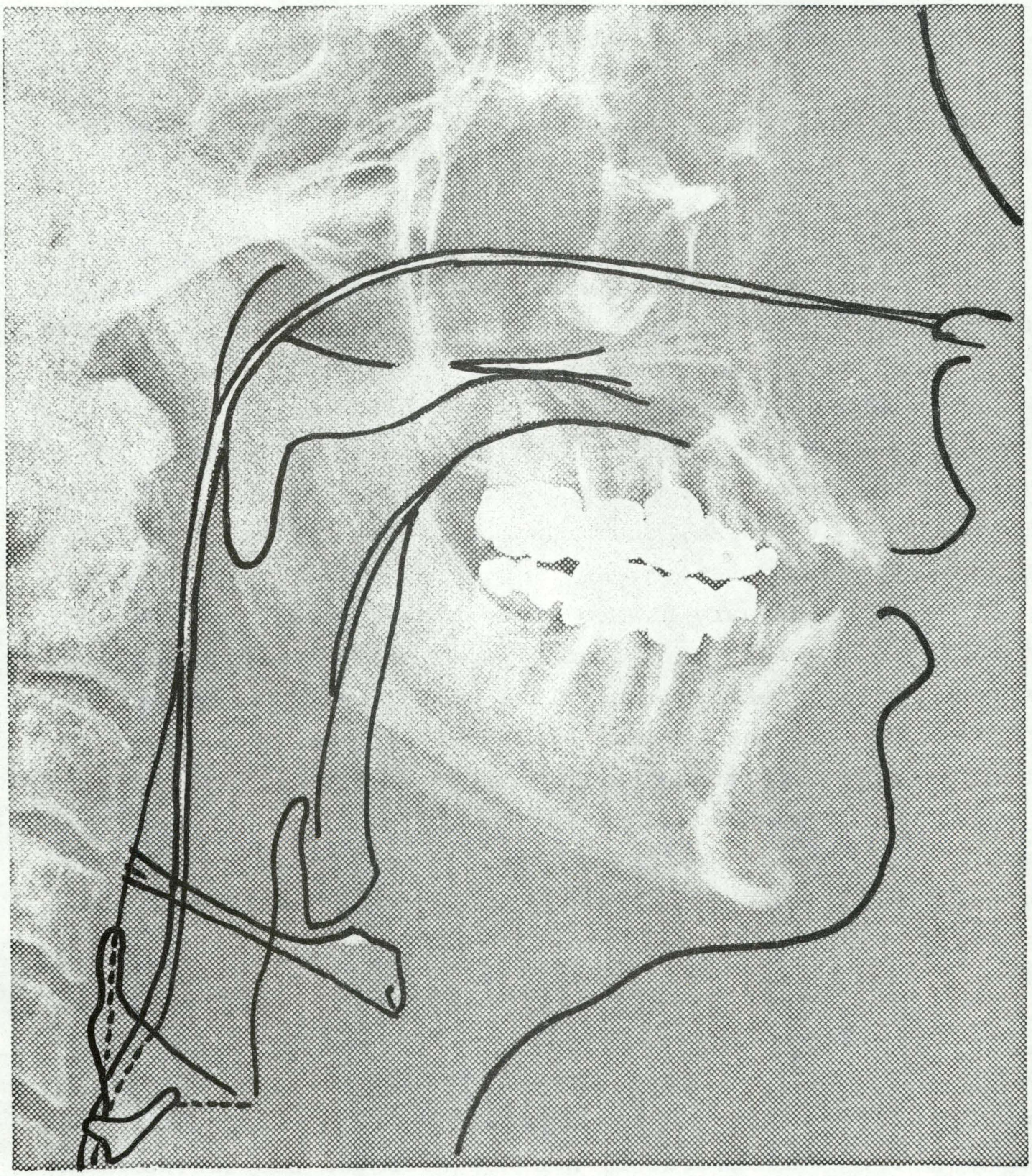
A GLOTTOGRAPHIC STUDY OF SOME DANISH CONSONANTS

Børge Frøkjær-Jensen, Carl Ludvigsen, and Jørgen Rischel
(1971)

This is a reprint of a paper published in the festschrift to Eli Fischer-Jørgensen (Form and Substance, 1971). We have considered it expedient to include the paper in ARIPUC, since other papers on our glottographic research at the Institute of Phonetics have been published in this series. For ease of reference the paper is reprinted virtually without any changes. This means, of course, that the most recent research is not taken into consideration.

It is necessary now to state that the assumptions put forward in the last part of the paper must be taken with a good deal of reservation. Thus, EMG-recordings of the glottis muscles made by Eli Fischer-Jørgensen at the Haskins Laboratories give evidence that there is some activity also in Danish bdg (personal communication). The terms "passive gesture" and "active gesture", used to distinguish between the glottal conditions of bdg and ptk, may thus not be quite appropriate.

In order to throw further light on the problems dealt with in our papers on glottography we are going to work with fiberoptics so that the two approaches can be confronted with each other. Our laboratory has now also got the instrumentation necessary for EMG-recording.



