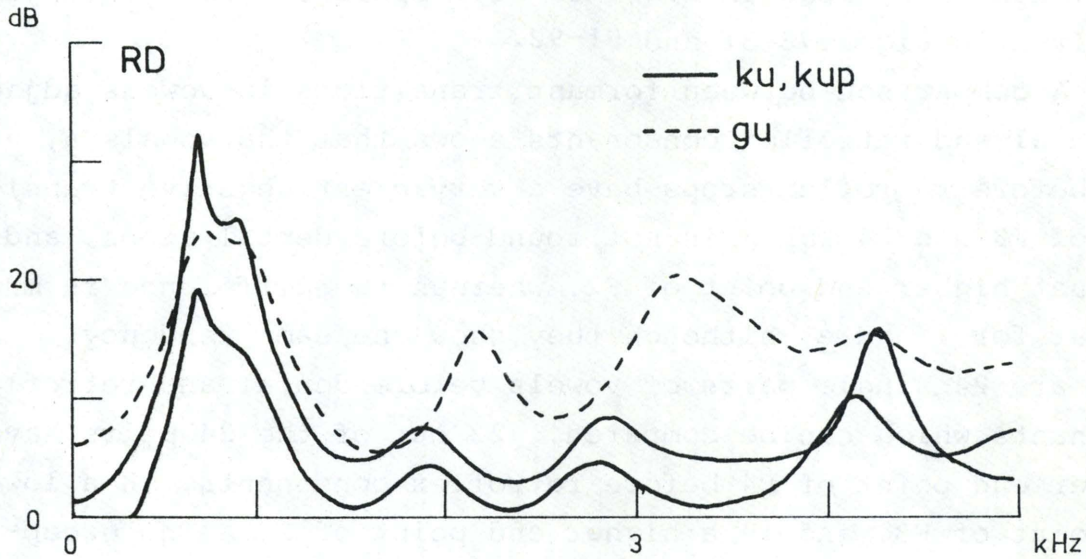


Figure 84

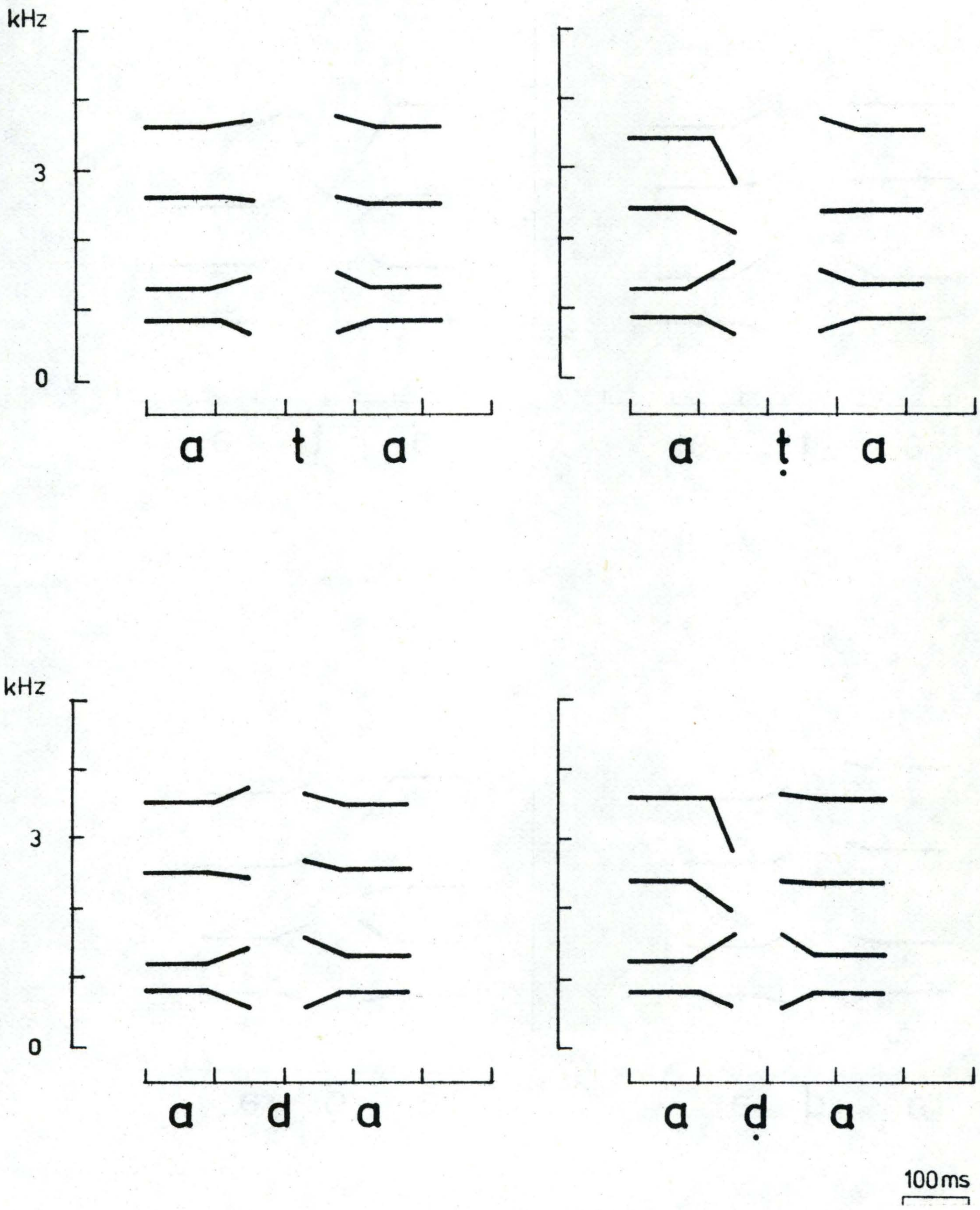
See legend to fig. 68.

The frequencies and extent of the transitions are given in tables 4-9 of the Appendix, and schematic drawings of the transitions are found in Figs. 85-90. Specimens of spectrograms are given in Figs. 78-81 and 91-92.

A comparison between formant transitions in vowels adjacent to dental and retroflex consonants shows that the vowels a, ə, u, o before retroflex stops have a very clear negative transition of F3 and F4 which is not found before dental stops, and a somewhat higher end point of F2, whereas the difference is much smaller for i and e, although they show the same tendency. There are 24 single pairs of vowels before dental and retroflex consonants which can be compared. 22 out of the 24 pairs have a lower end point of F4 before retroflex consonants, 18 a lower end point of F3, and 19 a higher end point of F2. The exceptions for F4 are oḍ and iḍ, for F3 all six examples of i and e, and for F2 uḍ and uṭ. The differences are highly significant for all the vowels taken in one group, but it is evident that the exceptions concerning e and i are systematic. They have negative transitions of F3 like the others, but the transitions do not go as far down. In one case (eḍ) the transition of F3 even goes up, but there was only one example, and in this case the following vowel was not e but i, and the positive transition of F3 is due to coarticulation with the following i, so this figure is misleading.

The lowering of F3 and F4 also affects the steady state frequency of the preceding vowels. This is true in 10 out of 12 averages for both F3 and F4, and this is also valid for e and i. The exceptions for F3 are oṭ and iṭ, for F4 aḍ and oḍ.

The vowels following dental and retroflex consonants do not show any consistent differences except that o has a lower F4 after retroflex consonants, and a a significantly lower F3 and a higher F2 after retroflex consonants.



<u>Figure 85</u>

Schematized spectrograms. Speaker RD.

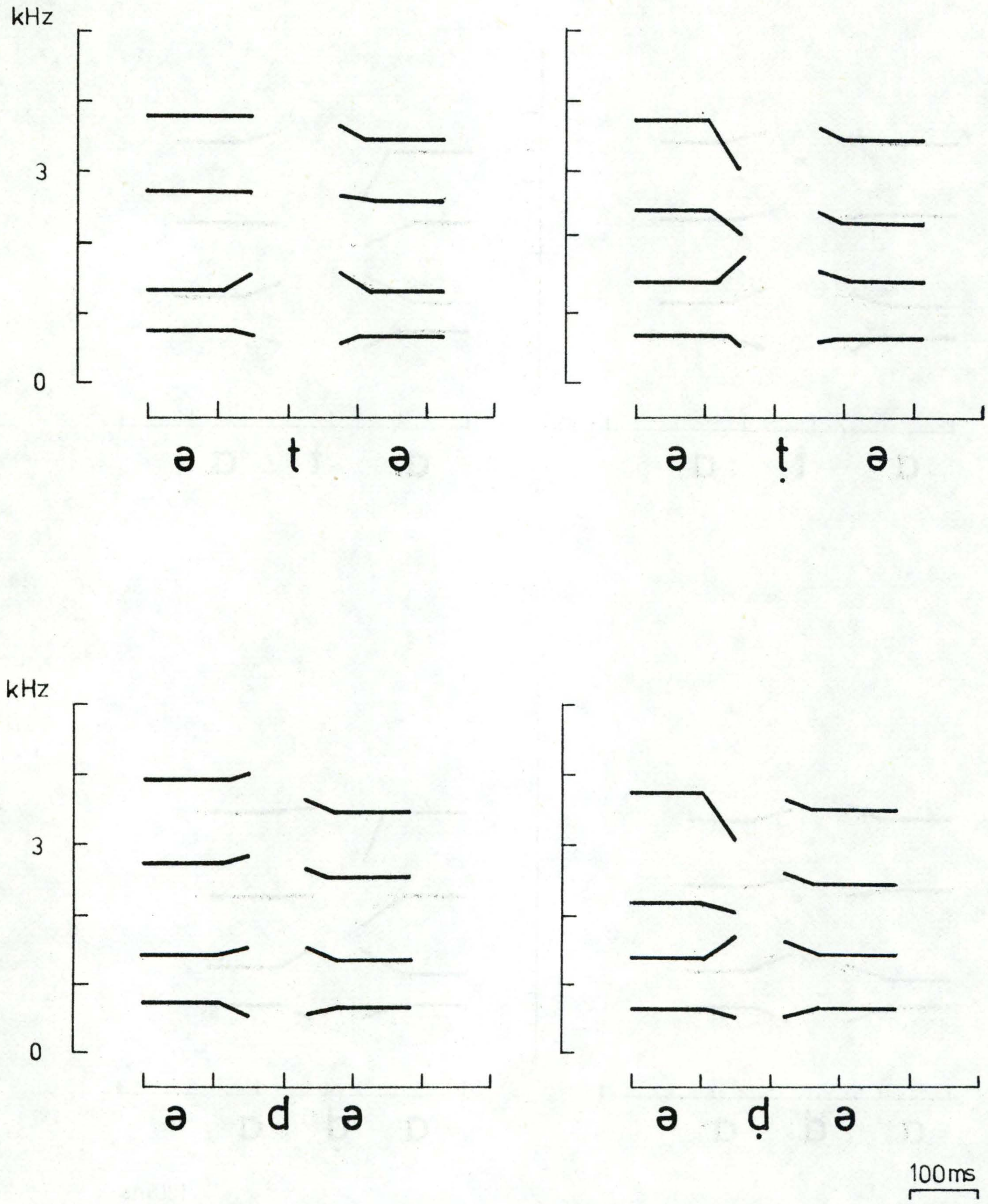


Figure 86

Schematized spectrograms. Speaker RD.

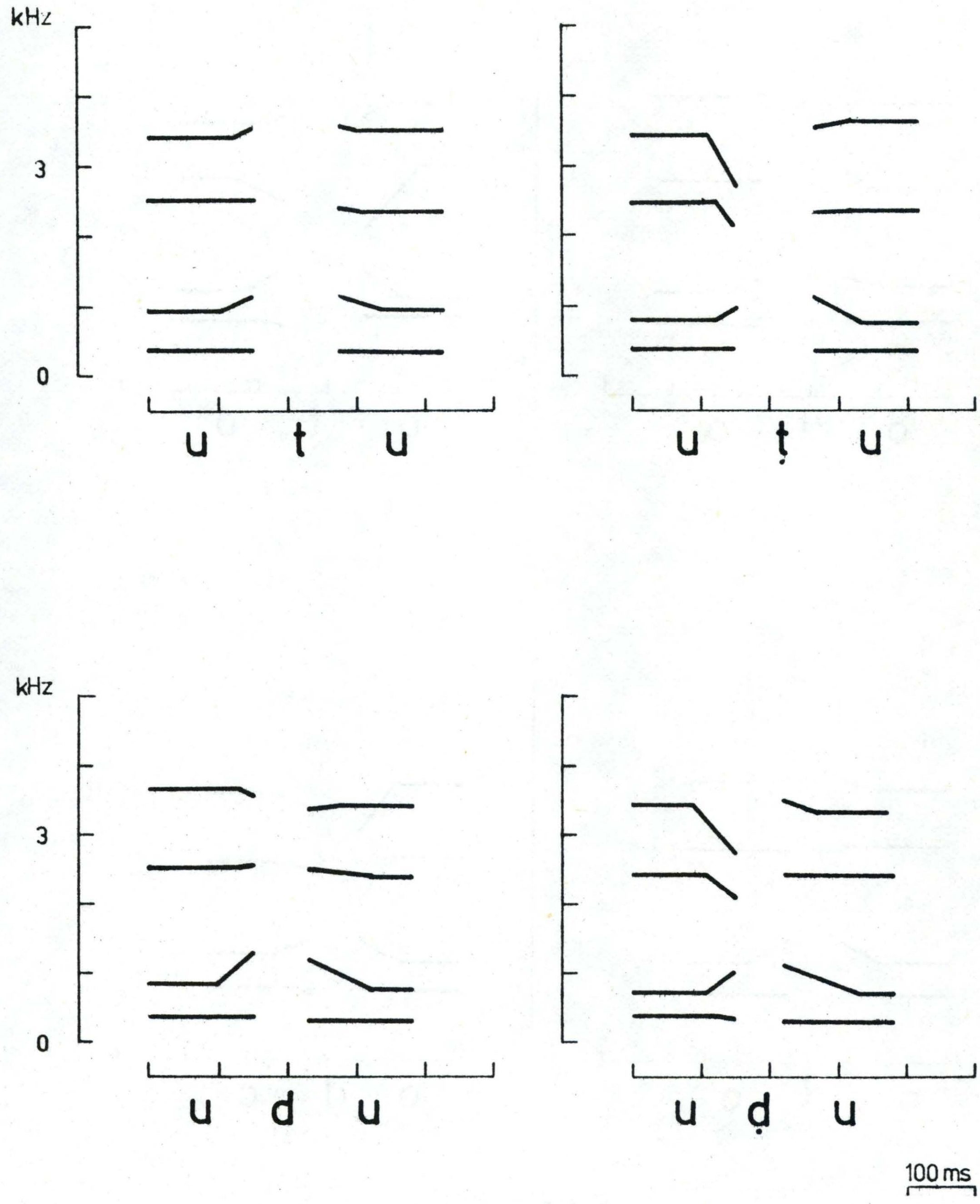


Figure 87

Schematized spectrograms. Speaker RD.

