SOME DATA ON NORTH GERMAN STOPS AND AFFRICATES

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Abstract: The present paper presents some data on voicing (3.1), duration (3.2), intra-oral air pressure (3.3), airflow (3.4), subglottal pressure (3.5), and lip pressure (3.6) of German stops and affricates. On the basis of these data the last section discusses some more general problems, viz. the features distinguishing ptk and bdg (4.1), the reduction of aspiration after s (4.2), the distinction between stops and affricates (4.3), differences due to place of articulation (4.4), "heightened subglottal pressure" (4.5), and the relation between air pressure and airflow (4.6).

1. Introduction

The present paper brings some data on duration, intra-oral and subglottal pressure, airflow, lip pressure, and (to a certain extent) voicing of North German stops and affricates. The material was collected in the course of the years 1955-1968. The main part, comprising stops and affricates in stressed position (lists I and II) was meant as a background material for a description of Danish stop consonants (which has never been completed). A smaller part (list III) comprising stops in unstressed position is taken from a material intended for the description of close and open contact in German (see Fischer-Jørgensen 1969) and not particularly set up for the purpose of analysing stops.

Although the material is restricted and, as far as the unstressed position is concerned, unsystematic, I have found it useful to publish it in a separate paper because relatively little has been published on North German stop consonant duration and, as far as I know, hardly anything on air pressure and airflow. Some (rather restricted) instrumental data on duration, particularly the duration of aspiration, can be found in E.A. Meyer (1901 and 1904), Hentrich (1925), Weitkus (1931), Schmitt (1931 and 1947), v. Essen (1934), Bennett (1935), and Rositzke (1944 and 1947). Some scattered data can be found in Zwirner and Zwirner's text lists (1936-37). A more comprehensive material on duration and voicing (but only comprising one person's pronunciation of t and d) is found in Bothorel-Witz and Pétursson (1972). The three most comprehensive studies (Lotzmann 1958/59 on aspiration, Meinhold and Stock 1963 and Esawa 1972 on voicing) are not instrumental (Meinhold and Stock have taken a few oscillograms for control), but based on auditory impressions. Lotzmann has not been accessible to me. Meinhold and Stock have listened to more than 1000 bdg-sounds in absolute initial position and in the position after voiceless sounds spoken by 34 professional speakers and actors (in connected texts). They have made the tape recordings at a speed of 30 ips and played them back at very slow speeds, and they have only made decisions on presence or absence of voicing. This seems to be a very reliable procedure. Esawa has listened to voicing of bdg and ptk in various positions in 90 samples of 5 minutes length from a connected text spoken by 90 subjects from all over Germany.

The emphasis of this paper is on the presentation of data, and I am not going into any details concerning the general problems of stop features and stop production. A detailed discussion of these problems can be found in my paper "Voicing, tenseness and aspiration in stop consonants" (1968), and a more recent treatment with a very useful survey of the literature is given in the paper by Bothorel-Witz and Pétursson (1972). But it is, of course, my hope that the data presented here may contribute not only to the description of German (and, ultimately, to the teaching of German) but also to the description of the distinctive features used to separate the two stop categories designated as ptk and bdg, and that it may throw some light on the mechanism of stop production. In the final section I will return briefly to these problems.

2. Subjects, material, and recordings

2.1 Subjects

The investigation is mainly based on six subjects: CH, WS, KV, HP, and (to a somewhat lesser degree) GJ and GR. For subsidiary information about the duration of unstressed stops recordings made by three further subjects (HT, HWL, and HL) have been used. They all speak various types of Standard Northern German except for GJ, who is from the Western part of Germany (Koblenz), but speaks Standard German.

CH (born 1934) grew up in Lübeck and Stettin and had at the time of recording (1955) been in Stockholm for one year.

WS (born 1939) grew up in Velbert in the Northern Rheinland. He has lived in Copenhagen since 1961. The main recording was made in 1966, two others in 1964 and 1968. He speaks German at home, and his German seems uninfluenced by Danish.

KV (born 1941) grew up in Elmshorn near Hamburg. At the time of recording he had been in Denmark for six months.

HP (born 1907) lived in Hamburg until the age of 28. He has stayed in Copenhagen since 1935, i.e. at the time of recording (1956) for 21 years. He is married to a Dane, and he reported that he spoke Danish at home, but German at his job. In spite of his long stay in Denmark he was included among the main subjects because he was within reach and because his German sounded all right. However, the measurements showed that he differed from the other subjects on several points, which could be due to Danish influence. He should therefore not be taken as a typical German speaker.

GJ (born 1912) grew up in Koblenz. At the time of the recording (1955) he had been several years in Copenhagen. He spoke German at home, and his German seems to be completely uninfluenced by Danish.

GR (born 1912) grew up in Berlin. At the time of recording (1955) he had lived for seven years in Stockholm. He speaks German at home, and his German seems quite uninfluenced by Swedish.

HT and HWL are from Northern Germany; HL from the Ruhr area.

2.2 Texts

The main material (list I) consisted of a series of words with initial stop or affricate in stressed position, preceded by an unstressed vowel and followed by one of the vowels a, i or u

The words used in most of the recordings were:

I	(a)	b	die Bahre, die Busze, die Biese
		d	die Dame, die Dusel, die Diebe
		g	die Gabe, die Guten, die Giebel
		p	die Paare, die Pute, die Pike
		t	die Tafel, die Tute, die Tiefe
		k	die Kate, die Kugel, die Kiefer
I	(b)	pf	die Pfanne, der Pfuscher, die Pfiffe
		ts	die Zahlen, die Zuber, die Ziege
		p	die Panne, die Puppe, die Pille
		t	die Tasche, die Tunke, die Tinte

In the case of GJ, GR, and CH's first recording (CH I) an earlier version of list Ib was used containing the words:

pf	die Pfanne, der Pfuhl, der Pfiff
ts	die Zahl, die Zunge, die Ziege
p	die Panne, der Putz, der Pilz
t	die Tat, die Tunke, die Tiefe.

List Ia was intended for a comparison between ptk and bdg, list Ib for a comparison between pt and the affricates. In the second version all words were made disyllabic, and p and t were followed by short vowels and could be compared to the words with long vowels in list Ia. But in this way the t-words got less comparable to the ts-words. However, as the differences are significant in both cases, this does not matter.

A subsidiary word list (called II) consisted of the words:

I	(c)	bdg	das Band, das Dach, das Gatt
			das Bett, das Deck, das Gift
		ptk	das Paar, das Tal, das Kalb
			das Pech, das Tempo, das Kind

This list was only spoken by GJ, GR, and CH.

The words appeared twice in the list in groups of three, the second time in reversed order, to avoid influence from rhythmic factors.

List I was intended for comparison with Danish, and was restricted to initial position. It contained, however, by chance some stops in unstressed medial position, and these have been included in the present investigation. They were supplemented by some words from list III.

List II consisted of a list of isolated words. The words utilized in the present paper were: piepen, Lippe, tapern, tappen, bieten, beten, bäten, baten, Betten, Latte, lieben, lebe, bibern, beben, Ebbe, bibbern, wieder, laden, Widder, Kladde.

2.3 Recordings and measurements

Tape recordings were made of lists I, II, and III, spoken by GJ and GR, lists I and II by CH, and lists I and III by WS and KV. The subsidiary data from subjects HT, HL, and HWL were also based on tape recordings. The recordings were made on professional tape recorders in sound treated rooms, those of GR and CH at the Technical High School in Stockholm, the others in Copenhagen. The tape recordings were used for mingographic registration comprising oscillograms and intensity curves. These curves, supplemented by spectrograms, were used for measurements of duration.

As start of the consonant closure that point has been chosen where the preceding vowel ends, i.e. where the intensity curve drops abruptly. The delimitation of the open interval (i.e. the distance from release of the closure to the start of the following vowel) was sometimes dubious in the case of voiced bdg, and some cases have been omitted from the averages.

Air pressure and lip pressure of HP and CH (lists I and III) were recorded in the Cardiologic Laboratory of the University Clinic (Rigshospitalet) in 1956 in cooperation with Oluf M. Thorsen. The intra-oral air pressure was recorded by means of a small plastic tube, seven cm long, with an outside diameter of 1.5 mm and a bore of 0.8 mm inserted into the mouth. It was connected to an electrical manometer (for more technical details see Fischer-Jørgensen and Tybjærg Hansen 1959). Lip pressure was recorded by means of a rubber bulb placed between the lips and connected to the manometer. The registration was made on an Elema oscillograph. The calibration was in mm H_2O. The velars were left out in these recordings of air pressure.

Airflow curves comprised lists I and III spoken by HP and KV. The instrument used was the aerometer built by Frøkjær-Jensen who assisted at the recordings. As the instrument could not be calibrated at the time, the measurements have been made in mm. These curves have also been used for measurements of duration.

A simultaneous recording of intra-oral and subglottal air pressure and of airflow was undertaken at the Institute of Phonetics in 1966. In this recording the tube used for picking up the intra-oral air pressure was inserted through the nose. The text was list I, and the speaker was WS. The subglottal pressure was recorded by means of a balloon placed in the oesophagus. This technique had been used by Schuhmacher (WS) for his investigation of German vowels, and he was kind enough to swallow the balloon once more for the recording of stops (for more technical details see Schuhmacher 1972). Unfortunately, the calibrations of these curves have disappeared, so that they had to be measured in mm. As both air pressure and airflow scales are linear, the relations between the values measured in mm will be correct, and generally only the relations are of interest, but for a comparison between the three types of registration the real values would have given more information. The word list was repeated four times, but only repetitions number three and four included subglottal pressure. For these two recordings the amplitude of the air pressure and airflow curves was reduced, but since the number of words was the same in all recordings a common mean has been taken of all four recordings. A specimen of

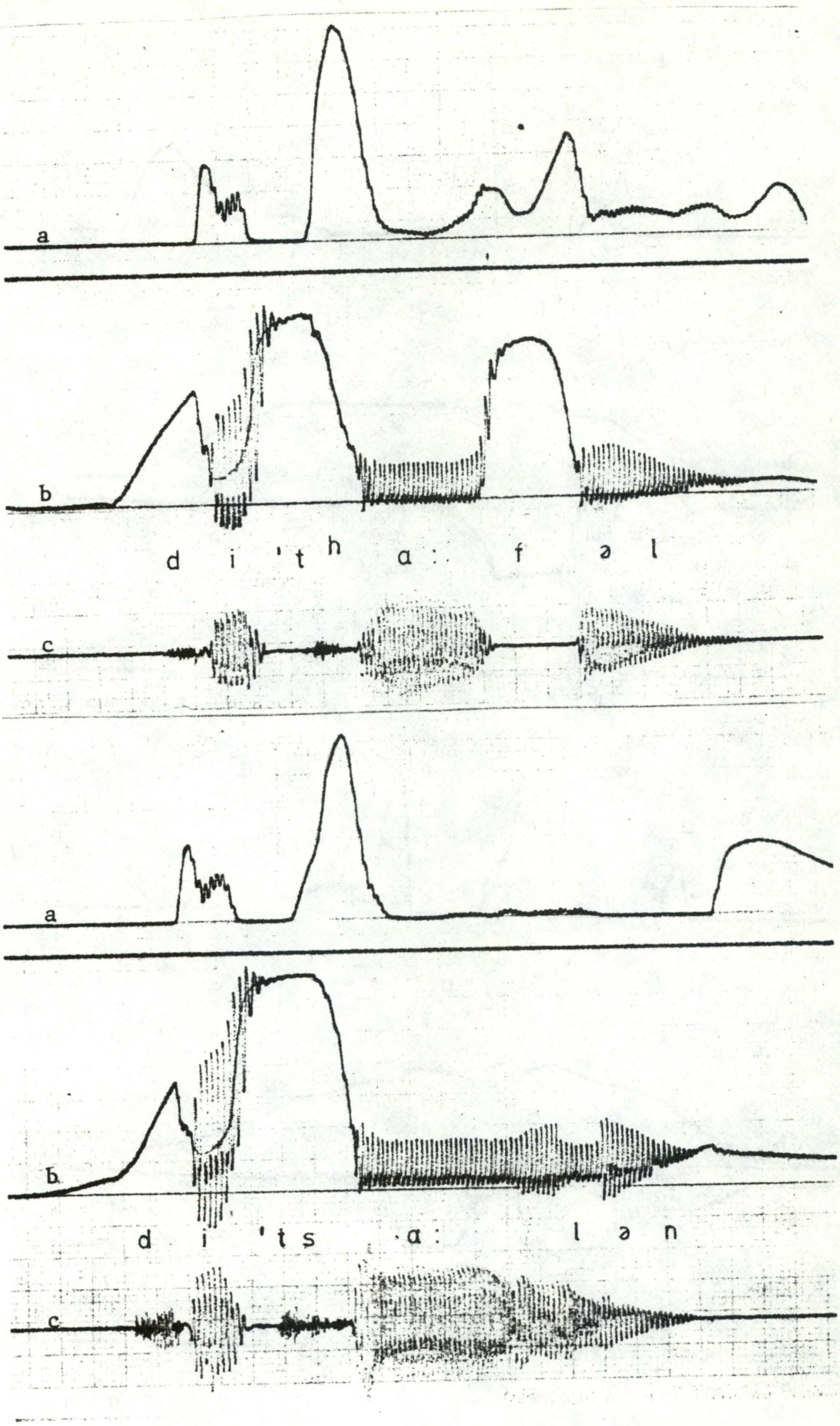

Figure 1

a) airflow, b) intra-oral air pressure,
c) oscillogram (subject WS).