X-ray photograph of a subject (BFJ) with the photo-transistor in position (some displacement of the photo-transistor either upwards or downwards from the position shown here can be tolerated without serious decrease of the signal amplitude).

1. Introduction

The acoustical and physiological properties of Danish stops and - to a lesser extent - fricatives have been the subject of several papers by Eli Fischer-Jørgensen.[1] Thanks to her research, Danish is among the languages in which such features as voicing and aspiration have been thoroughly examined. This is fortunate since Danish is typologically remarkable as far as the system of stop consonants is concerned. It has been found that the stops, i.e. the sets ptk and bdg, are all essentially unvoiced. The alveolar t is typically somewhat affricated but otherwise the distinction between ptk and bdg is in all essentials a matter of aspiration only. Measurements (including glottography) reveal a considerable and stable difference in the duration of the aspiration phase in the two sets of consonants.

The present paper is intended to contribute to this field of research by giving some data on the glottal behaviour in the different kinds of stops. This of course involves some kind of estimate of the degree of glottis aperture in the production of the different sounds. However we have found it especially worth-while to focus our interest on the temporal relationships among the various phases of the oral and glottal gestures involved, since these relationships have not received much attention in previous glottographic work.

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1) Eli Fischer-Jørgensen 1954, 1959, 1963, 1967, 1969, 1970.

In the present paper we give data of the kinds mentioned above for some Danish consonants, and we also venture some hypotheses on the minimum set of laryngeal "commands" required in order to generate the observed phenomena. The study is limited to labials, partly because this simplifies the problems since there is no affrication present, and partly because the choice of labials minimizes the risk of artifacts in the glottograms stemming from tongue movements (cf. section 3 below).

2. The instrumental set-up

The glottograms dealt with in this paper were made by means of the photo-electric glottograph described by Børge Frøkjær-Jensen (1968, 1969). Like those used by Malécot (1965) and Ohala (1966) it has the light source placed below the glottis, the light variations being picked up by a phototransducer inserted through the nose into the pharynx. The light from a light source fed with D. C. current is lead through a 40 cm long plastic rod, which can be tilted so as to stand in any desired angle to the larynx. The transducer together with its terminals was contained in a protecting polyethylene tube which was flexible and transparent and had an outer diameter of only 3 mm. This enabled us to perform the experiments without local anaesthesia.

Information concerning the timing of the maximum glottis aperture in relation to the lip closure and the offset/onset of vocal fold vibrations was obtained by using the instrumental set-up shown in Fig. 1.

Some recordings were made to check the set-up for synchronization of the different channels. These recordings were supplemented by simultaneous recordings of intra-oral air pressure.

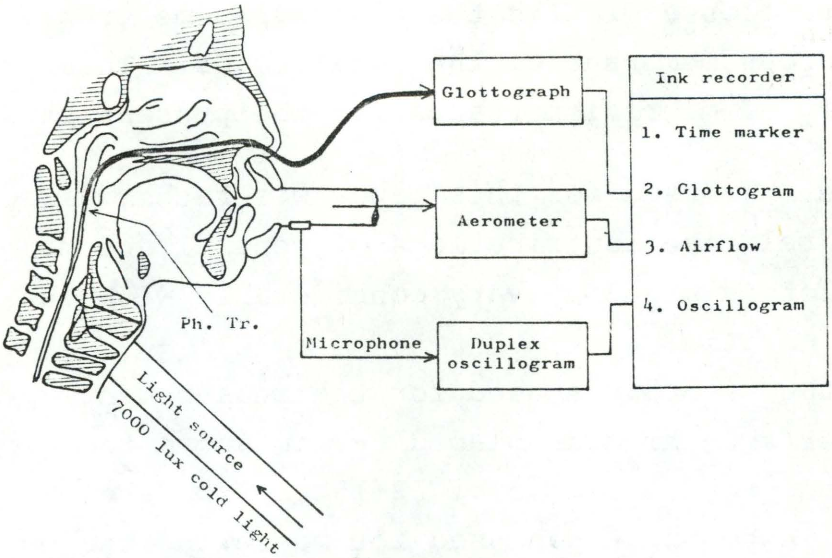

Fig. 1 Block diagram showing the instrumental set-up.

By means of the air pressure curve we have been able to register the time delay of the airflow curve caused by the inertia of the mechanical transducer in the aerometer. We have found this delay to be of the order of a few milli-seconds, which is of the same order as the exactitude of the measurements.

The glottogram and duplex oscillograms were also checked for synchronization. We observed that the moment of first formant excitation was somewhat less than one millisecond delayed in relation to the moment of vocal fold closure as seen in high speed glottograms. If we assume, in accordance with Miller (1959), that the first formant excitation coincides with the closing of the glottis, this difference agrees with the acoustical transmission time form glottis to microphone.

3. Positioning of light source and transducer

We state below some of the more important sources of uncertainty in glottographic observations.

1. With closed glottis there occurs some transillumination of the mucous membrane of the vocal folds. This problem is presumably of minor importance for the present study.

2. The PhTr used for this paper was rather directional. Thus the relative contributions of central and marginal parts of the glottis area may vary considerably with the distance from the glottis.