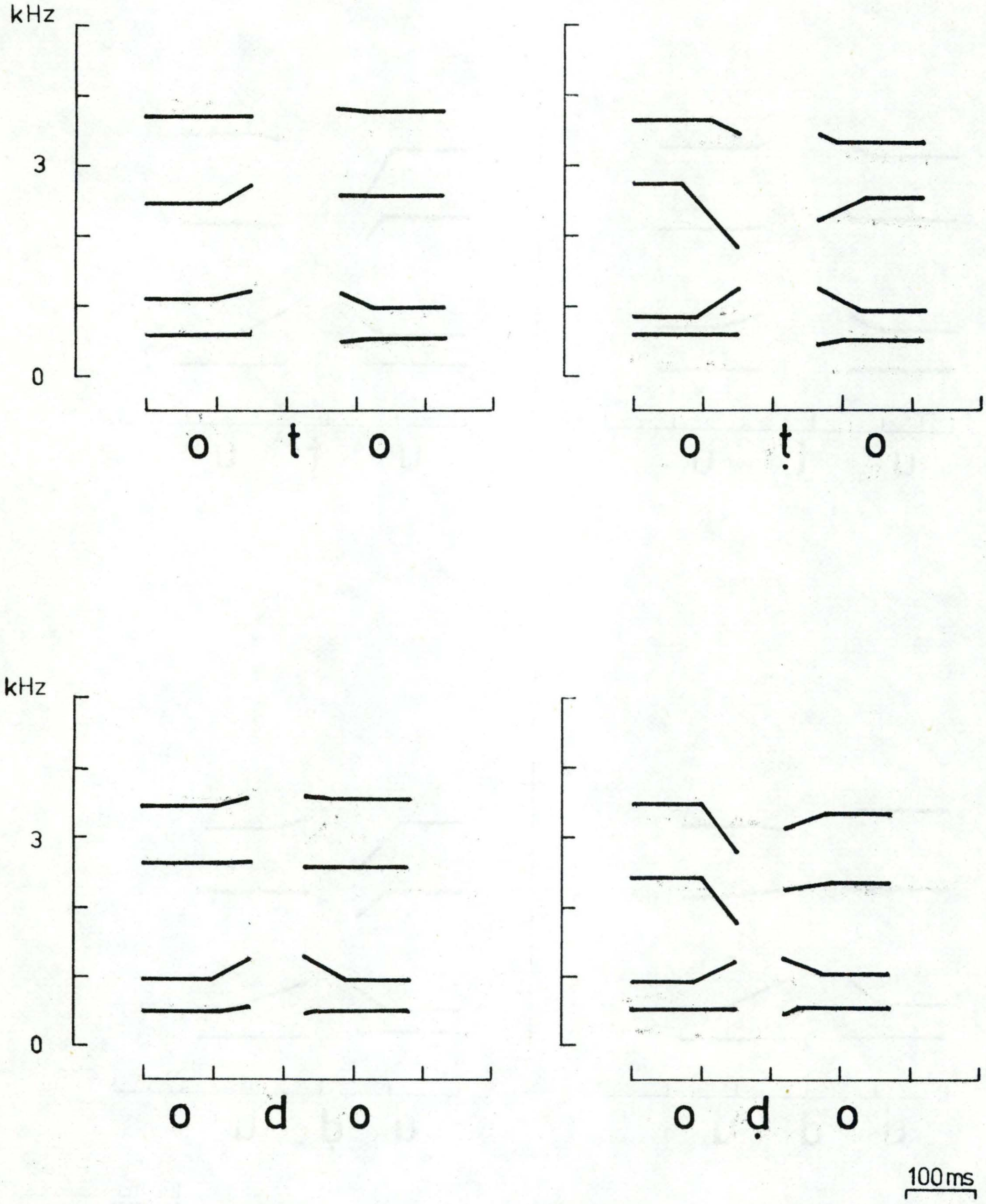


Figure 88

Schematized spectrograms. Speaker RD.

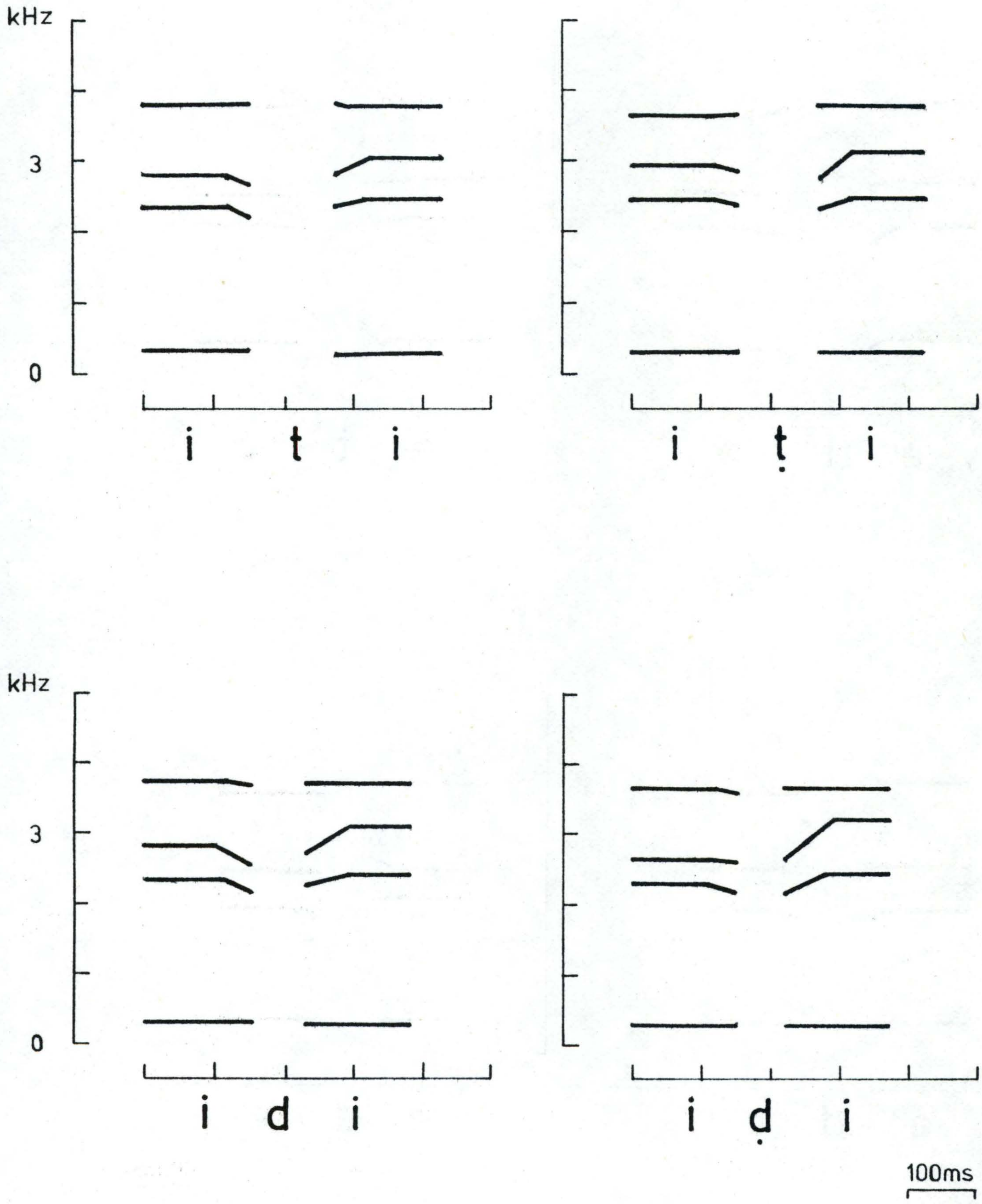


Figure 89

Schematized spectrograms. Speaker RD.

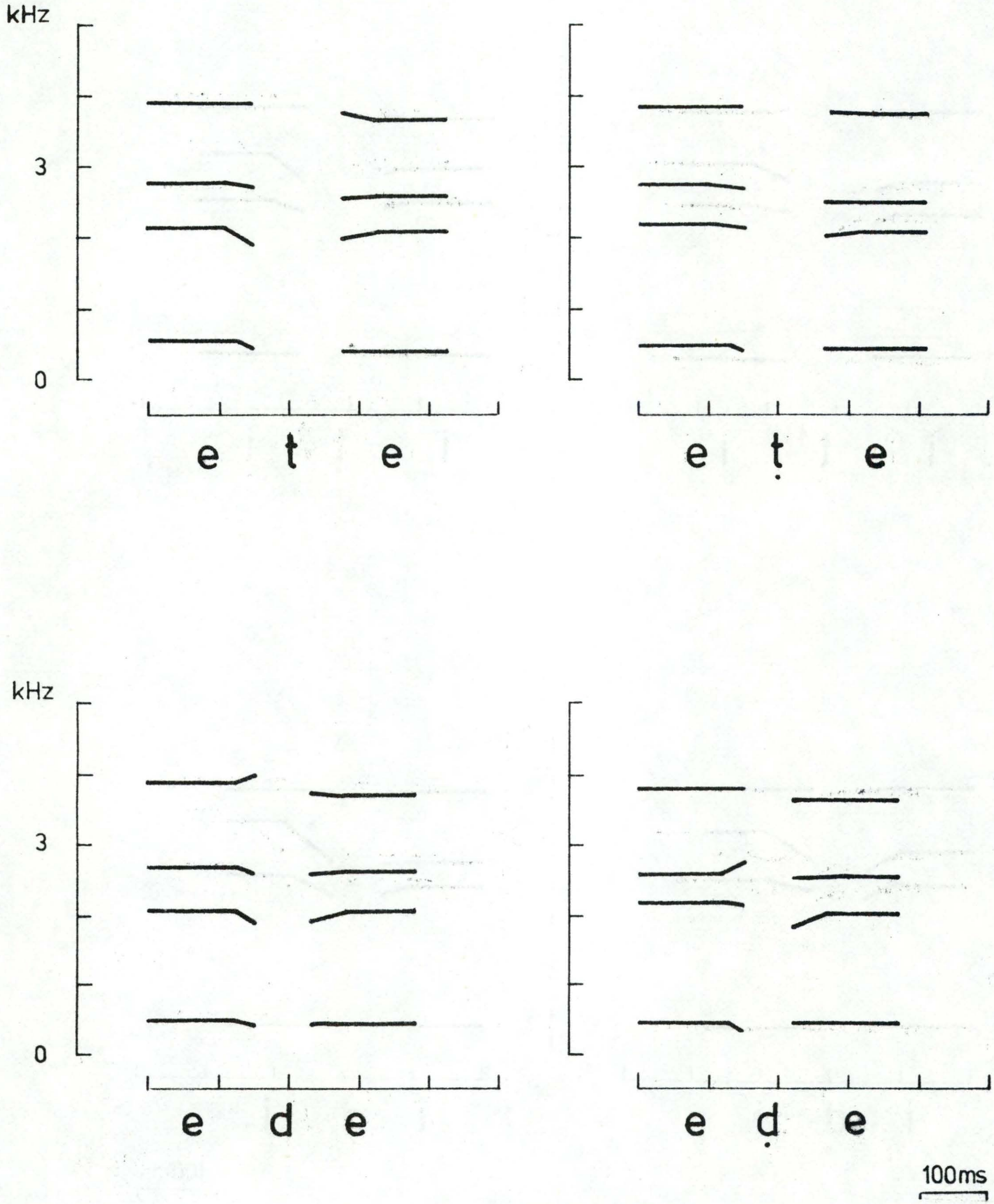


Figure 90

Schematized spectrograms. Speaker RD.

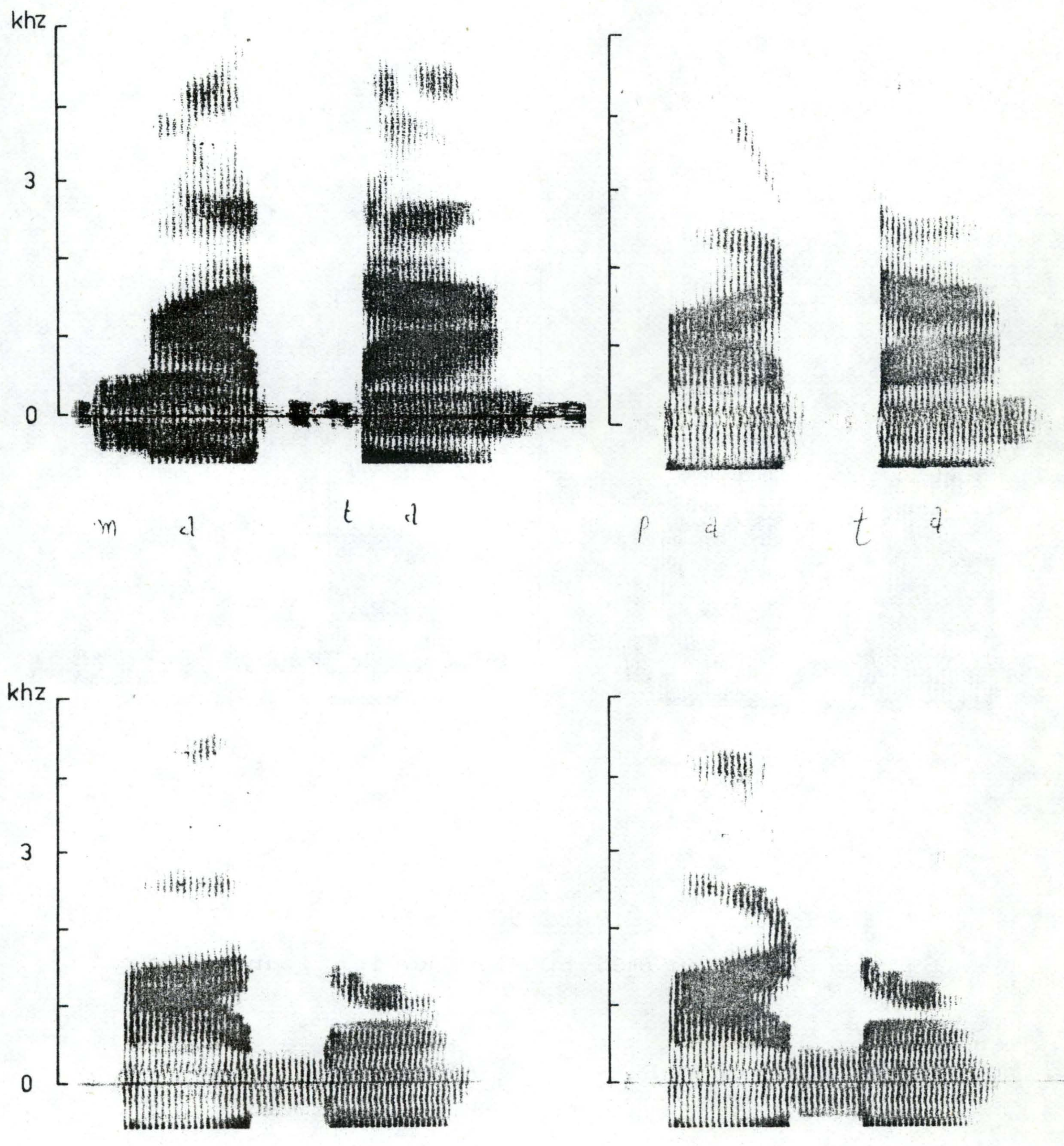


Figure 91

Sample spectrograms. Speaker RD.

