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TEMPORAL RELATIONS IN DANISH TAUTOSYLLABIC CV SEQUENCES WITH STOP CONSONANTS[1]

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Abstract: This paper presents some facts about the duration of closure and open interval in Danish stop consonants (5.1 - 5.2). 5.3 deals specifically with the relation between durations of closure, open interval and following vowel (1) in ptk vs. bdg, (2) depending on place of articulation of the consonant, (3) in connection with long and short vowels, (4) with high and low vowels, and (5) with rounded and unrounded vowels. In section 6 it is discussed whether the relations found are due to compensation within the CV sequence or to specific production mechanisms. It is suggested that only vowel length in (1) may be due to compensation.

1. Purpose

The purpose of this paper is to present some data on the temporal relations in CV sequences with Danish stops, and to discuss the possible explanations of these relations, in particular whether they can be assumed to be due to compensation phenomena or to specific physiological conditions.

2. Material

The Danish stop consonants are /ptk/ and /bdg/. These two classes are distinguished phonologically in syllable initial posi-

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1) This is an enlarged and revised version of Eli Fischer-Jørgensen 1979. It contains a much more extensive documentation, and some mistakes have been corrected. In the last section references to findings in other languages have been added, and more arguments and points of view are included in the discussion. I am very grateful to Birgit Hutters for a number of critical remarks which have resulted in considerable improvements of the paper. -

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sition before (sonorant consonant +) full vowels only. /ptk/ are voiceless aspirated stops [ph th kh]. /bdg/ are voiceless unaspirated stops [b̥ d̥ g̊]. Medially before [ə] and the weak endings ig [i] and ing [eŋ], as well as finally, only one set of stops is found, which is almost always pronounced as (very) weakly voiced [bdg] medially, whereas finally there is free variation between [ph th kh] and [b̥ d̥ g̊], [ph th kh] being used mainly in absolute final position. This paper deals exclusively with the position in which /ptk/ and /bdg/ are distinguished, and only the position before stressed vowels is taken into account.

Some of the material presented is not of recent date. But these old recordings have either not been utilized at all, or only partly so, or for other purposes. They have been supplemented with one rather extensive more recent recording, which is part of an EMG-investigation. The recordings are either spectrographic (indicated by the letter S) or mingographic (indicated by the letter M). The latter recordings comprise duplex oscillograms, Fo curves, and intensity curves. In cases of doubt they have been supplemented by spectrograms.

S1 (1952) contains 17-45 words spoken by 9 different speakers. As the occurrence of different stops under different conditions is not very regular, this list is only referred to very briefly. (S2 is a very short list not utilized in this paper.)

S3 (1954) comprises 60 words of the type CV:nə, where C represents /p t k b d g/ and V the 10 long Danish vowels /i: e: ɛ: a: y: ø: œ: u: o: ɔ:/. It has been spoken twice by two subjects (No. 5 and No. 9) and once by one subject (No. 6).

S4 (1954) comprises 30 words of the type CVC, where C- and -C are phonetically identical [ph th kh], and V represents the ten short Danish vowels. This list was spoken twice by two subjects (No. 5 and No. 9) and once by one subject (No. 6).[1]

S5A and B (1956) comprise 18 different words of the type CV:lə and CVlə, where C represents /p t k/. In S5A the vowels are /a(:) i(:) u(:)/, in S5B only /a(:)/ occurs. The lists have been spoken by 5 subjects (Nos. 1, 5, 6, 8, and 9), S5A 6 times and

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1) The recordings of lists S3 and S4 were made in Stockholm through the courtesy of Gunnar Fant at a time when we did not yet have any sonagraph in Copenhagen.

S5B 12 times.

S6 (1957) comprises 60 words of the type CV:lə, where C represents /p t k/ and /b d g/ and V the ten long Danish vowels. This list has been spoken once by 3 subjects (Nos. 5, 6, and 9).

M1 (1964). M1A comprises 9 words of the type CVCə, where C- and -C are phonetically identical and represent [bdg] and V is short /i y u/. M1B comprises 12 words of the type CVCə, where C- is /p t k b d g/ and -C always [d]; V is short /u/ and /i/. M1A has been spoken 12 times and M1B 6 times by 7 subjects (Nos. 1, 2, 5, 7, 10, 11, and 12).

M2 (1974) comprises 12 words of the type CV:lə or CVlə, where C represents /p t k/ and /b d g/ and V /a(:)/ and /i(:)/ (for Nos. 7 and 17 also /u(:)/. This list has been spoken 10 times by 6 subjects (3, 4, 7, 13, 15, 18), 6 times by 2 subjects (14 and 16), and twice by 2 subjects (2 and 17).[1]

The lists contain a mixture of existing words and nonsense words, except for the last list (M2), which contains existing words only. In list M2 the phonological vowel length is different for /i/ and /a/ except where velars are involved. This has given some restrictions on the comparisons of vowels.

On the whole, the purpose has been somewhat different for different lists. S4, S6 and M1 consisted of isolated words which do not permit the measurement of the closure duration. In S3 the words were preceded by [ɔ] ('and') (but subject No. 6 made a small pause after it, so that his closures cannot be measured). The words of S5 and M2 were said in a frame: [di sæ:] —— or [han sæ:] —— or [de vɑ —— di sæ:] or [de heðɒ] —— ("they said ——", "he said ——", "it was —— they said", and "it is called ——").