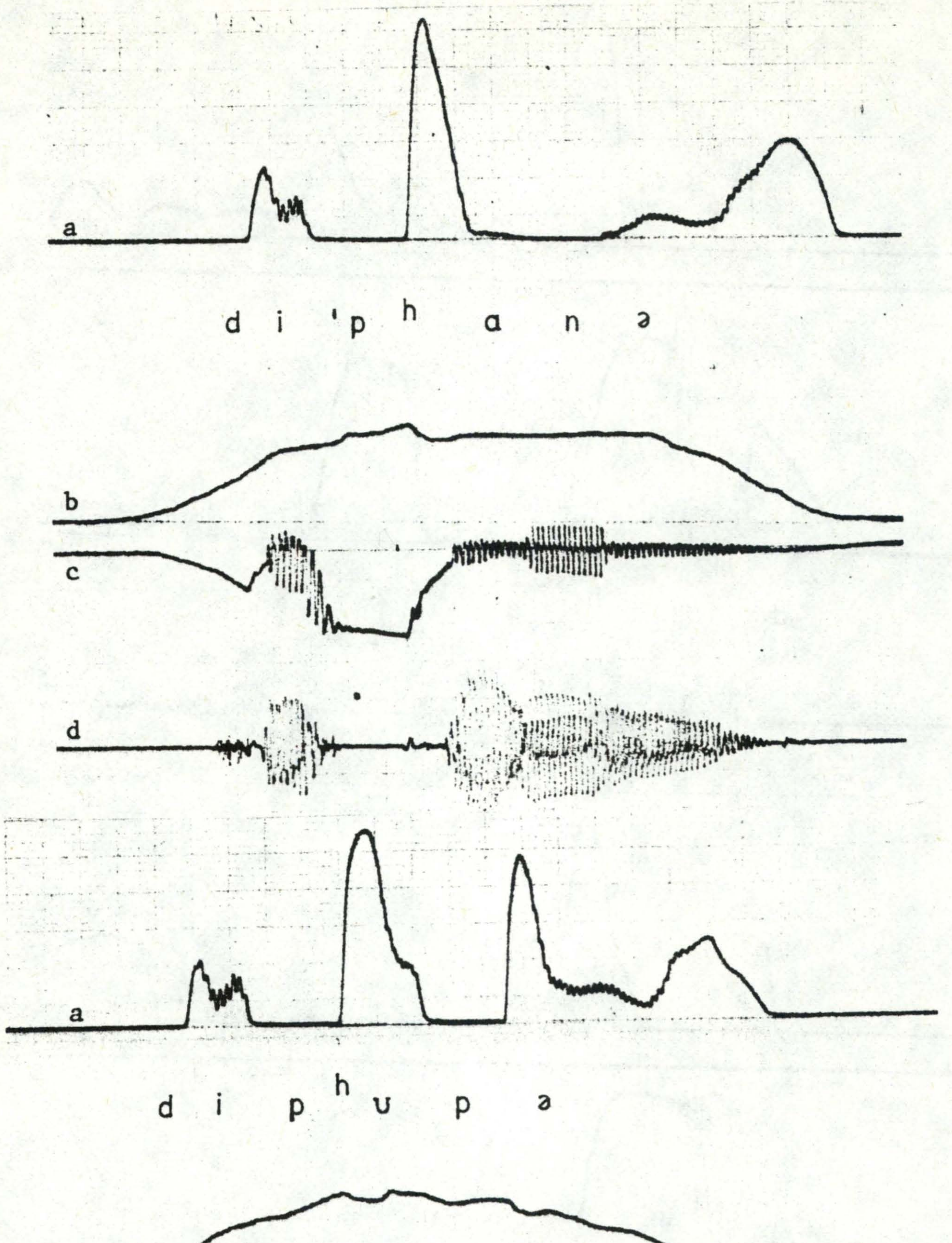

Figure 2

a) airflow
b) subglottal pressure
c) intra-oral pressure (inverted)
d) oscillogram

these two types of curves is shown in fig. 1. These curves have also been used for measurements of duration.

The duration of voicing has been measured in all the curves of the six principal subjects, and in the case of total voicelessness and complete voicing the measurements are safe, but in the numerous cases of partial voicing with decreasing amplitude the delimitation is rather arbitrary, and depends to some degree on the amplification used in the individual recording. For a material recorded at different times and with different instruments the measurements can be compared only with great caution.

A good deal of the measurements and computations have been made, according to my instructions, by Oluf M. Thorsen, Kirsten Gregersen, Karsten Vogel, Jente Andresen, H.P. Jørgensen, and Mimi Jacobsen.

3. Results

3.1 Voicing

As mentioned in section 2.3 I am somewhat sceptical as to the exact measurement of voicing where it is only partial. This section will therefore not contain large tables of averages, but some information is necessary as background for the judgement of other parameters.

3.1.1 ptk

The stops ptk are always voiceless in this material except for 20-30 ms of weak voicing in the beginning after a voiced sound. But it should be kept in mind that the list consisted of isolated words. In connected speech ptk may be voiced (see Esawa 1972).

3.1.2 bdg

As for bdg their degree of voicing is very variable depending on stress and preceding sounds.

3.1.2.1 bdg in initial position in stressed syllable

(a) Absolute initial position

The main material (list I) did not contain any examples of this type (the d of unstressed "die" was always voiceless). But there are a number of examples in list III. CH, HP, and KV always have voiceless bdg in this position, GJ and GR normally have voiceless bdg with a few random exceptions, whereas WS varies unsystematically between voiced and voiceless b and d, but always has voiceless g.

(b) Initial position after word boundary preceded by s (s#'CV)

The material only contains 30 examples of bdg in this position spoken by CH, GJ, and GR. They are always completely voiceless. GJ has also voiceless bdg after other voiceless sounds (see Fischer-Jørgensen 1952, p. 123).

(c) Initial position in stressed syllable after word boundary preceded by unstressed vowel ($_{\circ}$V#'CV)

The main part of the material consists of words of this type. bdg in this position are normally partly voiced, but there is a large variation between subjects and also in the recordings of the same subject and the same word. As a rough indication of the variation between subjects the following values may be given (duration of voicing in % of the closure):

GJ 75%, GR 61%, WS 54%, KV 49%, CH II 40%, CH I 28%, HP II 20%, and HP I 14%.

GJ has a number of fully voiced examples, GR only one. The voiced portion is always found in the first part of the closure, never at the end, and the amplitude of the vibrations is always decreasing, which makes the delimitation dubious in many instances.

HP's percentage of voicing corresponds to 10-30 ms. The averages are often very slightly higher for bdg than for ptk, but there is complete overlapping. His bdg must therefore be considered voiceless in this position.

3.1.2 Medial position before unstressed vowel after stressed vowel ('VCə)

In this position bdg are often fully or almost fully voiced, with decreasing amplitude of the vibrations. This is true of all subjects: GJ, GR, CH, WS, and KV.[1] The voicing often stops at the release, but may also continue through the release. This is almost always the case for GJ and GR, and often for WS. The degree of voicing in CH's recording is very variable. She may have fully voiced or almost voiceless bdg. She has sometimes less voicing after short than after long vowel. In the case of HP there are great differences between different recordings. In one recording he has more than 50% voicing, in another the consonants are practically voiceless. KV has voiceless bdg after short vowel (e.g. Widder), fully or partly voiced bdg after long vowel.

The great variation in the voicing of bdg confirms the observations by Esawa (1972), who finds that complete or partial voicelessness is found very often, also in Northern Germany in all positions of the word, and it is also in agreement with the indications of Bothorel-Witz and Pétursson (1972) on the voicing of d. The finding that bdg are completely voiceless after s and, in most cases, voiceless in absolute initial position is in agreement with Meinhold and Stock (1963), who found only 1.3% of voiced bdg after a voiceless sound (and they consider these few examples to be cases of hypercorrection) and 22.6% voicing initially with great individual variation (the individual percentages ranging from 14 to 100).

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1) Voicing was not measured for the subsidiary subjects.

Figure 3

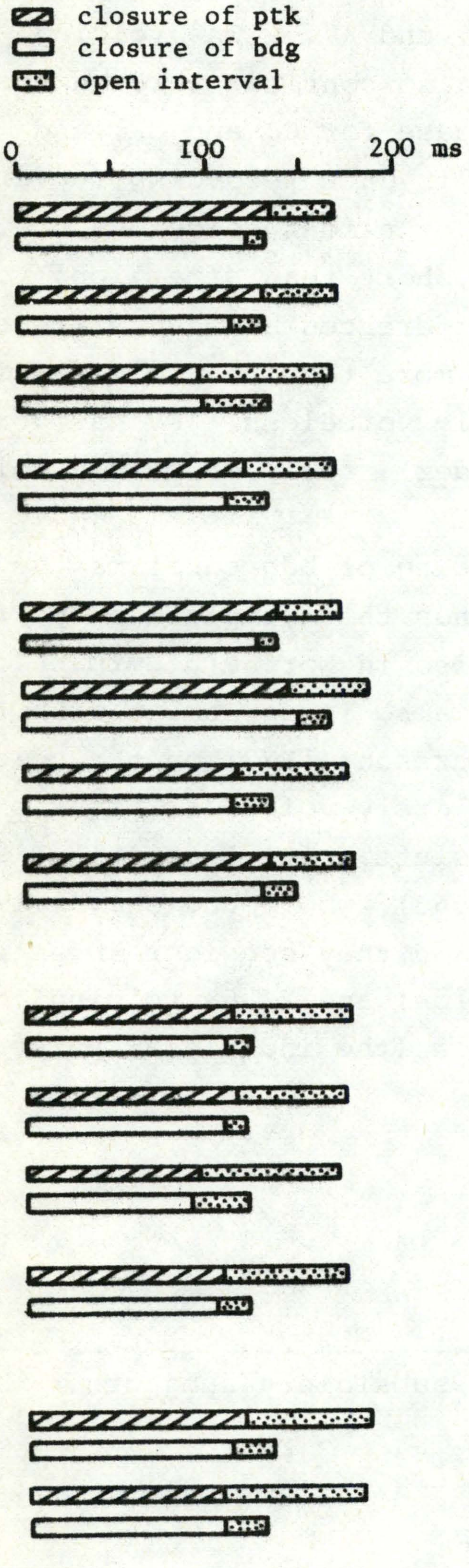

Table 1

Duration (in msec) of ptk and bdg in the position V'CV:

S = subject, N = number, C = consonant, cl. = closure, op.i. = open interval, tot. = total duration, % op.i. = op.i. in % of tot.

