VOICING, TENSENESS AND ASPIRATION IN STOP CONSONANTS, WITH SPECIAL REFERENCE TO FRENCH AND DANISH

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1. Introduction.

1.1. The present report is, to a great extent, a summary of two papers which will be published in 1969, (a) "Les occlusives françaises et danoises d'un sujet bilingue" (to appear in the Festschrift to A. Martinet, vol. II) and (b) "Observations sur les traits phonétiques distinguant ptk de bdg en français".*) Both of these papers contain an account of speakers, texts and instrumental set-up and a detailed presentation of the results in the form of tables of averages and diagrams. These facts will be presented rather briefly here, in section 2, with close line spacing. Instead, the report will mainly be concentrated on the general problems associated with the features of voicing**), tenseness and aspiration, their mutual relations (particularly the relation between tenseness and aspiration) and the problem of attributing the physiological and acoustic phenomena to these features. A special discussion is devoted to intra-oral pressure and F_1 transitions. (These problems are treated briefly at the end of the first-mentioned paper, and more extensively in the second paper.)

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*) The investigations have been carried out in the laboratory of our institute. I am grateful to Børge Frøkjær-Jensen for help. The work has been subventioned by Statens almindelige Videnskabsfond.

**) The term "voicing" is used here in its traditional sense, indicating vibrations of the vocal cords. In many papers by members of the Haskins Group "voiced and voiceless stops" are simply used to indicate respectively bdg and ptk. But as bdg may be voiceless (in the traditional sense of the word) in many languages, and ptk are occasionally voiced in some languages, this terminology does not seem to be very practical, and it may sometimes be rather confusing.

Readers mainly interested in the general problems may skip section 2 containing the results of the measurements (with the exception of Table I, p. 80 below, which gives a summary of the results). Section 3 gives a brief survey of the stability of the differences, and section 4 contains a summary and discussion of the perceptual tests. In section 5 (general problems) references will be given to the more important points of section 2.

Some books and articles to which I did not have access when finishing the two papers are mentioned in this report, and the titles are added to the references at the end of the report, namely: Chomsky and Halle (1968), Delattre (1968), Halle and Stevens (1967), Ladefoged (1967), and Perkell (1965 a and b).

On some points the present report contains new facts and modifications of earlier hypotheses. It thus represents a later stage in the discussion of the problems than the two papers in print, although it appears before these.

1.2. The problem from which I started was the difficulty of describing tenseness and aspiration as belonging to the same feature, e.g. the difficulty of describing the phonetic differences between ptk and bdg as belonging to the same opposition in French and Danish, as required by Jakobson-Fant-Halle (1952, p. 38). Moreover I was puzzled by the tenseness difference in the narrower sense of the word, e.g. by the difficulty of giving a precise phonetic description of the difference between French ptk and Danish (voiceless) bdg, which are obviously different from a perceptual point of view (Danish bdg are not accepted as good French ptk), and which seem to differ only in respect of tenseness (fortis-lenis).

1.3. One way to throw some light on these questions is to analyse the pronunciation of bilingual speakers. It is, however, not quite easy to find persons who speak both French and Danish perfectly. The bilingual subject used in the first investigation, CHH, daughter of A. Martinet, speaks both languages fluently, and she has a normal Copenhagen pronunciation of the Danish stops (her bdg are perhaps slightly too "strong"); the only evident French influence found in her pronunciation of Danish concerns the rhythm. However, her French bdg are almost totally voiceless, perhaps due to Danish influence, and her French ptk are in some cases strongly aspirated and affricated. This pronunciation of ptk does not seem to be due to Danish influence. Exactly the same type of affrication was found in the speech of one of the other French subjects (SRO), and moreover it differs from the normal Danish aspiration and affrication in three respects: (a) it includes affrication of d before i, (b) it does not include aspiration before open vowels, (c) the aspiration before u is relatively weak, i.e. there is only affrication before front vowels. (In Danish ptk are strongly aspirated before all vowels, and t is always affricated.) This type of affrication is characteristic of Parisian (and Canadian) French, and, as a matter of fact, both CHH and SRO are from Paris.

This Parisian pronunciation makes the comparison more complicated. Of the three vowels used almost exclusively in this investigation (a, i and u) only a is preceded by really unaspirated ptk. On the other hand, the fact that CHH's French bdg are voiceless, has the advantage for the investigation that tense and lax voiceless consonants are found within one language.

1.4. CHH's French and Danish consonants must be seen on the background of normal Danish and French stops. For Danish I can refer to extensive but not yet fully processed data, and to a few papers (Abrahams (1949), EFJ (1954) and (1966), EFJ, Frøkjær-Jensen and Rischel (1966), and Frøkjær-Jensen (1967)).

Instrumental analyses of French stops are more numerous, but all of very limited size (see Rousselot (1891), (1897), (1899), Roudet (1900 a), (1900 b), (1910), Chlumsky (1922), Evertz (1929), Marguerite Durand (1936), (1956), Brunner (1953), Delattre (1940 a), (1949 b), Straka (1942), (1953), (1965), P. Simon (1961), (1967), Thorsen (1967), and K. Landschultz (1968)).

Experiments with synthetic stops identified by French listeners have been carried out by Marguerite Durand (1956). In the experiments with ptk versus bdg undertaken by the Haskins group the listeners were mainly Americans (cp. Libermann, Delattre and Cooper (1958), see also the summaries of the results given by Delattre (1958), (1961), (1964)). Delattre (1968) gives the perceptive cues for French phonemes, but nothing is said about the number of listeners.

The number of subjects used in my analysis of French stops is very restricted, partly because it was difficult to find good subjects, partly because I have preferred to undertake a thorough analysis of a few subjects, which would make it possible to find relations between the different phonetic factors and to draw some conclusions about the physiological mechanism.

The main subject, apart from CHH, was SRO. The supplementary subjects are indicated by the initials EH, JPP, JT, Sch, and MAS. Moreover I have had the opportunity to use material recorded by O. Thorsen and K. Landschultz. The stops of CHH and SRO were analysed from many points of view: position of the glottis, intra-oral pressure, airflow (only CHH), lip pressure, duration, voicing, intensity of the explosion and formant transitions. The stops of the supplementary subjects were only analysed in some of these respects. The stops of five Danish subjects have, with a few exceptions, been analysed in all the respects mentioned.

The text material used consists almost exclusively of words containing stop consonants in initial stressed position after unstressed vowel and before the vowels a, i or u, e.g. la panne, la balle, les pistes, les boules etc. The choice of this position was conditioned by the fact that in Danish ptk and bdg are not distinguished in final position, nor in medial position before ə.

2. Results of the measurements.

2.1. Physiological measurements.

2.1.1. Position of the glottis.

An endoscopic examination of the main French subject SRO gave the result that p was spoken with slightly open glottis. This result was corroborated by glottograms taken with the Fabre glottograph, showing higher electric resistance in the glottis for ptk than for bdg. Glottograms for JPP gave the same result (the number of word pairs were 99 for SRO and 84 for JPP).

Endoscopic examinations of Danish stops have shown that ptk are spoken with widely open glottis, bdg with slightly open glottis (the intercartilaginous part being normally closed in bdg). The difference in degree of opening has been corroborated by glottographic recordings.

Fabre glottograms of 72 French and 56 Danish word pairs with the vowel a spoken by CHH show a corresponding difference between ptk and bdg in the two languages. There is no clear difference between the languages as far as the maximum opening is concerned. However, it is not quite certain whether the plates were removed in between the two sessions, and since their placement may influence the maximum amplitude of the curve, this result must be taken with some reservation.

The place of the maximum in the two languages is, however, of interest. Both French and Danish subjects show a predominantly falling curve for bdg. French ptk have a predominantly rising-falling curve during the closure period, whereas Danish ptk have a rising curve up to the moment of explosion, followed by a fall (see EFJ, Frøkjær-Jensen and Rischel (1966), and Frøkjær-Jensen (1967)). Aspirated Danish ptk thus have a much wider glottis at the moment of explosion compared to unaspirated French ptk and to bdg.*) CHH's glottograms show this difference clearly for French and Danish t and k, whereas her Danish p has its maximum at the start of the closure period, although it is also aspirated (see the schematic average glottograms Fig. 1).

The curves of SRO and JPP are more irregular than those of CHH and the Danish speakers, and the French material needs corroboration. There may be individual differences (see Kloster Jensen (1956)).

2.1.2. Airflow.

The maximum airflow after the explosion of French stops has only been measured for JPP and CHH. They both have a stronger airflow after ptk than after bdg, but CHH (118 pairs) has a much smaller difference (t/d no difference, p/b k/g + a 2.9 l/m, + u, i 5.1 l/m) than JPP (38 pairs, 11.8 l/m, only a). In her Danish stop consonants CHH has a considerably greater difference between ptk and bdg (100 pairs, 15.0 l/m), and her Danish bdg have a somewhat weaker airflow than her French ptk (5.3 l/m). The curves of the Danish subjects have not been measured, but the difference is evident, and it may even be greater than that found for CHH. When the consonant is affricated, the airflow is relatively slow at the start.

2.1.3. Intra-oral air pressure.

The intra-oral air pressure of labial and dental stops has been measured (in cm H_2O) for the French subjects SRO (92 pairs) and EA (40 pairs). The peak pressure is evidently and significantly higher for pt than for bd, the pressure for the latter amounting to 49 and 45 per cent of that for pt for the two subjects. In an earlier kymographic recording of 15 pairs spoken by JT the percentage is 64. Thorsen found, for his 5 speakers, an average percentage of 61, and the measurement of

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*) See also Frøkjær-Jensen in this report p.12.

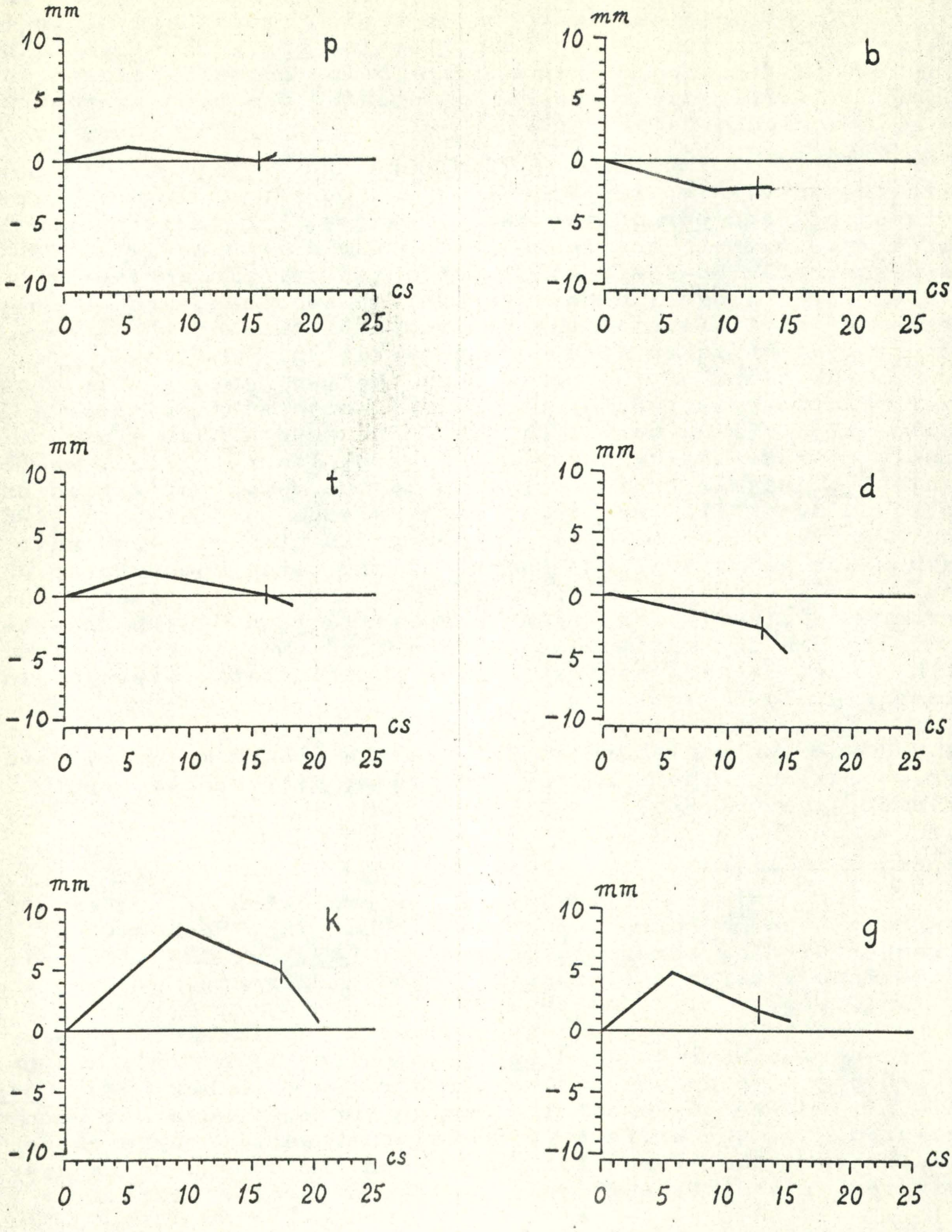

Fig. 1 a.