A restricted number of words with initial consonants other than stops have been measured for comparison, namely in list S3 30 different words (120 in all) with initial /f s h/, and in list M2 8 different words with /f v s h/ (672 in all) and 4 different words with /m n l/ only spoken by some subjects (136 in all).

The whole material comprises about 4000 tokens.

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1) This list was made for the purpose of an extensive EMG investigation, and the recordings and measurements have been made in cooperation with Jørgen Rischel, Birgit Hutters and Anders Löfqvist.

3. Subjects

There are 18 subjects; they were all students or teachers of phonetics (with one exception, No. 13 (MF), who is a phoniatrist). Phoneticians have the advantage that they are able to speak lists containing nonsense words more naturally and freely than phonetically naïve people. Four of the subjects grew up in Jutland: No. 1 OT, born in 1928, No. 2 BF, born in 1935, No. 3 PM, born in 1946, and No. 4 BM, born in 1947 (BM, however, moved to Copenhagen at the age of seven). Three grew up in Funen: No. 5 FJ (the author, born in 1911), No. 6 NK, born in 1915, and No. 7 JR, born in 1934, but only No. 6 is influenced by the dialect. Nos. 5 and 7 spoke Standard Danish at home, No. 5 also with playmates. Eleven subjects grew up in Copenhagen or in North Zealand: No. 8 KS, born in 1928, No. 9 BL, born in 1930, No. 10 KB, born in 1936, No. 11 BS, born in 1922, No. 12 HP, born in 1938, No. 13 MF, born in 1939, No. 14 HU, born in 1945, No. 15 JJ, born in 1949, No. 16 BH, born in 1945, No. 17 NR, born in 1942, and No. 18 LG, born in 1946).

4. Measurements and delimitation

The following measurements were made: (1) duration of the closure, (2) duration of the open interval, (3) duration of the following vowel. The beginning of the closure has been determined as the point where the vowel formants stop on the sonagrams, and the intensity and frequency curves go abruptly down on the mingograms. This may be about 1 cs before the real occlusion, but this point can be identified in a more consistent way on the curves.

The term "open interval" (which has been taken over from an early paper by Gunnar Fant) indicates the distance from the start of the release to the start of the vowel. It thus includes (a) the transient phase, (b) the frication phase, and (c) the aspiration phase (Fant 1960). It would have been preferable to make these further delimitations, but very often they could not be made with certainty (in S3 frication and aspiration have been delimited for t). Generally, "aspiration" is used in the sense of "open interval" for ptk, but it is not a very appropriate term for bdg. Fant (1970) uses "burst", but this may also indicate the release

transient only. More recently, (positive) VOT duration is used in the same sense. But, as the start of the vowel and not the start of the vibrations is chosen as limit in this investigation, "voice onset time" would be a slightly misleading term. In most cases start of vibrations and start of vowel coincide. But when p and k are followed by an open vowel, particularly a, some speakers start the voicing before the vocal cords have come together, which gives low frequency voicing with gradual rise of the intensity curve and low rising Fo before the formants are fully developed (the vibrations are often very clearly seen on the oscillogram). In the present investigation pa and ka were spoken in this way by subjects No. 1, 4, 5, 13, 14, 16, and 18 and sometimes by Nos. 8 and 9.

Statistical significance has been tested by means of a simple pair test, based on averages for specific consonants, contexts, and subjects, and on a Poisson test.

The consonant following the vowel is not taken into account in this investigation. In disyllabics with long vowel (S3, S6 and parts of S5 and M2) the consonant belongs to the following syllable. In monosyllabics of the CVC-type (S4) it evidently belongs to that syllable, and in disyllabics with short vowel (M1 and parts of S5 and M2) it should probably be considered ambisyllabic. (Accordingly, the term "CV-syllables" used in my 1979 paper has in this paper been changed to the more correct "CV-sequences".) Since compensations are normally supposed to take place within the syllable, one might argue that the consonant should have been included. However, some earlier measurements seem to indicate that this measure would be irrelevant, at least for Danish. In Fischer-Jørgensen 1955 the duration of the consonant l was measured after phonologically long and short vowels and no significant difference found, and in Fischer-Jørgensen 1964 bdg were measured after long and short vowels (in list M1B) and no consistent difference found. Moreover, in a sample of words from list S3 (type: CV:nə) the consonant n has been measured, and no dependence on the initial consonant, nor on the degree of opening of the vowel was found. It therefore seemed legitimate to examine CV-sequences separately.

5. Results

5.1 Individual averages of the duration of closure and open interval

The average durations of closure and open interval for stop consonants in the various lists are shown in tables 1 - 6. Only in the cases where the words were spoken in a frame has it been possible to measure the closure (tables 1, 3, 4, and 6).