In the recordings used for the measurements presented in this paper the PhTr was placed 6-7 cm above the glottis. This corresponds to a distance of 12-13 cm from the outer nostril. An X-ray photo of JR was used for measuring the position of the PhTr.

3. Since the variations in the width of the glottis slit differ in the front and the back parts of the entire glottis, the results may be expected to vary according to the location of the PhTr.

4. Tongue movements often misplace the PhTr in vowels with pharyngeal narrowing, which can reduce the signal level considerably. In the case of unfortunate positioning of LS and PhTr, artifacts may also arise in the articulation of velar consonants.

5. A further series of complications have to do with the location of the LS and the direction of the light-beam entering the trachea. With light entering the trachea well below the larynx (the light conducting rod being pressed against the upper edge of the sternum) and directed along the neck towards the glottis, we get traces which agree with our expectations about the gross variations in aperture of voiceless consonants. This, however, requires that the PhTr is fixed in a relatively stable position in the pharynx.

In accordance with Ohala (1966) we did this by fixing the PhTr somewhat above the lower end of the transparent protecting tube which was swallowed into the oesophagus. If the PhTr is fixed in this way the output is reduced considerably, but without such fixing in the oesophagus the output is extremely sensitive to tongue movements.

On the other hand, with a nearly frontal light beam entering the front side of the thyreoid cartilage we get a trace with relatively bigger deflections for each vibratory cycle of the voiced sounds, and with less disturbance from tongue articulations even if the PhTr hangs freely. The difference between these two extremes is illustrated in Fig. 2.

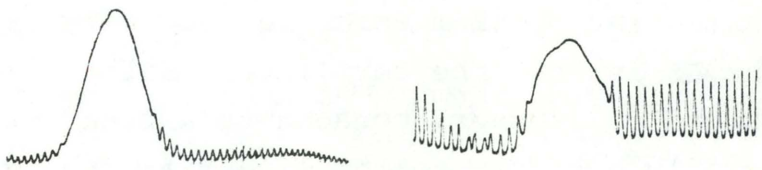

Fig. 2 Intervocalic p with LS placed in the two positions referred to in the text. (Subject JR)

This difference is understandable considering that the nearly horizontal light will pass between the vocal folds along their longitudinal axis and therefore be strongly modulated by small movements of the vocal folds and probably to a somewhat lesser degree by movements of the cartilaginous glottis. The opposite will be true with the light passing through the glottis from below at approximately right angles to the slit, especially if the PhTr hangs close to the back wall of the cavity, as it will probably do when the tube is fixed in the oesophagus. If the various aspects of the glottis behaviour are to be observed, it seems essential not to have the PhTr too close to the glottis. With the PhTr placed just above the cartilaginous glottis it is possible to register recordings where intervocalic voiced h shows a ripple-free peak of glottis aperture of the same size as that for aspirated stops and fricatives, whereas, in the more "normal" traces like those used for the present study (see below) h gives a curve with voice ripple and with less rise than for p and f.

In the present recordings the LS was placed in such a way that the light entered the neck slightly below the thyreoid cartilage. The curves obtained in this way are very similar to those obtained with a more "vertical" light beam, e.g. with a high degree of symmetry between the rising and falling parts of the curve for p, and we feel convinced that this is a reasonably realistic reproduction of the temporal variation in glottis aperture.

One particular problem which we face with certain placements of the LS is that the zero line[1] differs from one type of voiced sound to another, consonants and narrow vowels having generally a higher bottom line than open vowels. This phenomenon, which is most noticeable with frontal light, may partly be due to modulation of the light by slow up-and-down displacements of the vocal folds accompanying different degrees of oral constriction.

If this is true, it means that with small deflections of the glottogram there is no one-to-one relationship between glottis aperture and glottogram curve: a rise in the latter need not necessarily reflect an increase of glottis aperture. However, the shape of the vibratory cycle may be of help here. If the vibrations assume a nearly sinusoidal shape (as they do in voiced h), this is evidence that each fold vibrates freely, without touching during the vibratory cycle.

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1) i.e. the level of the glottogram supposed to represent closed glottis.

3.6. The output level of the glottograph may vary due to slight variations in the exact position of the subject in relation to the light source. Care should therefore be taken that the subject is comfortably seated so that e.g. excessive heating from the light source does not cause changes in his position.

4. Extraction of parameters

On the basis of the three traces recorded on the inkwriter (see Fig. 1 above) we have extracted seven parameters which may serve to give details about the glottal behaviour.

1) The total duration of each consonant: lip closure, explosion, and aspiration in the case of stops; the interval of fricative noise in the case of f. - The beginning of the consonant was taken to be the point in the oscillogram where the amplitude of periodic vibrations is rapidly reduced to a very small value, or these have practically ceased (this definition of the starting point makes sense with all the unvoiced obstruents in question, and in any case the possible error in determining the moment of implosion will be largely the same for p and b). In stops the implosion is of course seen in the airflow curve, but this does not suffice with f. - The end of the consonant was defined as the moment when normal vocal fold vibration is resumed. This point is seen clearly in the oscillogram.