Average glottograms of CHH's ptk and bdg in French

| = explosion

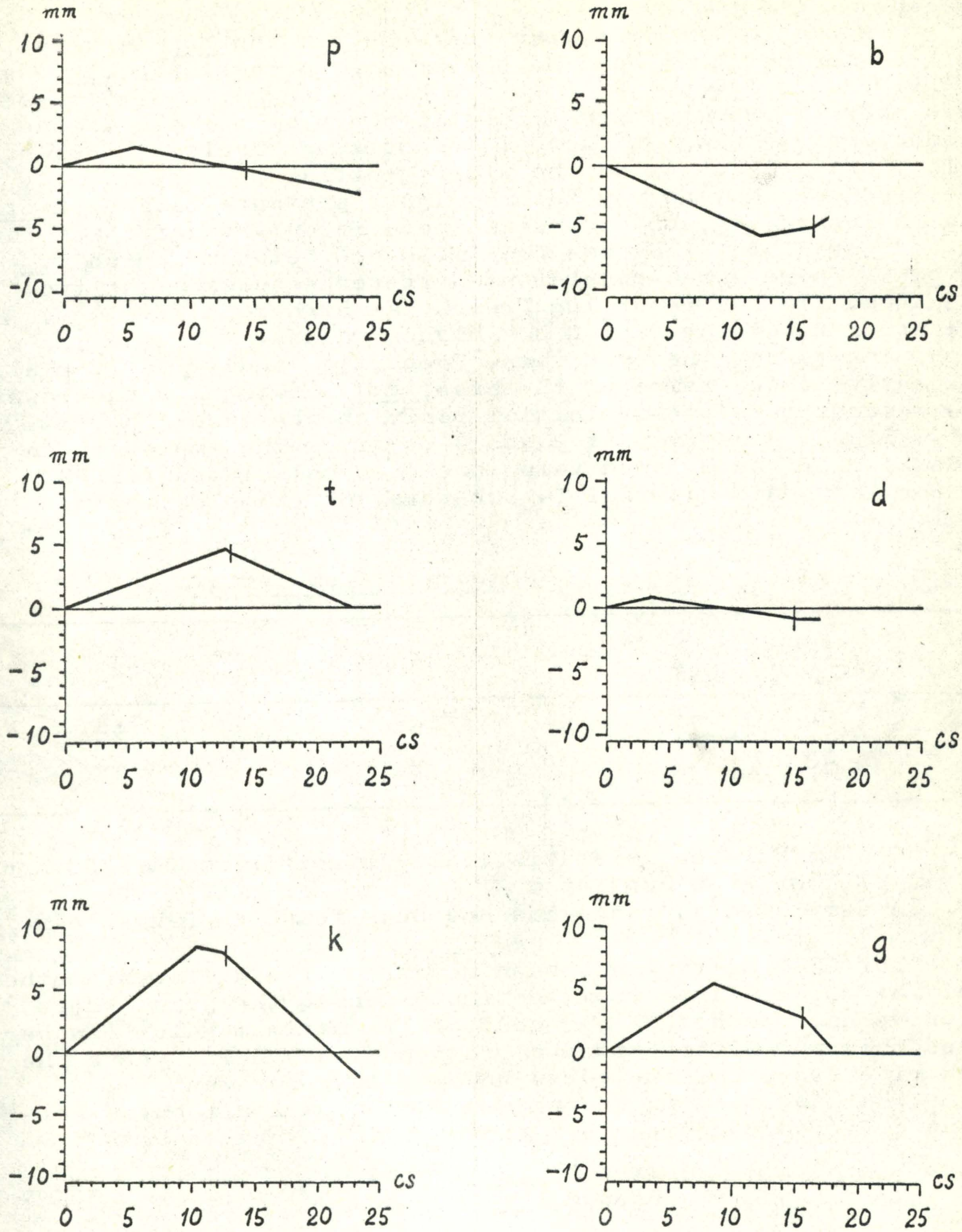

Fig. 1 b.

Average glottograms of CHH's ptk and bdg in Danish

| = explosion

81 further examples from his material gives an average of 71 per cent.

In Danish the difference between ptk and bdg is very small; some speakers have no difference, others have bdg slightly lower (around 92 - 96 per cent of ptk), and in these cases there is generally only a difference at the end of the closure, ptk showing an increase of pressure during the closure period, probably owing to the wider glottis.

CHH has a tendency toward higher pressure in French ptk than in French bdg, but the difference is only significant for p/b (92 per cent). She has no difference between Danish ptk and bdg. There is no consistent difference between the two languages. In one recording French has higher peak values, in another recording Danish has higher values.

Apart from the peak value French pt and bd differ significantly in the tempo of the rise, bd showing a much slower rise (except in sentence initial position where also pt have a slow rise). The rise at 2 and 4 cs after the implosion in percentage of the maximum value has been calculated for SRO and for Thorsen's material (4 subjects, 81 examples). The result is:

SRO:	2 cs per cent	4 cs per cent	Thorsen's subjects:	2 cs per cent	4 cs per cent
p	62	72	pt	68	92
b	48	52	bd	43	63

The difference is statistically significant for SRO and for two of Thorsen's subjects.

A similar difference has not been found in Danish air pressure curves.

For CHH the rise has been measured by a different method, namely as the distance from the implosion to the point where the curve has reached 85 per cent of its maximum value (in her curves this point very often corresponds to a point where the quick rise stops and the curve becomes more horizontal).

She has, both in French and Danish, a small but significant difference between ptk and bdg, the averages being:

French ptk	2.6 cs
French bdg	4.5 cs
Danish ptk	2.4 cs
Danish bdg	3.7 cs

It appears from these averages that there is practically no difference between her French and Danish ptk, and that Danish bdg is in between ptk and French bdg.

These values cannot be compared directly to the values given for the French subjects, but it is evident that 85 per cent rise in 4.5 cs for CHH's French bdg is considerably quicker than 52 and 63 per cent in 4 cs for the French subjects, and it is also evident that her ptk have a quicker rise than those of the French subjects.

The so-called pressure impulse, i.e. the area under the curve (measured by Lisker (1965) and Malécot (1966 a)) has not been calculated for these recordings, because I consider it a rather complicated measure combining three parameters (peak value, rise time and duration), which I prefer to give separately, and because it depends on the scales used. It would show a pronounced difference between French pt and bd, because all three parameters go in the same direction, and it would give a somewhat greater difference between CHH's French ptk and bdg than the difference in peak value for the same reasons. For Danish it would in many cases give slightly higher values for bdg than for ptk (depending on the scales used for pressure and duration), because bdg have a longer closure period, but often slightly lower peak pressure.

Both SRO, EA and CHH show an increase in pressure during the closure period of ptk with the maximum at or very close to the explosion. This may be due to the open glottis.

Unaspirated stops have an abrupt fall after the explosion, aspirated stops normally have a short abrupt fall followed by a slowing down, and affricated stops exhibit a slow fall from the start.

2.1.4. Lip pressure.

Lip pressure has been recorded by means of a rubber bulb and measured in mm on the curve for SRO (71 word pairs), Sch. (16 pairs) and JT (18 pairs). SRO and Sch. show a significant difference between p and b, the latter reaching 72 per cent (SRO) and 66 per cent (Sch.) of the peak of p. In JT's examples the stop consonant was in initial position in isolated words, and in this position the lip pressure is very irregular. Thorsen has found the lip pressure of b to be 7o - 89 per cent of that of p for four subjects.

CHH has only a slight tendency toward stronger lip pressure in her French p, but a significant, though small, difference in Danish, where b has stronger lip pressure than p, in accordance with the general tendency in Danish.

2.2. Acoustic measurements.

2.2.1. Voicing.

The French material (5 subjects) contains 41o examples of bdg; 87 per cent of these examples are voiced throughout, whereas 13 per cent of the examples are voiceless in the last part (on the average 23 per cent) of the closure period. There is only one example of overlapping with ptk. 29 examples in final position are fully voiced.

This is in accordance with earlier measurements (see particularly Evertz (1929) and Brunner (1953)). Thorsen's five subjects (Thorsen (1967)) also have fully voiced bdg both in intervocalic and in final position. I have also measured 174 examples of b from K. Landschultz' material (4 subjects, among whom also CHH). In intervocalic position these are all fully or partly voiced, and only CHH has less than 4o per cent voicing.

As already mentioned CHH has practically voiceless French bdg. There is, however, a slight but significant difference between ptk and bdg in that bdg show a slightly longer voiced interval in the beginning through assimilation to the preceding vowel:

French ptk	1.4 cs
French bdg	3.1 cs
Danish ptk	1.5 cs
Danish bdg	2.2 cs.

As it was the case with the tempo of the pressure rise, Danish bdg are in between ptk and French bdg (there are approximately 400 examples of each set). The variations are small except for French bdg, which vary between 1.0 and 13.5 cs. Four examples of b are fully voiced.

In curves of Danish intervocalic stops initially in a stressed syllable one finds generally 1-2 cs voicing, with a small, but unstable tendency for bdg to show more voicing than ptk. If such a syllable loses its stress in the sentence, bdg and sometimes ptk may become voiced, but they are still kept apart by means of the aspiration of ptk. Before weak syllables with ə there is only one series of stops. These often have (relatively weak) voicing.

2.2.2. Fundamental frequency of the following vowel.

The fundamental frequency of the following vowel has been measured for SRO. The vowel starts on a lower tone after bdg than after ptk in 75 out of 78 pairs (spoken in alternating order), the average difference being 27 cps.

A tendency toward a similar difference is found in one of the recordings of CHH, but not in the other recordings. The fundamental frequency has not been recorded for the other subjects.

In Danish no such difference has been found.

2.2.3. Intensity of the explosion.

The difficulty of separating the intensity of the explosion from the intensity of the voicing makes a comparison between ptk and voiced bdg rather problematic. An attempt to separate the two factors in SRO's stops by means of a high-pass filter with a cut-off frequency of 500 cps was not quite successful. On the one hand there was often some voicing left, on the other hand the filtering may have removed some of the explosion noise in labials, and in velars before u. The high-pass filtered intensity curve showed a significantly higher intensity for k than for g (although with much variation), but no clear difference for labials and dentals. A restriction to the curves in which all voicing had been removed did not give a better result. (The integration time was 2.5 ms.)

CHH's curves and the Danish curves did not present this difficulty, but they did not show any consistent difference either, except that Danish t has a weaker explosion than d. On the other hand the aspiration of p, k and particularly t is strong. CHH's Danish b and g tend to be slightly stronger than her French p and t.

A comparison between the explosions of French ptk and Danish bdg spoken by a larger number of subjects has been planned by the author. Such a comparison is possible when the intensity of the explosion is measured in relation to the following vowel provided that the words are said with normal voice effort (the quality of many Danish and French vowels is quite similar).

A preliminary comparison between the author's bdg and SRO's ptk gave the result that the Danish b was somewhat weaker than the French p, but nothing could be said about d/t and g/k.

On the whole the intensity of the explosion seems to be of very restricted importance.

(The number of explosions measured was rather restricted, because most of the intensity curves have been taken with a linear scale. A logarithmic scale is necessary when both explosions and vowels are to be measured.)

2.2.4. Intensity rise of the following vowel.

SRO's intensity curves of stop consonants before the vowels i and u (54 pairs) display a slower rise of the vowel after bdg than after ptk in 53 cases. JT has 1o pairs before u and Sch. 9 pairs. All of JT's pairs and 8 of Sch.'s 9 pairs have a slower rise after bdg. In the case of a (SRO 27 pairs, JT and Sch. 19) and e (JT and Sch. 19 pairs) one finds, however, rather the opposite tendency. (But from an auditory point of view a may perhaps also have a slower increase in loudness after bdg than after ptk, because in the former case F_1 starts at a lower frequency where the ear is less sensitive.)

Neither CHH nor the Danish subjects show any such difference. The rise of the vowel is in all cases rather abrupt, much like that of the vowels after ptk in French.

2.2.5. Duration of the closure period. *)

It has been shown in earlier work on the subject that French ptk have a longer closure period than bdg (e.g. Marguerite Durand (1936), Evertz (1929, pp. 22 ff.), P. Simon (1967, pp. 174 ff.)). The same has been found in the present investigation. The differences are small but relatively stable and statistically significant: SRO (221 pairs) 3.6 cs, JPP (82 pairs) 2.3 cs, EH (69 pairs) 4.8 cs, JT (18 pairs) 3.5 cs, Sch. (18 pairs) 4.o cs. In Thorsen's material the difference for JT is 3.6 cs. On the whole the closure period of bdg is about 8o per cent of that of ptk.

In Danish stops the relation is the opposite, bdg having a longer closure period than ptk. For labials and velars the difference is 2-3 cs, for dentals 4.5 cs (this difference according to place of articulation is obviously due to the particular shortness of the closure period of the strongly aspirated and affricated Danish t).

In accordance with the general difference between French and Danish, CHH has a longer closure period in ptk than in bdg in French (3oo pairs, 2.3 cs), and a shorter closure period in ptk than in bdg in Danish (283 pairs, 1.5 cs).

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*) Duration is here treated as an acoustic phenomenon because of the method of measurement.

The averages for the four sets are:

French	ptk	16.2 cs
French	bdg	13.9 cs
Danish	bdg	13.7 cs
Danish	ptk	12.2 cs

Danish and French bdg are almost alike, but the other differences are stable and significant, though small.

Thorsen has found the differences in French to be particularly large and stable in sentence final position, where the closure of bdg is only 65 per cent of that of ptk. In the present material there is only a small number of final stops, they show a greater difference than the initial stops. In the interior of a sentence the difference between word final ptk and bdg does not seem to be stable, however (this appears from K. Landschultz' material).

2.2.6. The duration of the preceding vowel.

It has often been observed that the vowels in French are longer before voiced fricatives than before voiceless fricatives. Detailed measurements have been made by K. Landschultz (1968). P. Delattre (1939),(1940),(1962) has pointed out that the difference is also valid before stops, and this appears clearly from O. Thorsen's and K. Landschultz' materials. In the present texts there is only one comparable case (SRO 16 pairs, difference 2.5 cs).

2.2.7. Duration of the following vowel.

In SRO's recordings there are four comparable word pairs comprising 95 single pairs, and EH has one word pair (16 ex.). In all cases the vowel is longer after bdg than after ptk (with average differences from 1.4 to 3.8 cs). Similar relations have been found for Danish (EFJ (1964, p. 186) and English (Peterson-Lehiste (1960)) where it might be explained as a consequence of the aspiration. But in the French examples the difference in vowel duration is larger than the difference in duration of the open interval; thus it cannot be explained by the latter, but perhaps, as suggested by Delattre, by compensation of force of articulation. No measurements have been made for CHH.

2.2.8. Duration of the open interval.

The term "open interval" is used to designate the distance from the explosion to the beginning of the vowel. In French bdg this interval is usually voiced, in ptk and in Danish stops it is always voiceless. In the latter cases it is the same as "voicing lag".