S	N	C	cl.	op.i.	tot.	%op.i.
GJ	(6)	p	131	32	163	20
	(6)	b	118	11	129	9
	(6)	t	129	37	166	22
	(6)	d	111	18	129	14
	(6)	k	94	67	161	42
	(6)	g	96	35	131	27
	(18)	ptk	118	45	163	28
	(18)	bdg	108	21	129	24
GR	(12)	p	134	32	166	19
	(11)	b	124	9	133	7
	(12)	t	139	42	181	23
	(11)	d	143	17	160	11
	(12)	k	113	55	168	33
	(12)	g	108	22	130	17
	(36)	ptk	129	43	172	25
	(34)	bdg	125	16	141	11
CH	(6)	p	108	62	170	36
I	(6)	b	106	11	117	9
	(6)	t	109	58	167	35
	(6)	d	105	10	115	9
	(6)	k	91	71	162	44
	(6)	g	86	30	116	26
	(18)	ptk	102	64	166	39
	(18)	bdg	99	17	116	15
CH	(21)	p	113	66	179	37
II	(21)	b	106	20	126	16
	(23)	t	100	73	173	42
	(18)	d	101	21	122	17

Figure 3

(continued)

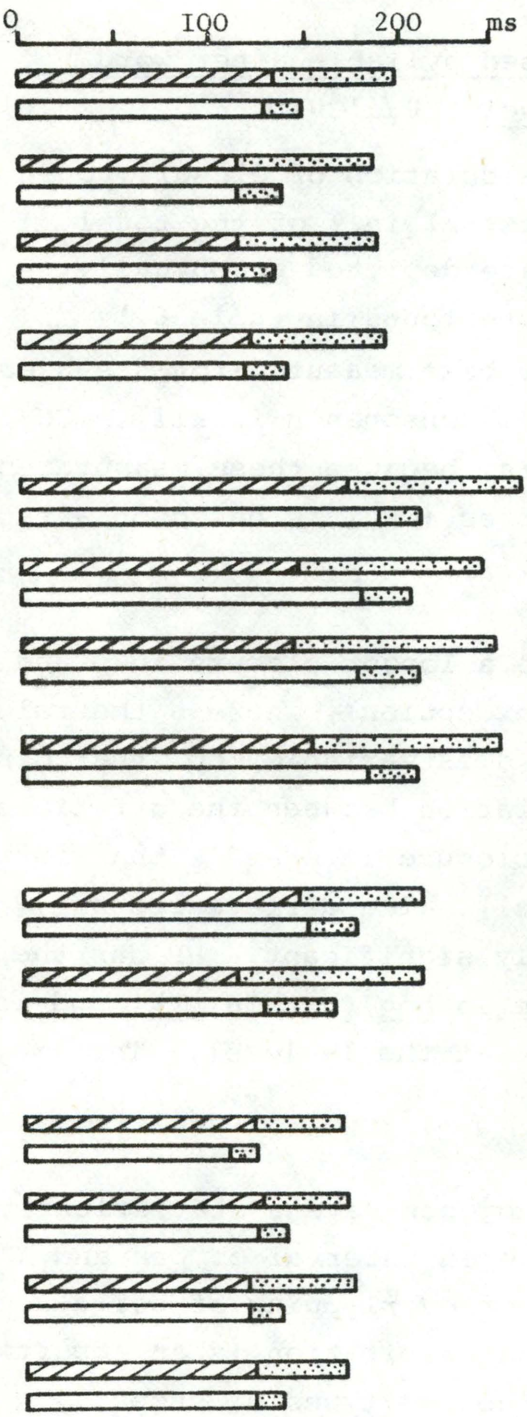

Table 1

(continued)

S	N	C	cl.	op.i.	tot.	%op.i.
WS	(24)	p	133	65	198	33
	(24)	b	129	19	148	13
	(24)	t	114	72	186	39
	(24)	d	114	24	138	17
	(24)	k	115	74	189	39
	(24)	g	108	26	134	19
	(72)	ptk	120	71	191	37
	(72)	bdg	117	23	140	16
HP I	(18)	p	170	92	262	35
	(18)	b	188	22	210	10
	(18)	t	145	96	241	40
	(18)	d	178	24	202	11
	(18)	k	142	108	250	43
	(18)	g	176	33	209	16
	(54)	ptk	152	99	251	39
	(54)	bdg	181	26	207	16
HP II	(16)	p	144	66	210	31
	(15)	b	149	26	175	15
	(18)	t	111	98	209	47
	(18)	d	126	37	163	23
KV	(12)	p	120	48	168	28
	(12)	b	108	15	123	13
	(12)	t	125	45	170	26
	(12)	d	122	16	138	12
	(12)	k	118	56	174	32
	(11)	g	117	18	135	13
	(36)	ptk	121	49	170	29
	(35)	bdg	115	16	132	13

3.2 Duration

3.2.1 Differences between ptk and bdg

3.2.1.1 Initial position in stressed syllable after word boundary preceded by unstressed vowel ($_{\circ}$V#'CV)

Table 1 gives a survey of the duration of closure, open interval, total length and open interval in % of the total length. In fig. 3 the same facts are depicted graphically. (The durations of pt from list Ib are found in table 6.)

Duration in this position has been measured for 6 subjects who have spoken list Ia and Ib (1092 consonants in all). CH II and HP II do not comprise the velars, because these measurements are taken from the air pressure curves (CH I is based on a tape recording, HP I on airflow curves).

(a) closure

Five of the six subjects have a longer closure in p and k than in b and g (GJ k < g forms an exception), whereas the relation between the closures of t and d is variable, cp. that Nina Thorsen (1971) found a variable relation between the durations of t and d in English, but longer closure in p and k than in b and g (in a more restricted material). The differences are, however, small and not statistically significant. HP has the opposite relation: a longer closure in bdg than in ptk, and in HP II the difference is significant at the 1% level. This may be due to Danish influence.

(b) open interval

It is evident that all six subjects have a statistically significant difference between the open interval of ptk and that of bdg. There is not one instance of overlapping of corresponding consonants. This means that aspiration is an important factor in the distinction between the two types of stops. But the duration of the aspiration shows considerable variation between subjects.

The general averages for all three stops in list Ia and b (in ms and as percentage of the total duration) are:

	GJ	GR	CH	WS	HP	KV
ms	45	40	61	68	94	48
%	28	24	33	36	40	28

The differences between the subjects cannot be due to dialectal background only. Of the three subjects with the shortest aspiration one is from Koblenz (GJ), one from Berlin (GR), and one from Hamburg (KV). This is peculiar since the subject who has the longest durations (HP) is also from Hamburg. His very long aspirations may be due to his slow tempo of speech (only the absolute values are deviant), but may also be due to Danish influence.

The indications on the duration of aspiration in ptk found in the literature show a considerable variation. Some have found still shorter aspirations than the minimum found in the present material, e.g. Meyer (1904) p 24, t 26, and k 32 ms (in his own North German pronunciation), Weitkus (1931) 36 ms for t (22%), v. Essen (1934) 22, 22, and 25% for p, t, and k, respectively; others have found durations corresponding to our maximum: Schmitt (1947): t 92 ms, 39%, Bothorel-Witz and Pétursson (1972): t 80 ms open interval (50%). Of the 80 ms 48 are described as "duration of explosion", which probably means: fricative phase. This distinction has not been made in the present investigation.

(c) total duration

Mainly due to the consistent difference in open interval the total duration of ptk is always greater than that of bdg, and the difference is significant for all consonant pairs and all subjects, in almost all cases at the 1 or 0.1% level.

3.2.1.2 Stressed position after word boundary preceded by s (s#'CV)

Three subjects: GJ, GR, and CH have spoken list Ic containing examples of the type: das Band, das Pech, etc. Table 2 contains the average durations, and in fig. 4 they are given in graphical form.

Figure 4

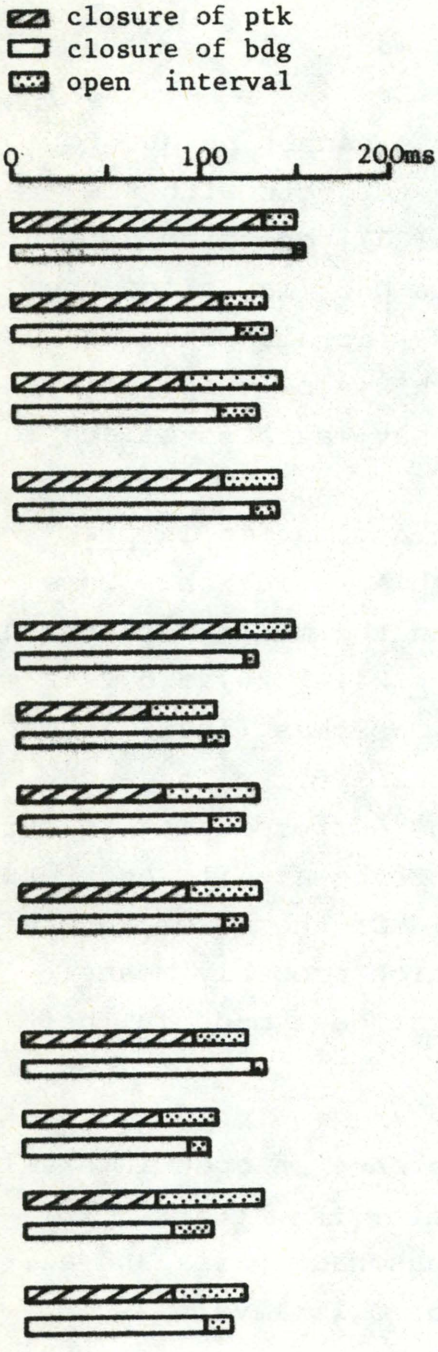

Table 2

Duration of ptk and bdg in the position s-'CV

S	N	C	cl.	op.i.	tot.	%op.i.
GJ	(2)	p	132	15	147	10
	(2)	b	148	5	153	3
	(2)	t	108	25	133	19
	(2)	d	117	18	135	13
	(2)	k	88	52	140	37
	(2)	g	108	20	128	16
	(6)	ptk	109	31	140	22
	(6)	bdg	124	14	138	10
GR	(4)	p	115	31	146	21
	(4)	b	120	6	126	4
	(4)	t	69	34	103	33
	(4)	d	96	14	110	13
	(4)	k	76	49	125	39
	(4)	g	100	18	118	15
	(12)	ptk	87	38	125	30
	(12)	bdg	105	13	118	11
CH	(4)	p	90	28	118	23
I	(4)	b	120	6	126	4
	(4)	t	71	30	101	30
	(4)	d	86	11	97	11
	(4)	k	69	54	123	44
	(4)	g	76	20	96	21
	(12)	ptk	77	37	114	32
	(12)	bdg	94	12	106	11

(a) closure

In the position after s the relations between the closures of ptk and bdg are reversed compared to the position after vowel. The material is small, but the relations are stable and statistically significant at the 1% level. Compared to the position after vowel, GJ has a slight shortening of ptk and a lengthening of bdg (-9 and +16 ms, respectively). The two others have shortening in both types, but most for ptk (GR -42, -20 ms, CH -25, -6 ms).

(b) open interval

Compared to the position after vowel the aspiration of ptk has been shortened considerably and the open interval of bdg slightly, but there is still a consistent difference without any overlapping. After vowel the difference between ptk and bdg was: GJ 24 ms, GR 55 ms, and CH 47 ms, whereas after s it is 17, 25, and 25 ms, respectively. GJ's p and t are practically unaspirated. We shall come back to this problem in section 4.

(c) total duration

Since both closure and open interval have been shortened more in ptk than in bdg, the difference in total duration is no longer significant and sometimes reversed.

3.2.1.3 Medial position before unstressed ə after vowel ('VCə)

The material was not set up for the purpose of investigating this position (in the following called unstressed position) and does not allow of a systematic comparison between the six consonants, but the main characteristics will be mentioned briefly.

(a) comparison with the stressed position

The relations between stressed and unstressed ptk are rather variable and irregular. After a long vowel the closure may be either shorter or longer than in stressed position, the same subject may have different relations for different consonants, and different relations in different recordings. Also the duration of the aspiration is rather irregular in unstressed ptk. GJ, GR, CH and KV have practically unaspirated stops in this position; whereas WS and HP have rather long aspirations (see table 3). KV has, however, a somewhat longer aspiration in a different recording than in the one used here.

Table 3

Open interval (in ms) of ptk in position 'VCə

	GJ	CH I	CH II	GR	KV	WS	HP II
p	15	26	22	11	13	23	31
t	26	27	43	20	14	61	66
k	33	29		24	14	46	-

bdg show much more regularity than ptk. They are shortened in unstressed position for all subjects. As the material contained relatively many examples of b, this consonant is chosen as an example in table 4.

Table 4

Duration (in ms) of the closure of b in stressed and unstressed position (V'bV: and 'V:bə)

S	GJ	GR	CH	HP	WS	KV
N	6/6	11/6	26/30	33/27	24/8	12/16
V'bV:	118	124	106	169	129	108
'V:bə	93	66	80	82	85	82

These differences are statistically significant. CH, HP, and WS have also a number of d's in this position. Their average durations are 60, 54, and 68 ms. Similar relations have been found for other subjects.

(b) ptk versus bdg after long vowel

As ptk are only slightly longer or shorter in unstressed position after a long vowel than in stressed position, and bdg are always considerably shortened, the consequence is a clear difference in the duration of the closure between ptk and bdg in this position. The average difference for the recorded examples is 44 ms, and this difference is evidently significant. Table 5 compares the closures of p and b, t and d (after long vowel) for a number of subjects, including some of the subsidiary subjects (HWL, HT, and HL).

Table 5

Duration (in ms) of the closure of p vs. b and t vs. d in position 'V:Cə

S	CH	HP	HT	KV	HWL	HL
N	19/15	36/27	15/12	25/30	6/8	6/9
p	107	135	122	121	85	124
b	80	82	65	82	60	72

S	HP	WS	HT	KV
N	72/12	36/12	35/6	27/6
t	123	97	108	93
d	54	68	49	65

As for the open interval of ptk and bdg HP has a clear distinction and WS has a significant distinction with some overlapping for p/b. On the other hand, KV has complete overlapping. GJ, GR, and CH have a distinction between the averages but with some overlapping (in CH II the difference is significant for t/d). But, as the open interval of bdg is often very difficult to measure and the number restricted, the averages are not always quite reliable.