Table 1

List S3. Average durations of closure in cs and open interval in cs and in % of closure + open interval (ptk and bdg + ten long vowels)

			p			t			k		
S		N	clos.	op.i.	%	clos.	op.i.	%	clos.	op.i.	%
5	FJ	20	8.8	5.2	37	6.9	7.1	51	8.6	6.1	42
6	NK	10	(14.2)	5.4	-	(11.5)	7.1	-	(12.4)	6.6	-
9	BL	20	11.1	6.2	36	8.8	9.2	51	9.7	6.4	40
			b			d			g		
5	FJ	20	10.4	1.2	10	10.3	1.2	10	10.6	1.6	13
6	NK	10	(17.0)	1.5	-	(15.9)	1.7		(15.2)	2.7	-
9	BL	20	14.5	1.5	9	14.2	2.0	12	12.6	2.7	18

Table 2

List S4. Average durations of open interval in cs for ptk + ten short vowels + ptk.

S		N	p	t	k
5	FJ	20	5.3	6.3	6.2
6	NK	10	3.7	6.2	6.5
9	BL	20	4.1	6.9	5.6

Table 3

List S5. Average durations of closure in cs, and open interval in cs and in % of closure + open interval (ptk + a(:) u(:) i(:)).

			p			t			k		
S		N	clos.	op.i.	%	clos.	op.i.	%	clos.	op.i.	%
1	OT	30	9.5	7.8	45	8.8	8.5	49	9.6	8.1	46
5	FJ	30	8.4	6.2	42	5.7	8.9	61	7.6	7.0	48
6	NK	30	11.9	4.8	29	9.4	8.2	47	10.0	7.7	44
8	KS	30	8.8	5.3	38	7.0	7.5	52	8.0	6.4	44
9	BL	30	10.0	7.7	44	7.1	9.3	57	8.3	7.8	49

Table 4

List S6. Average durations of open interval of ptk and bdg in cs (ptk and bdg + ten long vowels).

			p	t	k	b	d	g
5	FJ	10	6.3	6.5	6.3	1.7	1.8	2.4
6	NK	10	6.0	8.5	7.9	2.2	2.9	3.9
9	BL	10	8.2	9.4	8.4	2.4	3.0	4.2

Table 5

List M1. Average durations of open interval of ptk and bdg in cs (M1A: bdg + short i y u M1B: ptk and bdg + short i u).

		M1A				M1B					
S	N	b	d	g	N	p	t	k	b	d	g
1 OT	36	3.7	3.2	3.9	12	5.7	6.8	7.0	2.2	2.6	4.0
2 BF	36	1.8	1.9	2.5	12	5.3	5.4	6.5	1.9	2.3	2.9
5 FJ	36	1.5	2.4	2.2	12	5.0	6.4	6.0	1.4	1.6	2.5
7 JR	36	1.8	2.2	2.7	12	5.6	5.7	6.8	2.0	2.2	2.9
10 KB	36	2.2	1.9	3.0	12	7.3	7.8	8.3	2.0	2.0	3.3
11 BS	36	2.5	2.1	3.1	12	6.7	8.4	9.1	2.8	2.6	3.4
12 HP	36	2.2	2.2	3.2	12	7.6	9.2	9.4	1.9	2.2	3.4

Table 6

List M2. Average durations of closure in cs and open interval in cs and in % of closure + open interval (ptk and bdg + a i (u)).

			p			t			k		
S		N	clos.	op.i.	%	clos.	op.i.	%	clos.	op.i.	%
2	BF	4	12.0	6.3	34	8.5	9.5	53	9.0	9.3	51
3	PM	20	8.6	6.0	41	7.1	7.7	52	7.9	7.0	47
4	BM	12	9.8	7.6	44	8.5	8.9	51	9.7	9.6	50
7	JR	30	8.1	8.1	50	7.0	8.5	55	7.8	7.9	50
13	MF	20	13.4	9.2	41	14.2	10.7	43	15.3	9.6	39
14	HU	20	9.6	7.8	45	8.7	8.8	50	9.4	9.4	50
15	JJ	20	13.2	10.1	43	9.2	12.8	57	10.5	11.5	52
16	BH	12	10.2	9.5	48	8.1	11.8	59	9.3	10.4	53
17	NR	6	13.0	10.3	44	9.0	13.5	60	10.5	11.8	53
18	LG	20	7.9	8.8	53	5.5	12.2	69	7.6	10.8	59

			b			d			g		
S		N	clos.	op.i.	%	clos.	op.i.	%	clos.	op.i.	%
2	BF	4	13.8	0.8	5	12.5	2.0	14	10.3	3.0	23
3	PM	20	9.7	1.7	15	9.3	3.0	24	8.4	3.4	29
4	BM	20	13.2	1.1	8	10.6	2.0	16	11.5	2.8	20
7	JR	30	9.7	1.2	10	9.8	1.9	16	9.3	2.7	23
13	MF	20	17.7	1.2	6	16.1	2.1	12	17.9	2.7	13
14	HU	12	11.0	1.5	12	11.0	2.2	17	11.0	2.7	20
15	JJ	20	15.0	1.1	7	14.2	2.4	14	13.1	3.8	22
16	BH	12	13.3	1.1	8	12.1	2.9	19	11.6	3.4	23
17	NR	6	18.3	0.9	5	16.5	1.9	10	16.3	2.2	12
18	LG	20	11.8	1.1	9	11.1	3.0	21	11.6	3.1	23

5.2 Range of open interval in ptk and bdg

The difference between Danish /ptk/ and /bdg/ is one of aspiration. Both sets are voiceless, and /ptk/ cannot be considered to be more fortis than /bdg/ since /bdg/ have a longer closure and a tendency towards stronger organic pressure. As shown in table 7, there is a clear difference in the average duration of the open interval for /ptk/ vs. /bdg/ for all subjects, and no subject shows any overlapping of single tokens in this material. In connected

texts and particularly in unstressed position, cases of overlapping may, however, occur (this was found in an older kymographic material).