2) Duration of lip closure in the case of stops. This parameter was extracted from the airflow curve, and the results were checked by means of the duplex oscillogram.

3) Duration of the glottal opening phase measured from the moment of lip closure or labiodental constriction to the point of maximum height in the glottogram.[1]

4) Glottis aperture.

As for glottis aperture the information is qualitative only: roughly speaking, the curve goes up if the glottis opens, and vice versa, but the set-up cannot be calibrated with living larynges (van den Berg 1968). In order to get a numerical measure we have given the peak of each (fully

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1) This is not a measure of the total duration of the glottal opening gesture. The duration of a complete abduction of the vocal folds is rather long (according to our glottograms it lies in the range 60-120 ms for sounds produced with large glottis aperture such as p, t, f, s), and it goes without saying that in rapid speech this comparatively slow movement is anticipated in the preceding sound. In some recordings of rapid speech by JR the entirety of the preceding voiced sound (vocoid) is characterized by a rise of the glottogram, i.e. increased leakage through the glottis. This anticipation of glottis opening has been observed earlier by Eli Fischer-Jørgensen (1963, p. 36) on the basis of flow and pressure measurements. - In the present paper we have made no attempt to determine the total durations of the glottal opening and closure movements (these are very difficult to define by mere inspection of curves), but it goes without saying that such measurements will be of paramount importance for the solutions of problems like these: (1) how is the closing gesture "triggered"?, (2) is the opening movement braked by the closing movement, i.e., is there a possible undershoot effect in the peak value? The answers to these questions must await future research.

aspirated) p in the text the prescribed value of 1.00 and normalized the peak value measured for other consonants with reference to the nearest p. This enables us to get an impression of the relation in size between the curves for different consonants.

Moreover, the following differences have been calculated and used as parameters:

5) Duration of lip closure minus duration of glottal opening phase (as defined above). This parameter gives a negative value if the glottal maximum occurs after the explosion; it gives a positive value if the maximum occurs before the explosion. The parameter refers to stops only.

6) We have calculated the relative values for parameter No. 5, i.e. as fractions of the total durations (parameter No. 1).

7) Finally, we have calculated the glottal closing phase of the consonant segment as the total duration minus the glottal opening phase (in the sense of parameter No. 3).[1]

With the fricative f the parameters reduce to:

1) Total duration (= par. No. 1 of stops).
2) Duration of glottal opening phase (= par. No. 3 of stops).
3) Glottis aperture (= par. No. 4 of stops).
4) Duration of glottal closing phase (= par. No. 7 of stops).

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1) Like parameter No. 3 this is not a measure of the total lapse of time from one extreme of glottal state to the other. The end point of the closing movement cannot be seen clearly since the curve rounds off smoothly in the beginning of the following vowel.

5. The linguistic material

The opposition between aspirated stops (ptk) and unaspirated stops (bdg) in Danish is confined to certain positions, which may be subsumed under the common term "strong position". In other positions there is only one series of stops, but in return there is a distinction of stop : fricative not only in labials but also in alveolars and velars. For details see Rischel (1970).

We have considered it our primary task to provide reliable data on the distinction between p and b word initially in a stressed syllable, which is the strong position par excellence. As these consonants are both unvoiced, it is interesting to compare their glottal gestures to that found in a voiceless continuant, and we have therefore included words with f in the material presented in this paper. The consonants were represented by three series of minimally different, meaningful words: Peder-beder-feder (with long [e:]), pinde-binde-finde (with short [e]), and Pelle-bælle-fælle (with short [ɛ]). The words within each series were said in random order, each word occurring six times. The reason for confining the material to sequences with front vowels was that this minimizes the risk of disturbing effects from tongue articulation. The differences among the vowels in the three sets did not seem to influence the parameters of the consonant significantly.

Since we were interested in studying the combined opening and closing glottal gesture of the consonants, each word was said after a carrier sentence (Det hedder: "it is called") ending in a vocoid sound. Since this preceding sound is open and rather back, the choice of carrier sentence is questionable (see section 3 above on coarticulation artifacts). We made some control recordings with a carrier sentence ending in a front vowel (Du skal sige: "you must say"). These generally gave a more pronounced voice ripple for the preconsonantal segment, but the glottograms of the consonants were very similar in both cases, and there seems to be no reason to suspect the carrier sentence of distorting the recordings in any essential way.

In addition to these sets of words we have recorded a considerable amount of material with stops, fricatives and h in other positions. These include clusters of consonants with or without an intervening juncture, single consonants in word internal position, and consonants in word final position followed by a vowel. The position before juncture is a weak position; in absolutely final position there is more or less free variation between aspirated and unaspirated stop (the aspiration here can be explained as a boundary signal). We have symbolized the neutral labial stop in this type of position by B. Some minor parts of the additional material will be commented upon later in this paper.