The result is that there is a tendency to distinguish the open intervals of ptk and bdg in this position, but this distinction is rather inconsistent.

The open interval has not been measured for the subsidiary subjects.

(c) ptk and bdg after short vowel

The preceding tables only included the position after long vowel. After short vowel there is more irregularity.

German only possesses a very small number of words with bdg after short vowel. List III, which was spoken by 10 subjects in all, contained some words of this type (bibbern, Kladde, Widder, Egge). Most subjects (GJ, WS, HT, HL, HWL) had a slightly longer stop in these words, others (CH, GR, HP, and partly KV) showed a considerable lengthening of the stop. The extremes are WS, who had a difference of 1 ms between bdg after long and short vowel, and HP who had a difference of 90 ms (and this cannot be Danish influence). Those who have lengthened consonant normally pronounce it with less voicing.

As for ptk, most subjects have also a somewhat longer consonant after a short vowel than after a long vowel. This is true of 5 subjects out of 6 for p, and for 8 and 7 out of 10 for t and k, but the differences are often small. Only CH, GR, and HP (who had also long bdg after short vowel) have an appreciable lengthening.

Because of these irregularities the relations between bdg and ptk are not so clear in this position. bdg have longer closures than ptk in some cases, but as the words with bdg are very rare, this is less essential.

The tendency to longer and only partly voiced b after short vowel has been observed by Hentrich (1925). Rositzke (1944) found t and k, but not p, to be slightly longer after short vowel, cf. also E.A. Meyer (1901 a and b).

3.2.2 Differences between stops and affricates

Recordings of affricates have been made by GJ, GR, CH, WS, HP, and KV. The values of the durations of closure and fricative phase are given in table 6 and displayed in graphical form in fig. 5.

All subjects have a shorter closure and, conversely, a longer open interval in pf and ts than in p and t (the only exception is KV's pf). As the difference in open interval is larger than the difference in closure, the total duration of the affricates is in all cases longer than that of the stops, the averages ranging from 111% (HP I) to 142% (CH I).

Table 6 contains 8 pairs of averages for each place of articulation, thus 16 pairs of averages for closure, open interval, and total duration. As for the closure there are 5 cases which are not statistically significant, whereas all differences of aspiration and all but one difference of total duration are significant, normally at the 0.1% level.

Figure 5

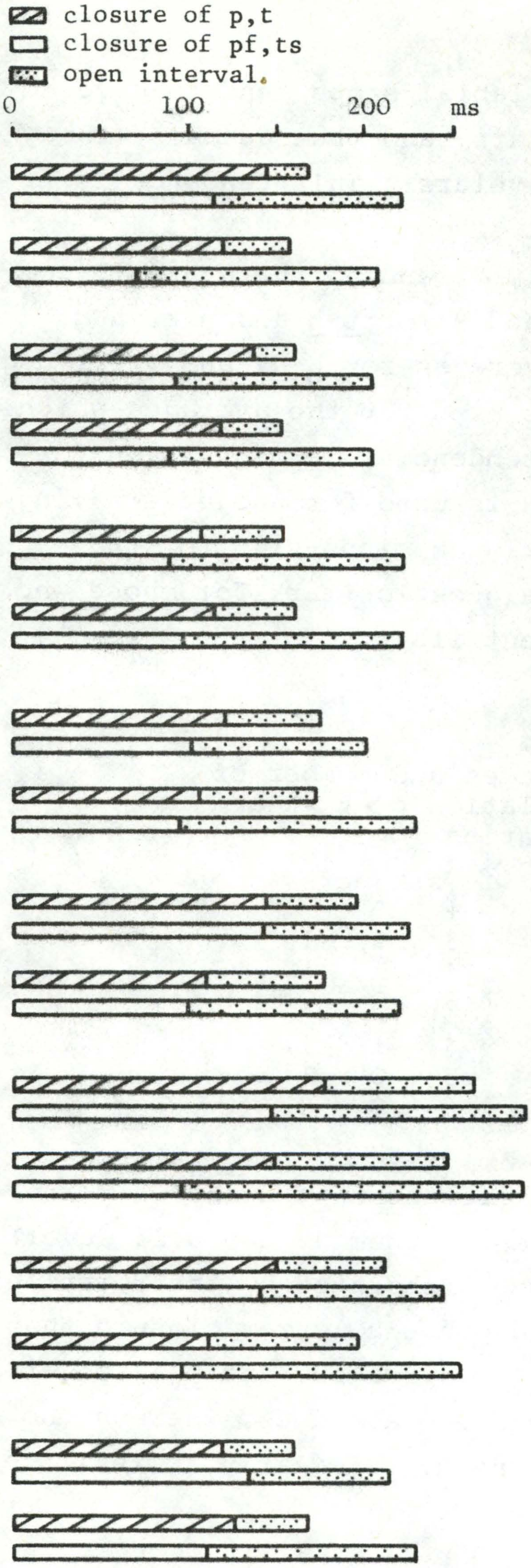

Table 6

Duration of p,t and pf,ts in the position V-'CV

S	N	C	cl.	op.i.	tot.	%op.i.
GJ	(3)	p	142	25	167	15
	(3)	pf	113	107	220	49
	(3)	t	118	38	156	24
	(3)	ts	70	138	203	68
GR	(6)	p	137	23	160	14
	(6)	pf	91	112	203	55
	(6)	t	118	33	151	22
	(6)	ts	88	114	203	56
CH I	(7)	p	105	46	151	30
	(5)	pf	89	131	220	60
	(6)	t	112	47	159	30
	(6)	ts	95	125	220	57
CH II	(18)	p	117	55	172	32
	(20)	pf	101	99	200	50
	(24)	t	104	66	170	39
	(20)	ts	94	134	228	59
WS	(24)	p	142	52	194	27
	(24)	pf	141	83	224	37
	(24)	t	108	68	176	39
	(24)	ts	98	121	219	55
HP I	(18)	p	175	86	261	33
	(18)	pf	145	145	290	50
	(18)	t	147	99	246	40
	(18)	ts	95	193	288	67
HP II	(13)	p	148	62	210	31
	(11)	pf	139	104	243	43
	(17)	t	109	86	195	44
	(18)	ts	94	158	252	63
KV	(12)	p	117	40	157	26
	(12)	pf	131	80	211	38
	(12)	t	124	42	166	25
	(12)	ts	109	118	227	52

3.2.3 Differences due to place of articulation

3.2.3.1 Closure

It has often been found that labial stops tend to have a longer closure than dentals and velars, and that dentals (though less often) tend to be longer than velars. This tendency is also found in the present material.

In stressed position (table 1, 2, and 6) there are 19 comparable pairs of averages for p-t and 9 for t-k and p-k, and there are 11 comparable pairs of averages for b-d, and 9 for d-g and b-g. In table 7 a plus sign is used for the averages which are in agreement with the general tendencies, a minus sign for the others. Similarly, a plus-sign is used for subjects having the mentioned difference consistently, a minus-sign for those having the opposite relation, and a question mark for those who show different relations in different lists.

Table 7

Number of pairs of averages and number of subjects showing the relation p > t > k and b > d > g for closure duration

	averages		subjects		
	+	-	+	?	-
p > t	15	4	3	2	1
t > k	7	2	4	1	1
p > k	9	0	6	0	0
b > d	9	2	4	1	1
d > g	8	1	5	0	1
b > g	8	1	6	0	0

For four of the six subjects the differences p > k and b > g are statistically significant (for three of them at the 0.1% level).

This tendency can be further corroborated by the relations found in unstressed position. Here p has a longer closure than t in 13 out of 15 comparable pairs of averages, and p a longer closure than k in 8 out of 11 comparable averages, whereas the relation between t and k is more random. Similarly, b is longer than d in all 8 comparable pairs.

Finally in the affricates pf is found to have a longer closure than ts in 7 out of 8 averages.

Bennett (1935, p. 16-21) has found similar relations: b > d, b > g, but g > d.

3.2.3.2 Open interval

For the open interval the opposite tendency has often been found, k > t > p and g > d > b.

This tendency is still more obvious in the present material. This is illustrated in table 8 which is set up in the same way as table 7.

Table 8

Number of pairs of averages and number of subjects showing the relation k > t > p and g > d > b for open interval duration

	averages		subjects		
	+	-	+	?	-
k > t	9	0	6	0	0
t > p	17	2	4	1	1
k > p	9	0	6	0	0
g > d	9	0	6	0	0
d > b	11	0	6	0	0
g > b	9	0	6	0	0

The same relation is found for the fricative phases of ts and pf. In all 8 pairs of averages the fricative part is longer in ts than in pf. In figs. 6, 7, and 8 the average values of closures and open interval for the stressed stops of tables 1, 2, and 6, respectively, have been plotted in a diagram with closure vertically and open interval horizontally. A comparison between the three places of articulation (connected by lines) shows that there is in most cases an inverse relationship between the duration of closure and open interval (i.e. the lines follow mostly the direction from upper left to lower right).

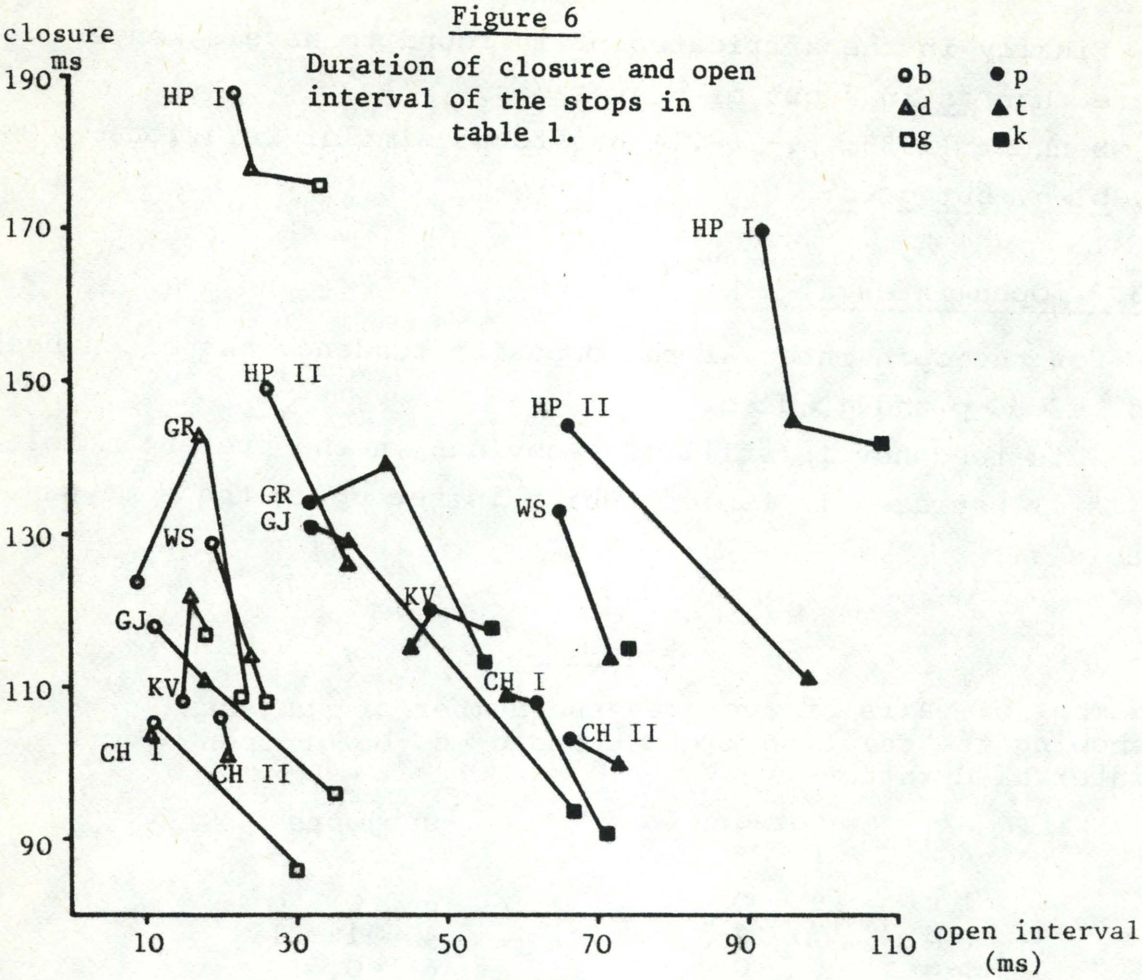

Figure 6

Duration of closure and open interval of the stops in table 1.