Table 7

Differences in cs between the open intervals of ptk and bdg. Averages for the individual subjects on the basis of lists S3, S6, M1B and M2.

S	1	2	3	4	5	6	7	8	9	10
p > b	3.5	4.5	4.3	6.5	4.1	4.4	5.3	-	5.3	5.3
t > d	4.2	5.3	4.7	6.9	5.5	5.5	5.1	-	7.0	5.8
k > g	3.0	6.0	3.6	6.8	4.0	4.0	4.6	-	4.6	5.0

S	11	12	13	14	15	16	17	18	average
p > b	3.9	5.7	8.0	6.3	9.0	8.4	9.4	7.7	6.0
t > d	5.8	7.0	8.6	6.6	9.8	8.9	11.6	9.2	6.9
k > g	5.7	6.0	6.9	6.7	7.7	7.0	9.6	7.7	5.8

Moreover, the open interval of /ptk/ contains aspiration noise and /t/ is affricated, most strongly before high vowels (see section 5.3.4). The open interval of /bdg/ may, however, also contain some noise, particularly in di and gi.

The duration of the open interval of ptk is very variable. The individual averages vary between 3.7 and 10.3 cs for p, 5.4 and 13.5 cs for t, and 5.6 and 11.8 cs for k, and in single tokens the aspiration may be as short as 3.0 cs (p for subject No. 6) and as long as 17 cs (t (+ i) for subjects No. 15, 16, and 17).

Variations between different lists spoken by the same subjects are mostly due to the following vowel, the aspiration being longer before high vowels (see section 5.3.4). That may be the reason why list S5, which contains two high vowels and one low vowel, shows relatively longer values for subjects No. 5, 6, and 9 than list S3. However, M1 with high vowels only (u and i) has relatively short aspirations compared to S5 (subject No. 1) and M1 (subjects No. 2 and 7). The type of word may play a role here. Words of the type pidə, tidə, kidə, bidə, etc. containing short vowels surrounded by stop consonants may invite to rattling off the list.

The same is still more tempting for list S4: pip, pep, pɛp, pap, etc. do not sound like real words, the occurrence of the same consonant before and after the vowel being relatively rare except in onomatopoeia. Particularly subjects 6 and 9 have extraordinarily short aspirations for p (3-4 cs), and No. 6 has hardly any aspiration noise. This list has therefore not been included in the general means for the open interval in the following. There is no general tendency to shorten the aspiration before short vowels. List S5 was intended to test this assumption. It contained words with long and short vowels of the type talə, ta:lə, tulə, tu:lə, etc., but of 45 comparable pairs of averages (3 consonants x 3 vowels x 5 subjects), 21 had a longer and 21 a shorter aspiration before long vowels, and 3 had the same duration.

The differences between individual subjects reveal a tendency due to dialectal background and age. In table 8 the individual duration averages of the open interval of ptk were combined into three groups: A Non-Copenhageners, B Copenhageners born before 1939, and C Copenhageners (and subjects grown up in North Zealand) born after 1939. There is a tendency to increasing duration of aspiration from group A through B to C. The difference between groups A and C is significant at the 0.1% level.

No. 4 (BM) has been left out in the means because he moved from Jutland to Copenhagen at the age of 7, and he evidently does not belong in the group of non-Copenhageners.

No. 8 (KS) has shorter aspirations than the other Copenhageners. His ptk do in fact sound almost unaspirated in some cases, and in a listening test some of his intended p's and k's were heard as b's and g's (the same was true of some of NK's p's).

The year 1939 as the limit between group B and C has nothing magical in it. It is an artefact of the material. With more subjects, another year might have been chosen as an appropriate dividing line. Relatively long aspirations may also be found with subjects born earlier. E.A. Meyer (1904) has measured the duration of the aspiration in a few words spoken by a Copenhagener, and he found the values 7.8 and 10.0 cs for p and 11.5 cs for t. Moreover, H. Abrahams, who has undertaken a kymographic investigation of his own speech (1949), gives the range for p as 7-9 cs and mentions that the aspiration of t and k often goes beyond 10 cs (he is born in Copenhagen 1907). In the list S1, which is

Table 8

Individual average durations of the open interval of ptk, grouped according to dialectal background and age.
A Non-Copenhageners
B Copenhageners born before 1939
C Copenhageners born 1939 and later.[1]

				p	t	k
A.						
Non-Copenh.	1	OT	(1928)	6.8	7.7	7.6
	2	BF	(1935)	5.8	7.5	7.9
	3	PM	(1946)	6.0	7.7	7.0
	[4	BM	(1947)	7.6	8.9	9.6]
	5	FJ	(1911)	5.7	7.2	6.4
	6	NK	(1915)	5.1	7.7	7.2
	7	JR	(1934)	6.6	7.1	7.4
	average		(N = 322)	6.0	7.5	7.3
B.						
Copenh.	8	KS	(1928)	5.4	7.5	6.4
	9	BL	(1930)	7.4	9.3	7.5
	10	KB	(1936)	7.3	7.8	8.3
	11	BS	(1922)	6.7	8.4	9.1
	12	HP	(1938)	7.6	9.2	9.4
	average		(N = 150)	6.9	8.4	8.1
C.						
Copenh.	13	MF	(1939)	9.2	10.7	9.6
	14	HU	(1945)	7.8	8.8	9.4
	15	JJ	(1949)	10.1	12.2	11.5
	16	BH	(1945)	9.5	11.8	10.4
	17	NR	(1942)	10.3	13.5	11.8
	18	LG	(1946)	8.8	12.2	10.8
	average		(N = 98)	9.3	11.5	10.6