TABLE 1

Subject: BFJ

	Parameter	Mean value	S.D.	No. of tokens	99% conf.
p	1 total duration	174.00 ms	12.08 ms	17	8.49
	2 dur. of lip closure	107.23 ms	10.79 ms	17	7.58
	3 dur. of glot. open.	117.47 ms	12.47 ms	17	8.76
	4 glottis aperture	1.00	0.00	17	0.00
	5 par. 2 minus par. 3	-10.23 ms	9.12 ms	17	6.41
	6 par. 5 div. by par.1	-0.05	0.05	17	0.03
	7 par. 1 minus par. 3	56.52 ms	8.00 ms	17	5.62
b	1 total duration	142.17 ms	21.30 ms	17	14.97
	2 dur. of lip closure	130.29 ms	21.71 ms	17	15.25
	3 dur. of glot. open.	51.94 ms	10.84 ms	17	7.62
	4 glottis aperture	0.20	0.05	18	0.03
	5 par. 2 minus par. 3	78.35 ms	17.32 ms	17	12.17
	6 par. 5 div. by par. 1	0.54	0.06	17	0.04
	7 par. 1 minus par. 3	90.23 ms	17.59 ms	17	12.36
f	1 total duration	173.33 ms	10.66 ms	18	7.23
	2 dur. of glot. open.	75.83 ms	6.52 ms	18	4.42
	3 glottis aperture	1.04	0.14	18	0.10
	4 par. 1 minus par. 3	97.50 ms	8.52 ms	18	5.78

The whole material was recorded (parts of it several times) with each of the three authors of this paper acting as a subject. We all speak Standard Danish, though with some minor (to some extent dialectal) differences. On visual inspection our glottograms are on the whole very similar.

6. Statistical treatment of glottis behaviour in initial p,b,f

In accordance with the research plan outlined above we measured a number of photo-electric glottograms of word initial p, b, and f and submitted the data to extensive statistical treatment. The results reveal certain properties of the temporal relationship between movements of the glottis and of the upper speech-organs, and they also show the durations of various phases of glottal activity. These general findings are further used as a reference framework in the study of unvoiced consonants in other environments.

TABLE 2

Subject: CL

	Parameter	Mean value	S.D.	No. of tokens	99% conf.
p	1 total duration	166.94 ms	15.82 ms	18	10.73
	2 dur. of lip closure	93.61 ms	8.36 ms	18	5.67
	3 dur. of glot. open.	96.66 ms	10.28 ms	18	6.98
	4 glottis aperture	1.00	0.00	18	0.00
	5 par. 2 minus par. 3	-3.05 ms	6.21 ms	18	4.21
	6 par. 5 div. by par. 1	-0.02	0.04	18	0.03
	7 par. 1 minus par. 3	70.27 ms	8.65 ms	18	5.87
b	1 total duration	130.00 ms	15.81 ms	18	10.72
	2 dur. of lip closure	113.05 ms	12.96 ms	18	8.79
	3 dur. of glot. open.	46.94 ms	11.89 ms	18	8.07
	4 glottis aperture	0.41	0.14	18	0.09
	5 par. 2 minus par. 3	66.11 ms	7.58 ms	18	5.14
	6 par. 5 div. by par. 1	0.51	0.06	18	0.04
	7 par. 1 minus par. 3	83.05 ms	9.09 ms	18	6.17
f	1 total duration	161.66 ms	15.99 ms	18	10.85
	2 dur. of glot. open.	75.27 ms	11.81 ms	18	8.01
	3 glottis aperture	0.86	0.14	18	0.09
	4 par. 1 minus par. 3	86.38 ms	13.59 ms	18	9.21

In order not to mix data from possibly different populations we carried out the statistics for each subject separately. Furthermore, we estimated whether data pertaining to the same consonant but taken from different words (e.g. Peder, pinde, Pelle) belonged to the same statistical population. As this seemed to be the case we did not find it necessary to maintain a statistical distinction between them.

Tables 1-3 show the statistical output for each of the three subjects, BFJ, CL, and JR.

TABLE 3

Subject: JR

	Parameter	Mean value	S.D.	No. of tokens	99% conf.
p	1 total duration	136.94 ms	7.88 ms	18	5.34
	2 dur. of lip closure	76.66 ms	6.41 ms	18	4.35
	3 dur. of glot. open.	81.94 ms	7.09 ms	18	4.81
	4 glottis aperture	1.00	0.00	18	0.00
	5 par. 2 minus par. 3	-5.27 ms	6.52 ms	18	4.42
	6 par. 5 div. by par. 1	-0.03	0.04	18	0.03
	7 par. 1 minus par. 3	55.00 ms	8.22 ms	18	5.57
b	1 total duration	100.55 ms	7.45 ms	18	5.05
	2 dur. of lip closure	84.16 ms	9.27 ms	18	6.29
	3 dur. of glot. open.	35.00 ms	7.85 ms	18	5.33
	4 glottis aperture	0.32	0.13	18	0.08
	5 par. 2 minus par. 3	49.16 ms	10.03 ms	18	6.80
	6 par. 5 div. by par. 1	0.48	0.08	18	0.05
	7 par. 1 minus par. 3	65.55 ms	9.05 ms	18	6.14
f	1 total duration	120.55 ms	13.16 ms	18	8.92
	2 dur. of glot. open.	44.16 ms	6.00 ms	18	4.07
	3 glottis aperture	1.01	0.17	18	0.11
	4 par. 1 minus par. 3	76.38 ms	9.04 ms	18	6.13

7. Results of the statistics

The data given in the preceding section show that the glottis adjustment in p differs in several respects from that of b:

(1) the aperture is much bigger in p than in b,

(2) p shows typically a nearly symmetric opening-closing change of the state of the glottis, whereas in b a relatively greater part of the total duration of the consonant segment is occupied by the closing movement,

(3) in p the moment of maximum glottis aperture falls rather close to (generally slightly after) the moment of explosion of the oral closure, whereas in b it comes much before the moment of explosion.