In French stops there is a significant difference between the open intervals after ptk and bdg, but it is difficult to summarize the results in a few indications of averages because the variation is rather large. The interval is relatively long after velars and relatively short after labials, and it is longer before close vowels than before open vowels (these are general tendencies found in many other languages). The single

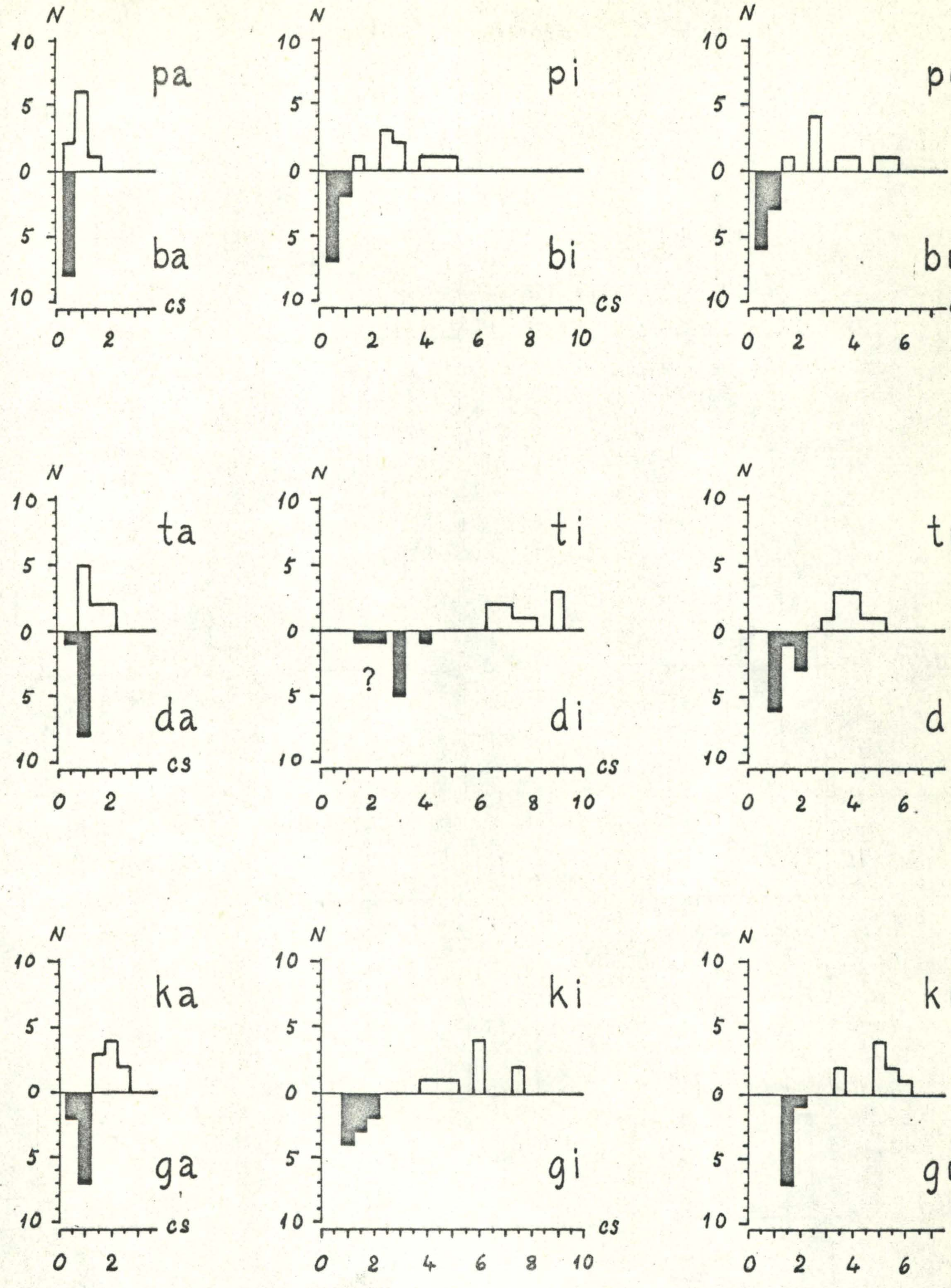

Fig. 2.

Duration of the open interval (SRO)

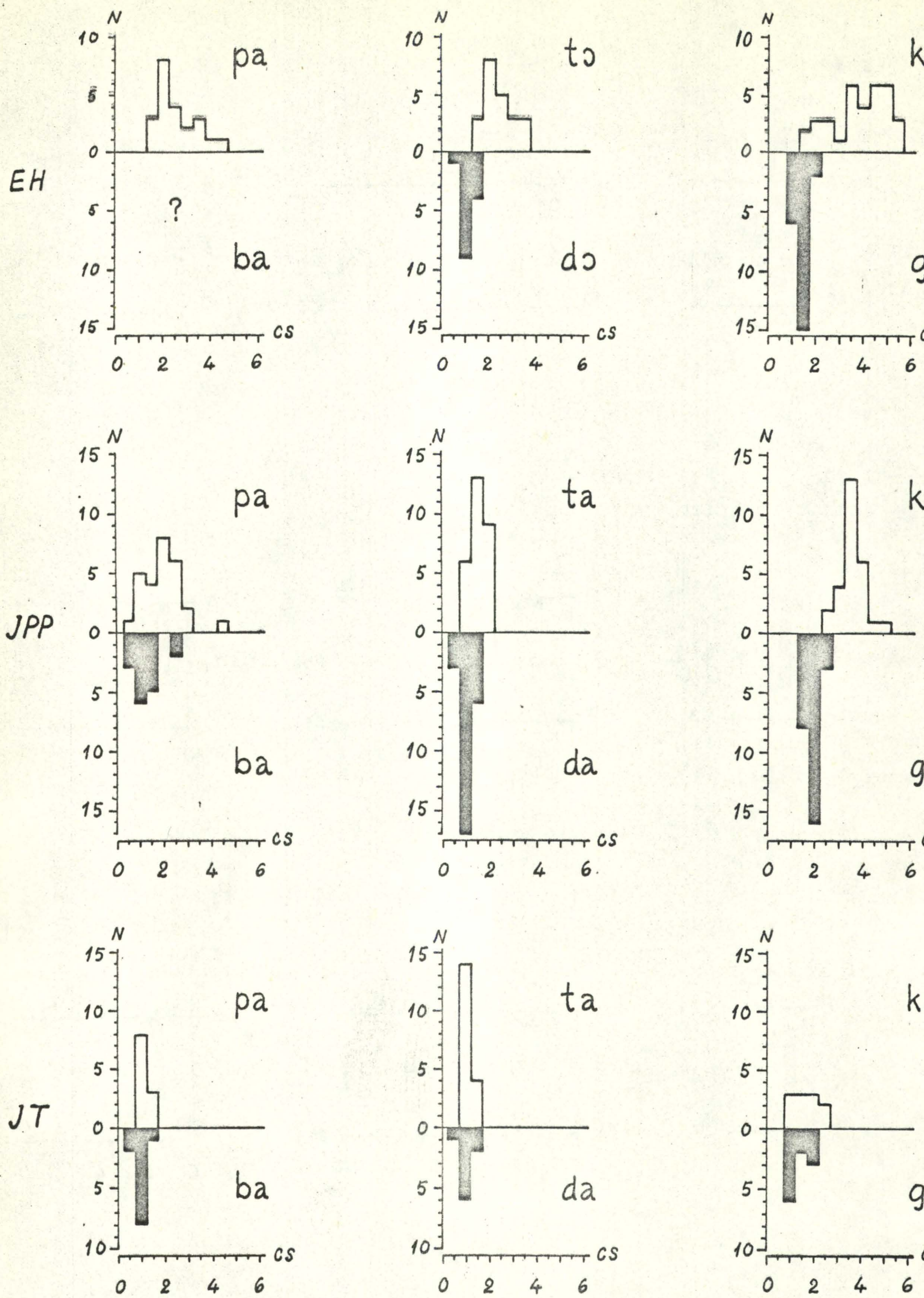

Fig. 3.

Duration of the open interval (EH, JPP, JT)

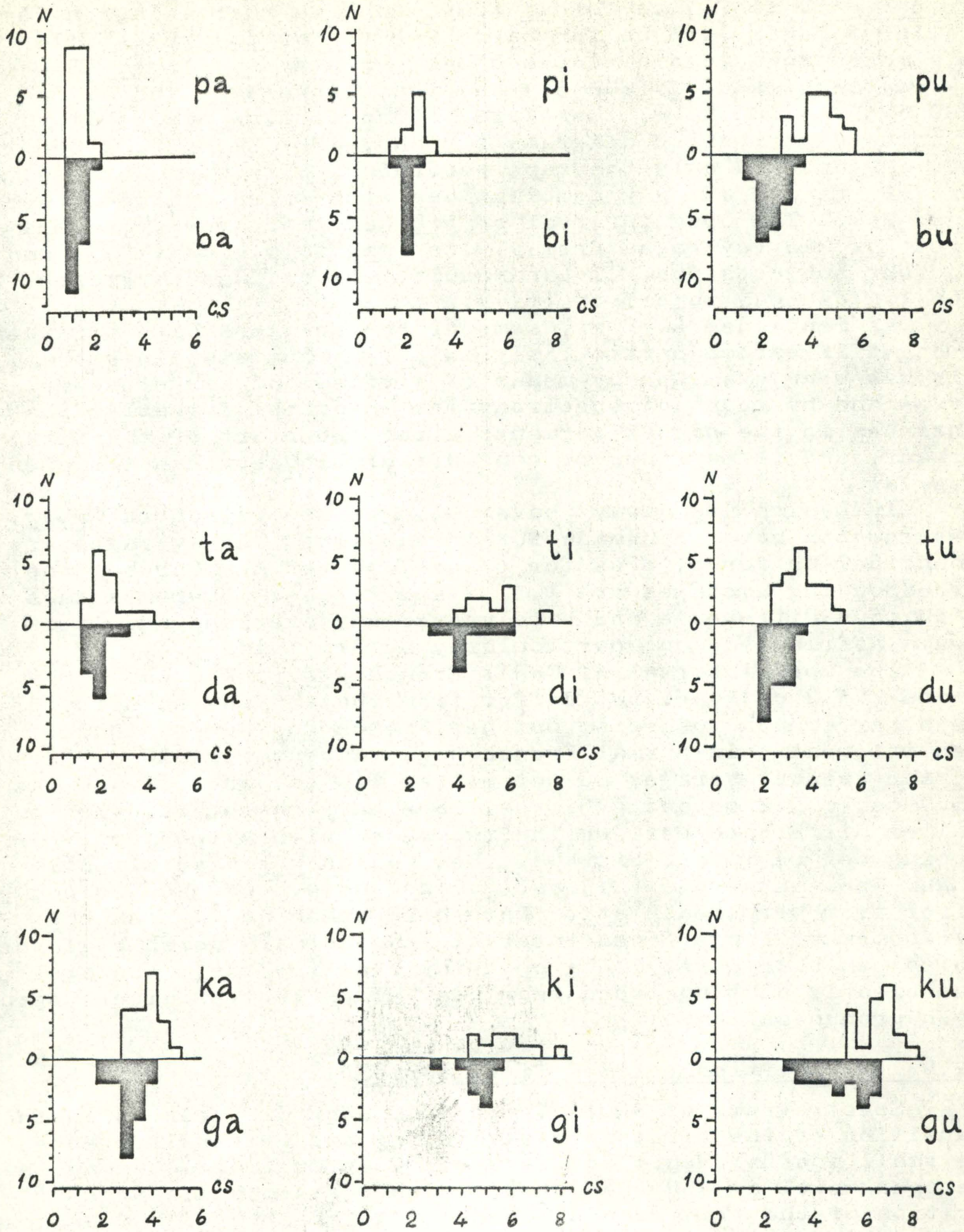

Fig. 4.
Duration of the open interval (CHH, French)
(only tape recordings)

averages of the open interval of ptk thus vary between o.9 cs for pa (MAS) to 7.7 cs for ti (SRO), and as the variation is smaller for bdg (o.5 cs for ba to 2.3 cs for di) there will be a more pronounced difference between e.g. ki and gi (SRO 4.4 cs) or ti and di (SRO 5.4 cs) than between pa and ba (SRO o.5 cs). I have, therefore, found it more practical to give the distribution diagrams for SRO, JPP, EA, JT and CHH (for SRO and CHH only the tape recordings have been utilized, for JPP, EA and JT only combinations with a are included), see Figs. 2-4. The open interval of ptk has, moreover, been measured for MAS (averages from o.9 cs (pa) to 5.4 cs (ku)), and for four subjects from K. Landschultz' recordings (averages from 1.2 cs (pa) to 6.7 cs (ti)).

As mentioned earlier, some of the speakers have a rather strong affrication particularly in ti, di but also in ki. This has been examined by means of airflow and air pressure curves and by means of spectrograms. In di the fricative phase continues in the higher formants after the start of the first formant, and it may thus be considerably longer than the open interval.

In Danish ptk always have a longer aspiration than bdg. Measurements have been made for 1o subjects. The averages are around 6-7 cs for p, 8 cs for t and 7 cs for k. For bdg the corresponding averages are 1.5, 2 and 2.5 cs. There is thus an obvious difference and hardly ever any overlapping. t is always affricated, but particularly before i and y.

The open interval of CHH's French ptk (p 2.6 cs, t 3.9 cs and k 5.2 cs) does not differ from that of the majority of the other French subjects, but her French bdg have a longer open interval than normal French bdg. Except for SRO di (2.4 cs) the French averages do not exceed 1.9 cs, whereas CHH has b 1.9 cs, d 3.2 cs and g 3.8 cs. She has, therefore, also a smaller difference between the two sets, with extensive overlapping before a (see Fig. 4). Her Danish bdg have slightly longer open intervals (2.3 cs, 3.9 cs and 4.8 cs) and do not differ from her French ptk. Both her French and Danish bdg have somewhat longer open interval than normal Danish bdg. Her Danish ptk have a very long open interval (9.7 cs), and are thus clearly distinguished from bdg. This is typical of Copenhagen pronunciation.

2.2.9. Transitions of the first formant.

Spectrograms of SRO, JT and Sch. show differences in the transition of the first formant. For i and u the differences are small and difficult to measure. They are more obvious in the open vowel a. SRO has here a higher start and a shorter duration of the transition after ptk than after bdg, but because of her high fundamental an exact measurement has not been possible. The measurements have thus been restricted to 71 spectrograms with initial stops and 31 with final stops from the recordings of JT, and 2o spectrograms with initial stops from the recordings of Sch., all containing the vowel a.

Before final stops the F_1 transition differs significantly in four respects (the differences are given in parentheses): before ptk the transition stops at a higher frequency (+ 189 cps), the interval is thus smaller (- 214 cps), the duration shorter (- 3.7 cps), and the tempo (measured in cps/cs) slower

(- 16) before ptk than before bdg. After initial stops the same four differences are found: ptk start at a higher frequency (JT +79 cps, Sch. +72 cps), the interval is smaller (JT -59 cps, Sch. -80 cps), the duration is shorter (JT -0.8 cs, Sch. - 1.2 cs), and the tempo is slower (JT and Sch. -4 cps/cs). But all these differences are much less pronounced initially than finally. In addition a fifth difference can be seen initially: the distance from the explosion to the top of the transition is slightly shorter after ptk (JT and Sch. - 0.5 cs).