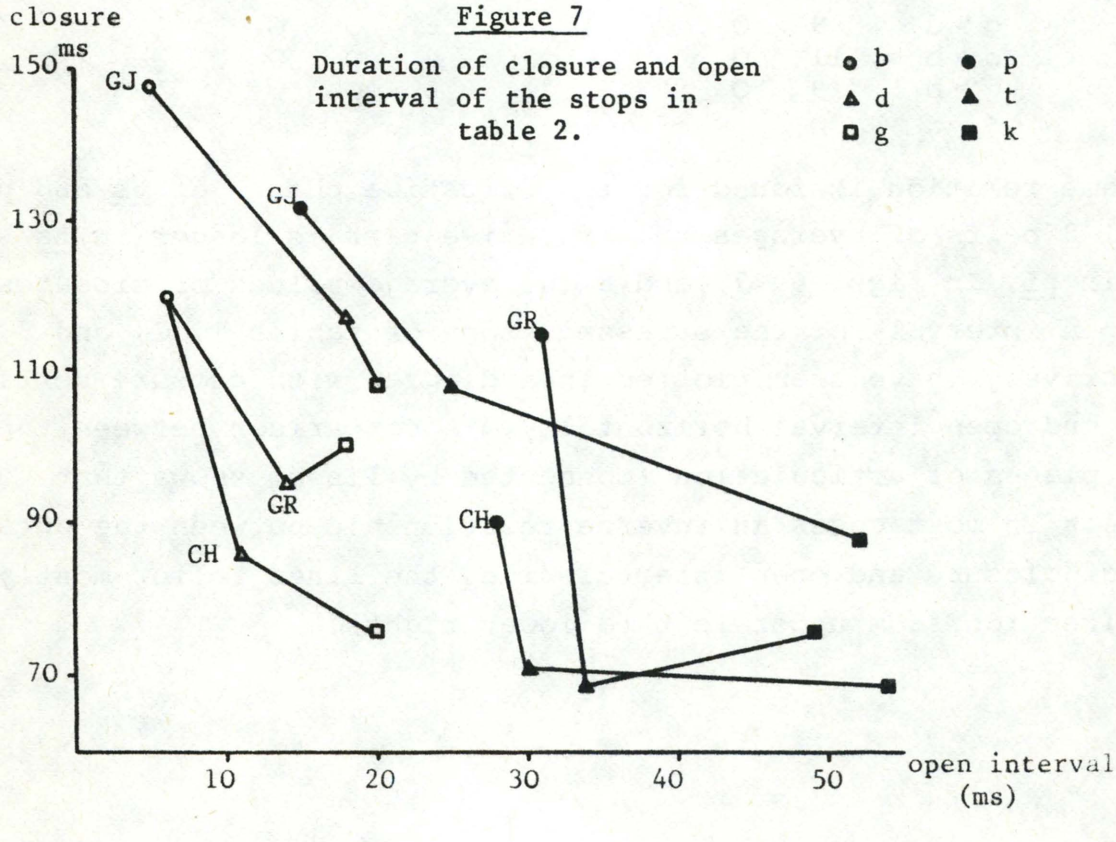

Figure 7

Duration of closure and open interval of the stops in table 2.

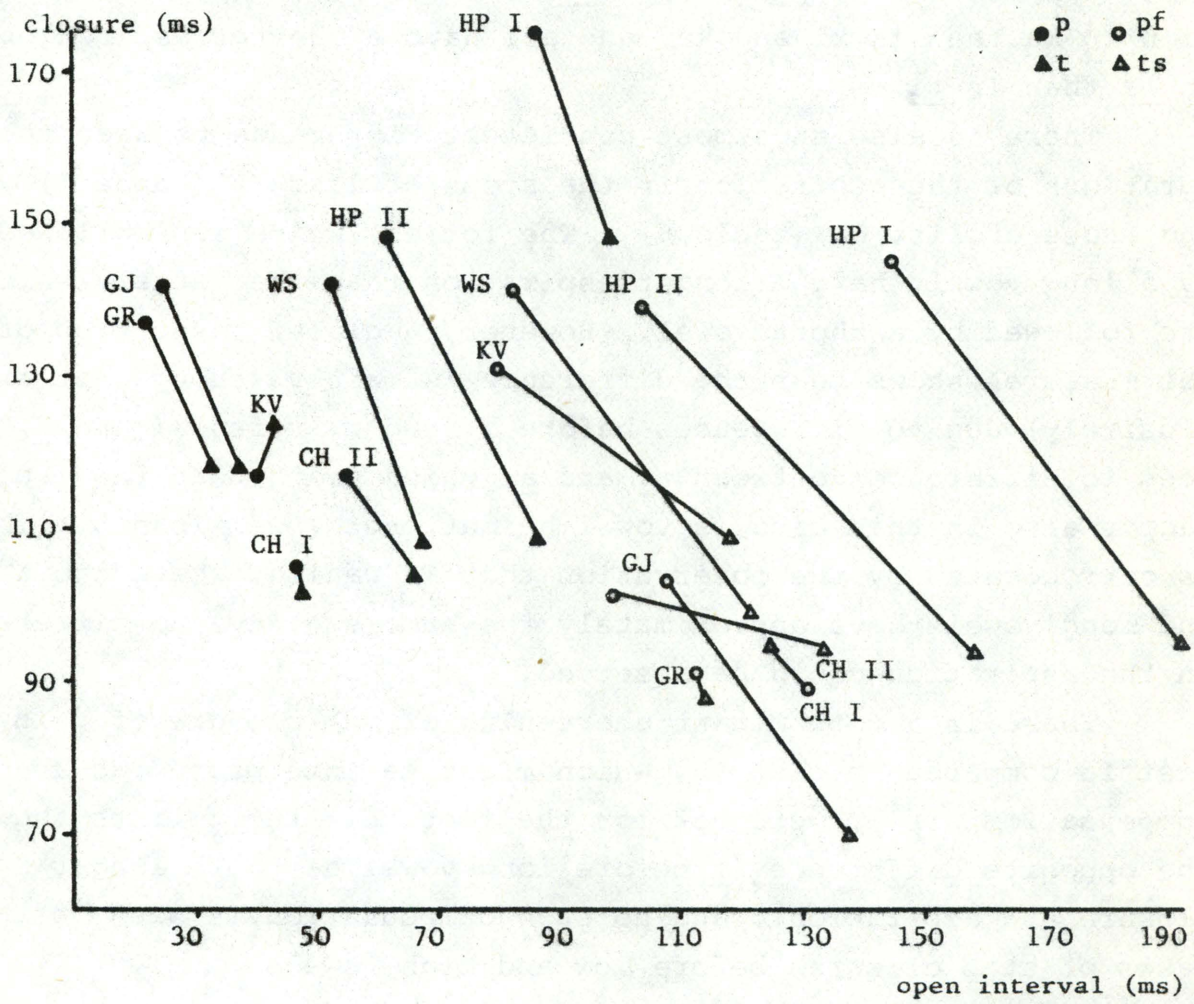

Figure 8

Duration of closure and open interval in the stops and affricates of table 6.

3.2.4 Differences due to the following vowel

It has also often been observed that the open interval tends to be longer before high vowels than before low vowels. This tendency can also be seen in the present material, though less consistently. In list Ia four of the six subjects have a longer aspiration in pu than in pa and pi, and a shorter aspiration in ka than in ki and ku, and all have a shorter aspiration in ta than in ti.

There is also an almost consistent difference between the durations of the aspiration in the stops of list Ia (table 1) and those of list Ib (table 6). The former, which are followed by a long vowel, have a longer aspiration than the latter, which are followed by a short vowel. However, a closer inspection of the measures shows that the difference is mainly (though not exclusively) due to differences before i: and u: versus I and U, less to differences between a: and a, which means that the crucial factor also in this case is vowel height, not vowel length. This is corroborated by the observation that in Danish, where short and long vowels have approximately the same quality, no difference in the aspiration could be observed.

There is a concomitant shortening of the closure of p in list Ia compared to list Ib, which might be interpreted as a compensation, if it were not for the fact that the t-lists show the opposite difference (t before long vowel has both longer closure and aspiration), and no such compensation is seen in the cases of stop closures before low and high vowels.

3.3 Intra-oral air pressure

Intra-oral air pressure has been recorded for subjects CH, HP, and WS.

3.3.1 Stressed position ($_{\circ}V$#'CV)

3.3.1.1 Peak pressure

Peak pressure averages in stressed position are given in table 9.

Table 9

Intra-oral air pressure (peak pressure) of stops and affricates in stressed position (V'CV)

S	L	N	C	mm H_2O	N	C	mm H_2O			
CH		(14)	b	43	(17)	d	50			
	(a)	(16)	p	53	(15)	t	59			
	(b)	(13)	p	58	(19)	t	59			
		(13)	pf	56	(16)	ts	62			
HP		(23)	b	86	(17)	d	110			
	(a)	(22)	p	90	(17)	t	104			
	(b)	(14)	p	108	(17)	t	106			
		(10)	pf	90	(18)	ts	116			
				mm[1]			mm			
WS		(24)	b	18.9	(24)	d	20.6	(24)	g	20.7
	(a)	(24)	p	19.8	(24)	t	20.1	(24)	k	20.8
	(b)	(24)	p	20.3	(24)	t	20.8			
		(24)	pf	18.3	(24)	ts	20.3			

The two sets of pt values are averages of list Ia and of list Ib in which the consonants stand before long and short vowel, respectively. The averages are slightly higher before short vowel. There is a tendency for p to have higher air pressure than b, and a tendency for dentals (and velars) to have higher air pressure than labials (but the latter tendency is reversed in unstressed position). However, none of the differences are significant except for that between p and b of subject CH, which is signifi-

1) As mentioned in section 2.3, WS's curves had to be measured in mm since the calibration curve had disappeared.

cant at the 5% level. CH and HP differ as to the voicing of b and d, HP having voiceless bd, CH 40% voicing of the closure; and as there is normally an inverse relation between air pressure and voicing, it is understandable that CH has a more consistent difference between pt and bd in air pressure. But it is astonishing that WS, who has 68% voicing in bd, has no difference in peak air pressure. He has, however, a slower rise of the curve in bdg. The peak value of the affricates do not differ from that of the stops.

3.3.1.2 Decay of pressure

The three types of consonants are, however, clearly distinguished by the decay of the pressure curve, bdg having an abrupt decay, ptk a somewhat slower decay, and the affricates a very slow decay. Moreover, it often happens that the pressure of the affricates continues to rise after the release, particularly in ts, so that the maximum is found in the fricative part of the consonant (cf. fig. 1). In HP's ts the distance from release to maximum is 142% of the duration of the closure. On the other hand, KV's pf has a shorter distance from implosion to maximum than his p, and this is therefore not a reliable measure of affrication. It has been attempted to quantify the differences in decay by two measures: (a) the distance (in ms) from the release to the point where the decay has reached 50% of the peak value, and (b) the fall in pressure value 20 and 40 ms after the release, indicated in % of the peak value. Table 10 shows the average values of these measures for p and t (list Ia and Ib combined) and for pf, ts. No measurements have been made for bdg, since they always fall abruptly. In fig. 9 the same differences are depicted graphically. The differences between p and pf and t and ts are evidently significant.

Table 10

Decay of intra-oral air pressure in stops and affricates
(a) distance from release to 50% pressure value (in ms)
(b) fall in pressure value 20 and 40 ms after the release in % of the peak value.

S	N	C	dist. ms	pressure fall +20ms %	pressure fall +40 ms %	N	C	dist.	pressure fall +20ms %	pressure fall +40 ms %
HP	(30)	p	17	56	82	(34)	t	56	20	41
	(10)	pf	57	22	48	(18)	ts	141	4	4
WS	(48)	p	41	30	53	(48)	t	46	27	44
	(24)	pf	70	3	18	(24)	ts	105	1.5	2
CH	(29)	p	11	74	90	(34)	t	21	53	78
	(12)	pf	65	3	25	(16)	ts	107	-10	16

Apart from the differences between stops and affricates it also appears from the table that stops tend to have a slower decay in t and k than in p (except for pu/tu). They also have a slower decay before u and i than before a, particularly when the vowel is long (list Ia). These differences correlate with tendencies observed in the duration of the aspiration, and similar tendencies are found in Danish stops. The differences according to following vowel (list Ia) have been quantified in the same way as the differences between stops and affricates. They are depicted in graphical form in figs. 10 A and B. The number of examples included in the averages of different vowels are 4-7 for CH, 6 for HP, and 8 for WS, HP's distance values for pV: (list Ia) have disappeared. HP has a very slow decay in ti, i.e. he has affrication. This may be Danish influence.

3.3.2 Unstressed position ('VCə)

In unstressed positions all consonants have a lowered peak pressure. The average values for the examples found in list Ia and b are given in table 11.