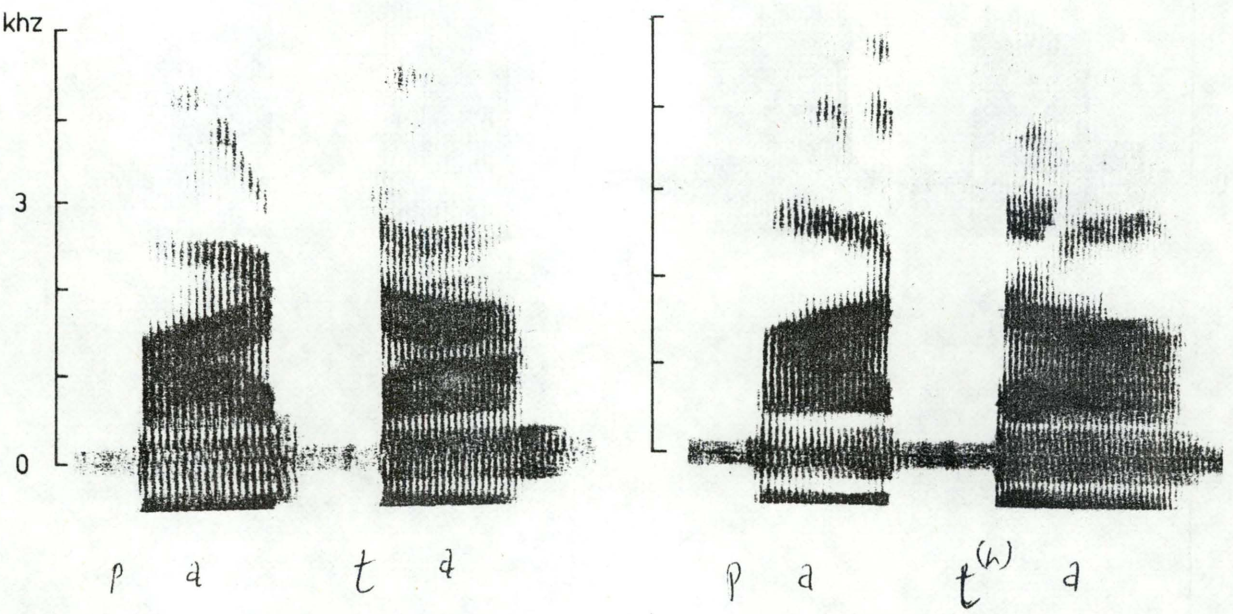


Figure 92
Sample spectrograms. Speaker RD left, and RT right.

In Figs. 93-95 the average transitions of the formants of preceding vowels have been set up in a graph showing how the formants of different vowels converge.

For F2 it is possible to set up a locus with tolerable precision. It is evidently higher before retroflex consonants than before dental consonants. If we take the average between the two end points of the falling and rising transitions which are closest together, those of e and ə, the result is 1672 and 1737 Hz for the dentals t and d, respectively, and 1950 and 1958 for the retroflex stops ṭ and ḍ, respectively. If we extrapolate from the direction of the close transitions of e and ə they will meet at approximately 50 ms distance, as they should according to the Haskins experiments (but the other vowels won't, and they should not be expected to, either, in real speech). This method gives 1700 for dentals, and 2000 and 2200 for ṭ and ḍ, respectively. Thus it can be said that there is a locus around 1700 Hz for dentals, and around 2100 Hz for retroflex stops.

As for F3 and F4, the transitions are not as regular, and it can only be said that an F3 locus for dental t and d must be somewhat below 3000 Hz, approximately at 2700 Hz, which is in good agreement with what has been found earlier. As for F4, it could be somewhat above 3500 Hz, but this is rather guesswork.

F3 and F4 in retroflex consonants, on the other hand, do not point to a definite frequency, but simply go steeply downward, except for e and i which show very little influence at all (e before ḍ goes upwards which is due to coarticulation with a following i, as mentioned above). The lowest point reached by the F3 transitions is 1800 Hz, and that reached by the F4 transitions is 2750 Hz.

RT's spectrograms show quite similar transitions of F3 in retroflex consonants, but he rarely has any transition of F4 (see Fig. 92).

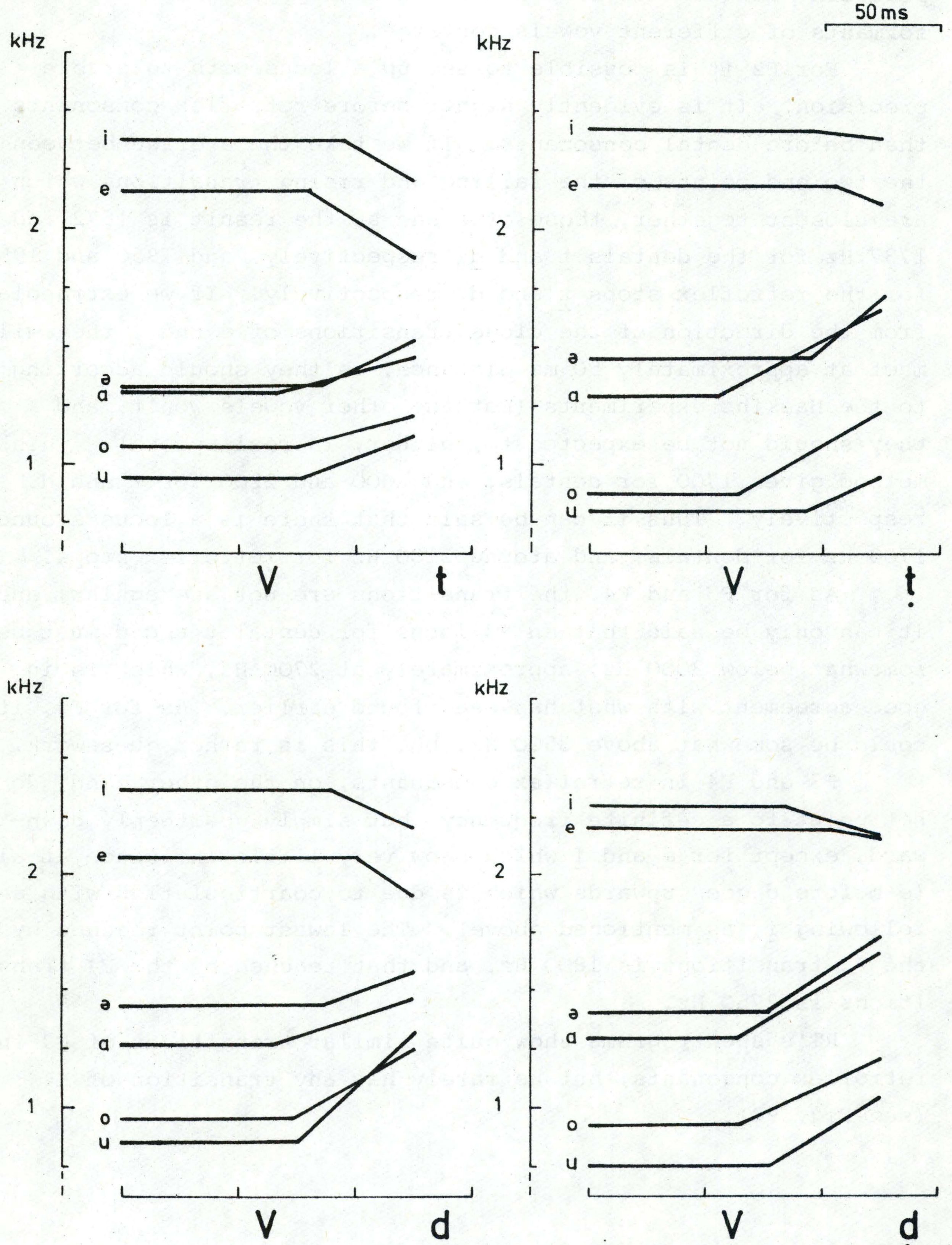


Figure 93

Schematized F_2 movements. Speaker RD.

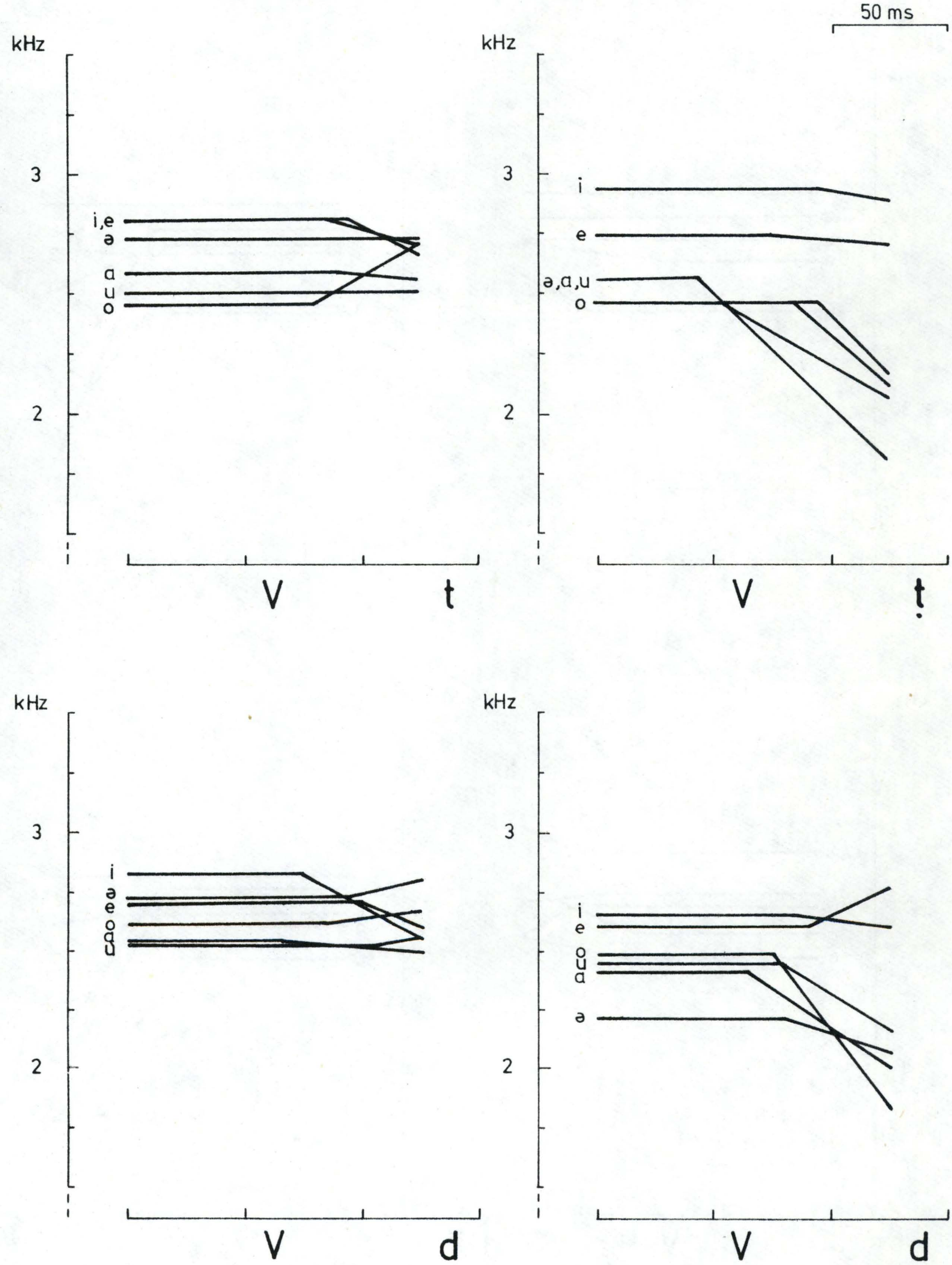
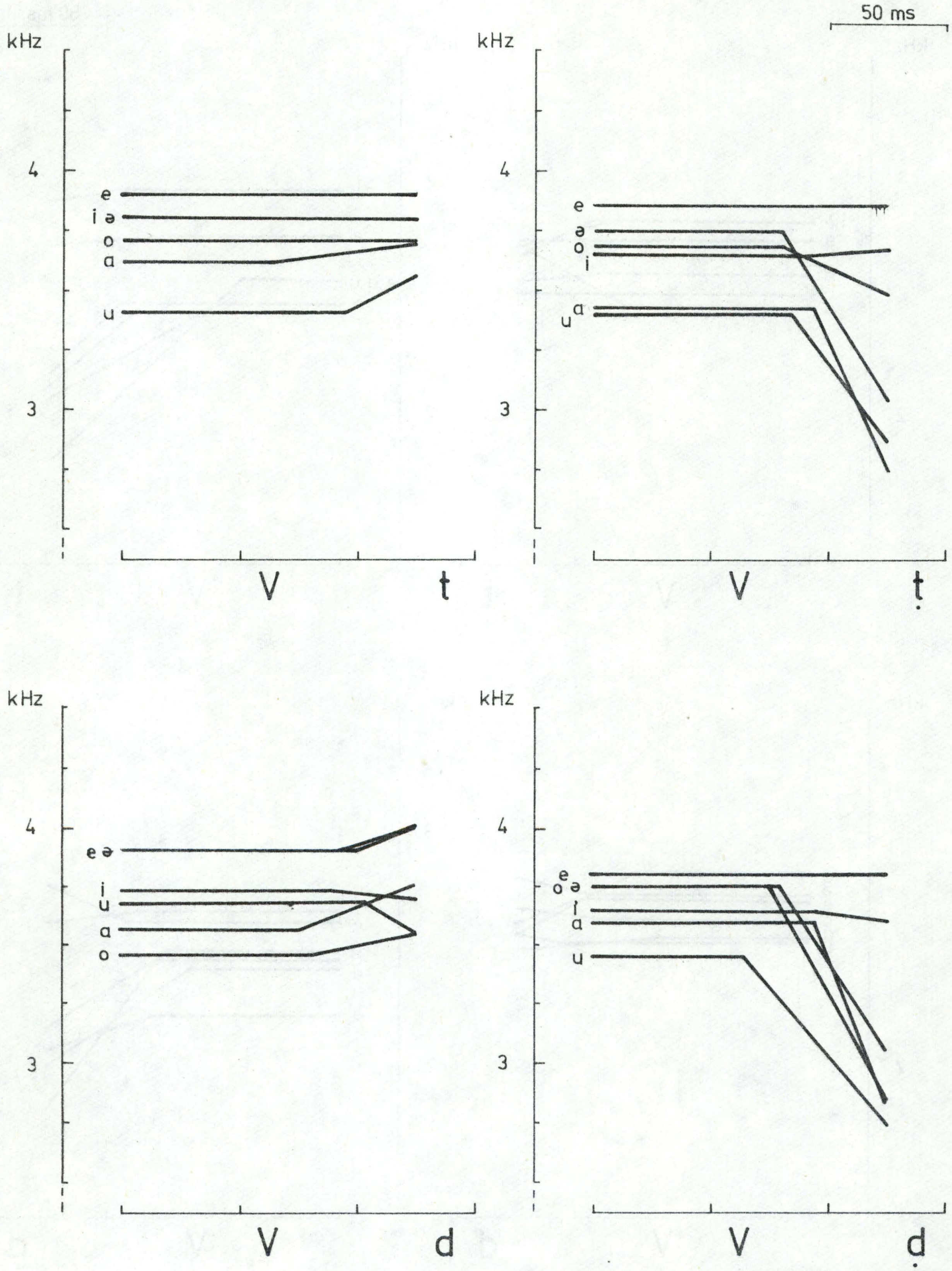