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1) 1-4 (born in Jutland) and 5-7 (born in Funen) are ordered chronologically. In groups B and C the ordering is not strictly chronological, because I did not want to change the numbering of my 1979 paper.

not utilized in full here, two Copenhageners (born 1899 and 1909) have several examples with aspirations of more than 10 cs. It should also be kept in mind that subjects 10, 11 and 12 have only spoken list M1, which has relatively short aspirations for the other subjects. On the other hand, No. 13 (HU), born 1945, has relatively short aspirations. This is not an accident due to the list in question. In the fiberoptic investigation undertaken by Birgit Hutters (1979), utilizing some of the same subjects, No. 13 (HU) also has shorter aspirations than Nos. 13 (MF) and 18 (LG). She has also recorded subject No. 5 (FJ) of group A, who shows considerably longer aspirations in this recording (1979) than in those used in the present investigation (recorded 1954-1963), viz. p 7.0 cs, t 9.8 cs, and k 9.0 cs. This may be due to a recent influence from Advanced Copenhagen speech, but it may also be due to a slower overall tempo in the fiberoptic recording, since the relative values (p 39%, t 56%, and k 51%) are hardly different from the earlier recordings.

In contradistinction to the absolute durations of the open interval, the relative durations do not show any difference between groups A and B (but it can only be calculated for two subjects of group B, 8 and 9, and, as mentioned above, 8 is not typical of group B).

The averages for the three groups are given in table 9.

Table 9

Average relative durations of the aspiration of ptk in groups A, B and C (see table 8).

	p	t	k
A (subjects 1,2,3,5,6,7)	40%	52%	47%
B (subjects 8 and 9)	39%	53%	45%
C (subjects 14 - 18)	47%	59%	53%

Subject 13 (MF) has not been included in the average because she has spoken extremely slowly and particularly with very long closures; her relative values (p 41%, t 43%, k 39%) are therefore very low compared to the other subjects of group C. That this is in fact due to her slow speed of delivery can be seen by comparing these values with those obtained in the investigation made by Birgit Hutters, where the absolute duration of MF's aspiration was

approximately the same as in the present investigation, but where the relative durations were 54, 61, and 48%.

On the whole, it must be kept in mind that the different lists are not exactly comparable, and that tempo may play a role. In order to get a clear picture of the differences, more subjects should be included and they should read the same lists. But the tendency found in the three groups is in complete agreement with the general auditory impression of an increasing aspiration in modern Copenhagen pronunciation of ptk.[1]

The open interval of bdg shows much less variation than that of ptk. The range of the average durations is 1.1 to 2.2 cs for b, 1.5 to 3.0 cs for d, and 1.8 to 4.0 cs for g, and there is no consistent difference between the three groups of subjects, A, B, and C, which were set up for ptk. The average durations for these three groups are given in table 10.

Table 10

Average duration of the open interval of bdg in cs for the groups A (Non-Copenhageners), B (Copenhageners born before 1939) and C (Copenhageners born in 1939 and later), based on lists S3, S6, M1B and M2.

A				B				C			
N	b	d	g	N	b	d	g	N	b	d	g
160	1.7	2.3	3.0	66	2.2	2.3	3.4	90	1.2	2.4	3.0

This means that the larger difference between the open intervals of ptk and bdg found in table 7 for subjects 13-18 is almost exclusively due to a longer aspiration of ptk.

One might have expected those subjects who have very long open intervals in ptk to have a corresponding lengthening of the open intervals of bdg, but this is only true to a certain extent. It is true of d and g for subjects No. 15, 16 and 18 but not for subjects No. 14 and 17 (see table 6) and, on the other hand, No. 1 and No. 3, who have rather short aspirations of ptk, have rather long open intervals of d and g (they have almost the same dialectal background in Northern Jutland, which might perhaps play a role). The lengthening for these 5 subjects is above all due to an affrication of di and gi. The averages for di and gi for these subjects are given in table 11.

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1) Abrahams 1949 sees this development as a continuation of the Germanic and Old High German consonant shifts.

Table 11

Average duration of the open interval of di and gi in cs for subjects 1, 3, 15, 16, 18, based on lists M1B and M2.

S	1	3	15	16	18
N	6	10	10	6	10
di	2.9	4.0	3.4	4.0	4.4
gi	4.2	4.2	5.4	5.1	3.3

Single tokens may have as long an open interval as 6.0 cs (di) and 7.0 cs (gi). As ti and ki have still longer open intervals, this does not lead to any overlapping, but it means that the VOT-boundary may be around 7.0 cs before the vowel i for some subjects, which is higher than what is generally found in other languages (e.g. Lisker and Abramson 1964). Zlatin (1974) has, however, found a high perceptual VOT-boundary for g/k in English (6.5 cs).