In Danish spectrograms of stop consonants before the vowel a a rising transition is generally seen after bdg, but only sometimes after ptk, and in the latter case it is normally rather short (except after strongly affricated t), but the distance from the explosion to the top of the transition is not shorter than in bdg.

Velars generally have longer transitions than dentals, and these in turn have longer transitions than labials. No difference can be seen in CHH's recordings. - Table I, p. 80 gives a survey of the results described in section 2.

3. Stability of the differences.

It appears immediately from Table I that French ptk and bdg are distinguished by a large number of cues, at any rate in the position investigated. This position has been chosen because it allows a comparison with Danish. In final position before obstruents (e.g. une robe courte) there will not be much more left than a small difference in the duration of the closure and of the preceding vowel (see Thorsen 1967), and perhaps a difference in the transition (but this has not been investigated).

The stability of the differences seen as the percentage of word pairs distinguished by each difference is shown in Table II. Sonority and closure duration seem to be very stable cues. - But this need not be the same as perceptual relevance.

4. Perceptual relevance of the acoustic cues.

4.1. French stops.

For the French stops no testing has been undertaken by the author, but the problem has been investigated by Marguerite Durand (1956) and by P. Delattre (1968). The main result of M. Durand's experiments is that the tempo and length of the transition and the duration of the closure are more important cues than voicing. But the problem is how she has painted the "voice bar". Voicing in French stops is normally quite strong and not restricted to frequencies around 120 cps, and it is

Table I

Summary of the phonetic differences between ptk and bdg in French and Danish

		N Fr.	French S. excl. CHH ptk-bdg	Danish S. incl. CHH $p^h t^h k^h$-b̥d̥g̊	CHH(Fr.) ptk-b̥d̥g̊	CHH Fr.Dan. ptk-b̥d̥g̊
A. Physiological						
1. glottis max.open	VA	2	>	>	>	> ?
2. airflow	VA	1	>	>	>	>
3. intra-oral press.peak	V	2+	>	(>) or =	(>)	?
4. intra-oral press.rise	V	2+	>	=	>	>
5. lip pressure	T	3+	>	<	(>)	=
B. Acoustical						
1. voicing	V	5+	< D	(<)	<	<
2. Fo of vowel	V	1	<	=	=	=
3. intensity of explosion	T	1	=(k>g) D	=	=	(<)
4. intensity rise of vowel	T?	3	>iu =a	=	=	=
5. duration of closure	T	5+	> D	<	>	>
6. duration of preceding vowel	T	1+	<			
7. duration of following vowel	T/A	2+	<	<		
8. duration of open interval	A	5+	>iu D >a	>	>iu (>)a	=
9. transition of F1	T/A	3	< (D)	(<)	= ?	

V means voicing, T = tenseness, and A = aspiration. These letters refer to the subsequent discussion. VA means: both V and A, T/A means: either T or A. N(Fr.) indicates the number of French subjects of the present investigation besides the bilingual subject CHH, who is included in the Danish subjects because of her voiceless bdg. + after a figure means that further materials (from Thorsen and K. Landschultz) are taken into account. > means that ptk have a higher degree of the given parameter than bdg. A small > indicates a very small difference. ( ) indicates that the difference is not significant. D means: mentioned by Delattre.

Table II

Stability of the differences between French ptk and bdg
Percentage of pairs distinguished.

	Voicing			Duration of closure period			Duration of open interval		
S	p/b	t/d	k/g	p/b	t/d	k/g	p/b	t/d	k/g
SRO	loo	loo	loo	loo	loo	92	loo	86	loo
JPP	loo	loo	loo	97	96	75	94	85	97
EH	loo	loo	loo	86	93	89	-	93	83
JT	loo	loo	loo	loo	loo	loo	78	74	78
Sch.	loo	loo	loo	89	loo	loo	84	89	loo

	Duration of preceding vowel			Duration of following vowel			Intensity of explosion			Fo of following vowel		
S	p/b	t/d	k/g	p/b	t/d	k/g	p/b	t/d	k/g	p/b	t/d	k/g
SRO	89	76	89	8o	82	loo	52	35	85	loo	loo	97

Transitions of formants (initial position)

S	Frequency Start	Frequency Interval	Duration	Distance from explosion
JT	89	89	78	89
Sch.	89	loo	89	67

Intensity rise of vowel

S	i,u	a
SRO	98	15
JT	loo	47
Sch.	89	33

	Resistance in the glottis			Airflow			Lip Pressure	Intra-oral Pressure Peak		Intra-oral Pressure Rise
S	p/b	t/d	k/g	p/b	t/d	k/g	p/b	p/b	t/d	p/b
SRO	loo	loo	loo				96	loo	loo	83
JPP	96	loo	loo	88	loo	75				
EH								loo	loo	

very clearly audible in normal French bdg. New experiments should therefore be undertaken with French listeners and with precise indication of the frequency and intensity of the "voice bar".

Delattre (1968) sets up 6 acoustic cues which determine the identification of stops as ptk rather than bdg; (a) a longer hold (closure period), (b) shorter preceding vowel, (c) a cutback in the first-formant transition (i.e. later start - or weak start - of F_1 compared to higher formants), (d) a stronger turbulent noise in the explosion, (e) absence of "voice bar", (f) sometimes aspiration. He does not give any ranking of these six factors.

F_1 cutback (c) is shown to be an effective cue for American listeners by Libermann, Delattre, Cooper (1958), but the authors identify this cue with aspiration (f), and they find that the cue is more effective when the beginning of the higher formants is noisy and suggest that the pattern playback may give good results without this noise because of its general background noise. This sounds probable. F_1 cutback without noise in the higher formants is an unrealistic cue. Natural speech has never earlier start of higher voiced formants.

Delattre correlates the F_1 cutback with "the unusual degree of pressure that prevails as the organs come into contact" (1968, p. 214). Probably he thinks of air pressure, but the correlation does not seem convincing. In the earlier paper (1958) the authors quoted Fant, who has said that F_1 is weakened by the large resonance chamber below the open glottis, which seems to be a better explanation. Delattre correlates "aspiration" with a delay in the vibration of the vocal cords, and as this is also due to the open glottis, we come again to the conclusion that F_1 cutback and aspiration are not two different cues.

If F_1 cutback (c) is left out, the five remaining cues (a b d e f) correspond to the acoustic differences Nos. B 5, 6, 3, 1 and 8 of Table I. As for B 2 (fundamental frequency start of the following vowel) Fujimura (1959) has found it to be a very effective cue for one Japanese listener and to have some effect for five American listeners. It might thus be worth while to try it out on French listeners. Intensity rise and duration of the following vowel have, as far as I know, not been tested.

As for point 9 of Table I (F_1 transition), I do not think that this is covered by "F_1 cutback" or "aspiration". I shall return to this problem in section 5.1.

4.2. Danish stops.

The number of cues is more restricted for Danish stops, but the difference of aspiration is so stable and so clear and audible that it is quite sufficient. Danes are therefore inclined to identify unaspirated stops of other languages (e.g. French, Dutch, Hindi) as bdg and to hear aspirated bdg in Hindi as ptk. (A test showing this reaction has been undertaken by the author.)

The importance of the aspiration has also been shown by a tape-cutting experiment using Danish words with initial ptkbdg followed by the vowels a, i and u (1 to 3 examples of each combination). 21 Danish listeners (all phoneticians or dialectologists) were asked to identify the word as an existing or (in some rare cases) possible Danish word. When the explosion was removed from words with initial ptk, they were still correctly identified as ptk in 95 per cent of the cases (with the exception of one word with pu heard as fu), and there were only 4 bdg-answers out of 378 (1 per cent). When, on the other hand, the aspiration was removed, there were 86 per cent bdg-answers and only 7 per cent ptk-answers. When the explosions in p and b, t and d, k and g were interchanged, there was no change in the perception. The explosion is thus of very little importance in this respect.

Aspiration is partly a question of distance from the explosion to the start of the vowel (open interval), partly a question of noise during the interval. For the Danish affricated t the noise is very important. If this noise is replaced by a pause of 6-7 cs, the t is only identified in 10 per cent of the cases; it is heard as p in 15 per cent and as d or b in 27 per cent of the cases. - For p and k an explosion followed by a pause of 6-7 cs before the start of the vowel is still identified as p-k in 5o per cent of the cases (with 26 per cent b-g-answers). - If the explosion of g and b is placed at a distance of 6-7 cs from the vowel, the most common answer is b or g (62 per cent), whereas only 18 per cent of the examples were heard as p-k. This is probably not a question of the explosion but of the transitions of the vowel, for a k-explosion placed at this distance before -ilə (cut from gilə) gives 86 per cent answers in favour of g and none in favour of k, and a g-explosion at 6 cs from a u originally preceded by k gives 34 per cent answers in favour of k and 38 per cent in favour of g (in these cases only two different words were used).

The opposite experiment, i.e. the introduction of aspiration noise in the brief interval between bdg-explosions and the vowel, has not been tried, but cutting from the beginning in words with initial ptk or fsh gives the result that there is a limit somewhere between 4 and 2 cs, where the majority of the listeners start hearing bdg instead of ptk. This means that a short noise interval is not sufficient to provoke ptk-answers.

4.3. CHH's stops.

In CHH's pronunciation of French the number of acoustic cues is strongly restricted compared to normal French. The length of the preceding vowel is not relevant for initial stops, and the differences in initial voicing and in the duration of the closure and of the open interval are very small, and they are still smaller when French ptk and Danish bdg are compared. One may, therefore, ask whether it is at all possible to distinguish these types of stops. To check this a test was set up consisting of "words" of the type apa, aba, etu etc. cut out of one of the CHH's recordings of French and Danish words (French: la balle, la panne, les tours, etc., Danish: [a panən, a baljən] etc.). There were two examples with each consonant before a, i and u from each language, i.e. in total 36 French and 36 Danish "words". There was no audible difference between the French and Danish vowels. The words were played back in random order and repeated three times each. In test No. 1 all words were mixed. Test No. 2 contained only French words (and there was a forced choice between French ptk and bdg), test No. 3 contained only French ptk and Danish bdg (and the choice was between these consonants), test No. 4 contained only French words, but given in pairs apa - aba, etc.

Unfortunately only a small number of listeners have up till now listened to the tapes: 4 Danish phoneticians who know French well and who also know the pronunciation of CHH, CHH herself, and (for tests 2 and 3) two French listeners (teachers of French, but with no phonetic training). The different groups of listeners agreed to a very large extent, but the French listeners were somewhat less successful than the others.

On the whole the result was positive. When all four types were mixed, both Danish and French ptk were identified correctly in 78 to 100 per cent of the cases, but French bdg were very often heard as Danish bdg, and Danish bdg as French ptk. In tests 2, 3 and 4 the percentages of correct identification were the following:

Table III

Listeners	Test 2		Test 4	Test 3	
	French ptk	French bdg	French ptk/bdg	French ptk	Danish bdg
CHH	100%	83%	94%	94%	67%
Danish	92%	79%	90%	93%	60%
French	89%	61%	75%		

It appears from the table that CHH's Danish bdg are often heard as French ptk (they have a somewhat longer open interval than normal Danish bdg). Apart from this the identification is good. It is interesting to note that the identification of words presented in pairs is not very much superior to the identification of words in random order. This is in agreement with Libermann (1957).

As the differences in initial voicing and the duration of the closure seemed to be the most stable cues, it was tried to remove the preceding vowel and the beginning of the closure, and these new tests 2a and 3a were presented to the same listeners:

Table IV

Listeners	Test 2a		Test 3a	
	French ptk	French bdg	French ptk	Danish bdg
CHH	78%	89%	72%	83%
Danish	83%	74%	88%	67%
French	67%	67%		

The main difference from tests 2 and 3 is that more bdg have been identified correctly and that some ptk have been heard as bdg. Probably the long duration of the closure in French apa ata etc. in tests 2 and 3 has favoured ptk-responses. In tests 2a and 3a only the explosion and the open interval were left as cues, but the identification is still quite good. A detailed analysis of the single cases has shown that the intensity of the explosion does not play any role, whereas the duration of the open interval seems to be important. Most of the mistakes concern examples of bdg with relatively long open interval and ptk with relatively short open interval. There is, however, a number of cases which cannot be explained in this way, e.g. ta-da. One of the examples of French ta having 1.5 cs open interval is heard as ta by the majority, whereas the other, with 2.o cs open interval, is heard as da by the majority, and Danish da (2.5 cs) is heard as da in all cases.

It is possible that oscillograms taken at great speed might reveal small differences in the explosions or in the noise level of the open interval, which do not appear clearly in intensity curves taken with an integration time of 2.5 ms.

At any rate the large overlapping between the durations of the open interval before a, which is found in CHH's recordings as well as in those of the other French subjects (see Figs. 2-4) makes it necessary to look for other cues.

In these voiceless stops "open interval" is synonymous with "voicing lag". And the importance of this cue has been demonstrated by Liberman, Delattre, Cooper (1958) for American listeners and by Abramson-Lisker (1965) and Lisker-Abramson (1967) for Spanish and Thai listeners. The fact that the Spanish listeners have their crossing point to the right of the limit in their natural speech is partly paralleled by the French listeners in the present test, at any rate for pa/ba, but both the Spanish and the French listeners have probably been familiar with languages having voiceless bdg initially (Danish and American English), and this may have influenced their judgements.

5. General problems.

5.1. Aspiration and tenseness.

5.1.1. As mentioned above aspiration and tenseness have been combined into one feature by Jakobson-Fant-Halle (1952). On the basis of the results of the measurements of French and Danish stops this does not seem advisable. One would e.g. have to say that tense consonants are characterized (a) by a longer closure period (in French) or by a shorter closure period (in Danish), (b) by higher lip pressure (in French) or by lower lip pressure (in Danish), (c) by a higher intra-oral pressure (in French) or not by this difference (Danish), (d) perhaps by a more abrupt opening of the closure (French)*) or by a relatively slow opening (Danish)**), etc. Item (c) may be due to the combination with voicing in French, but the other cues are really contradictory. Tenseness and aspiration must, therefore, be separated as two different features. Da-

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*) if the interpretation of the transitions of F_1 is correct.