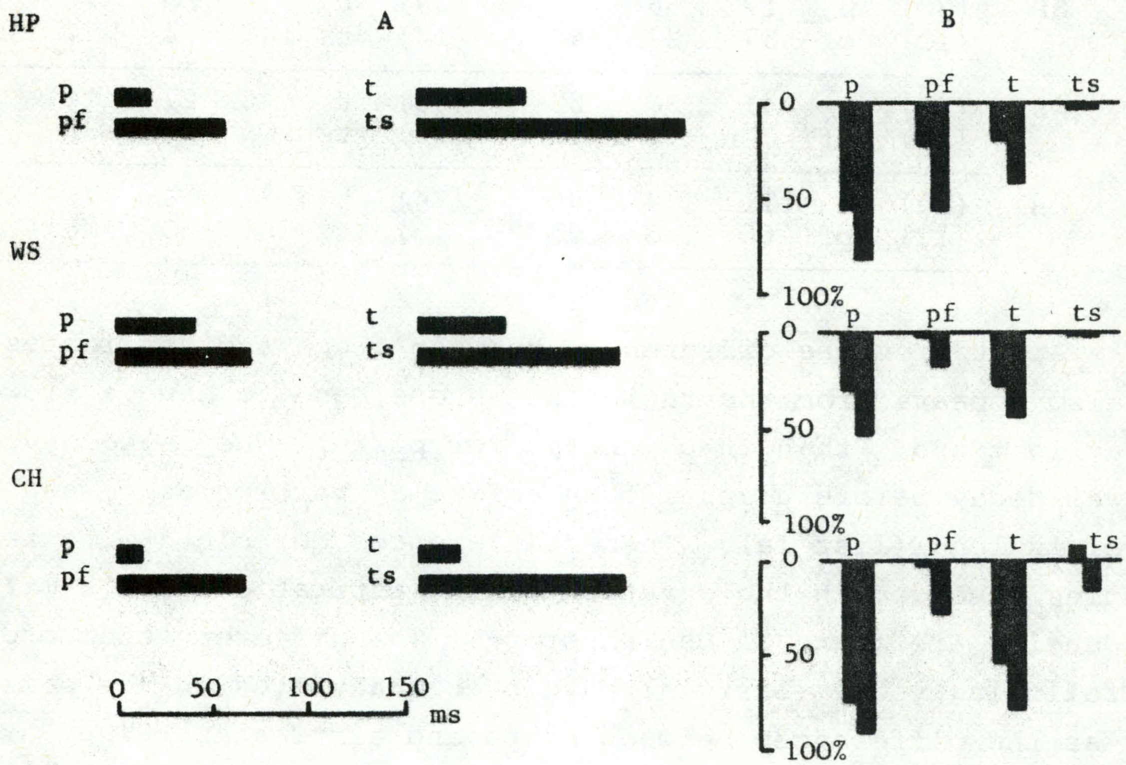

Figure 9

Decay of intra-oral air pressure

A. Distance from release to 50% of peak value

B. Decay 20 and 40 ms after release in % of peak value.

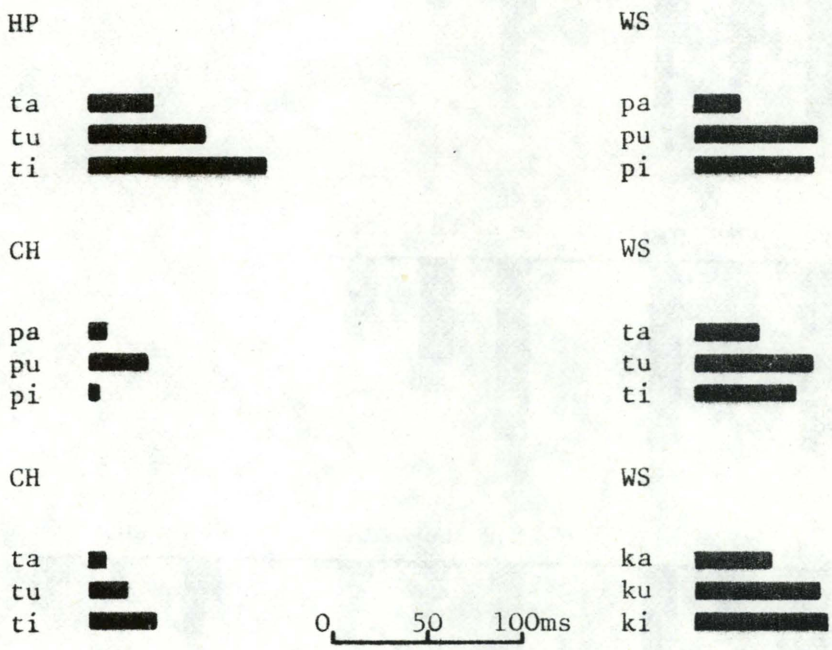

Figure 10A

Decay of intra-oral air pressure before different vowles. Distance from release to 50% of peak value.

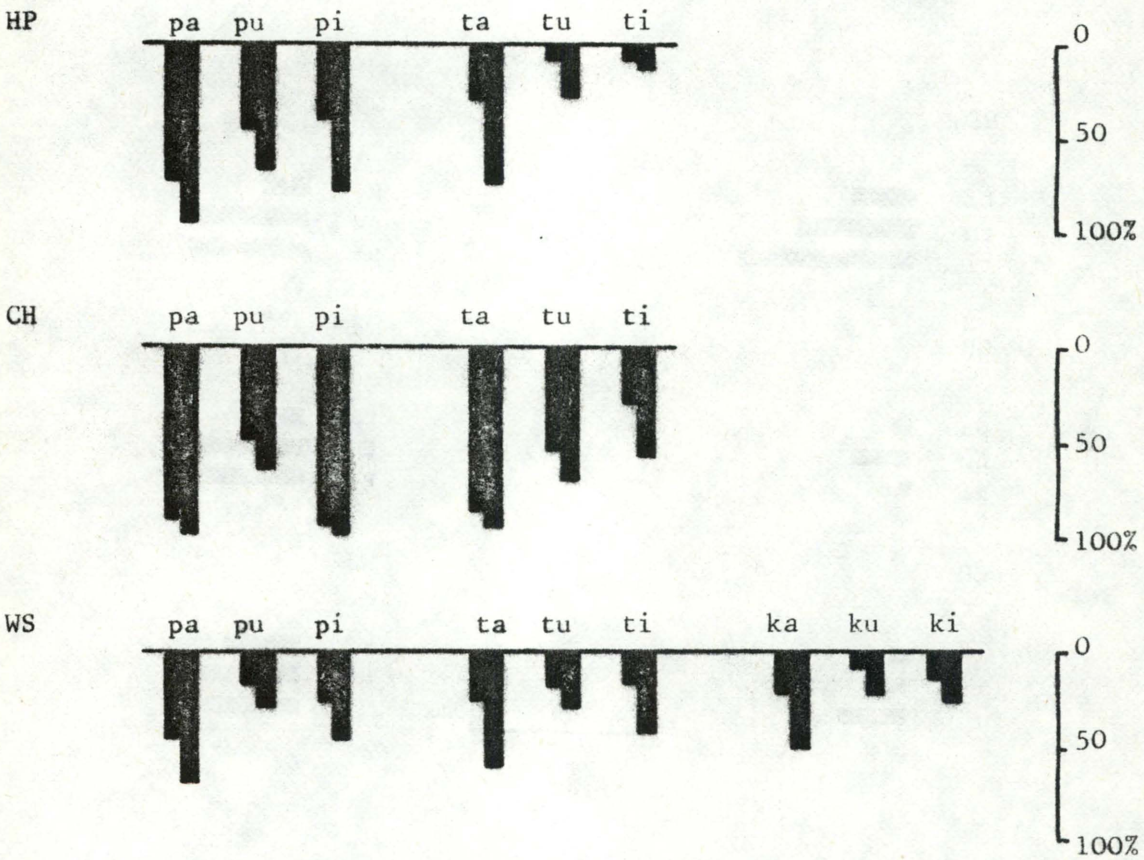

Figure 10B

Decay of intra-oral air pressure before different vowels. Decay 20 and 40 ms after release in % of peak value.

Table 11

Intra-oral air pressure (peak pressure averages) in stops in medial position before unstressed vowel after stressed vowel ('VCə)

S	N	C	mm H_2O	N	C	mm H_2O	N	C	mm
CH	(16)	p	49	(20)	t	46			
	(22)	b	27	(7)	d	19			
HP	(6)	p	98	(18)	t	78			
	(12)	b	86	(7)	d	54			
			mm			mm			mm
WS	(8)	p	18.1	(32)	t	16.9	(8)	k	17.6
	(32)	b	11.6		d	-	(16)	g	12.0

The peak pressure of ptk is only slightly lowered in unstressed position (cf. table 9), and the same is true of HP's voiceless b and d, but the fully voiced bdg spoken by CH and WS have a considerably weakened pressure in unstressed position compared to initial bdg, and there is therefore a significant difference both between their bdg in stressed and unstressed position and between their ptk and bdg in unstressed position. The pressure curves of unstressed bdg also have a slower rise. The difference between stressed and unstressed position also appears clearly from an inspection of the individual words containing two stops. WS has, for instance, seven words of this type (Puppe, Pute, Tute, guten, Pike, Diebe, Gabe) with 8 examples of each, and the peak pressure is always lower in the second stop except for one example of Pike and two of Puppe.

3.4 Airflow

Airflow recordings have been made of the subjects HP, WS, and KV.

3.4.1 Stressed position (˳V#'CV)

3.4.1.1 Peak values

The average peak values for ptk, bdg, and the affricates in stressed position after vowel are given in table 12, and a graphical display is found in fig. 11.

Table 12

Airflow (peak values) of stops and affricates in stressed position ($_{\circ}$V#'CV) ((a) before long vowel, (b) before short vowel). Number of examples: HP and KV 12, WS 17.

S		C	mm	C	mm	C	mm
HP		b	14.2	d	10.8	g	6.5
	(a)	p	18.6	t	18.1	k	18.3
	(b)	p	23.3	t	22.7		
		pf	17.1	ts	12.5		
WS		b	19.0	d	16.0	g	13.5
	(a)	p	28.0	t	26.4	k	22.8
	(b)	p	29.7	t	33.7		
		pf	21.6	ts	21.5		
KV		b	34.4	d	27.0	g	15.6
	(a)	p	40.8	t	36.3	k	30.5
	(b)	p	53.2	t	46.2		
		pf	37.7	ts	23.0		

All three subjects have a clear difference between ptk and bdg. Furthermore, they all have higher peak values in p and t than in pf and ts. These differences are all significant at the 0.1% level (KV's p/b at the 1% level). There is further a tendency for the peak value to be higher before short than before long vowels (6 pairs), and to be higher in labials than in dentals (12 pairs with one exception), and in dentals than in velars (6 pairs with one exception).