5.3 Relations between closure, open interval and following vowel

5.3.1 Differences between /ptk/ and /bdg/

The relatively long open interval of ptk involves a shortening both of the closure and of the following vowel compared to bdg. Only lists S3 and M2 permit a comparison of both closure and vowel shortening. The averages for the subjects of these two lists are given in table 12, divided into two groups: A (Non-Copenhageners + BL from group B, whose durations in S3 are of the same order as those of group A) and C (Copenhageners born in 1939 and later).

Table 12

Differences between ptk- and bdg-sequences: open interval, closure, and following vowel, in cs, and differences in total CV length in cs. A(+B): subjects 2, 3, 4, 5, 7, 9; C: subjects 13-18 (lists S3 and M2).

	A(+B)			C		
	N=87 p>b	t>d	k>g	N=90 p>b	t>d	k>g
open int.	+5.3	+6.5	+5.1	+8.2	+9.0	+7.6
closure	-2.2	-3.3	-1.6	-3.5	-4.6	-3.0
total cons.	+3.1	+3.2	+3.5	+4.7	+4.4	+4.6
vowel	-1.4	-2.4	-1.5	-2.4	-1.9	-2.1
CV	+1.7	+0.8	+2.0	+2.3	+2.5	+2.5

In lists S6 and M1 and for subject 6 in S3, only aspiration and vowel duration can be compared. The averages are given in table 13.

Table 13

Differences between ptk- and bdg-sequences: open interval and following vowel in cs for subjects 6 (list S3), 5, 6, and 9 (list S6) and 1, 2, 5, 7, 10, 11, 12 (list M1B).

N		p>b	t>d	k>g
124	open int.	+4.3	+5.1	+4.3
	vowel	-1.3	-1.3	-1.1

The difference in closure between ptk and bdg is very stable and significant at the 0.1% level. A comparison of the individual averages (with separate means for consonants before i and a in list M2 and before high, mid, and low vowels in list S3) gives 78 comparable pairs. Of these, 75 have a longer closure in bdg than in ptk, 2 have a slightly longer closure in ptk (0.5 and 0.6 cs), and one has the same duration. On the average, the difference between t and d is somewhat larger than that between p and b and between k and g. The shortening of the vowel after ptk compared to bdg is also consistent and significant at the 0.1% level. Out of 113 comparable pairs of averages in lists S3, S6, M1B and M2, 102 have a longer vowel after bdg, 9 have a slightly longer vowel after ptk (0.1 - 1.1 cs), and 2 have the same duration.[1] On the average, the vowel is less shortened than the closure, but this is not consistent, and there are individual differences. No. 16 shortens the vowel more in all cases, whereas No. 17 and No. 18 show definitely more shortening of the closure in all cases.

In figs. 1-3 the relations are shown graphically for list M2. The numbers at the bottom indicate the subjects. The values for the individual subjects are combined by lines in order to make the consistency stand out more clearly. It should be noticed that

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1) If the delimitation between aspiration and vowel is made at voicing start, the difference in vowel duration after ptk and bdg will be somewhat less regular.