**) obvious for the affricated t, dubious for p/b.

nish stops are distinguished by aspiration, French stops by a combination of tenseness and voicing. In Chomsky-Halle (1968, pp. 324-326) aspiration and tenseness have also been separated as two different features. They suppose that aspirated stops have heightened subglottal pressure. This may be possible, but it has not been proved. It seems to have been inferred from differences in supraglottal pressure. When the glottis is wide open as in Danish ptk there will probably not be much difference between supraglottal and subglottal pressure. But in the cases where the vocal cords are closer together, it is more difficult to draw any conclusions. In the many cases where Danish b has the same supraglottal pressure as p one may well conclude that the subglottal pressure can hardly be higher than in p (for otherwise the vocal cords would start vibrating), but one cannot know whether it is lower than in p. If it is lower bdg may be said to be less tense as far as the expiratory muscles are concerned, but as noticed by Chomsky-Halle, the articulatory mechanisms for subglottal and supraglottal tension are different and independent, and the two types must be kept apart.

The use of the term tenseness (or fortis-lenis) as restricted to the supraglottal cavities is in accordance with Rousselot (1897, p. 583) and Straka (1963, pp. 60-61), whereas Delattre uses the term in a wider sense.

The description given by Fant (1960, pp. 224 and 279) of tense and lax stops is evidently a description of aspirated and unaspirated stops. He underlines the importance of an open glottis for the airflow, and of a slow opening of the constriction which causes a longer noise interval.

5.1.2. Duration of following vowel. In some respects aspiration and tenseness may produce similar results. One of these is the duration of the following vowel. Shortness of the vowel after ptk may simply be due to the aspiration which delays the vibration of the vocal cords (e.g. in Danish and English), or it may perhaps be a compensation of effort (e.g. in French, where the difference in vowel length is greater than the difference in open interval, whereas it is the opposite in Danish).

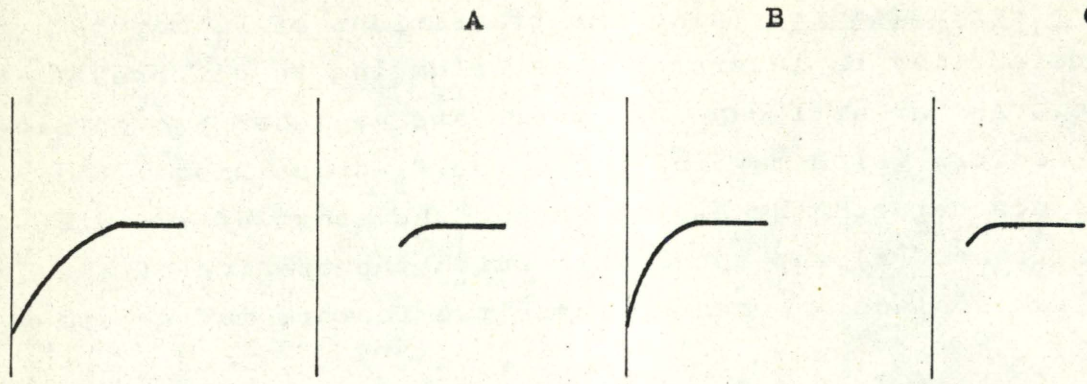
But a combination of tenseness and moderate aspiration is probably not excluded. It may be true of British English.

5.1.3. F_1-transitions. Also the transitions of F_1 may be ambiguous and may be interpreted as belonging to different features. As far as I can see, there are at least two physiological factors which may influence the F_1-transitions: (A) the distance between the explosion and the start of the glottal vibrations, (B) the speed with which the opening of the closure takes place. Moreover these two factors may be combined (C).

In Fig. 5 a sketch is given of the possible acoustic consequences of these two physiological factors. In case A, where there is a longer distance from the explosion to the start of the glottal vibrations (a longer "voicing lag") in p than in b, the F_1-transition after p will display (a) a shorter duration, (b) a higher start (and consequently a shorter frequency interval - this is not an independent factor); but there will not be any difference in the distance to the top of the transition (c) nor any difference in the tempo of the transition (d). In case B, where a quicker movement of the speech organs is assumed for p, there will be (a) a shorter duration of the transition, (c) a shorter distance to the top of the transition, (d) a quicker tempo of the transition, but not a higher start (b).

The experiments with F_1-cutback correspond to possibility A. This situation is found in languages with aspirated ptk, e.g. Danish, where the aspiration is probably the only cause of the difference in F_1-transition. M. Durand's experiments correspond to possibility B. This situation might be found in a language without any difference in open interval between ptk and bdg, but with fortis (or tense) articulation of ptk.

Possibility C corresponds approximately to what was found in French (see section 2.2.1o). This will give (a) a shorter duration, (b) a higher start (and consequently a smaller frequency interval), (c) a shorter distance to the top of the transition, and (d) in the case of straight transitions a quicker tempo of the transition after p than after b;



F_1 transition for p:	aspirated p	unaspirated p	slightly aspirated p
	movement = b	quicker movement	quicker movement
a) shorter duration	+	+	+
b) higher start	+	0	+
c) shorter distance from the explosion to the top of the transition	0	+	+
d) quicker tempo of transition	0	+	–(+)

Fig. 5. Sketch of possible F_1 transition

but as the transitions are normally curved, only the upper flat end of the curve will remain, and the tempo of the remaining part of the transition may thus be slower than that of the whole transition after b.

The difference in distance to the top is very small in the French examples; on the other hand the difference in open interval is also very small, and the high start of ptk is therefore probably due to a very quick movement of the speech organs in the first centisecond after the explosion. Fujimura (1961), who has filmed the movement of lip opening in p and b spoken by an American subject, has found that the lips may move very quickly during the very first centisecond.

In final position we have the same situation, since both the cessation of the vibrations and the quick movement of the organs influence the transitions.

There may also be cases where a long aspiration conceals the transitions completely so that nothing can be said about the movement of the speech organs. This is often the case in Danish.

The obvious differences found finally in French are in good agreement with the observations of P. Simon (1967), who has found that X-ray films point to a more energetic closing movement of French p than of b, and also with the electro-myographic analysis carried out by Öhman, Leanderson and Persson (1966), showing a stronger muscular activity at the implosion of p than at the implosion of b (cp. also Harris et al. (1965)). On the other hand, the differences found initially in the French spectrograms and the results of M. Durand's perceptual tests are in conflict with P. Simon's observation that the opening movement is slower in p than in b, and with the corresponding findings of Öhman et al. for initial p, which shows less muscular activity than b. To this it must be added that Fujimura has found a more rapid movement for p only initially in an isolated word, not after unstressed ə; but it appears from Fujimura's information about the open interval after p that the examples after ə were spoken with aspiration (4.7, 5.2, and 5.4 cs), whereas the examples in initial position were practically unaspirated (1.2, 1.9 and 3.5 cs). Öhman's speaker was apparently Swedish, and has also had aspirated p, and both Rousselot (1897) and M. Durand (1956) have observed a slower opening movement in aspirated stops. The only cases contradicting the results obtained for JT and Sch. are thus the observations of P. Simon. It is possible that the number of frames (5o per second) has not been sufficiently high to allow quite precise observations of these very quick movements.

One might perhaps think of other factors influencing the F_1-transitions, e.g. the difference in the size of the pharyngeal cavity, ptk apparently having a smaller pharyngeal cavity than voiced bdg (see later section 5.3.3.). According to Gunnar Fant, this could, however, only cause a difference of about lo per cent in the starting frequency of F_1 after ptk and bdg. The tension of the cavity walls might also be assumed to have some influence, but too little is known about this factor.

It thus seems that similar, though not in all respects identical differences in F_1-transitions may be ascribed to two different features: (1) aspiration, (2) tenseness, reflected in the rapidity of the movements of the speech organs.

5.2. Voicing and aspiration.

Lisker and Abramson (1964, cp. also Abramson-Lisker 1965) have proposed to combine voicing and aspiration into one feature: voice onset timing (VOT), the important thing being the timing between voice onset and explosion. In voiced stops the voicing starts well before the explosion (they have "voicing lead"), in unaspirated voiceless consonants the voicing starts at the explosion or immediately afterwards, and in aspirated consonants voicing starts well after the explosion (they have "voicing lag").

This is a possible solution for a good number of languages, and it is a very simple solution (but it can, of course, not be combined with the binary feature theory). Some cases, however, make difficulties: (a) in some languages bdg are voiceless in initial position after a pause and after voiceless sounds, but often partly voiced after voiced sounds (e.g. North German, English, and, sometimes, French). Probably Lisker-Abramson would consider this voicing as an example of weak "edge vibrations", which do not count. But the voicing may be quite strong, and there is often free variation with full voicing. This type is evidently different from unaspirated ptk. As the voicing is always in the first part of the closure in this type of voicing, it cannot be a case of voicing lead, but it might perhaps be fitted into the scheme as a more complicated fourth type. (b) More problematic is the case of the Indian aspirated mediae. Lisker-Abramson consider these as having breathy voice or murmur, not ordinary voicing (1964, pp. 4o3 and 419). Ladefoged is of the same opinion (1967, pp. lo and 74 ff.), but he still considers voicing and aspiration as belonging to two different dimensions: (a) glottal constriction (including murmur) and (b) glottal timing. In any case this type cannot be fitted into Lisker-Abramson's VOT-dimension.

5.3. Voicing and tenseness.

5.3.1. Lisker and Abramson also want to get rid of tenseness. I do not think this is possible. One may mention (a) CHH's distinction between ptk and bdg in French, which before open vowels is based on the duration of the closure period, and on the very small difference in initial voicing, and only before close vowels also on the open interval ("voicing lag"). (b) The case of ptk in Swiss German, which differ from bdg mainly by the duration of the closure period and the organic pressure (bdg may be weakly voiced, but they may also be voiceless). (c) The Korean stops (Kim 1965), which are also difficult to describe by means of voicing and aspiration only.

I am, however, inclined to consider the intra-oral pressure as belonging to the voicing feature and not to the tenseness feature, although it has often been considered as the most important aspect of tenseness.

5.3.2. Intra-oral pressure and organic pressure. It is often assumed that there is an intimate relation between the intra-oral air pressure and the organic pressure at the point of articulation: the higher the air pressure, the stronger must the organic pressure be in order to maintain the closure (e.g. Otto Jespersen (1914), and more recently Malécot (1956 and 1968) and Delattre (1965)). As the intra-oral air pressure might also influence the airflow, and thus indirectly the intensity of the explosion, it must be considered as a principal factor of the tenseness feature.

This hypothesis sounds very plausible, but it is contradicted by various findings of the present investigation and also by the results of other investigations. It is true that e.g. French stops are characterized both by a higher intra-oral pressure and by a higher lip pressure, but this need not be a mechanical dependency.

Firstly, there are some languages which have a difference in air pressure between ptk and bdg, but no clear difference in lip pressure, see e.g. for American English the electro-myographic investigations of Harris, Lysaught, Schwey (1965) and the measurements of mechanical pressure made by Malécot (1966 b). However, in this case the differences in air pressure are not too clear either.

Moreover, in Danish b has generally slightly lower air pressure, but higher lip pressure than p.

This inverse relation is also found in Gujarati, which has four types of stops. In 16 word series, pronounced with alternating order of the words (subject RD), ph had higher air pressure than p in 13 cases, and bh higher air pressure than b in 16 cases, but the aspirated consonants had lower lip pressure than the unaspirated ones (see Table V A 3-4 and Fig. 6).

Of particular interest is the behaviour of the nasal consonants. These have practically always a much lower intra-oral air pressure than the oral stops, but the lip pressure of m is almost the same as that of p or b. This is seen in the above-mentioned American investigations, and I have found these relations often in recordings from various languages.

It is also interesting that air pressure maximum and lip pressure maximum do not coincide in time, the maximum lip pressure occurring normally in the first half of the closure and the air pressure maximum at the end of the closure period. Table VI,A contains the average values for the two main subjects of this investigation. For SRO the two pressure curves were recorded simultaneously, for CHH the averages are from two different recordings. When the lip pressure is at its maximum, the

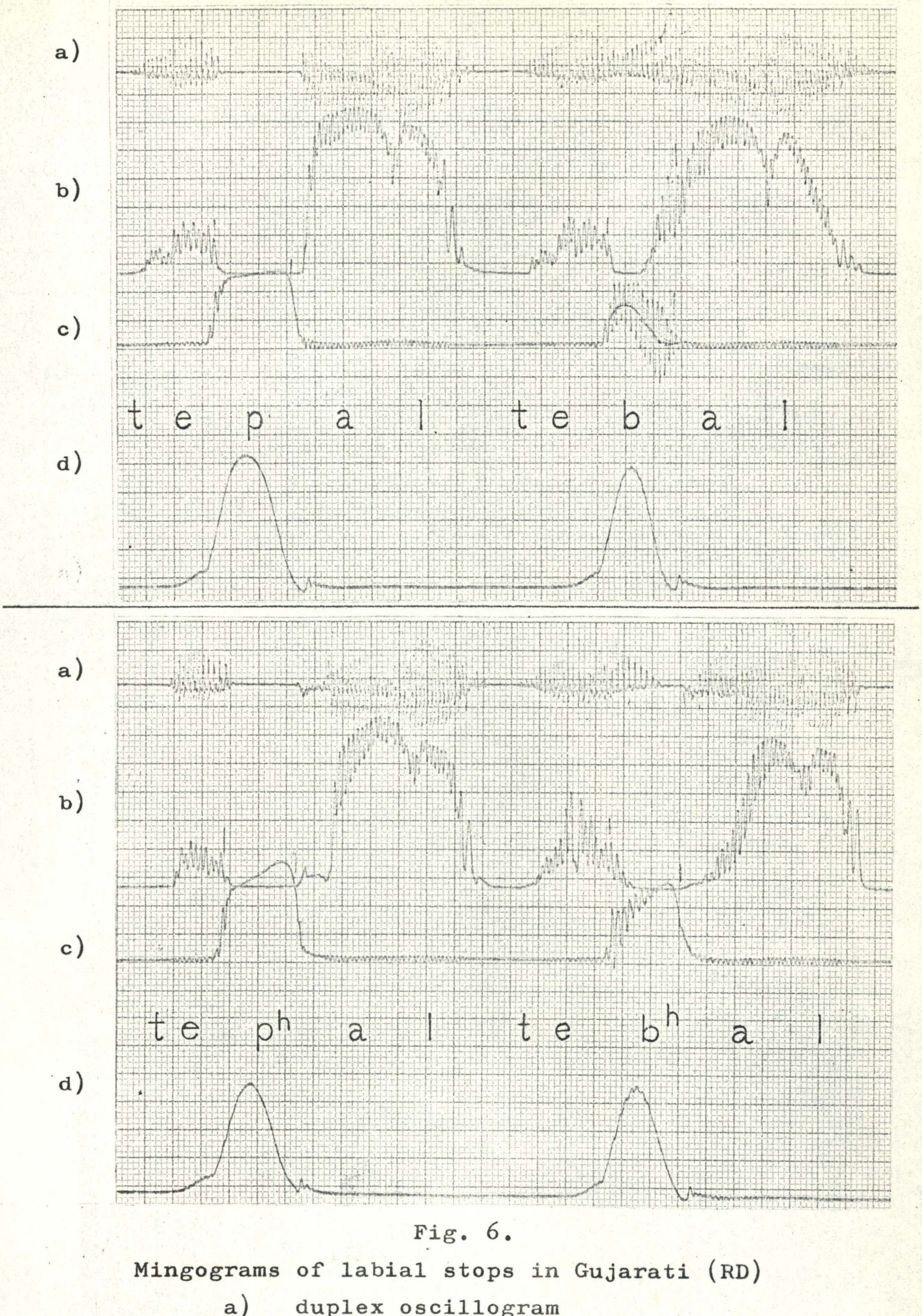


Fig. 6.