Figure 94

Schematized F_3 movements. Speaker RD.



<u>Figure 95</u>

Schematized F_4 movements. Speaker RD.

D. Comparison with formant transitions adjacent to other stop consonants

List IX, spoken by RD only, also contains examples of labial, palatal, and velar stops before the six vowels (in connection with a there are also examples after the vowel). Measurements of vowel transitions after these consonants were made for the purpose of comparing them with the transitions after dental and retroflex consonants. This comparison was interesting, particularly because Stevens and Blumstein (1975) have shown that retroflex and velar consonants before a can be synthesized with the same transitions (but with different bursts).

The material is rather restricted. There are examples of all vowels following labial, velar, and palatal stops, but normally only one example of each, so that the results should be taken with some reservations. As for preceding vowels, the material comprises a + p b k g, ə+g, and i+k. The tables containing the frequencies of transitions with these consonants have been left out here (they are found in the thesis), but schematic diagrams of the transitions are given in Figs. 96-101. The curves are arranged so that they can be compared with Figs. 85-90 containing dental and retroflex stops.

A comparison between Fig. 85 and Fig. 96 shows that there is a high degree of similarity between the transitions of the vowel a following a velar consonant and a following dental or retroflex consonant. As for a preceding a, the transitions of F2 and F3 are very much alike for velars and for retroflex stops, but F4 has a clearly different transition. There is also similarity between the formant transitions of ə before retroflex and velar consonants, but in the case of a preceding ə there is a clear difference not only in F4, but also in F2 and F3. As for the other vowels, the material comprised only CV syllables with velars (except ik). In these cases there is a difference in F2, which has a positive transition in u and o after retroflex stops but a level transition after a velar stop, whereas i and e have negative F2-transition after a retroflex stop, but rising or level transition after a velar stop. Thus the similarity in

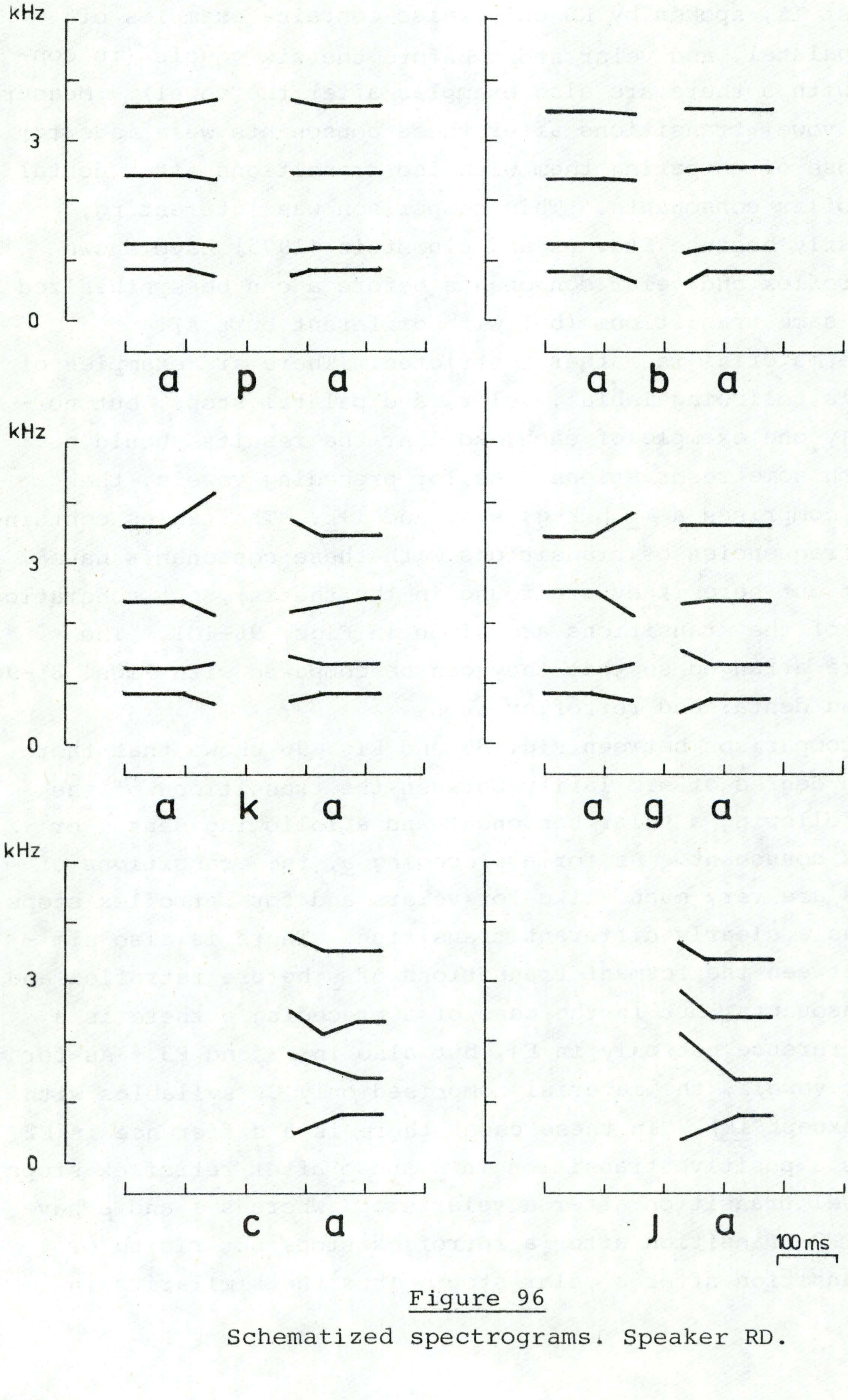


Figure 96

Schematized spectrograms. Speaker RD.

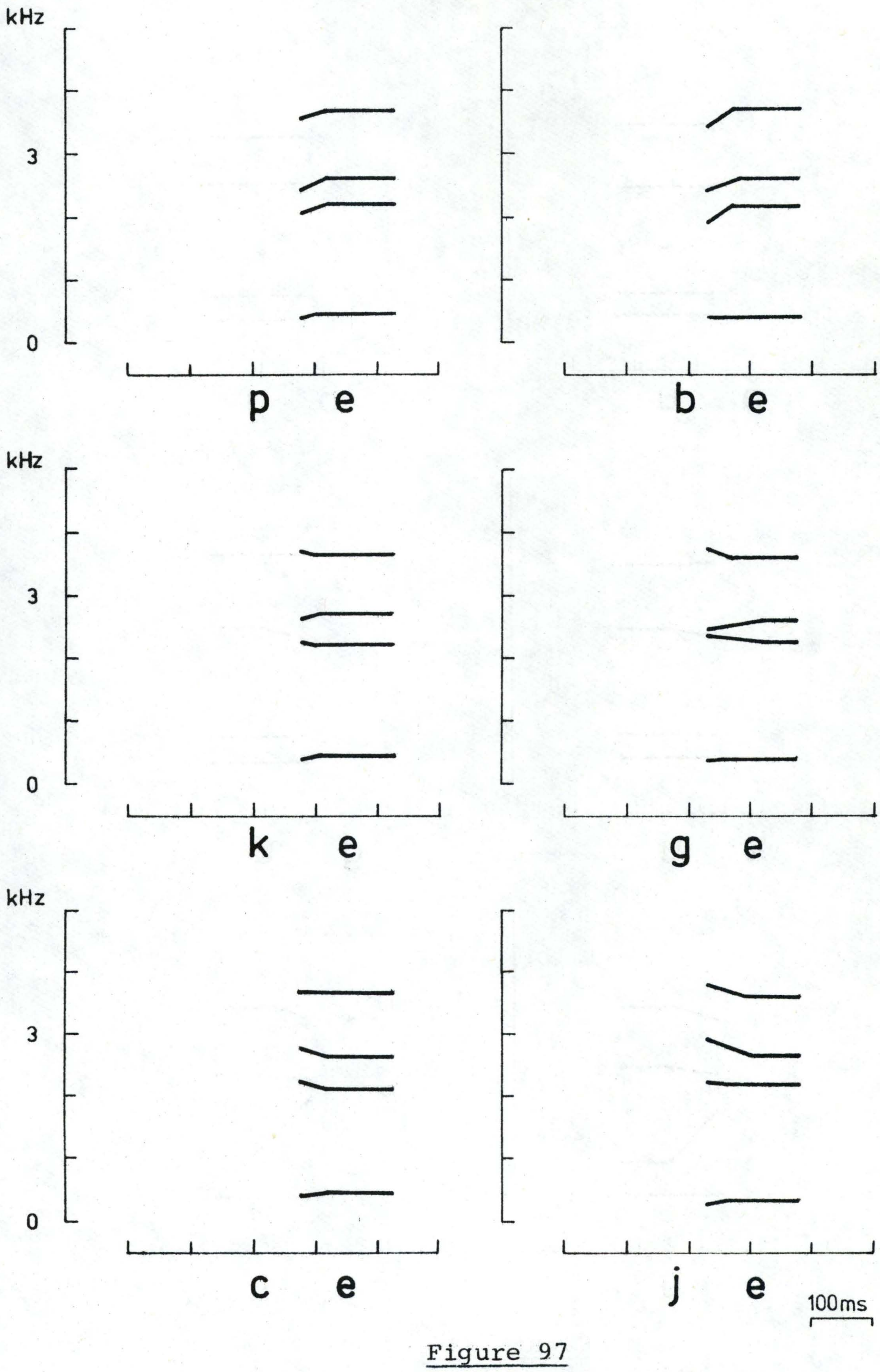


Figure 97

Schematized spectrograms. Speaker RD.

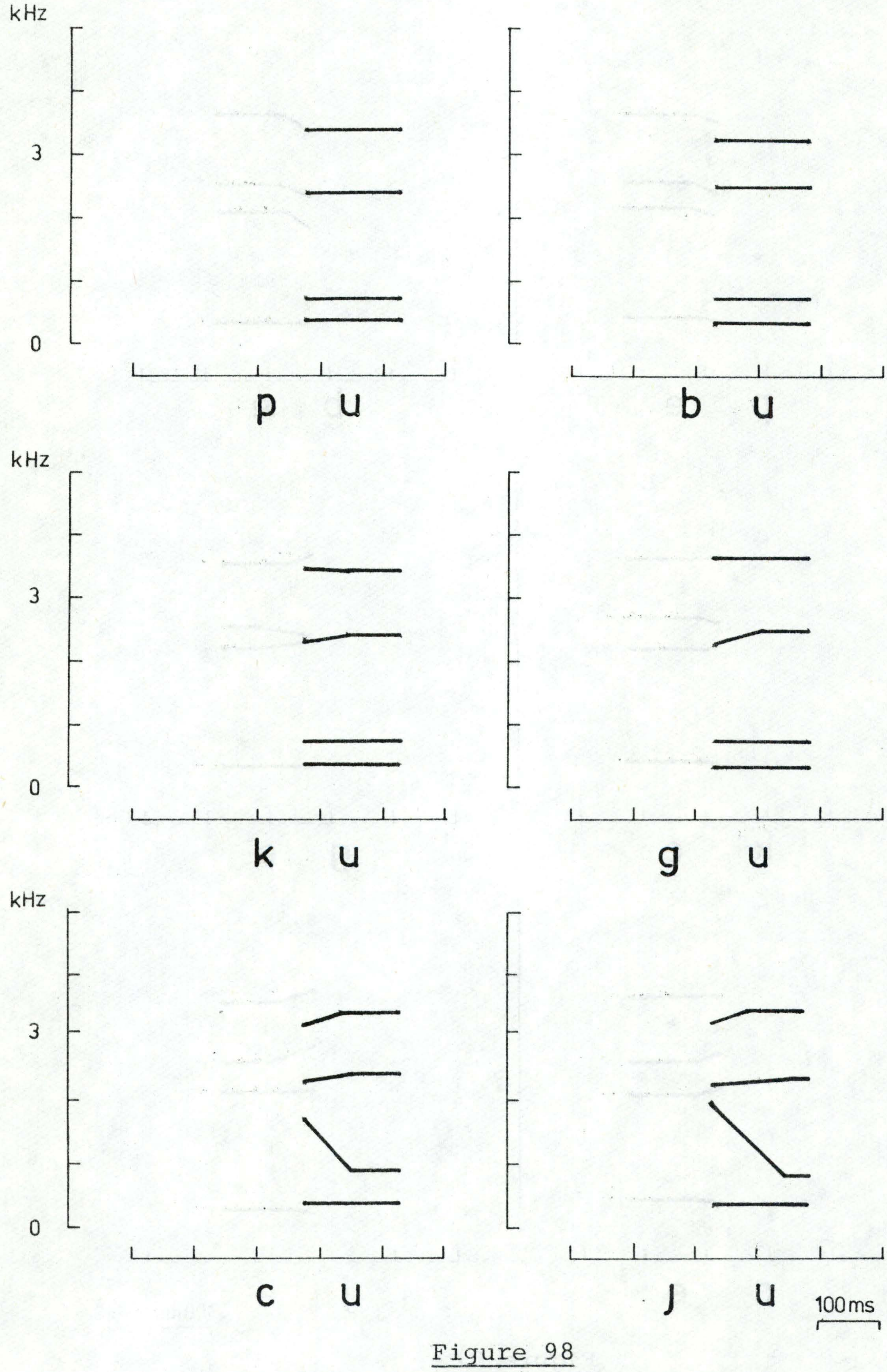


Figure 98

Schematized spectrograms. Speaker RD.