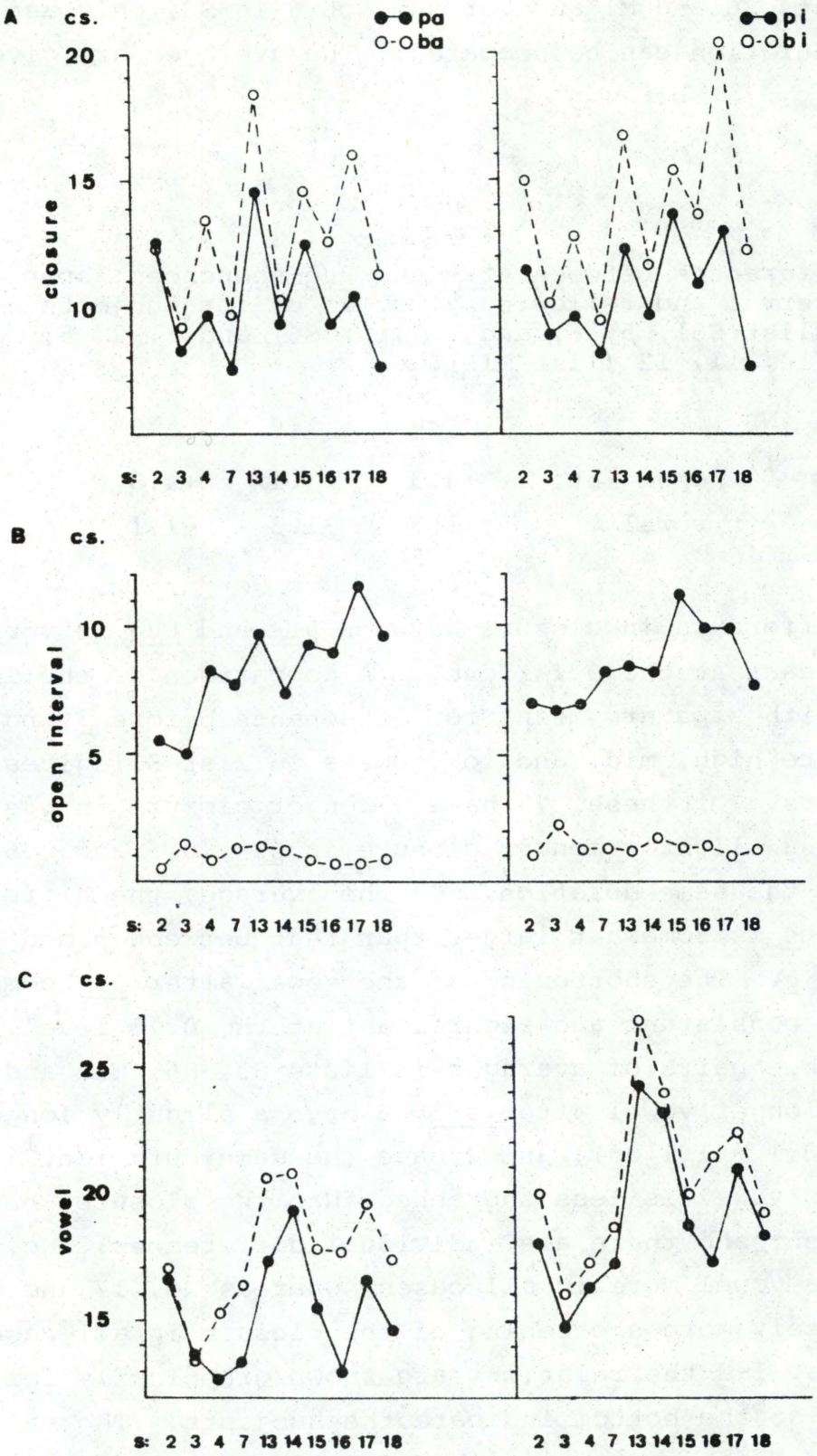

Figure 1

Duration of closure, open interval and vowel
List M2 (S = subject number)

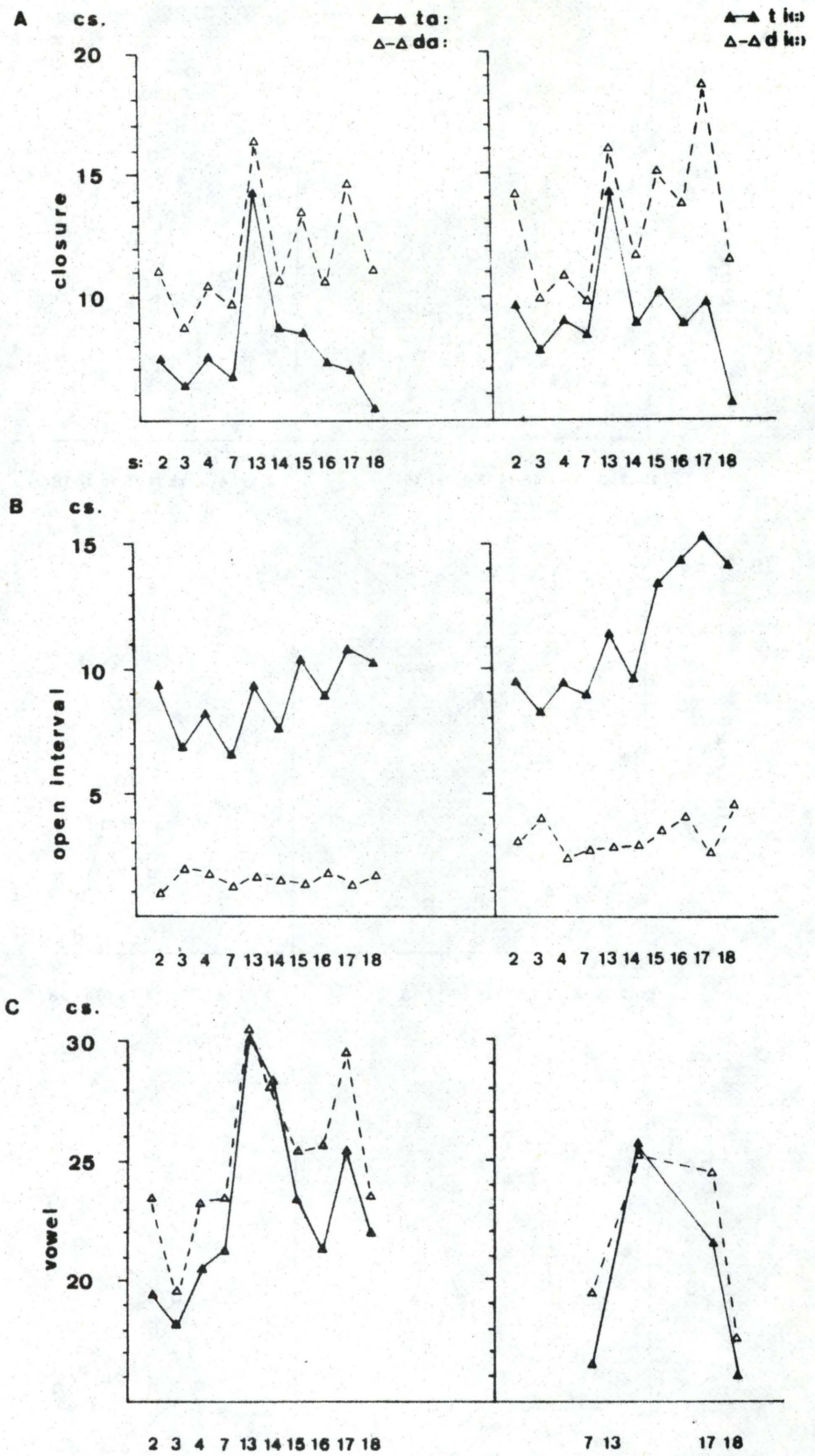

Figure 2

Duration of closure, open interval and vowel.
List M2 (S = subject number)