Mingograms of labial stops in Gujarati (RD)

a) duplex oscillogram
b) intensity curve
c) intra-oral air pressure
d) lip pressure

Table V

Relations between p ph b and bh in 16 word series pronounced in alternating order (Gujarati).

A.

1	Degree of voicing	$ph\text{-}p \overset{(16)}{<} bh \overset{(12)}{<} b$
2	Intra-oral air pressure	$ph \overset{(13)}{>} p \overset{(15)}{>} bh \overset{(16)}{>} b$
3	Lip pressure	$p \overset{(11)}{>} ph \overset{(12)}{>} b \overset{(14)}{>} bh$
4	Duration of closure period	$p\text{-}ph \overset{(12)}{>} b\text{-}bh$

B.

	Intensity of voicing		Intra-oral air pressure	
	b	bh	b	bh
rising	16	0	0	16
falling	0	16	16	0

Table VI

Time relations between intra-oral air pressure and lip pressure.

A. Distances

		SRO (list B) p	SRO (list B) b	CHH p	CHH b
	N	38	38	36/27	36/27
1. Distance from the implosion to the lip pressure maximum		6.9	6.o	7.3	5.9
Distance in percentage of the duration		34%	38%	41%	37%
2. Distance from the implosion to the air pressure maximum		18.3	13.o	17.9	15.1
Distance in percentage of the duration		95%	82%	1oo%	1oo%

B.

		p	b
	N	38	38
Intra-oral air pressure measured at the point of maximum lip pressure, and indicated in percentage of the maximum air pressure		79%	68%

C. Air pressure and lip pressure in percentage of the corresponding maximum pressures, measured at 7o% of the distance from implosion to explosion.

	SRO pa	SRO pi	SRO pu	SRO ba	SRO bi	SRO bu	CHH pa	CHH pi	CHH pu	CHH ba	CHH bi	CHH bu
Air pressure (rising)	92%	93%	87%	8o%	83%	8o%	98%	96%	95%	95%	95%	97%
Lip pressure (falling)	74%	72%	62%	71%	71%	61%	72%	56%	43%	63%	42%	2o%

air pressure has only reached 79 per cent (p) or 68 per cent (b) of its maximum value. The fact that the lip pressure maximum is reached earlier than the air pressure maximum is not in itself sufficient to contradict the hypothesis, but the crucial point is that it decreases rapidly again, while the intra-oral air pressure is still rising. Table VI,C gives the values for the two pressures at an arbitrary point of the closure period (at 7o per cent distance from the implosion). At this point the lip pressure has decreased considerably, particularly before u, and particularly in CHH's recordings, which are more typical than those of SRO (the rubber bulb used for SRO had somewhat more inertia, and her curves do not always reach zero at the explosion). Similar relations have been found in curves of Danish, German and Gujarati. The lip pressure seems to increase and decrease independently of the air pressure (see also Figs. 6 and 8a).*)

From all these facts one must draw the conclusion that intra-oral air pressure and lip pressure are independent factors. And this has two consequences: (1) that lip pressure, when it is not a mechanical result of the air pressure, must be an independent factor of tenseness, (2) that air pressure need not belong with this feature.

5.3.3. Intra-oral air pressure and voicing. The intra-oral air pressure seems to be much more intimately related to voicing.

A comparison between different languages shows that in languages where bdg are voiced, these have a much lower intra-oral air pressure than ptk (e.g. French), whereas in languages where they are voiceless the difference is very small (e.g. Danish and the French spoken by CHH). Also within the same

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*) In a discussion at the Technical High School in Stockholm, where I gave a lecture on these problems in February 1969, Sven Öhman and J. Liljencrantz objected that the mechanical lip pressure does not only depend on the muscular activity of the lips, but also on the air pressure , and the early decrease in lip pressure might be due to the air pressure. This is possible, but a glance at Fig. 6 shows that the lip pressure decreases in exactly the same way in voiced b as in the other consonants, although the air pressure is very low and reaches zero before the explosion.

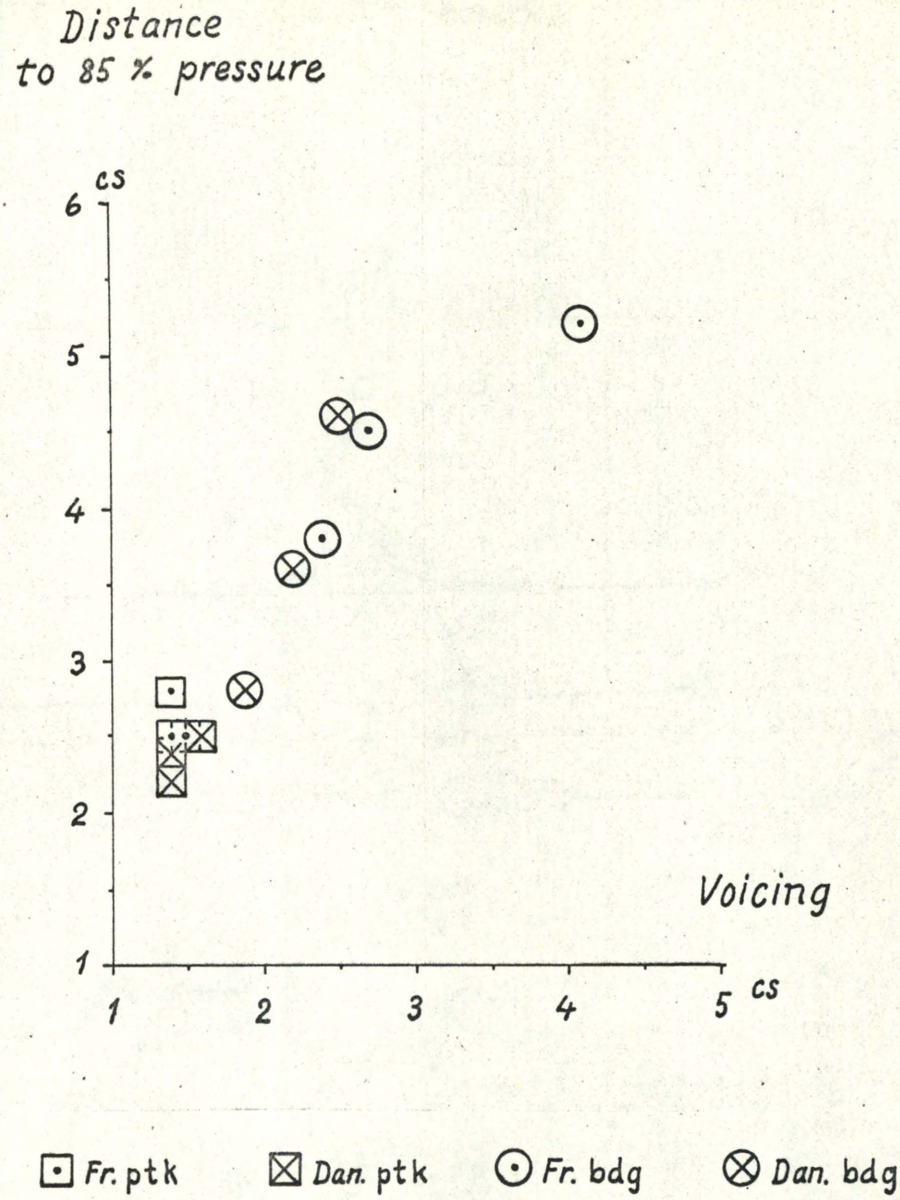

Fig. 7.
Correlation between voicing and intra-oral air pressure

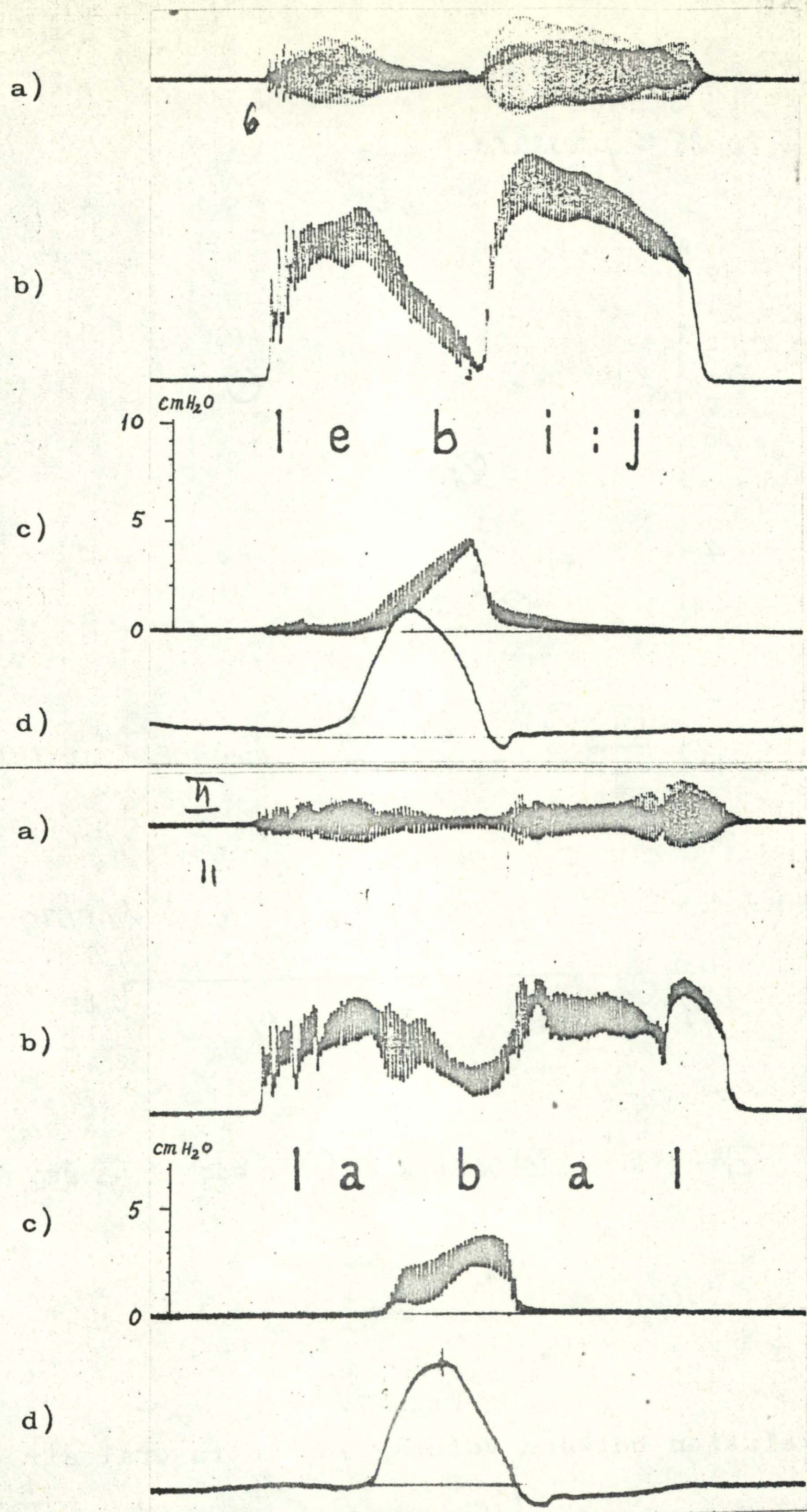

Fig. 8 a.