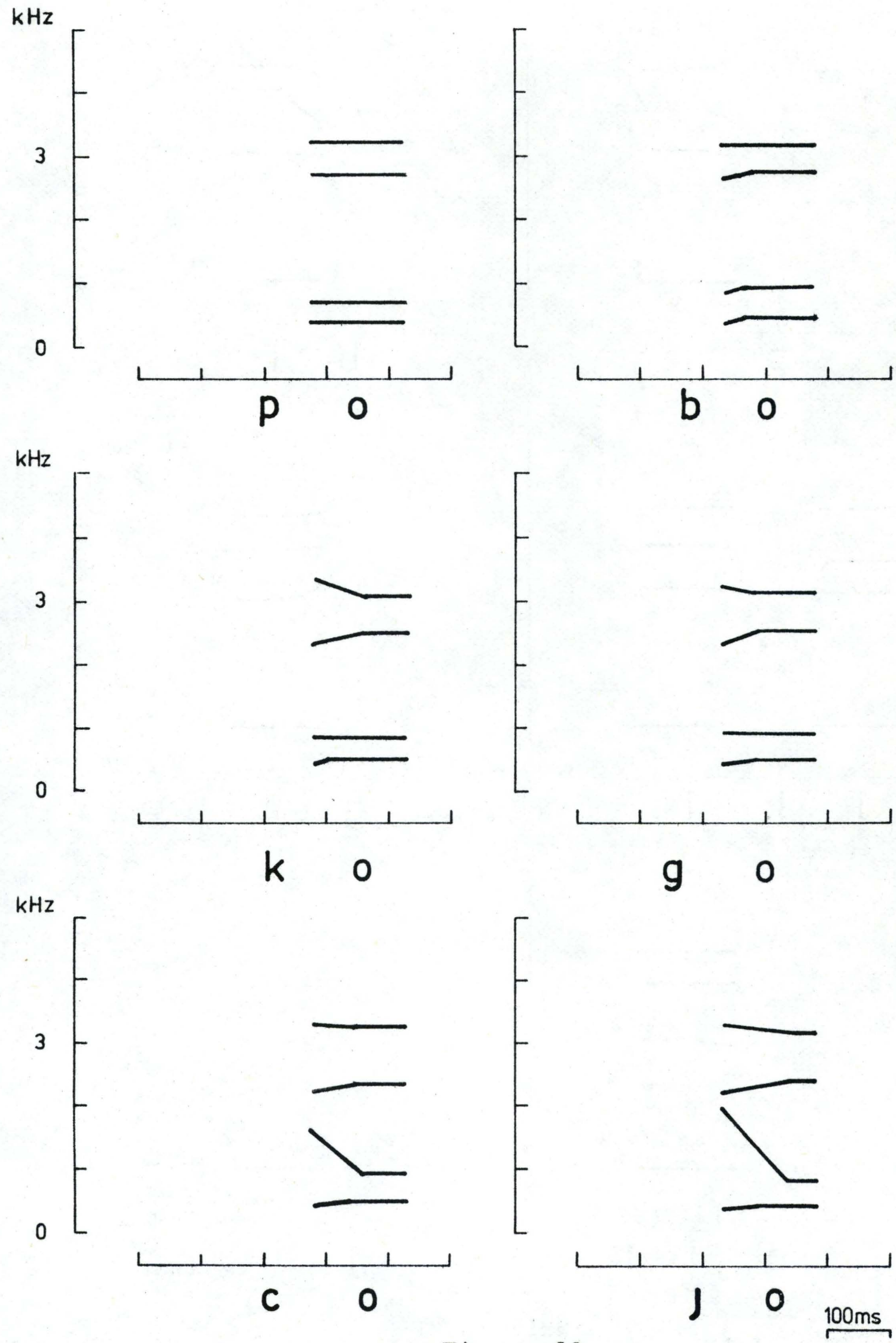


Figure 99

Schematized spectrograms. Speaker RD.

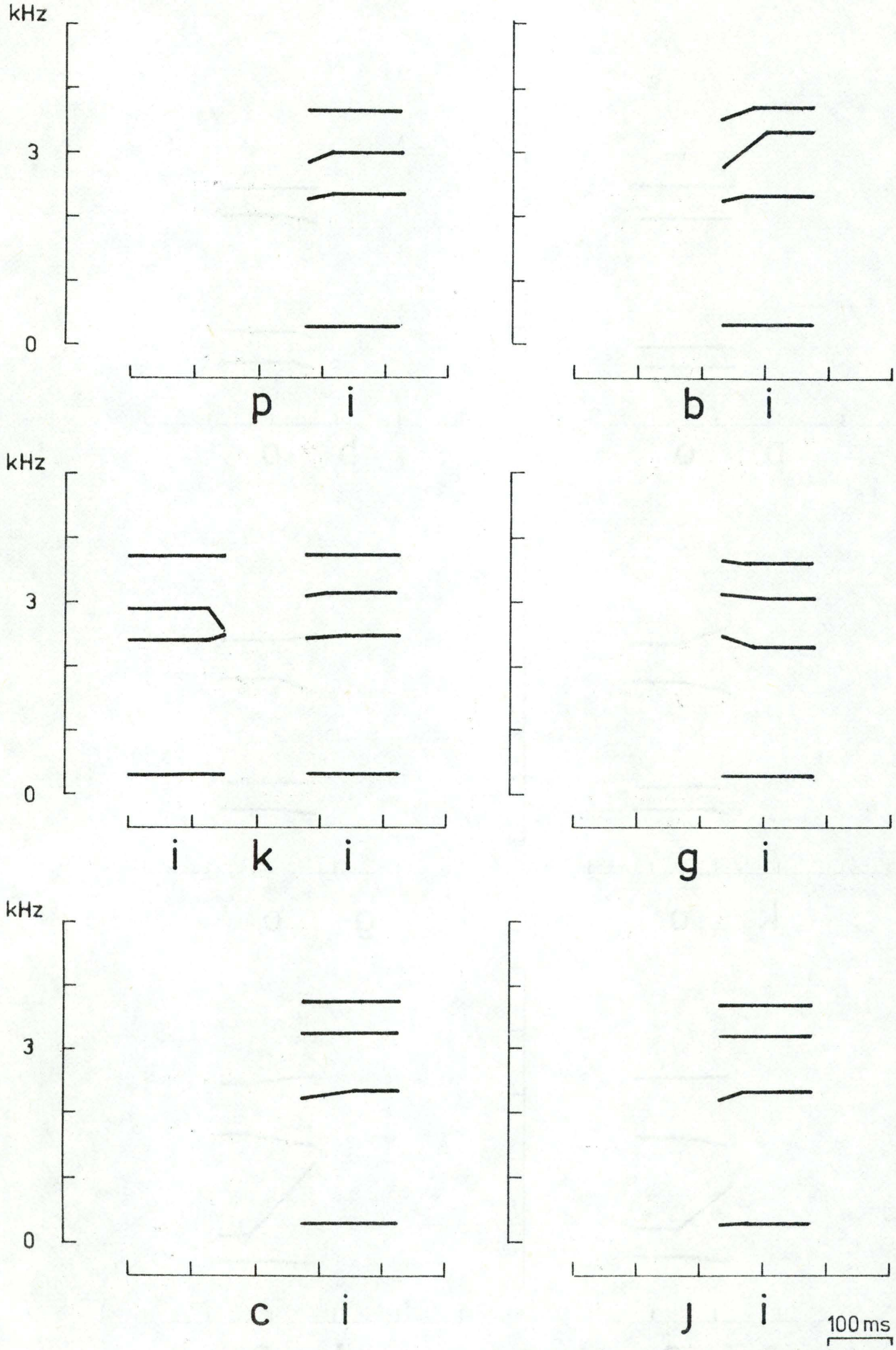


Figure 100

Schematized spectrograms. Speaker RD.

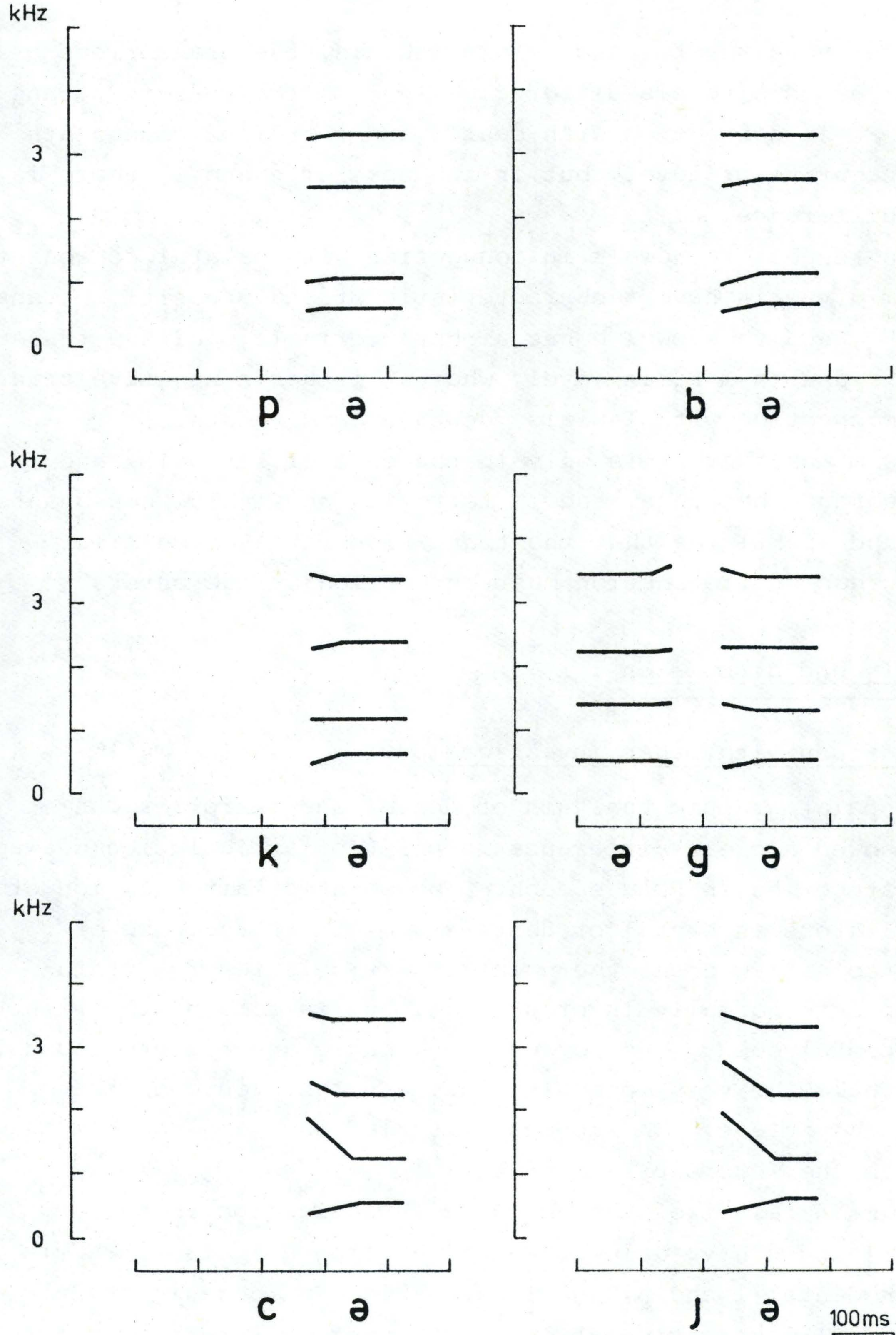


Figure 101

Schematized spectrograms. Speaker RD.

formant transitions between retroflex and velar consonants is only valid for *a* and *ə* after (but not for *a* and *ə* before) the consonant.

As for vowels after and before labials, the transitions of F_2 in back and mid vowels differ clearly from the positive transitions of F_2 in connection with dental and retroflex consonants in being negative or level, but in the case of *e* and *i*, there is not much difference.

With respect to vowels in connection with palatal consonants, back and mid vowels have a characteristic strongly positive transition of F_2, and the vowel *e* has a characteristic positive transition of F_3, and in *i* F_3 is level, whereas it has a negative transition in connection with labials, dentals, and velars.

This means that it is only in the case of retroflex and velar consonants before *a*, and in retroflex and labial consonants before *i* and (partly) *e* that the transitions are very similar and the burden of distinction must be carried by the bursts.

4. Summary and discussion

4.1 Comparison with other investigations

The palatographic analysis of dental and retroflex consonants showed a clear difference in point of articulation between the two categories in RD's speech. The point of articulation of the dental stops is dental or denti-alveolar (in the case of *r* mostly alveolar), whereas the point of articulation for retroflex consonants normally is prepalatal, but in combination with *i* rather postalveolar. Retroflex *ḷ*, *ṇ*, and *ṛ* are flapped sounds, and *ḷ* and *ṇ* may be very open with only a slight touch in the middle of the palate. The tongue is curled back and touches the palate with the lower surface of the tip.