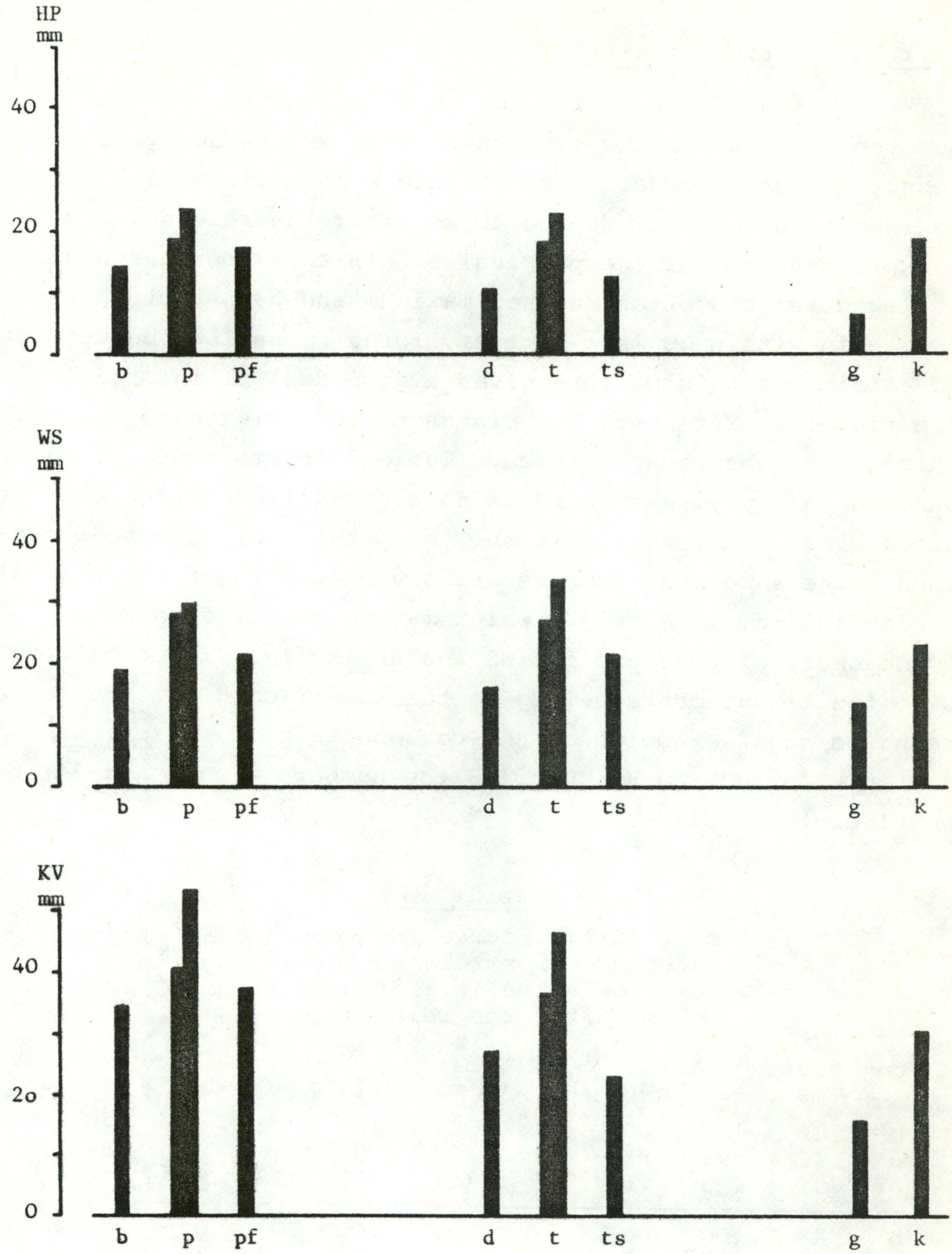

Figure 11

Airflow, peak values. For ptk the left column indicates the position before long vowel, the right column before short vowel.

3.4.1.2 The rise of airflow

The rise of the airflow curve after the release has been measured by means of the same parameters as the decay of the pressure curve in order to facilitate a comparison, i.e. the rise has been measured 20 and 40 ms after the release, and it is expressed in % of the peak value. In the stop consonants the airflow curve has often reached maximum and has started going down again within 20 ms. However, for a comparison between stops and affricates this measure gives a good deal of information (see fig. 1). Moreover, the distance from release to the peak of the curve has been measured. Table 13 contains the values found in this way. As there is no clear difference between stops before short and long vowels the two ptk-series have been combined. The same measurements are given in form of a graphical display in fig. 12 A and B, which may be compared to the display of the decay of pressure for WS and HP in fig. 9; but only for WS do the measurements belong to the same recording. The averages are based on 12 examples of the consonants b, d, g, pf, ts, and 24 of ptk for HP and KV. For WS the numbers are 17 and 34, respectively.

Table 13

Rise of airflow curve in stops and affricates
(a) distance from release to maximum (in ms)
(b) airflow value in % of peak value 20 and 40 ms after the release.

	C	dist. ms	flow +20	flow +40	C	dist. ms	flow +20	flow +40	C	dist. ms	flow +20	flow +40
HP	b	13	100	100	d	18	100	100	g	24	*	100
	p	42	92	98	t	62	59	86	k	65	53	84
	pf	119	13	26	ts	151	22	46				
WS	b	19	100	100	d	21	100	100	g	25	100	100
	p	26	90	99	t	39	71	99	k	45	54	95
	pf	65	31	66	ts	104	16	35				
KV	b	13	100	100	d	12	100	100	g	14	100	100
	p	16	100	100	t	23	94	100	k	43	67	98
	pf	69	21	34	ts	108	19	38				

*) HP's g has not quite reached 100% at 20 ms distance (the distance to the peak is 24 ms), but the measurement is missing.

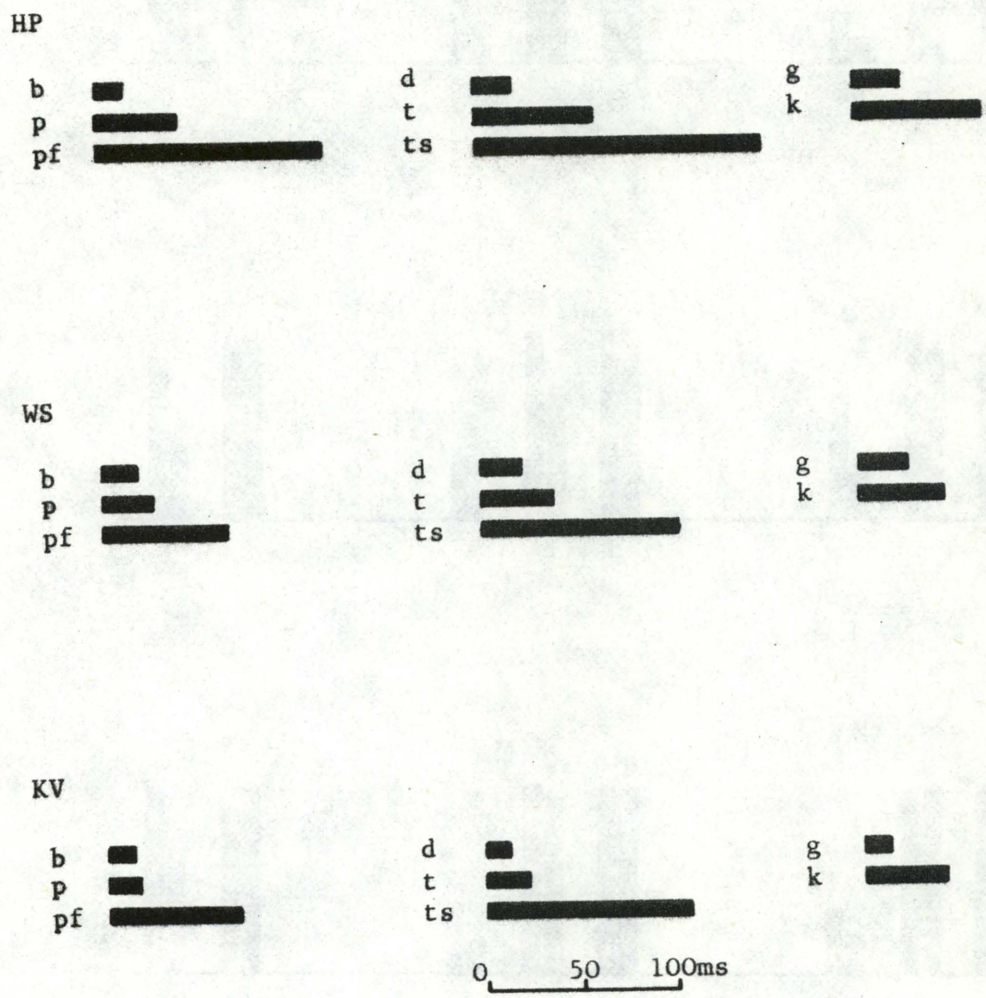

Figure 12A

Rise of airflow. Distance from release to peak (in ms).

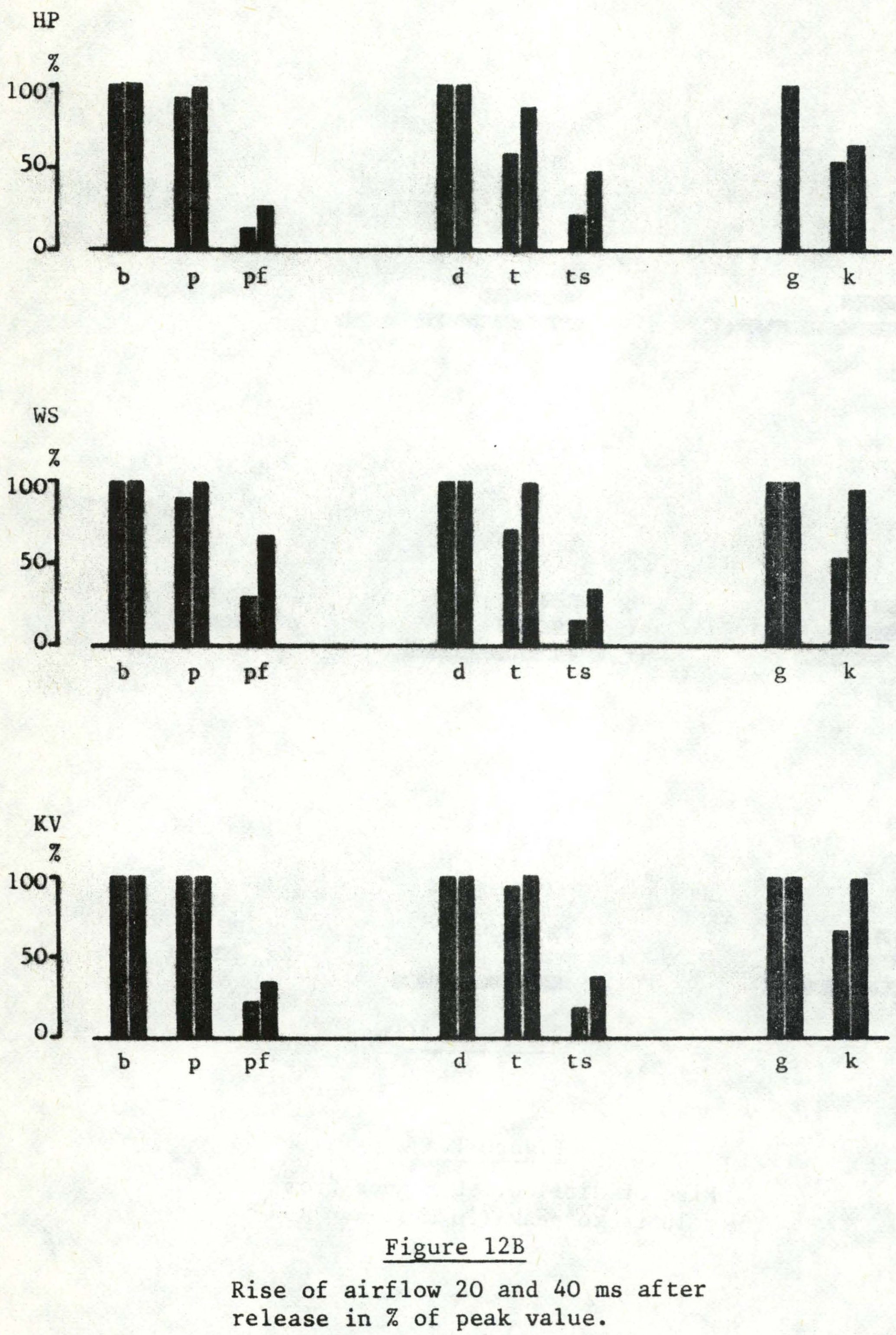

Figure 12B

Rise of airflow 20 and 40 ms after release in % of peak value.

It appears from table 13 that the airflow rises more quickly in bdg than in ptk and more quickly in ptk than in pf and ts. There are no exceptions to these relations in the averages, except that p and t may reach 100% like bdg. Moreover, it appears that labials rise more quickly than dentals and these more quickly than velars. The only exception is the relation b-d in KV's curves, but these were rather dubious to delimit. These relations are the same as those found in the decay of pressure. There are also some differences according to vowels, but they are rather inconsistent.

3.4.2 Unstressed position ('VCə)

In unstressed position the peak of the airflow is normally lower than in stressed position. The values for WS and KV are given in table 14.

Table 14

Airflow (peak value) in unstressed position ('VCə)

S	N	C	mm	N	C	mm	N	C	mm
WS	(6)	p	24.6	(24)	t	23.9	(6)	k	25.0
	(24)	b	11.9		d	-	(12)	g	11.5
KV	(4)	p	36.3	(16)	t	24.1	(4)	k	27.1
	(16)	b	26.0		d	-	(8)	g	17.9

These values are somewhat lower than those for the stressed position except for WS k and KV g.

Generally the second of two stops in a sequence 'CV̥CV has a lower peak airflow than a preceding stressed stop, but there are many exceptions. Not only has t in guten a much stronger airflow than g, but also in the cases of same type of consonant can this relation be found, e.g. WS Diebe, Giebel, Pute. There is a significant difference between p-b and k-g.

3.5 Subglottal pressure

Subglottal pressure has only been recorded for WS. The pressure has been measured at the point of release. This is at the same time normally the maximum of the whole word. The averages for the stressed position are given in table 15.