Mingograms showing the relation between voicing and intra-oral air pressure (SRO)

a) duplex oscillogram
b) intensity curve
c) intra-oral pressure
d) lip pressure

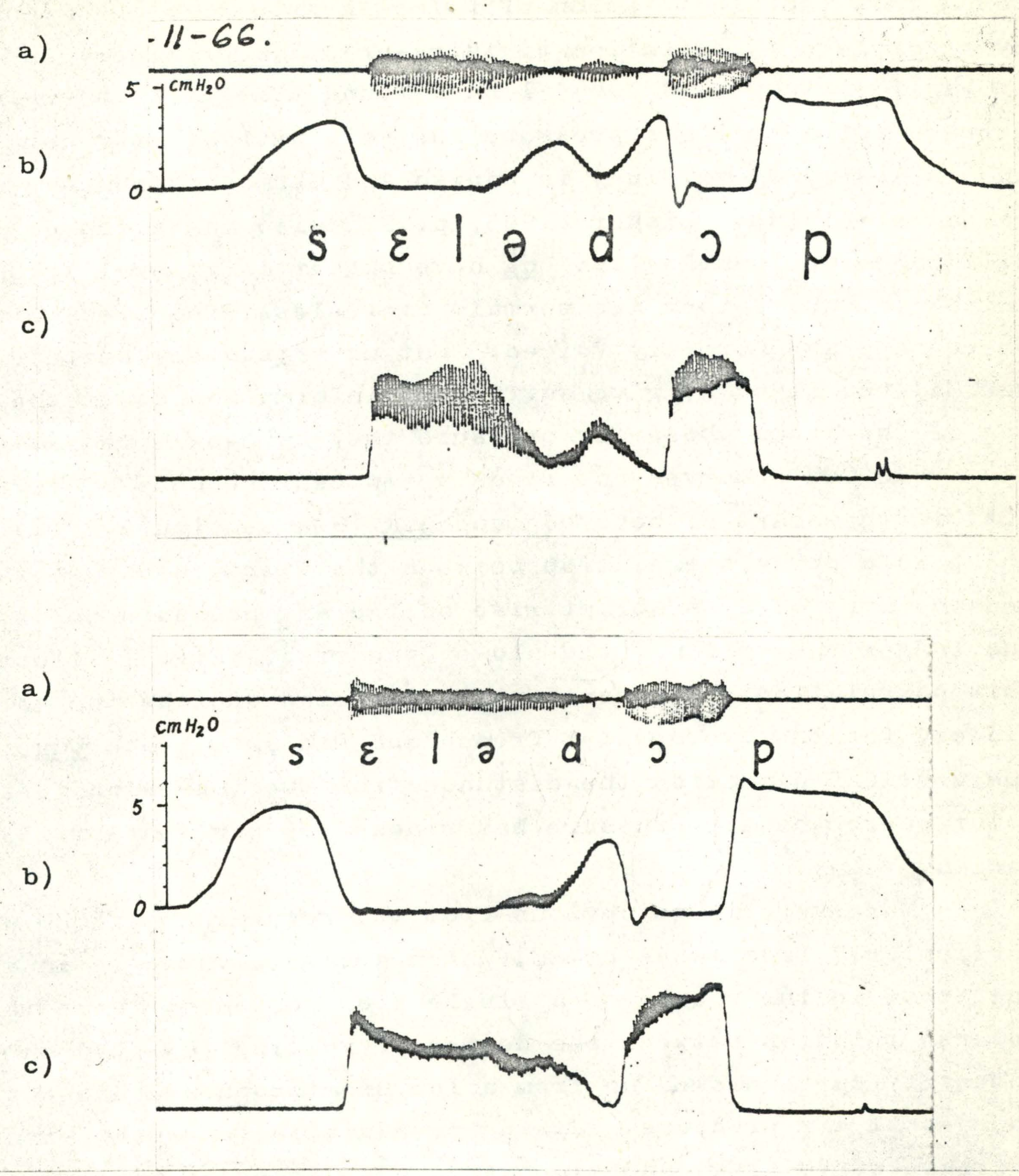

Fig. 8 b.

Mingograms showing the relation between voicing and intra-oral air pressure (EH)

a) duplex oscillogram
b) intra-oral air pressure
c) intensity curve

language this relation can be observed. O. Thorsen (1967) has found that the assimilation of voice in French is accompanied by a complete assimilation of intra-oral air pressure, and in an earlier study (EFJ 1964) I have found a negative correlation between intra-oral air pressure and voicing (both for duration and intensity of voicing) in Danish and German consonants with variable voicing. Lisker (1965, p. 12) also makes the observation that American English bdg have higher intra-oral pressure initially, where they are normally voiceless, than medially, where they are normally voiced. But unfortunately neither he nor Malécot (1966 a) give sufficient information about the voicing of the stops whose air pressure they have examined.

In CHH's curves one finds a few centiseconds of voicing just in the start of both bdg and ptk (see section 2.2.1.), and there is a close correlation between the averages of voicing and the more or less abrupt rise of the air pressure curve: the longer the voicing, the slower the rise. Fig. 7 illustrates this correlation. The horizontal dimension depicts the voicing (in cs) for the averages of French and Danish ptk and bdg, and the vertical dimension the distance from the implosion to the point where the air pressure has reached 85 per cent of its maximum value.

Moreover, it is obvious from the recordings of SRO and particularly from those of EH, which are more variable in voicing, that in the course of a single stop consonant there is an inverse relation between the degree of voicing (as seen on the intensity curve picked up from a larynx microphone) and the intra-oral air pressure. Rising pressure is connected with a decrease of voicing, and vice versa. A number of mingograms demonstrating this inverse relation are shown in Fig. 8. The curves form almost perfectly symmetrical figures.

Finally the same inverse relation is found in the curves of Gujarati. It appears from Table I,A,1-2 that the voiced stops have a lower air pressure than the voiceless stops, and that bh has less voicing but a higher air pressure than b. Moreover, Table VI,B shows that in all cases b has increasing voicing and falling air pressure, whereas bh has decreasing voicing and rising air pressure (see also Fig. 6).

The intimate relation between voicing and air pressure is thus quite obvious. The problem is what is cause and what is effect.

Abramson-Lisker try to derive all the differences from the position of the glottis and the timing relations between glottis movement and oral closure. This is certainly very important, but the mechanism seems to be somewhat more complicated.

(A) It is evident that if the glottis is wide open it cannot vibrate, and the pressure during the oral closure will be high. And if the closure is released before the glottis is closed the stops will be aspirated.

But perhaps "closure lead" would be a better terminology than "voicing lag". For, according to Rothenberg (1968, p. 74) (see also Ventsov 1966), the opening and closing movement of the glottis requires a certain time (the minimum being 8-lo cs, and the average somewhat longer), whereas the oral closure duration can be varied more freely. This view can be supported by the observation that Danish aspirated stops have very short closure periods, often 6-9 cs in stressed syllables in running speech, and the strongly aspirated <u>t</u> has a shorter closure period than <u>p</u> and <u>k</u>. CHH's glottograms in Fig. 1 also show that, at any rate for <u>k</u>, the difference between her French and Danish stops is rather a difference in the duration of the closure than in that of the glottal movement.

(The Gujarati speaker RD has no consistent difference in closure duration between <u>ph</u> and <u>p</u>, although the tendency toward shorter closure in <u>ph</u> is obvious.)

However, if the glottis is relatively narrow, which is probably often the case in unaspirated <u>ptk</u> e.g. in French or Russian, the movement can hardly be assumed to require the same time as when it is wide open, and the reasoning of Rothenberg may not hold.

(B) If, on the other hand, the glottis is narrow, voicing is not excluded, but apart from a narrower glottis it requires a subglottal overpressure.

In Danish <u>bdg</u> the glottis seems to be relatively open at the implosion, and the supraglottal pressure is built up in the course of 2-3 cs at the same rate as the supraglottal pressure in <u>ptk</u>. Therefore, although the glottis becomes more closed during the oral closure period, the consonant will remain voiceless. It is the degree of opening of the glottis during the implosion phase which is important.

Even if there is only a slight opening in the start of <u>bdg</u>, it will not take many centiseconds before the supraglottal pressure becomes too high to allow voicing, if no other mechanism intervenes. This development is accelerated by the effect of the rising supraglottal pressure on the vibratory mode of the vocal cords: the opening phase becomes longer and more air comes through (see Fant 1960, pp. 266-267 and Halle-Stevens 1967, p. 268).

If the supraglottal pressure is drastically decreased, the vocal cords will immediately start vibrating. This has been shown by Ventsov (1966) by means of the following set-up: The subject speaks into a wide tube, which is closed at the opposite end. During the closure of a stop consonant the experimenter can open the tube by means of a valve, so that the air escapes. Under these conditions Russian p becomes immediately voiced, and Ventsov draws the conclusion that the vocal cords must be relatively close. During a stay in Leningrad I had the opportunity to use the instrument, and it turned out that Danish b becomes voiced when the valve is opened, whereas Danish p remains voiceless, except when the opening takes place in the beginning of the closure period. This confirms the observations of the different degree of glottal opening in Danish p and b.

In normal speech the supraglottal pressure can be reduced by an enlargement of the cavities. This mechanism has been observed for Bengali voiced stops by Senn (1935), for Dutch by Slis (1967), for English by Perkell (1965 a and 1965 b), and it can also be observed in the X-ray pictures of Russian stops by H. Koneszna and Zawadowski (1956). The enlargement is normally achieved by an expansion of the pharynx or a lowering of the larynx. This allows voicing to continue in bdg. If the supraglottal air pressure is very much reduced, the stop may become implosive. In Gujarati implosive stops occur as free variants of voiced stops.

Perkell (1965) and Chomsky-Halle (1968) consider the difference in supraglottal cavity size between ptk and bdg as an effect of tenseness: in ptk the walls are tense and stiff and cannot be expanded, in bdg they are lax and are expanded passively by the air pressure. Rothenberg (1968) does not consider a passive expansion as sufficient for a longer continuation of voicing, and assumes that there is also an active expansion, and moreover there is the possibility of letting some air escape through a leakage in the velic closure. I am inclined to think that Rothenberg is right. Danish bdg do not display any expansion, but they are not tense consonants. I think the expansion is due to muscular activity and that it has the purpose of making voicing possible, i.e. that it is part of the mechanism of voicing. The reduction of the pressure is a means to an end. It is also difficult to understand why Perkell considers the widening of the pharynx in bdg as passive and typical of lax consonants, whereas the widening of the pharynx in i versus I is considered as a feature of the tense vowel (1965 a).

5.3.4. Duration. The longer duration of the closure period in e.g. French ptk is normally considered as belonging to the tenseness feature, and the shortening of the preceding vowel as a consequence of the force of the consonant (e.g. Delattre 1939, 1940, 1941). This seems plausible, since the difference is particularly stable in languages which have a clear difference in organic pressure too, e.g. French, Swiss German, and Korean. Cp. also that Danish b has both stronger lip pressure and longer closure duration than p. Rothenberg, on the other hand, considers the length of the consonant closure as a means to avoid aspiration (1968, pp. 83-84). But, as observed above, this argument presupposes the assumption of a widely open glottis for these consonants, and this can hardly be assumed.

Halle-Stevens (1967, p. 269) and Chomsky-Halle (1968, p. 301) explain the longer vowel before voiced stops and fricatives as a delay caused by the time required for adjusting the vocal cords to the configuration appropriate for consonant vibrations. But this adjustment may be a mechanical consequence of the articulatory constriction, which does not require particularly long time. It is not quite convincing either why this adjustment cannot start during the vowel just as the opening before voiceless consonants; as a matter of fact many airflow curves show a rise at the end of the vowel before voiced stops, although it is not as high as before voiceless consonants. Chomsky-Halle mention that before nasals, which do not require any adjustment, the vowels are shorter than before voiced stops. I have not found any confirmation of this for German, nor is such a difference found in the measurements of Czech vowels by Per Jacobsen (this volume pp. 135-142).

The assumption that it is the adjustment of the vocal cords for consonant vibrations which lengthens the vowel is also contradicted by the following two facts: (1) When French bdg vzʒ become voiceless through assimilation to a following consonant they still preserve (at least part of) their lengthening effect on the preceding vowel (Thorsen 1967). (2) Also French speakers who normally have voiceless vzʒ (CHH and her sister ThM) have longer vowels before these consonants than before fsʃ, although the difference is somewhat smaller (K. Landschultz 1968). This is also valid for bdg (EFJ 1969). Sometimes these consonants have partial voicing, but the preceding vowel is not longer in these cases than in cases with completely voiceless vzʒ (oral communication from K. Landschultz).

6. Final remarks.

6.1. As it appears from the preceding pages, I am inclined to keep voicing, aspiration and tenseness as three separate phonetic features. By phonetic feature I mean the general phonetic dimensions which may be utilized for distinctive purposes in various languages. Two different phonetic features may be combined to one complex phonemic feature (e.g. tenseness and voicing in French stops, rounding and front-back in Spanish vowels).

The criterion for keeping phonetic features apart must be their independency. One must not be a mechanical consequence of the other.

In 5.1. above arguments were given for keeping tenseness and aspiration apart, the differences being exemplified by a comparison between French and Danish ptk. They seem to be independent, and they may be combined in different ways.

As for tenseness and voicing, there seems to be a certain affinity in the sense that voiced stops are generally lax; however, according to the most common description of voice assimilation in French, French ptk may become voiced while remaining tense. At any rate the assimilation of duration does not seem to be complete. The total assimilation of intra-oral pressure may be due to the fact that intra-oral pressure is part of the voicing feature (Thorsen 1967).

Voicing and aspiration may be combined as proposed by Abramson-Lisker as steps in the same dimension if Indian aspirated bdg are left out of consideration, but somehow these must belong to the voicing dimension, which means that in any case aspiration can be combined with two different steps in this dimension. - Moreover, it is too simple to consider voiced stops, unaspirated stops and aspirated stops as steps in one dimension. Voicing requires an extra mechanism, not only a certain position of the glottis.

6.2. The phonetic qualities described for French and Danish can be tentatively distributed on these three features in the following way (see also Table I):

Voicing.

Voiced stops - as compared with voiceless stops - are characterized physiologically by having a narrow glottis (whereas the glottis in voiceless stops may be wide or narrow); moreover they have a larger pharynx cavity, and consequently a lower supraglottal pressure permitting vibrations of the vocal cords, whereas the higher supraglottal air pressure in the voiceless stops prevents the vocal cords from vibrating. Voiced stops have also less airflow.

Acoustically, voiced stops are characterized by periodic sound at a low frequency during the closure, and by a lower start of the fundamental of the following vowel, whereas voiceless stops have silent closure and a higher start of the vowel.

Aspiration.

Physiologically, aspirated stops are characterized (as against unaspirated stops) by having a wider glottis opening and by the fact that the release of the oral closure takes place at a time when the glottis is still relatively wide open, which causes a strong airflow after the explosion.

Acoustically, aspirated stops are characterized by a long open interval with noise at the frequencies of or leading toward the formants (above F_1) of the following vowel; moreover they exhibit a high start and short duration of the F_1-transition.

Tenseness.

Physiologically, tense stops are characterized by having a stronger organic pressure and a longer closure period than lax stops, and probably by a quicker and more precise movement of the articulating organs.

Acoustically, they are characterized by a longer closure period and a shortening of the preceding vowel and, to some extent, of the following vowel, perhaps also by a stronger intensity of the explosion (this is still to be proved) and a quicker intensity rise of the following vowel, and finally by a shorter distance from the explosion to the top of the transition and by a shorter transition.

In CHH's French stops there was a certain difference of aspiration before i and u - but before a tenseness seemed to be the only distinguishing feature. However, no difference was found neither in the explosions nor in the transitions. As mentioned above, it cannot be excluded that differences in explosion type might be found by a more appropriate technique. Spectrograms did not reveal any difference in the frequency of the explosions (cp. Halle, Hughes, Radley 1957).

It is obvious that this distribution is very preliminary, and, on the whole, there are still so many unsolved problems that much of what has been said on the preceding pages has the character of speculations. We need more investigations of subglottal pressure, of glottis opening, of muscular activity and organic pressure, of the intensity and type of the explosions and of the transitions.