The main result of the acoustic investigation is that retroflex *ḷ* and *ṇ* have a lower F3 and F4 (for *ṇ* F4 is often missing) than dental *l* and *n*, and *ḷ* has a high F1 (because of its open and vowel-like articulation). Moreover, all retroflex consonants have a lowering effect on the transitions of F3 and F4

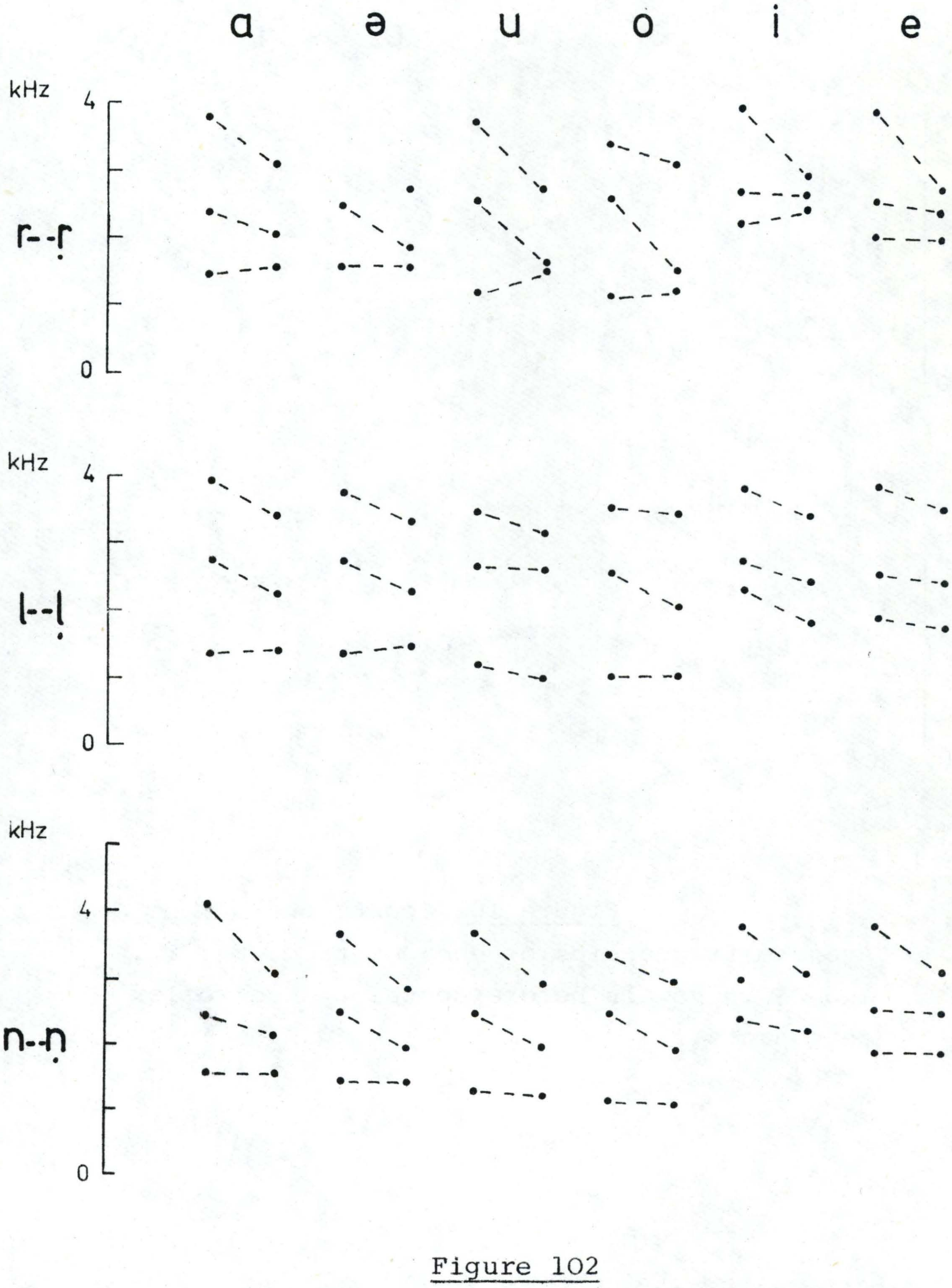


Figure 102

Average frequencies of end points of F_2, F_3, and F_4 in vowels before dental and retroflex consonants. (Continued next page).

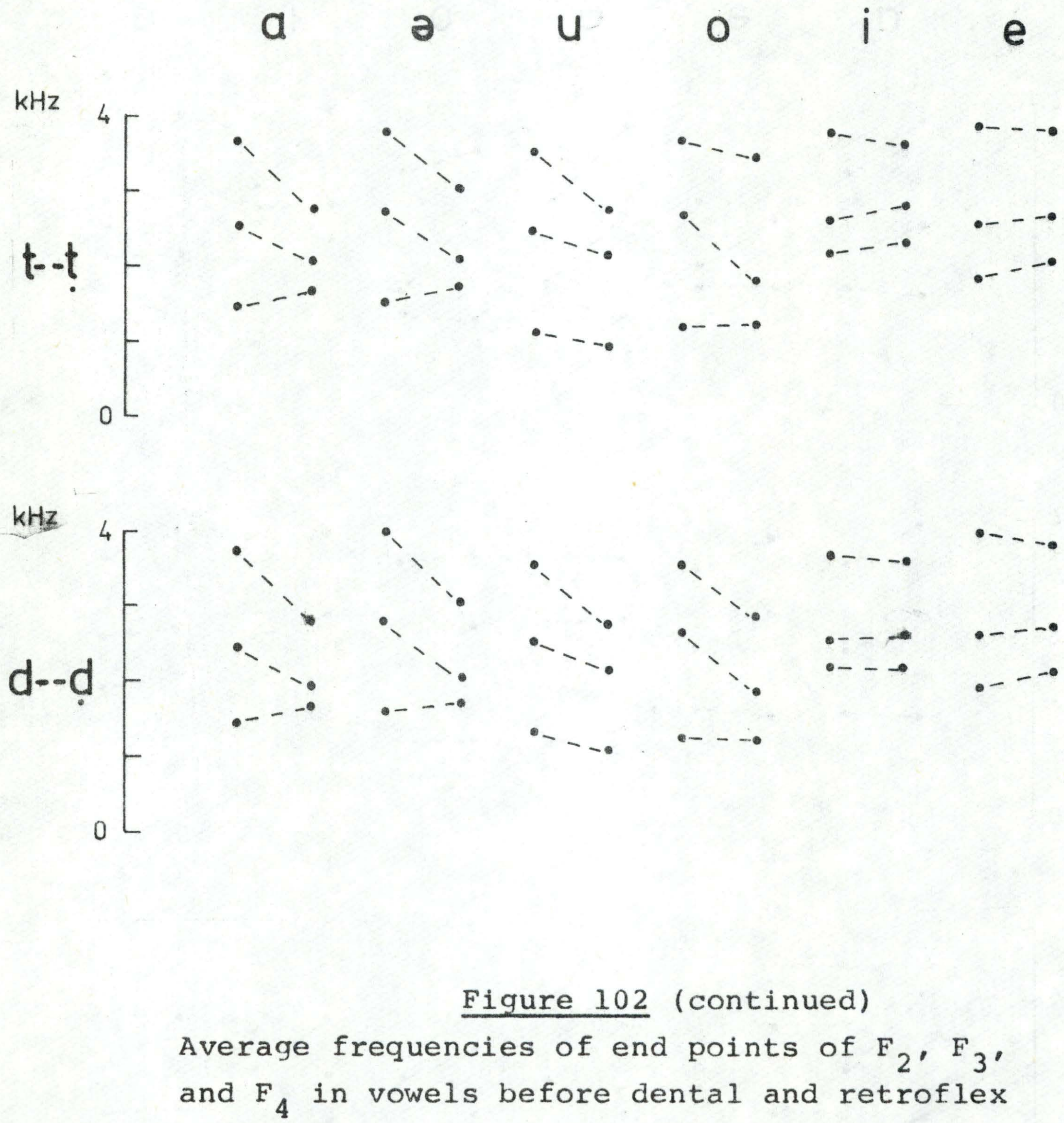


Figure 102 (continued)

Average frequencies of end points of F_2, F_3, and F_4 in vowels before dental and retroflex consonants.

of the preceding vowel (compared to dental consonants). The effect of stop consonants on the transitions of i and e is, however, small. But the frequencies of the steady state part of F3 and F4 of these vowels tend to be lower. And this tendency is also found in other vowels before retroflex stops and (for F4) in vowels before nasals and liquids. The effect of retroflex consonants on the following vowel is much more irregular but still clear for the vowel a. It may, therefore, not be accidental that retroflex nasals and liquids are not found initially in Gujarati nor that retroflex consonants are on the whole less common before front vowels (Bhat 1974).

The burst has more energy at lower frequencies in retroflex stops than in dental stops, and for RT there is a peak around 3000 Hz (somewhat higher for i and lower for o).

Compared to the results of Ramasubramanian and Thosar's (1971) investigation of Tamil retroflex stops there is agreement on the main point, i.e. that F3 is lowered in vowels adjacent to retroflex stops as compared to dental stops. There is also agreement in the finding that retroflex ḷ had a lower F3 than dental l. For retroflex ṇ they indicate a higher F3, which is somewhat surprising and not in agreement with the findings of the present investigation. Moreover, they indicate a higher F2 both in retroflex ṇ and ḷ; this is difficult to compare with the present measurements, since they only give an average value, and F2 differs according to the surrounding vowels. They have not measured F4.

On the basis of their experiments with synthesis they set up a number of loci, different for front, central, and back vowels (which is not in agreement with the locus concept of the Haskins group), and also terminal frequencies found to be efficient for the synthesis of retroflex stops. For F3 they have lower loci and lower terminal frequencies of the vowels in retroflex than in dental consonants, but their locus for dental stops (2000 Hz) seems extraordinarily low. For F2 they assume a higher terminal frequency in a in combination with dental stops than with retroflex stops (1590 vs. 1450 Hz), which is not in agreement with the present measurements. In the table on p. 78 the end points of F1 of the vowels are indicated as 350 Hz in combination with dentals, and 300 Hz in combination with velars both for i, u, and a, although the locus of all consonants is indicated to be 200 Hz, and i and u have F1 at 280. This must be a misprint, which also appears from the schematic drawings of their synthetic stimuli on p. 83-84.

Still more confusing is what they say about bursts. On p. 78 the poles are indicated to be 3500, 6000, and 4500 Hz for t, 2600, 3900, and 2000 for ṭ, and 3500, 6000, and 4500 Hz for k; but on p. 82 it is said that the poles for retroflex stops are 3500 and 6000 Hz (which were the frequencies indicated for dental and velar stops on p. 78), and that there is a zero at 4500 Hz (mentioned as a pole on p. 78). In the drawings of their synthetic stimuli they only indicate the lower pole, which is in agreement with the indication on p. 78, thus 3500 for dentals and velars, and 2600 for retroflex stops. It is surprising that they use the same burst frequencies in front of a, u, and i. A ka and a ku with a burst at 3500 Hz are completely unrealistic, and one wonders how these syllables sound. Nothing is said about the perceptual tests which must have been used in their experiments with synthesis.

Much more interesting is the article by Stevens and Blumstein (1975). They have taken some spectrograms of t and ṭ in intervocalic position spoken by 3 Hindi speakers. The spectrograms of aṭa reproduced on p. 220 show strongly negative transitions for F3 and F4 of the preceding vowel for two of the informants. (The spectrogram of the third informant does not show the higher formants.) The formants of the following vowels differ, one informant having no rise in F3 or F4. This difference between preceding and following vowels with less evident transitions in the following vowel is in agreement with the findings of the present investigation, and so is the negative transition of F3 and F4 and the transition of F2 in the first a. The differences between the bursts which are said to be lower in the retroflex consonant (around 2700-3000 Hz) are not very evident in the published spectrograms.

The results of their perceptual tests with synthetic stops in CV syllables with the vowel a are clear. Stimuli with a positive transition of F3 in combination with a burst between F3 and F4 are heard as ta, a straight or negative transition of F3 combined with a somewhat lower burst (between F3 and F4) gives ṭa, and a lowering of the burst to the level of F3 has the effect that the listener hears ka.

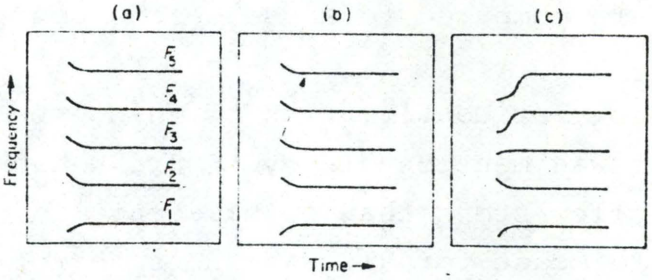
There are, however, some differences in the reactions of the 8 listeners. Some hear ṭa even when F3 has a slight positive transition. Since the position of the burst and the transition of F3 are not varied independently, it is not possible to say what has been more important for the listeners. But it is shown that the addition of a rising F4 increases the number of retroflex-responses. The main characteristic of retroflex consonants is said to be a clustering of F2, F3, and F4 in a relatively narrow frequency region. In order to illustrate this point, the end points of F2, F3, and F4 in vowels before dental and retroflex consonants of the present investigation are compared graphically in Fig. 102. The tendency is evident, although F2 does not always contribute to the result. In this picture the dashed lines do not depict formant transitions; they simply combine the end points of formants before dental and before retroflex consonants to make the difference more clear.

4.2 The relation between articulation and acoustic result

Stevens and Blumstein also try to explain the acoustic differences between the formant transitions before dental and retroflex consonants on the basis of their production. F2 in consonants with an apical place of articulation is said to depend on the cavity behind the closure. This may explain why the vowels a and ə were found to have a higher end point of F2 before retroflex consonants than before dental consonants in this investigation (with ən as the only exception). When the tongue tip is curled back, the cavity behind the place of articulation gets shorter and must have a higher resonance (the consonantal section of ḷ also has a higher F2 after a and ə). For the other vowels this difference is not consistent. For e and i it is found before stops but not before ḷ, ṛ, ṇ. The manner of articulation of the consonant also seems to play a role. Before ṛ the end point of F2 is higher (except in eṛ), before ṇ it is only higher in aṇ (and this is only due to the word paṇi which should not have been included in the average).

F3 and F4 are - according to Stevens and Blumstein - usually associated with the cavity behind the constriction in dental consonants, and they are generally higher than F3 and F4 of the adjacent vowels so that these get positive transitions. In the present material most fourth formants of the vowels have positive or straight transitions before dentals (see Figs. 93-95). But F3 has negative transitions in i, e, and partly a. i and e seem to have a higher F3 than the locus for the dental F3 (this was also found for Danish, see Eli Fischer-Jørgensen 1954).