Table 15

Subglottal pressure at the point of release of stops and affricates (˳V#'CV)

S	N	C	mm	N	C	mm	N	C	mm
WS	(24)	p	13.9	(24)	t	15.9	(12)	k	15.8
	(11)	b	15.5	(12)	d	15.3	(12)	g	15.6
	(9)	pf	13.4	(12)	ts	15.0			

There is no consistent difference between the peak values of *ptk* and *bdg*. But the pressure curves of *ptk* differ from those of *bdg* and the affricates by having a small dip starting at the release and ending approximately 10 ms after the start of the vowel. This dip is deeper before *a* than before *i* and *u* (see fig. 2), corresponding to the quicker escape of air at the release before *a* and the quicker drop in intra-oral air pressure. The dip is slightly deeper before *i* and *u* in list Ib, which has short (and thus lower) *i* and *u*. The differences are very small, but hardly quite accidental. The measurements are given in table 16.

Table 16

Size of dip after the release of *ptk* (in mm)

	pa	pu	pi	ta	tu	ti	ka	ku	ki
(Ia)	2.8	0.8	1.1	2.5	1.4	1.2	2.8	0.9	0.9
(Ib)	2.3	1.0	1.6	2.9	1.9	1.6			

Such dips are not found after *bdg*, and only rarely in the affricates. In some cases, however, a dip is found in affricates but not at the release, but later, when the airflow starts to rise more quickly and the intra-oral pressure goes down.

After the dip the curve rises somewhat again, but it does not reach the value from before the dip. This is particularly true of the dip after a (see fig. 2). The result is that at the start of the vowel ptk have normally a lower subglottal pressure than bdg (see also Ohala 1974). These values (measured 10 ms after the start of the vowel) are given in table 17.

Table 17

Subglottal pressure of the stops at the start of the vowel (in mm)

WS	p	12.9	t	14.6	k	14.3
	b	15.3	d	15.3	g	15.6

After affricates and bdg the curve sometimes rises very slightly after the release, particularly before u.

Unstressed syllables rarely have a separate peak. In most cases the second stop in words of the type Tute has a slightly lower subglottal pressure than the first, but it may have the same pressure or (in two cases) a somewhat higher pressure.

In voiceless sounds the sub- and supraglottal pressure should be approximately the same. Unfortunately it could only be measured in mm. But there should at least be a close correlation between the measurements. This is also found in so far as p has a lower pressure than t, pf a lower pressure than ts, and p a slightly higher pressure than pf in both cases. But the relation does not hold for t-ts, and it does not hold in single cases (see the values of intra-oral peak pressure in table 9; the relations remain the same if only those recordings are included which comprise both intra-oral and subglottal pressure).

3.6 Lip pressure

Lip pressure has been recorded for CH and HP. The averages are given in table 18. Before stressed vowel CH has a slightly higher pressure in p than in b, but HP has the opposite relation. Before unstressed vowel both have higher lip pressure in p than in b, but in both cases the variation is very large and the differences non-significant. CH has often assimilated a following syllabic n to the labial stop and this seems to result in a higher lip pressure. If these examples are discarded the average of her unstressed b will be 6.3 mm H_2O and the difference from p quite clear, but in that case the average is only based on 4 examples.

Table 18

Lip pressure of p and b in the positions ˳V#'CV and 'VCə

S	N	C	mmH_2O	N	C	mmH_2O
CH	(24)	'p	11.7	(12)	'b	10.6
	(16)	˳p	13.3	(16)	˳b	12.3
HP	(36)	'p	25.2	(18)	'b	33.5
	(12)	˳p	22.0	(16)	˳b	17.8

3.7 Intensity of the explosion

The intensity of the explosions has been measured in dB on the mingograms for CH, GJ, and GR. However, the measurement of intensity of such brief bursts of sounds on mingograms with a certain integration time and even some high pass filtering (these were the first mingograms, taken in 1955) is rather unreliable, and there is no sense in giving tables with exact values. The only thing that can be said is that there was a certain tendency for ptk to have higher intensity than bdg, but with extensive overlapping and great variation, and that the affricates had evidently weaker explosions than the stops.

4. Summary and discussion

4.1 The distinction between North German ptk and bdg

It seems evident that a common description of North German and South German stops is not possible. In Southern Germany ptk are normally unaspirated and bdg are voiceless even in rather educated speech. The problem is whether all North German speakers can be said to have the same distinctive features.

4.1.1 Aspiration and voicing

Aspiration is obviously an important factor in the distinction between ptk and bdg in stressed position. In unstressed position ptk may be almost unaspirated, but there is still a difference in airflow and often a small difference in open interval.

In unstressed position there is, however, also, in practically all cases, a difference in the degree of voicing (we must here leave HP aside since he may be influenced from Danish). Such a difference is not consistently found in stressed position after a vowel, it is very rarely found in absolute initial position, and never after s.

In order to produce a voiced stop, two conditions must be fulfilled: The glottis must be relatively narrow, and there must be a pressure drop across the glottis. After a vowel the glottis will be narrow and the pressure drop may be sufficient for some time, but after a voiceless sound it is probably not sufficient that the vocal cords are approached. Because of the open position of the glottis during the preceding voiceless sound, the intraoral air pressure will be rather high already at the implosion, and a command for an enlargement of the cavities will probably be necessary. After a pause it may be somewhat easier to produce a voiced stop since nothing prevents the glottis from narrowing down, and the subglottal pressure is rising. In our small material all stops were voiceless after an s in the preceding word, but Esawa (1972) quotes various examples of more or less voiced stops in this position.

Those Germans who have, or may have, voiced stops after voiceless sounds (and perhaps also those who have initial clearly audible voicing) may be assumed to have a separate command for an enlargement of the cavities, leading to a lower pressure, and thus to have voicing as a particular factor. For others the voiced stops after voiced sounds may be a simple case of assimilation (see also Schmitt 1947, and Meinhold and Stock 1963), so that voicing cannot be considered a separate factor. The difference from Danish, which normally has voiceless bdg even after voiced sounds in stressed position (but normally weak voicing in unstressed position), is only one of degree, and might perhaps be due to a slight difference in glottal opening. This is pure speculation, since nothing is known about the opening of the glottis in German stops. But it is not unplausible.

One may also speculate further and set up the hypothesis that North German is now developing in the same direction as Danish. It is conspicuous that the data on aspiration in older descriptions (Meyer 1904, Weitkus 1931) indicate much shorter aspirations than modern descriptions. The objections to the traditional requirement of voiced bdg in all positions have also been increasing. This may be accidental, but it may also reflect a development, i.e. North German may be on its way to a new sound shift, and in such a situation there will be much vacillation.

4.1.2 Fortis-lenis

Some phoneticians think that the common distinction between German ptk and bdg in stressed and unstressed position is one of tenseness (Schmitt 1947, Bothorel-Witz and Pétursson 1972). I have not found much evidence for this assumption in the present material. In languages where a fortis-lenis difference is more evident, e.g. in French or in Swiss German (see Fischer-Jørgensen 1972 and Dieth and Brunner 1943), this difference is consistently realized by a longer closure duration and higher organic pressure in the tense consonant. But the difference between the closure duration of ptk and bdg in stressed position in the present material is small and not significant (whereas there is a difference in unstressed position). The same is true of lip pressure. Some think that differences in intra-oral air pressure may be suggestive of a fortis-lenis opposition, but this difference is not consistent either in the present material. The intensity of explosion was also very variable (see section 3.7). It is possible that the assumption of a fortis-lenis opposition can be corroborated by other facts, e.g. higher speed of the movement of the articulators and consequently quicker formant transitions, higher EMG activity of the relevant muscles, etc., but this remains to be demonstrated.

4.2 ptk after s

The examples of ptk after an s in the preceding word showed a remarkable shortening, not only of the closure but also of the aspiration. This should perhaps be seen in the light of the well known fact that after an s of the same word ptk in Germanic languages have not undergone either the Germanic or the High German sound shift. Kim (1970) has suggested that this should be due to the fact that the opening-closing movement of the glottis necessary for p may start in the s and therefore come to an end earlier. Frøkjær-Jensen, Ludvigsen, and Rischel (1971) have found such common one-peaked glottis movements in glottograms of combinations of voiceless consonants. Pétursson (1976, p. 188) has found the same in Icelandic.

4.3 The distinction between stops and affricates

The measurements undertaken have shown the affricates to have shorter closure, longer open interval, slower decay of intra-oral air pressure, slower rise of airflow and less intensity of the explosion compared to stops. This suggests a weaker and slower articulation.

4.4 Differences due to place of articulation and following vowel

The measurements of German stops have corroborated other findings pointing to some more universal tendencies (see e.g. Ilse Lehiste 1970, p. 27-30). The following tendencies have been found: labial stops have longer closure, shorter open interval, quicker rise of airflow, higher airflow peak, and (as far as ptk are concerned) quicker decay of intra-oral air pressure than dental stops. The same relations hold, although with less consistency, for dental stops compared to velar stops. Moreover, the degree of openness of the following vowel is of importance, the open interval being shorter and the decay of both intra-oral and subglottal air pressure quicker before a than before i and u.

It seems very plausible to assume that the differences due to following vowel must depend on the degree to which the flow of air is impeded by constrictions in the oral cavity: The low vowels permit a quicker escape of air and consequently a shorter open interval.

A similar reasoning may then be applied to the place of articulation of the stops: the labials have no constriction in the oral cavity and permit a quicker escape of air, resulting in a quicker decay of air pressure, a quicker flow of air, a higher peak airflow, and a shorter open interval than dentals and velars. Moreover, it may be assumed that the tongue tip moves more quickly than the bulk of the tongue, and perhaps the lips more quickly than the tongue tip, and this would give the same results. The relative speed of the movements might be concluded from the duration of formant transitions measured from the point of release. This distance was found to be shorter in the order labial $<$ dental $<$ velar in French stops (see Fischer-

Jørgensen 1972)[1]. As for the relation between closure durations, which are normally in inverse relation to the durations of open interval, the order being labial > dental > velar, it might perhaps be interpreted as a compensation phenomenon. In this connection it would have been of interest to measure the duration of the following vowel, but the consonants following the vowel were too different in the present material to allow of such measurements. (In Danish there is not only an inverse relation between open interval and closure duration but also between open interval and following vowel for ptk compared to bdg, but the reduction of the closure is considerably more pronounced than that of the vowel. As for the difference between the different places of articulation t, which in Danish is strongly affricated, has also a clearly shorter duration of the closure, whereas the shortening of the vowel is about the same for the three consonants.) Instead of interpreting the closure durations as caused by compensation phenomena, one might also think of direct physiological mechanisms. It might, for instance, be assumed that as the closure of p can take place quite independently of preceding and following vowels, it may start earlier and last longer (to decide this it would be necessary to measure preceding vowels, too). Moreover, the closure may be more firm at the lips than e.g. at the place of articulation of k and g (in Danish it is quite evident that t has a rather loose and thus a short closure as is also the case with German affricates).

More investigations are needed on this point.

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1) A confirmation for German stops might be sought in Vieregge (1969), but the mathematics of this book exceeds my capacity of understanding.

4.5 The assumption of heightened subglottal pressure in aspirated sounds

It is well known that Chomsky and Halle have assumed a higher subglottal pressure in aspirated sounds. In the present material no such difference was found between ptk and bdg. On the contrary, there was a small dip in the pressure during the aspiration (also found in other languages, cf. Ohala 1972 and 1974), and it is remarkable that even in such small details as the larger dip before a subglottal pressure seems to depend on the conditions in the supraglottal cavities. One might, perhaps, modify the hypothesis of Chomsky and Halle by speaking of increased pulmonary effort instead, i.e. by assuming that in order to produce a rather constant subglottal pressure during different sound types, a higher effort of the expiratory muscles would be needed for sounds with a wide open glottis and with escape of air through the mouth, i.e. for aspirations, h, and - to a certain extent - fricative sounds. If the pressure went up again after the dip, this might be an argument in favour of such an assumption, but, as shown in section 3.5, the pressure only rises very slightly and is lower than the pressure in bdg at the start of the following vowel. It is, however, astonishing that during affricates it very often happens that subglottal and supraglottal pressure remain at the same level, even if there is a rather considerable escape of air. But in order to prove that this requires more energy on the part of the expiratory muscles more investigations are needed, and the curves will have to be calibrated.

4.6 Air pressure and airflow

It has often been assumed that the degree of air pressure during the closure determines the amount of airflow at the explosion. But in the present material there is no close correlation between these two phenomena. For instance, in a word like guten the g has a higher intra-oral pressure than the t, but the latter a much higher peak airflow. And the consistent difference in airflow between ptk and bdg is not paralleled by a corresponding difference in air pressure. What is probably more important for the airflow is the degree of opening of the glottis at the moment of release. (See also Pétursson 1976, p. 180.)

4.7 Final remarks

It appears clearly from this investigation that much more research needs to be done before we can give a sufficiently well documented description of stop production in general and of German stop production in particular.

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