P.S.: After having completed this report my attention was drawn to the paper by Abramson and Lisker "Laryngeal Behavior, the Speech Signal and Phonological Simplicity", Status Report on Speech Research, Haskins Laboratories 11 (1967), pp. 23-33, in which the authors draw some general conclusions from their various experiments with stop consonants.

I agree in considering voicing and supraglottal air pressure as closely related and in pointing to the possibility that the widening of the pharynx in voiced stops may be an active process, but not in the general conclusions, since the authors maintain that voice onset timing may be the only fundamental feature distinguishing categories of stops in various languages.

References:

Abramson, Arthur S. and Leigh Lisker. 1965. "Voice Onset Time in Stop Consonants: Acoustic Analysis and Synthesis", Status Report on Speech Research, Haskins Laboratories 3.1.

Brunner, Rudolf. 1953. "Die Stimmhaftigkeit der französischen und zürichdeutschen Lenislaute", Zeitschrift für Phonetik 7, pp. 153-196 und 289-319.

Charbonneau, abbé René. 1955. La palatalisation de t/d en Canadien-Français: Etude de phonétique expérimentale (Montreal).

Chlumsky, J. 1922. "Les consonnes anglaises comparées aux consonnes françaises à l'aide du palais artificiel et de l'observation directe", Revue de phonétique 4, pp. 189-218.

Chomsky, N. and M. Halle. 1968. The Sound Pattern of English (New York, Evanston, London).

Cooper, F.S., P. Delattre, A.M. Liberman, J.M. Borst and L.J. Gerstman. 1952. "Some Experiments in the Perception of Synthetic Speech Sounds", JASA 24,6, pp. 597-606.

Delattre, Pierre. 1939. "Durée vocalique et consonnes subséquentes", Le Maître Phonétique 67 (= Studies in French and Comparative Phonetics 1966, pp. 130-132).

Delattre, Pierre. 1940a. "Anticipation in the Sequence: Vowel and Consonant-Group", The French Review 13 (= Studies in French and Comparative Phonetics 1966, pp. 122-.27).

Delattre, Pierre. 1941. "La force d'articulation consonantique en français", The French Review 14, pp. 220-232, (= Studies in French and Comparative Phonetics 1966, pp. 111-120).

Delattre, Pierre. 1958. "Les indices acoustiques de la parole", Phonetica 2, pp. 108-118 and 226-251.

Delattre, Pierre. 1961. "Le jeu des transitions de formants et la perception des consonnes", Proceedings of the IV International Congress of Phonetic Sciences, pp. 407-417.

Delattre, Pierre. 1962. "Some Factors of Vowel Duration and their Cross-Linguistic Validity", JASA 34 pp.1-2. (= Studies in French and Comparative Phonetics 1966, pp. 133-140).

Delattre, Pierre. 1964. "De la hiérarchie des indices acoustiques pour la perception de la parole", Proceedings of the V International Congress of Phonetic Sciences (Münster), pp. 244-251.

Delattre, Pierre. 1968. "From Acoustic Cues to Distinctive Features", Phonetica 18, pp. 198-230.

Denes, P. 1955. "Effect of Duration on the Perception of Voicing", JASA 27, pp. 761-764.

Dieth, E. und R. Brunner. 1943. "Die Konsonanten und Geminaten des Schweizerdeutschen experimentell untersucht", Festschrift Jud. Romanica Helvetica 20, pp. 737-762.

Durand, Marguerite. 1936. Etude expérimentale sur la durée des consonnes parisiennes. Bibliothèque du "français moderne" (Paris).

Durand, Marguerite. 1956. "De la perception des consonnes occlusives: questions de sonorité", Word 12, pp. 15-34.

Evertz, Erich. 1929. Beiträge zur Phonetik der südfranzösischen Plosive:eine experimentelle Untersuchung (Bonn).

Fabre, Ph. 1961. "Glottographie respiratoire", Comptes rendus des séances de l'Académie des sciences 6, pp. 1386-1388.

Fairbanks, Grant et Murray S. Miron. 1958. "Effects of Vocal Effort upon the Consonant-Vowel Ratio within the Syllable", JASA 29, pp. 621-626.

Falc'hun, F. 1965. "L'énergie articulatoire des occlusives", Phonetica 13, pp. 31-36.

Fant, Gunnar. 1958. "Modern Instruments and Methods for Acoustic Studies of Speech", Acta Polytechnica Scandinavica.

Fant, Gunnar. 1960. Acoustic Theory of Speech Production (Mouton).

Fischer-Jørgensen, Eli. 1954. "Acoustic Analysis of Stop Consonants", Miscellanea Phonetica II, pp. 42-59.

Fischer-Jørgensen, Eli. 1963. "Beobachtungen über den Zusammenhang zwischen Stimmhaftigkeit und intraoralem Luftdruck", Zeitschrift für Phonetik, Sprachwissenschaft und Kommunikationsforschung 16, pp. 19-36.

Fischer-Jørgensen, Eli. 1964. "Sound Duration and Place of Articulation", Zeitschrift für Phonetik etc. 17, pp. 175-208.

Fischer-Jørgensen, Eli. 1966. "Phonetic Analysis of Danish Stop Consonants", Annual Report of the Institute of Phonetics, University of Copenhagen 1, pp. 31-33.

Fischer-Jørgensen, Eli. 1969. "Les occlusives françaises et danoises d'un sujet bilingue", Festschrift Martinet 2 (in print).

Fischer-Jørgensen, Eli, Børge Frøkjær-Jensen and Jørgen Rischel. 1966. "Preliminary Experiments with the Fabre Glottograph", Annual Report of the Institute of Phonetics, University of Copenhagen 1, pp. 22-3o.

Frøkjær-Jensen, Børge. 1967. "A Photo-Electric Glottograph", Annual Report of the Institute of Phonetics, University of Copenhagen 2, pp. 5-19.

Fujimura, Osamu. 1959. Some Characteristics of Stop Consonants.(Cleveland). 4 pp.

Fujimura, Osamu. 1961. "Bilabial Stop and Nasal Consonants: A Motion Picture Study and its Acoustical Implications", Journal of Speech and Hearing Research 4, pp. 233-247.

Gendron, Jean-Denis. 1966. Tendances phonétiques du français parlé au Canada (Paris).

Gimson, A.C. 1962. An Introduction to the Pronunciation of English (2nd ed. 1964).

Halle, M., G.W. Hughes and J.P.A. Radley. 1957. "Acoustic Properties of Stop Consonants", JASA 29, pp. 1o7-116.

Halle, M. and K. Stevens. 1967. "On the Mechanism of Glottal Vibration for Vowels and Consonants", MIT QPR no. 85, pp. 267-27o.

Harris, Katherine S., Gloria Lysaught and Malcom M. Schvey. 1965. "Some Aspects of the Production of Oral and Nasal Labial Stops", Status Report on Speech Research, Haskins Laboratories 2.1.

Jakobson, Roman, G. Fant and M. Halle. 1952. Preliminaries to Speech Analysis: The Distinctive Features and Their Correlates (Technical Report no. 13. Massachusetts Institute of Technology).

Jakobson, Roman and M. Halle. 1962. "Tenseness and Laxness", Selected Writings, pp. 55o-555.

Jespersen, Otto. 1914. Lehrbuch der Phonetik, 5. Auflage (1932).

Kaneko, Naomichi. 1961. "An Experimental Observation and Phonetic Analysis of Opposite Consonants such as /p/ : /b/", Study of Sounds IX, pp. 53-64.

Kim, Chin-W. 1965. "On the Autonomy of Tensity Feature in Stop Classification (with special reference to Korean Stops)", Word 21, pp. 339-359.

Kloster Jensen, M. 1956. "Zur Glottalität der reinen Tenues", Zeitschrift für Phonetik 9, pp. 344-359.

Koneczna, H. et W. Zawadowski. 1956. Obrazy rentgenograficzne glosek rosyjskich (Warszawa).

Ladefoged, P. 1967. Linguistic Phonetics. Working Papers in Phonetics, UCLA 6.

Landschultz, Karen. 1967. "Duration of French Vowels Before Fricatives", Annual Report of the Institute of Phonetics, University of Copenhagen 2, pp. 1o9-118.

Liberman, Alvin M. 1957. "Some Results of Research on Speech Perception", JASA 29,1, pp. 117-123.

Liberman, Alvin M., P.C. Delattre and F.S. Cooper. 1958. "Some Cues for the Distinction between Voiced and Voiceless Stops in Initial Position", Language and Speech 1, pp. 153-167.

Liberman, Alvin M., F.S. Cooper, K.S. Harris and P.F. Macneilage. 1962. "A Motor Theory of Speech Perception", Speech Communication Seminar, Stockholm.

Lindblom, B.E.F. 1967. "Vowel Duration and a Model of Lip Mandible Coordination", Quarterly Progress and Status Report, Speech Transmission Laboratory Stockholm 4/1967, pp. 1-29.

Lisker, Leigh. 1957. "Closure Duration and the Intervocalic Voiced-Voiceless Distinction in English", Language 33, pp. 42-49.

Lisker, Leigh. 1965. "Supraglottal Air Pressure in the Production of English Stops", Status Report on Speech Research, Haskins Laboratories 4.3.

Lisker, Leigh. 1966. "Measuring Stop Closure Duration from Intra-oral Pressure Records", Status Report on Speech Research, Haskins Laboratories 7/8.5.

Lisker, Leigh, and Arthur S. Abramson. 1964. "A Cross-Language Study of Voicing in Initial Stops: Acoustical Measurements", Word 2o, pp. 384-422.

Lisker, Leigh, and Arthur S. Abramson. 1966. "Some Effects of Context on Voice Onset Time in English Stops", Status Report on Speech Research, Haskins Laboratories 5/6.1.

Lisker, Leigh, A.S. Abramson, F.S. Cooper and M.H. Schvey. 1966. "Transillumination of the Larynx in Running Speech", Status Report on Speech Research. Haskins Laboratories 5/6, 4.1.

Lisker, Leigh, and Arthur S. Abramson. 1967. "The Voicing Dimension: Some Experiments in Comparative Phonetics", Status Report on Speech Research. Haskins Laboratories 11. 9-16.

Lotz, John, Arthur S. Abramson, Louis J. Gerstman, Frances Ingemann and William J. Nemser. 196o. "The Perception of English Stops by Speakers of English, Spanish, Hungarian and Thai: A Tape-Cutting Experiment", Language and Speech 3, pp. 71-77.

Malécot, André. 1955. "An Experimental Study of the Force of Articulation", Studia Linguistica 9, pp. 35-44.

Malécot, André. 1966a. "The Effectiveness of Intra-Oral Air-Pressure-Pulse Parameters in Distinguishing Between Stop Cognates", Phonetica 14, pp. 65-81.

Malécot, André. 1966b. "Mechanical Pressure as an Index of 'Force of Articulation'", Phonetica 14, pp. 169-180.

Malmberg, Bertil. 1943. Le système consonantique du français moderne: Etudes de phonétique et de phonologie=Etudes Romanes de Lund VII.

Öhman S., R. Leanderson and A. Persson. 1966. "EMG Studies of Facial Muscles Activity in Speech II", Speech Transmission Laboratory, Stockholm. Quarterly Progress and Status Report 1/1966, pp. 1-5.

Perkell, J. 1965a. "Studies of the Dynamics of Speech Production", MIT QPR no. 76, pp. 253-257.

Perkell, J. 1965b. "Cineradiographic Studies of Speech: Implications of a Detailed Analysis of Certain Articulatory Movements", Congrès International d'Acoustique, Liège, Paper A 32.

Peterson, Gordon E. and Ilse Lehiste. 1960. "Duration of Syllable Nuclei in English", JASA 32, pp. 693-703.

Rothenberg, Martin. 1968. The Breath-Stream Dynamics of Simple-Released-Plosive Production. Bibliotheca Phonetica 6.

Roudet, L. 1900a. "De la dépense d'air dans la parole", La Parole 2, pp. 201-230.

Roudet, L. 1900b. "Recherches sur le rôle de la pression sousglottique dans la parole", La Parole 2, pp. 599-612.

Roudet, L. 1910. Eléments de phonétique générale.

Rousselot, J.-P. 1891. Les modifications phonétiques du langage etudiées dans le patois d'une famille. (Paris).

Rousselot, J.-P. 1897. Principes de phonétique expérimentale I (Paris). 2e édition 1924.

Rousselot, J.-P. 1899. "Etude de prononciations parisiennes", La Parole 1, pp. 481-549.

Senn, A.C. 1935. "An Experimental Study of Bengali Occlusives", Proc. II Congr. Phon. Sc., pp. 184-193.

Simon, Pela. 1961. "Les consonnes françaises et leurs variations dans la chaine parlée d'après des films radiologiques", Proceedings of the IV International Congress of Phonetic Sciences (Helsinki), pp. 241-249.

Simon, Pela. 1967. Les consonnes françaises: mouvements et positions articulatoires à la lumière de la radiocinématographie (Paris).

Slis, I.H. 1967. "What Causes the Voiced-Voiceless Distinction?", IPO Annual Progress Report 2, pp. 71-76.

Slis, I.H. and P.H. Damsté. 1967. "Transillumination of the glottis during voiced and voiceless consonants", IPO Annual Progress Report 2, pp. 1o3-1o9.

Straka, Georges. 1942. "Notes de phonétique générale et expérimentale", Bulletin de la faculté des lettres de Strasbourg 1.

Straka, Georges. 1952. "La Prononciation Parisienne", Bulletin de la faculté des lettres de Strasbourg 1 -45.

Straka, Georges. 1963. "La division des sons du langage en voyelles et consonnes peut-elle être justifiée?", Travaux de linguistique et de littérature 1, pp. 17-99.

Straka, Georges. 1965a. Album Phonétique (Quebec).

Straka, Georges. 1965b. "Naissance et disparition des consonnes palatales dans l'évolution du latin au français", Travaux de linguistique et de littérature 3,1, pp. 117-167.

Thorsen, Oluf M. 1966. "Voice Assimilation of Stop Consonants and Fricatives in French and its Relation to Sound Duration and Intra-Oral Air-Pressure", Annual Report of the Institute of Phonetics, University of Copenhagen 1, pp. 67-76.

Ventsov, A. 1967. O rabote golosovykh svyazok pri glukhikh smychnykh intervokalnykh soglasnykh. Mekhanizmy recheograzovaniya i vospriatiya slozhnykh zvukov.