The cavity in front of the constriction is so small in dentals that it has a very high natural frequency which is of no importance. But in retroflex consonants, where the tongue is curled back, the front cavity is larger and, according to Stevens and Blumstein, its resonance comes into the vicinity of F3 and F4. When the tongue moves down from the consonant to the vowel, the size of the cavity decreases rapidly, and the resonance increases rapidly. This is depicted in Fig. 103 (Fig. 2 in Stevens and Blumstein 1975). They explain in the text that two formants cannot intersect physically. When they come close together they are displaced upwards and downwards.



Schematic representation of formant movements at release of consonants produced by raising tongue blade. Part (a) shows falling trajectories of all formants above F_1 for a dental place of articulation; the same trajectories are shown in part (b), together with a dashed line indicating the movement of the front-cavity resonance for a retroflex consonant; the resulting trajectories of the formants at the release of a retroflex consonant are given in (c).

Figure 103

(after Stevens and Blumstein 1975)

We thus get a picture with a lowered F3 and a rising F4 and F5 in CV syllables. In Stevens 1973 it is shown on the basis of calculations of the resonances of the vocal tract that if the place of articulation is about 12.8 cm from the glottis (that is, slightly behind the denti-alveolar place of articulation), F4 is lowered and comes close to F3, and the graph shows that still further back F3 is lowered and comes close to F2. This is quite in agreement with Fant, who says that retroflex consonants with a postalveolar articulation have F4 close to F3, and retroflex consonants with palatal articulation have F3 close to F2 (1968, p. 239).

In the palatographic investigation RD's retroflex consonants were found to have a palatal place of articulation, except for the consonants in the environment of i, which had a postalveolar place of articulation. We might, therefore, expect to find a more exclusive lowering of F4 rather than of F3 in the environment of i, and perhaps e. This is, on the whole, confirmed in the present investigation when the end points before retroflex consonants are compared to those before dental consonants (Fig. 102).

We might also look for confirmation of this expectation in a different way: It was mentioned above that RD had a shorter VOT value of his retroflex stops than of his dental stops, whereas this was not the case for RT. Now RD's retroflex stops are generally spoken with the tip of the tongue curled back, and according to Stevens (1973) consonants made with the tip of the tongue have a shorter VOT value than those made with the blade because the tip moves more quickly. It might therefore be assumed that RT's retroflex stops were not completely retroflex, but that the blade took part in the constriction. This is in agreement with the fact that his retroflex stops sound more similar to the dental stops than those of RD. Moreover, the spectrograms of his dental and retroflex consonants were also more similar. However, it seems that there is some conflict between the assumption of a more advanced articulation and the acoustical theory referred to above, for RT's consonants were more similar because he very rarely has any transition of F4 (see Figs. 67 and 92), and if his place of articulation is not as far back, he should rather have been expected to have more lowering of F4 than of F3.

Finally, it is supposed by Stevens and Blumstein that when the tongue goes down and the front cavity decreases in size and thus increases its resonance, F4 should not be influenced until a certain decrease has taken place, about 20 ms after the release. Conversely, it might be expected that when the tongue tip moves up to the retroflex position, we should first see a fall in F4 and then in F3 as it comes close to the palatal place of articulation. But this is not the case. The steep rise of F4 generally starts immediately after the release, and the fall of F4 in the preceding vowel generally starts later than the fall in F3. In a single case (RD's piḷi, Fig. 104) there is first a downward transition of F3 in the first i, and then a downward transition of F2 (and conversely in the second i). This really looks as if there is a cavity which increases gradually in size, first influencing F3 and then F2. But similar pictures are never found for F4 and F3.

We have thus had some difficulties in applying the very plausible explanations given in Stevens and Blumstein to our material. But that may be due to the fact that the relations between cavities and formants are extremely complicated, and F3 and F4 may be influenced by both the back and the front cavities. Generally, a quickly descending F4-transition before a retroflex stop is clearly seen in the spectrograms, whereas the preceding steady state part of F4 is very weak or almost missing, and in these cases F5 is stronger (see, e.g., paṭa in Fig. 91).

Stevens and Blumstein do not mention the asymmetry in the spectrograms of retroflex stops, i.e. the fact that the lowering of F3 and F4 is much more pronounced in the preceding than in the following vowel. Asymmetries can also be found in connection with other consonants, but they are much more evident in connection with retroflex stops. A glance at the figures 57-59, 61-62, 64-65, and 85-95 will show that the transitions of preceding and following vowels are much more symmetric in combination with dentals than in combination with retroflex consonants. This may be explained by the following two points: (1) the movement up to the place of articulation is probably slower than the movement down; (2) when the closure is made with the lower surface of the tip, the contact is probably moved somewhat forward before the tip goes down. In the flapped consonants it is evident that the tip slides forward along the palate. This means

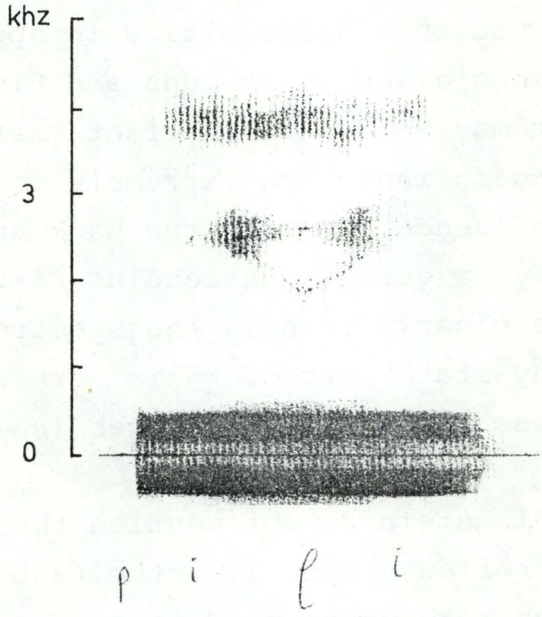


Figure 104

Spectrogram of [piḷi]. Speaker RD.

that at the release the place of articulation is less retracted, the size of the front cavity has already decreased, and the transitions will not be so clearly different from those of the dentals. This is also the explanation given by Bhat (1974). Bhat also mentions that in a tap consonant like alveolar r the tip may move inward so that it ends in a more retroflex position. This is confirmed in the spectrograms of r in the present investigation, which may sometimes show a rising F4 in the following vowel, whereas the retroflex ṛ has a falling F4 in the preceding vowel (see Fig. 57, ərə and əṛə).

4.3 The distinctive feature of retroflex consonants

According to Roman Jakobson retroflexion belongs together with rounding and pharyngealization as different manifestations of the feature "flat" (see Jakobson, Fant, Halle 1952, p. 34 and 49). Acoustically flat phonemes are characterized by a downward shift and/or weakening of some of their upper frequency components. This description is in full agreement with the lowering of F4 and F3 found in the present investigation, as well as by Ramasubramanian and Thosar, and by Stevens and Blumstein. Articulatorily they are said to be produced by a decreased back or front orifice of the mouth resonator and a concomitant velarization which expands the mouth resonator (Jakobson, Halle 1968, p. 431-32). In Jakobson, Fant, Halle 1952, an elongation of the mouth resonator is mentioned as the most important characteristic. This description still requires verification. It is not improbable that the hollowing of the tongue body behind the tip in the retroflex articulation entails a certain velarization; even an alveolar r is considered to entail a certain velarization; but to confirm this assumption it would be necessary to make X-ray photos of retroflex consonants. The picture given in Stevens and Blumstein 1975 of Polish retroflex ḍ does not show any velarization, nor any elongation of the mouth cavity. And the physiological explanation of the lowered F3 and F4 given by Stevens and Blumstein is not based on the cavity behind the constriction but on the cavity in front of the constriction. This point requires further investigation.

APPENDIX

Table 1

Formant transitions of vowels adjacent to r and ṛ. (Number of examples in parentheses)

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(7) a + r				(2) r + a		
F_4	3563	3746	+183	3375	3800	+525
F_3	2593	2362		2275	2175	+100
F_2	1345	1440	+95	1425	1400	+25
F_1	870	605		588	775	-187
(6) a + ṛ				(3) ṛ + a		
F_4	3767	3075		3700	3700	0
F_3	2488	2033		2050	2325	-275
F_2	1292	1550	+258	1475	1500	-25
F_1	817	604	-213	641	783	-142
(1) ə + r				(1) r + ə		
F_4				2725	3775	-1050
F_3	2450	2450	0	2225	2425	-200
F_2	1425	1550	+125	1575	1550	+25
F_1	650	550	-100	550	725	-175
(1) ə + ṛ				(1) ṛ + ə		
F_4	3700	2700	-1000	2775		
F_3	2375	1825	-550	2400	2400	0
F_2	1325	1575	+250	1550	1500	+50
F_1	725	425	-300	525	625	-100

Table 1 (continued)

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(l)	u + r			(l)	r + u	
F_4	3700	3700	0		3700	
F_3		2550		2500		
F_2	950	1175	+225	1075	875	+200
F_1	375	375	0	350	350	0
(l)	u + ṛ					
F_4	3225	2750	-475			
F_3	2225	1650	-575			
F_2	975	1500	+525			
F_1	375	375	0			
(l)	o + r			(2)	r + o	
F_4	3650	3400	-250	3125	3600	-475
F_3		2575		1750	2100	-350
F_2	925	1150	+225	1200	1000	+200
F_1	525	525	0	575	575	0
(l)	o + ṛ			(2)	ṛ + o	
F_4	3600	3100	-500	3200	3650	-450
F_3	2275	1550	-725	1750	2500	-750
F_2	850	1250	+400	1250	1088	+162
F_1	500	400	-100	525	575	-50

Table 1 (continued)

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(2)	i + r			(2)	r + i	
F_4	3950	3950	0	3938	3950	-12
F_3	3013	2675	-338	2663	2988	-325
F_2	2463	2250	-213	2363	2563	-200
F_1	300	300	0	300	300	0
(2)	i + ṛ			(2)	ṛ + i	
F_4	3700	2900	-800	3950	3950	0
F_3	3200	2650	-550	2825	3300	-475
F_2	2388	2450	+62	2375	2463	-88
F_1	288	288	0	300	300	0
(1)	e + r			(1)	r + e	
F_4	3950	3900	-50	3925	3925	0
F_3	2800	2550	-250	2525	2700	-175
F_2	2300	2020	-280	2050	2225	-175
F_1	450	450	0	475	475	0
(1)	e + ṛ			(1)	ṛ + e	
F_4	3750	2750	-1000	3950	3950	0
F_3	2800	2400	-400	2550	2600	-50
F_2	2200	2000	-200	2000	2200	-200
F_1	500	300	-200	400	475	-75

Table 2

Formant transitions of vowels adjacent to l and ḷ.

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(6)	a + l			(4)	l + a	
F_4	3891	4016	+125	4088	4038	+50
F_3	2579	2716	+138	2599	2494	+75
F_2	1263	1341	+78	1369	1313	+56
F_1	854	650	-204	688	819	-131
(6)	a + ḷ			(2)	ḷ + a	
F_4	3754	3379	-375	3638	3800	-162
F_3	2546	2221	-325	2375	2438	-63
F_2	1283	1388	+105	1375	1400	-25
F_1	796	713	-84	725	763	-38
(1)	ə + l			(1)	l + ə	
F_4	3750	3750	0	3600	3200	+400
F_3	2650	2700	+50	2350	2225	+125
F_2	1325	1350	+25	1300	1450	-150
F_1	750	500	-250	750	750	0
(1)	ə + ḷ			(1)	ḷ + ə	
F_4	3600	3300	-300	3600	3750	-150
F_3	2350	2225	-125	2550	2700	-150
F_2	1300	1450	+150	1475	1450	-50
F_1	750	750	0	700	700	0

Table 2 (continued)

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(1) u + l				(1) l + u		
F_4	3500	3450	-50	3650	3650	0
F_3		2650		2550		
F_2	950	1200	+250	1300	975	+325
F_1	400	375	-25	425	425	0
(1) u + ḷ				(1) ḷ + u		
F_4	3300	3150	-150	3400	3400	0
F_3	2700	2600	-100			
F_2	800	950	+150	1100	1025	+75
F_1	375	375	0	400	400	0
(1) o + l				(1) l + o		
F_4	3650	3500	-150	3600	3550	+50
F_3		2550		2650	2650	0
F_2	950	1025	+75	1100	1050	+50
F_1	500	500	0	550	550	0
(1) o + ḷ				(1) ḷ + o		
F_4	3600	3400	-200	3600	3600	0
F_3	2475	2050	-425	2150		
F_2	850	1050	+200	1050	975	+75
F_1	525	550	+25	600	600	0

Table 2 (continued)

	Steady state	Trans. end	diff.		Trans. start	Steady state	diff.
(2) i + l				(2) l + i			
F_4	3825	3800	-25		3850	3888	-38
F_3	2903	2763	-150		2713	2875	-162
F_2	2425	2363	-62		2325	2463	-138
F_1	313	313	0		313	313	0
(2) i + ḷ				(2) ḷ + i			
F_4	3675	3375	-300		3725	3725	0
F_3	3038	2438	-600		2600	3050	-350
F_2	2350	1850	-500		2050	2325	-275
F_1	300	300	0		350	350	0
(1) e + l				(1) l + e			
F_4	3850	3850	0		3850	3850	0
F_3	2650	2550	-100		2550	2625	-75
F_2	2250	1900	-350		2000	2100	-100
F_1	525	525	0		500	500	0
(1) e + ḷ				(1) ḷ + e			
F_4	3725	3500	-225		3750	3850	-100
F_3	2525	2450	-125		2500	2600	-100
F_2	2200	1750	-450		2000	2100	-100
F_1	525	525	0		500	500	0

Table 3

Formant transitions of vowels adjacent to n and ṇ.