The shape of the glottogram for p is very similar to that for f (or s), i.e. aspirated stops and voiceless fricatives can be classified together as consonants with more open glottis, as against the unaspirated stop b, which is unvoiced like the others but produced with less open glottis.

Typical curves are shown in Fig. 3.

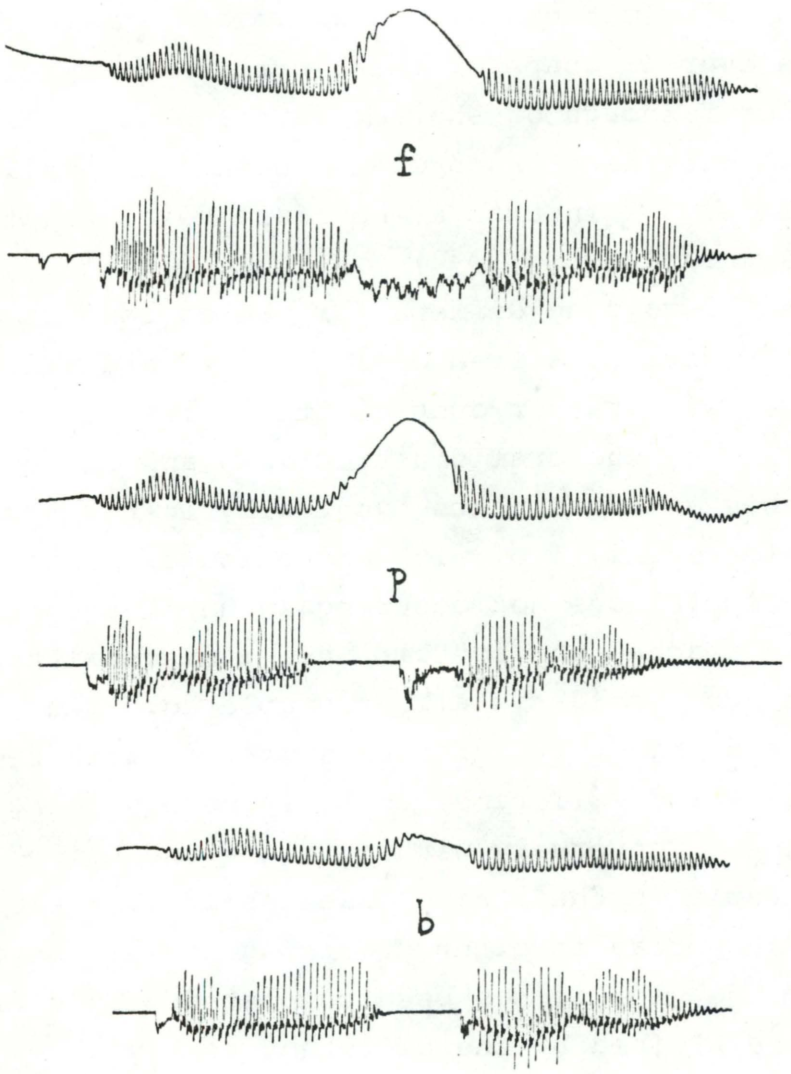

Fig. 3 Glottogram and duplex oscillogram of f, p, and b. Subject CL.

8. Degree of voicing

Inspection of glottograms of h in voiced environments shows that the overall shape of the glottogram is similar to that for p or f though of shorter duration and - under our "normal" conditions of recording - with less amplitude. It differs from p, b f in that it has full voice ripple throughout its duration.

The degree of voicing differs for the consonants in question. In h there is a free oral passage, and voicing is retained even with rather open glottis. In f the air-stream is impeded by the oral constriction, and the voice ripple diminishes and disappears eventually in the rising phase of the glottogram, i.e. with abduction of the vocal folds. Voice ripple does not occur again until the glottogram has nearly reached the bottom line, i.e. until the adduction of the vocal folds is almost completed. Thus, although the glottogram on f is rather symmetric with regard to rise time and fall time, there is more voicing in the rising phase. Conversely with p. Here the voice ripple ceases early in the rising phase (shortly after the implosion), whereas it often starts again well before the closing of the glottis has been completed. This difference can be explained by the different aerodynamic conditions: in the glottis opening phase there is oral closure in p and therefore more braking of the airstream than in f; in the glottis closing phase there is almost unimpeded oral passage in p and hence less resistance to the airstream than in f. Voicing with partly open glottis is apparently a matter of a sufficient velocity of air (H. von Leden, 1961, p. 668), cf. voicing of intervocalic h.