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(6)	a + n			(4) n + a		
F_4	4008	4088	+80	4088	4050	+38
F_3	2367	2413	+46	2475	2362	113
F_2	1342	1533	+191	1575	1418	157
F_1	933	863	-70	782	850	68
(6)	a + ṇ			(2) ṇ + a		
F_4	3841	3042	-799	3813	3850	-37
F_3	2250	2150	-100	2237	2300	-63
F_2	1325	1538	+213	1462	1450	+12
F_1	913	946	+33	900	900	0
(1)	ə + n			(1) n + ə		
F_4	3700	3700	0	3750	3750	0
F_3	2400	2525	+125	2500	2375	-125
F_2	1450	1450	0	1400	1525	+125
F_1	700	750	+50	700	700	0
(1)	ə + ṇ			(1) ṇ + ə		
F_4	3450	2850	-600	3700	3700	0
F_3	2325	1950	-375	2400	2475	-75
F_2	1400	1450	+50	1450	1450	0
F_1	775	775	0	800	800	0

Table 3 (continued)

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(l) u + n				(l) n + u		
F_4	3725	3725	0	3700	3700	0
F_3	2500	2500	0	2600	2600	0
F_2	1200	1325	+125	1100	850	+250
F_1	400	400	0	325	325	0
(l) u + ṇ						
F_4	3650	2975	-675			
F_3	2600	2000	-600			
F_2	650	1250	+600			
F_1	300	300	0			
(l) o + n				(l) n + o		
F_4	3625	3400	-225	3400	3600	-200
F_3	2500	2500	0	2500	2500	0
F_2	1000	1175	+175	1175	1125	+50
F_1	550	675	+125	700	675	-25
(l) o + ṇ				(l) ṇ + o		
F_4	3525	3000	-525	3650	3650	0
F_3	2500	1975	-525	2100	2475	-375
F_2	950	1125	+175	1050	1050	0
F_1	550	700	+150	750	725	+25

Table 3 (continued)

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(2)	i + n			(3) n + i		
F_4	3850	3850	0	3925	3925	0
F_3	3262	3075	187	2950	3208	-258
F_2	2563	2413	-150	2433	2633	-200
F_1	325	325	0	308	308	0
(2)	i + ṇ			(3) ṇ + i		
F_4	3763	3150	-613	3975	3975	0
F_3				2817	3333	-516
F_2	2425	2288	-137	2267	2638	-371
F_1	313	313	0	338	338	0
(1)	e + n			(1) n + e		
F_4	3850	3850	0	3825	3825	0
F_3	2650	2600	-50	2700	2800	-100
F_2	2200	1950	-250	2100	2225	-125
F_1	400	400	0	500	500	0
(1)	e + ṇ			(1) ṇ + e		
F_4	3750	3150	-600	3975	3975	0
F_3	2750	2525	-225	2800	2750	+50
F_2	2250	1925	-325	2000	2125	-125
F_1	400	400	0	550	550	0

Table 4

Formant transitions of the vowel a adjacent to dental and retroflex stops.

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(4) a + t				(7) t + a		
F_4	3613	3688	+75	3750	3607	+143
F_3	2588	2550	-38	2604	2504	+100
F_2	1300	1444	+144	1489	1310	+179
F_1	838	644	-194	661	829	-168
(5) a + d				(8) d + a		
F_4	3565	3750	+185	3675	3516	159
F_3	2530	2485	-45	2700	2575	+125
F_2	1255	1460	+205	1597	1344	253
F_1	845	610	-235	588	825	-237
(4) a + ṭ				(7) ṭ + a		
F_4	3425	2763	-662	3700	3564	+136
F_3	2444	2044	-400	2346	2368	-22
F_2	1281	1638	+357	1543	1332	+211
F_1	875	613	-262	668	846	-178
(6) a + ḍ				(8) ḍ + a		
F_4	3596	2833	-763	3644	3595	+50
F_3	2410	1995	-415	2406	2388	+19
F_2	1283	1654	+371	1662	1369	+294
F_1	842	613	-229	600	813	-213

Table 5

Formant transitions of the vowel ə adjacent to dental and retroflex stops.

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(1) ə + t				(2) t + ə		
F_4	3800	3800	0	3650	3475	+175
F_3	2725	2725	0	2638	2588	+50
F_2	1325	1525	+200	1513	1288	+225
F_1	750	675	-75	563	638	-75
(1) ə + d				(2) d + ə		
F_4	3900	4000	+100	3625	3463	+162
F_3	2725	2800	+75	2688	2588	+100
F_2	1425	1575	+150	1525	1363	+163
F_1	725	550	-175	575	625	-50
(1) ə + ṭ				(2) ṭ + ə		
F_4	3750	3050	-700	3600	3425	+175
F_3	2450	2100	-350	2425	2275	+150
F_2	1450	1725	+275	1600	1425	+175
F_1	675	525	-150	588	625	-38
(1) ə + ḍ				(3) ḍ + ə		
F_4	3750	3050	-700	3625	3517	+108
F_3	2200	2050	-150	2600	2467	+133
F_2	1400	1725	+325	1683	1492	+192
F_1	650	525	-125	517	642	-125

Table 6

Formant transitions of the vowel u adjacent to dental and retroflex stops.

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(2) u + t				(7) t + u		
F_4	3400	3550	+150	3540	3515	+25
F_3	2500	2500	0	2394	2369	+25
F_2	938	1125	+188	1121	939	+182
F_1	375	375	0	371	371	0
(2) u + d				(3) d + u		
F_4	3675	3550	-125	3325	3400	-75
F_3	2525	2550	+25	2500	2413	+88
F_2	850	1300	+450	1200	794	+406
F_1	400	400	0	358	358	0
(2) u + ṭ				(4) ṭ + u		
F_4	3400	2750	-650	3550	3625	-75
F_3	2450	2150	-300	2325	2350	-25
F_2	800	950	+150	1119	750	+369
F_1	400	400	0	375	375	0
(3) u + ḍ				(3) ḍ + u		
F_4	3450	2733	-717	3500	3350	+150
F_3	2433	2133	-300	2475	2475	0
F_2	750	1033	+283	1167	742	+425
F_1	375	375	0	375	375	0

Table 7

Formant transitions of the vowel o
adjacent to dental and retroflex stops.

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(1)	o + t			(3) t + o		
F_4	3700	3700	0	3775	3750	25
F_3	2450	2700	+250	2541	2533	+8
F_2	1075	1200	+125	1175	925	+250
F_1	600	600	0	475	500	-25
(2)	o + d			(4) d + o		
F_4	3450	3550	+100	3600	3556	+44
F_3	2613	2638	+25	2606	2600	-6
F_2	950	1243	+293	1294	963	+331
F_1	500	538	+38	450	475	-25
(2)	o + ṭ			(3) ṭ + o		
F_4	3688	3488	-200	3433	3367	67
F_3	2550	1825	-725	2242	2533	-292
F_2	875	1225	+350	1267	950	+317
F_1	588	588	0	475	508	-33
(2)	o + ḍ			(5) ḍ + o		
F_4	3500	2850	-650	3192	3367	-175
F_3	2475	1825	-650	2290	2380	-90
F_2	925	1200	+275	1280	1020	+260
F_1	550	550	0	480	530	-50

Table 8

Formant transitions of the vowel i adjacent to dental and retroflex stops.

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(2)	i + t			(5) t + i		
F_4	3800	3800	0	3785	3765	+20
F_3	2800	2650	-150	2820	3060	-240
F_2	2375	2200	-175	2335	2455	-120
F_1	313	313	0	290	290	0
(3)	i + d			(5) d + i		
F_4	3725	3692	-33	3705	3715	-10
F_3	2825	2550	-275	2710	3110	-400
F_2	2367	2192	-175	2250	2410	-160
F_1	308	308	0	295	295	0
(2)	i + ṭ			(5) ṭ + i		
F_4	3650	3675	+25	3755	3750	+5
F_3	2925	2875	-50	2745	3100	-355
F_2	2425	2388	-38	2290	2445	-155
F_1	313	313	0	300	300	0
(2)	i + ḍ			(4) ḍ + i		
F_4	3650	3600	-50	3688	3688	0
F_3	2650	2600	-50	2638	3200	-563
F_2	2300	2175	-125	2206	2444	-238
F_1	313	313	0	300	300	0

Table 9

Formant transitions of the vowel e adjacent to dental and retroflex stops.

	Steady state	Trans. end	diff.		Trans. start	Steady state	diff.
(1) e + t				(3) t + e			
F_4	3900	3900	0	F_4	3767	3683	+83
F_3	2800	2700	-100	F_3	2567	2600	-33
F_2	2175	1900	-275	F_2	2000	2100	-100
F_1	550	450	-100	F_1	417	417	0
(1) e + d				(3) d + e			
F_4	3900	4000	+100		3750	3725	+25
F_3	2700	2600	-100		2592	2633	-42
F_2	2075	1900	-175		1935	2092	-157
F_1	475	400	-75		408	425	-17
(1) e + ṭ				(4) ṭ + e			
F_4	3850	3850	0	F_4	3744	3719	25
F_3	2750	2700	-50	F_3	2531	2538	-6
F_2	2200	2125	-75	F_2	2050	2100	-50
F_1	475	400	-75	F_1	475	475	0
(1) e + ḍ				(3) ḍ + e			
F_4	3800	3800	0		3650	3650	0
F_3	2600	2750	+150		2533	2550	-17
F_2	2200	2150	-50		1867	2033	-166
F_1	450	350	-100		458	458	0

Table 10

Formant transitions of the vowel a adjacent to labial, velar, and palatal stops.

	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(2)	a + p			(7)	p + a	
F_4	3575	3675	+100	3643	3579	+64
F_3	2400	2350	-50	2450	2443	+7
F_2	1288	1263	-25	1175	1236	-61
F_1	838	725	-113	743	857	-114
(2)	a + b			(4)	b + a	
F_4	3500	3450	-50	3519	3538	-19
F_3	2388	2350	-38	2506	2563	-57
F_2	1275	1200	-75	1138	1213	-75
F_1	825	675	-150	631	831	-200
(2)	a + k			(3)	k + a	
F_4	3625	4175	+550	3692	3475	+217
F_3	2375	2113	-262	2183	2400	-217
F_2	1250	1325	+75	1425	1316	+109
F_1	850	650	-200	700	825	-125
(1)	a + g			(3)	g + a	
F_4	3400	3800	+400	3633	3617	16
F_3	2500	2100	-400	2325	2383	58
F_2	1200	1300	+100	1508	1308	+200
F_1	825	700	-125	517	775	-258

	Trans. start	Steady state	diff.	Trans. start	Steady state	diff.
(1)	c + a			(1)	ɟ + a	
F_4	3750	3500	+150	3700	3400	+300
F_3	2500	2300	-200	2800	2400	+400
F_2	1800	1400	+400	2100	1375	+725
F_1	500	800	-300	400	775	-375

Table 11

Formant transitions of the vowel ə adjacent to labial, velar, and palatal stops.

	Trans. start	Steady state	diff.		Trans. start	Steady state	diff.
(1)	p + ə			(1)	b + ə		
F_4	3250	3300	-50		3300	3300	0
F_3	2475	2475	0		2500	2600	-100
F_2	1000	1050	-50		925	1175	-250
F_1	575	600	-25		550	650	-100
(1)	k + ə						
F_4	3450	3325	+125				
F_3	2300	2375	-75				
F_2	1175	1175	0				
F_1	500	625	-125				
(1)	c + ə			(1)	ɟ + ə		
F_4	3525	3425	+100		3550	3350	+200
F_3	2475	2275	+200		2775	2225	+550
F_2	1900	1250	+650		2000	1250	+750
F_1	400	600	-200		400	625	-225
	Steady state	Trans. end	diff.		Trans. start	Steady state	diff.
(2)	ə + g			(3)	g + ə		
F_4	3425	3550	+125		3533	3400	+133
F_3	2200	2213	+13		2308	2300	+8
F_2	1413	1450	+37		1425	1333	+92
F_1	550	500	-50		475	567	-92

Table 12

Formant transitions of the vowel u adjacent to labial, velar, and palatal stops.

	Trans. start	Steady state	diff.	Trans. start	Steady state	diff.
(1) p + u				(1) b + u		
F_4	3400	3400	0	3250	3250	0
F_3	2400	2400	0	2500	2500	0
F_2	725	725	0	725	725	0
F_1	400	400	0	375	375	0
(4) k + u				(2) g + u		
F_4	3483	3433	+50	3650	3650	0
F_3	2350	2400	-50	2250	2500	-250
F_2	731	731	0	737	737	0
F_1	381	381	0	350	350	0
(1) c + u				(1) ɟ + u		
F_4	3200	3400	-200	3200	3400	-200
F_3	2275	2425	-150	2250	2350	-100
F_2	1725	900	+825	2000	850	+1150
F_1	400	400	0	375	375	0

Table 13

Formant transitions of the vowel o adjacent to labial, velar, and palatal stops.

	Trans. start	Steady state	diff.	Trans. start	Steady state	diff.
(1)	p + o			(1)	b + o	
F_4	3200	3200	0	3150	3150	0
F_3	2725	2700	+25	2650	2750	-100
F_2	700	700	0	800	850	-50
F_1	400	400	0	350	425	-75
(1)	k + o			(1)	g + o	
F_4	3350	3100	+250	3250	3150	+100
F_3	2300	2500	-200	2300	2550	-250
F_2	850	850	0	875	875	0
F_1	475	500	-25	450	500	-50
(1)	c + o			(1)	ɟ + o	
F_4	3300	3250	+50	3300	3200	+100
F_3	2200	2350	-150	2200	2400	-200
F_2	1625	950	+675	2000	875	+1125
F_1	425	500	-75	400	450	-50

Table 14

Formant transitions of the vowel i adjacent to labial, velar, and palatal stops.

	Trans. start	Steady state	diff.	Trans. start	Steady state	diff.
(3)	p + i			(2)	b + i	
F_4	3675	3675	0	3563	3725	-162
F_3	2875	3000	-125	2750	3350	-600
F_2	2283	2350	-67	2268	2350	-82
F_1	292	300	-8	313	313	0
				(3)	g + i	
				3650	3633	-17
				3167	3100	+67
				2483	2350	+133
				283	308	25
(1)	c + i			(1)	ɟ + i	
F_4	3750	3750	0	3700	3700	0
F_3	3250	3250	0	3200	3200	0
F_2	2350	2400	-50	2200	2325	-125
F_1	300	300	0	275	300	-25
	Steady state	Trans. end	diff.	Trans. start	Steady state	diff.
(1)	i + k			(4)	k + i	
F_4	3725	3725	0	3731	3731	0
F_3	2900	2550	-350	3100	3138	-38
F_2	2400	2500	-100	2433	2450	-17
F_1	300	300	0	306	306	0

Table 15

Formant transitions of the vowel e adjacent to labial, velar, and palatal stops.

	Trans. start	Steady state	diff.	Trans. start	Steady state	diff.
(1) p + e				(1) b + e		
F_4	3575	3675	-100	3400	3700	-300
F_3	2475	2600	-125	2400	2600	-200
F_2	2050	2200	-150	1875	2175	-300
F_1	400	450	-50	400	400	0
(1) k + e				(1) g + e		
F_4	3700	3650	+50	3750	3600	+150
F_3	2600	2700	-100	2450	2600	-150
F_2	2250	2200	+50	2350	2250	+100
F_1	400	425	-25	375	400	-25
(1) c + e				(1) ɟ + e		
F_4	3650	3650	0	3775	3600	+175
F_3	2750	2600	+150	2950	2675	+275
F_2	2200	2100	+100	2225	2200	+25
F_1	400	425	-25	275	375	-100

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