In b the voice ripple vanishes quickly, as in p, which suggests that b is no more "lax" than p, i.e. there is no apparent adjustment of the conditions in either the vocal folds or the pharyngeal cavity allowing the vocal folds to vibrate in spite of the oral closure.[1] The onset of voice follows almost immediately after the explosion. This agrees with the fact that the glottis is practically closed at this moment.[2]

Obviously the degree of vocal fold vibration in the Danish consonants in question (in the position referred to) is a symptom rather than an independent physiological feature. It can be explained in a straightforward way as conditioned by the interplay between glottis aperture and oral constriction (also cf. Fischer-Jørgensen 1970, p. 151).

9. Hypotheses about laryngeal commands in p, b, f, h

The glottis aperture in b is much smaller than the aperture found in p, f, h. Moreover, the duration of the opening movement is very short compared to the closing movement. There is no apparent reason to assume that this gesture is effectuated by neural commands; it can probably be explained by the aerodynamic conditions at the transition from vowel to consonant. Hence the opening-closing gesture in b will be referred to as the passive O-C gesture.

The glottis aperture in p is much greater than in b, the two curves differing significantly already during the lip closure phase. Thus the greater opening in p cannot be

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1) As proposed for voiced obstruents by Halle and Stevens (1968).

2) Eli Fischer-Jørgensen (1969, 1970) has found that voicing starts spontaneously if the closure is artificially released in Danish b, but not in Danish p.

explained by aerodynamic factors, and we therefore assume that it is due to neural commands. Hence the opening-closing gesture in p will be referred to as the active O-C gesture. Gestures similar to those of p are found in f.

The gestures of h are similar in shape to those of p and f, but the aperture is generally smaller. This applies to intervocalic voiced h as well as unvoiced h. In comparing the recordings of f and h we find that the airstream is greater for the second consonant, and hence the lesser amplitude of the glottogram might be explained as a Bernouilli effect. We therefore do not assume a difference in neural commands between h and p, f.

If we go back to our starting point, viz. that p is essentially the aspirated equivalent to b, it is interesting to see that this can be accounted for in terms of the O-C gestures. Provided that it makes sense to divide b roughly into two portions, one characterized by the (possibly aerodynamically conditioned) opening gesture, and the other by gradual adaption to conditions for voicing, then p may, to a first approximation, be conceived as a complex of two such portions, of which the first corresponds to the first part of b, whereas the second corresponds to h, i.e. with active glottis opening.

Similarly, f may be characterized by some kind of combined effect of aerodynamic force on the vocal folds and active glottis opening, but it remains to be found out when the active opening movement starts. There is of course no direct indication in the curves for p or f that the active opening should start later than the passive opening assumed to account for b.

An obvious way to check whether there is any likelihood that opening gestures add, is to compare sequences with p to sequences with B+h. The difficulty here is that there will be junctural phenomena involved, which may make the temporal relationships of the oral articulation of B+h different from those of p.

As a provisional test of this kind we recorded some compound words with post-junctural p, viz. søpølse, trepattet versus compound words with B+h, viz. kæphest, snaphaner.

This gave the following mean durations of the parameters (each representing six tokens, subject JR):

	søpølse	trepattet	kæphest	snaphaner
	ms	ms	ms	ms
parameter 1:	126	99	118	104
parameter 2:	65	55	56	46
parameter 3:	59	49	54	51
parameter 5:	6	6	2	-5
parameter 7:	67	50	64	53

These results show that the variation of respectively p and B+h as conditioned by the environments (and by free variation) exceeds the absolute difference between the averages for p and B+h (it must be admitted that the material is small). Similar tendencies have been found for BFJ and CL.

The measurements above refer to consonants between a vowel with strong stress and a vowel with reduced ("secondary") stress. When the second syllable has strong stress there is often some differences between p and B+h, the latter sequence being characterized by more voice ripple in the falling part of the glottogram than p. Moreover, the peak of maximum aperture tends to occur slightly later in B+h before stress, all of which points toward a more separate h gesture.

Examples of p versus B+h are shown in Fig. 4.

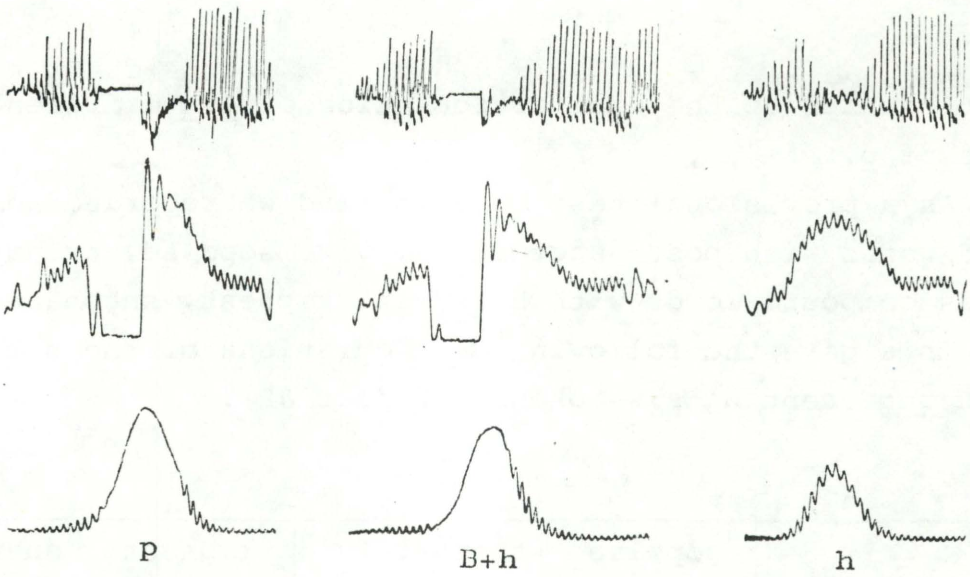

Fig. 4 Intervocalic p, B+h, and h (following syllable stressed). Subject JR. From top to bottom: Duplex oscillogram, aerometer curve, and glottogram.

We conclude from this that there is no reason to assume that the laryngeal commands for B+h under conditions of minimum juncture effect differ significantly from those for p. We have found in other recordings that (word final) B immediately followed by a vowel is similar to (word initial) b, but B and h add to give largely the same curve as p. It is not obvious that B+h should be able to give the same timing of the point of maximum glottis aperture as p unless we assume that the gestures of p is a summation of gestures similar to B and gestures similar to h. It goes without saying that these gestures, whose phonological counterparts are sequential, may overlap or even coincide in time, but this would then be true both of p and of B+h.

Additional types of sequences, which we have inspected are stop plus stop, i.e. B+p or B+b with or without stress on the following vowel, and s+ (aspirated) p versus p alone.

The words with two stops show that the longer hold of oral closure as compared to single stops does not cause the glottal aperture (considerably) to exceed that for respectively single p and single b, on the contrary we sometimes find a tendency toward two-peakedness (which one might wish to take as a boundary phenomenon). This suggests that the differences in glottis aperture observed by comparison of single consonants are not in the first place undershoot phenomena. Sequences like s+p sometimes show a greater aperture than single s or p in similar environments, but the difference is not stable.

The most important finding in connection with consonant combinations of various kinds is that in cases where two consecutive consonants form one peak of glottis aperture (this is the case in normal speed of pronunciation with all the sequences we have studied) this peak occupies the position one would expect if some kind of summation of opening took place. Thus in the sequence s+p the peak comes clearly before the explosion of p, whereas in single p it comes very close to (and mostly after) the explosion. This not only corroborates the summation hypothesis, but also shows that the turning point of the glottogram is not "triggered" by the oral explosion, which one might otherwise be tempted to believe by looking at the glottograms for single p.

In slow pronunciation sequences like s+p and B+p gradually assume a two-peaked shape, cf. Fig. 5. We do not know to what extent this should be explained by an intervening junctual phenomenon, or to what extent each consonant retains its opening and closing commands in such sequences.

We have even noticed slight tendencies towards such two-peakedness in the sequence B+b in very emphatic speech, but this may be due to a sudden rise of subglottal pressure in connection with the emphatic stress. It need not mean that there is an active opening gesture in b.

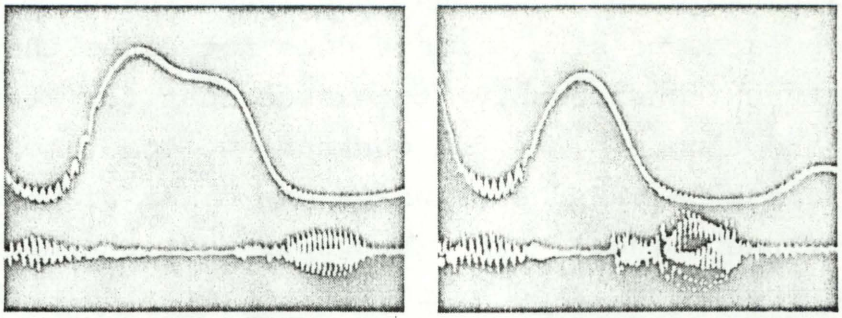

Fig. 5 Intervocalic s+p in slow and normal pronunciation (in the sequence *pas* *ˈpå!* "be careful"). Subject JR.

10. Conclusion

Glottographic investigation has corroborated the current conception of Danish p and b as differing essentially in aspiration. The consonants p, f, and h are all characterized by an opening-closing movement of the glottis with fairly equal duration of the opening and closing phases, and we assume the basic "command" to be the same for these three types of consonants. The consonant b which is unvoiced like p, f, has only a slight initial movement of the glottis toward open position, the rest of its duration being characterized by a slight closing movement. The maximum aperture is considerably smaller than for p, f,h. We assume the glottal behaviour of b to be a passive movement caused by the aerodynamic conditions. Inspection of glottograms of various consonant sequences suggests that if unvoiced consonants like those mentioned above occur in succession, there is a summation of the - passive or active - gestures belonging to the different consonants. Thus the sequence B+h exhibits a glottogram that is similar and often identical to that of p in analogous environments.

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