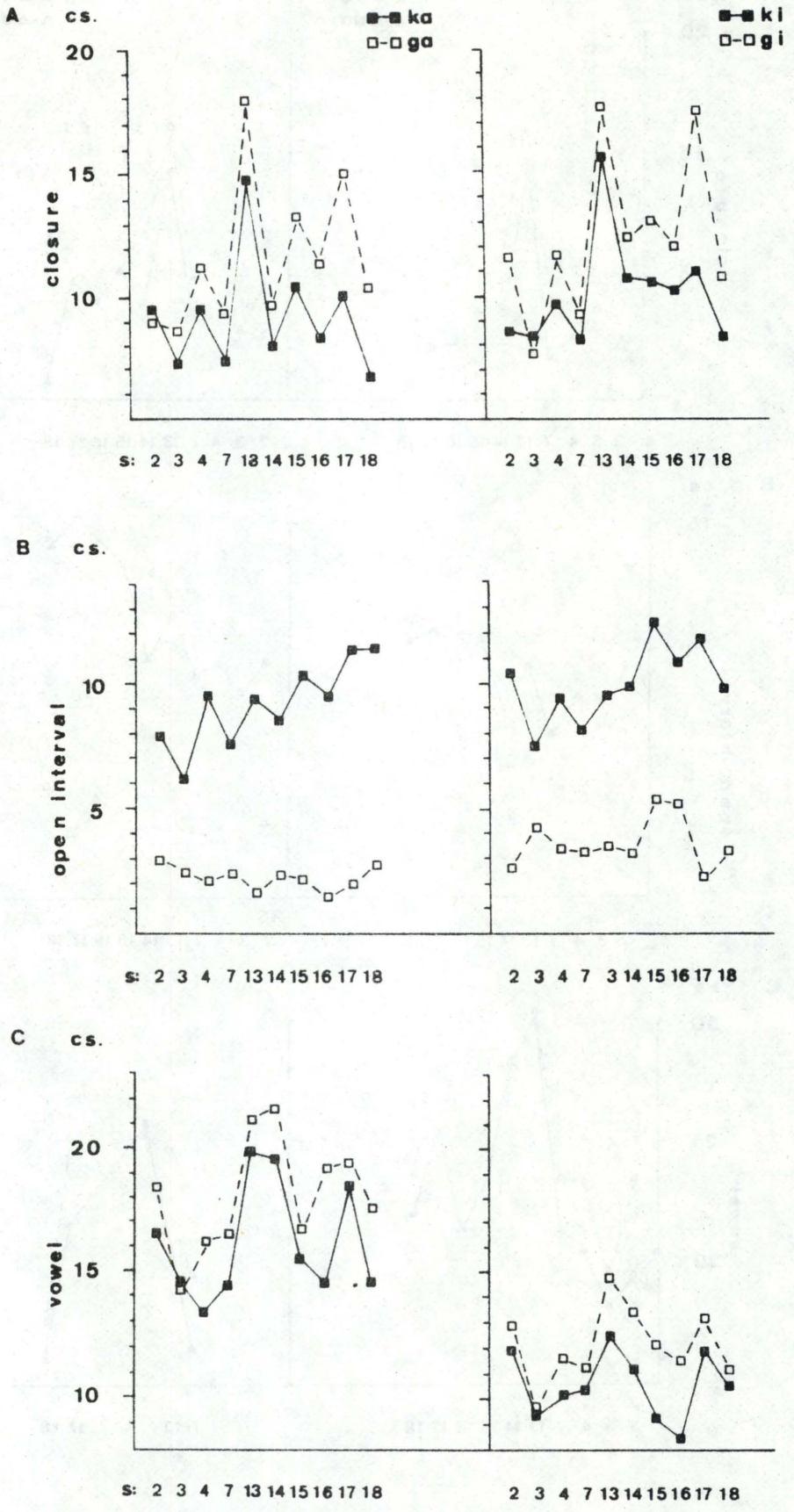

Figure 3

Duration of closure, open interval and vowel.
List M2 (S = subject number)

not all the absolute vowel durations are comparable. The words are: palə, balə, ta:lə, da:lə, kalə, galə, pi:lə, bi:lə, ti(:)ə, di(:)ə, kilə, gilə. In ti(:)ə, di(:)ə the vowel [i] is of variable length since there is no phonological distinction of duration before [ə]. The segmentation of [i] and [ə] was only safe for four subjects.

The high peaks in the closures and vowel durations of subjects 13 and 17 are due to slow speech. No. 14 did not speak slowly, but she has relatively long vowels. The rising slope of the graphs for the open interval reflects the tendency towards longer open intervals in modern Copenhagen speech. In ta the closure shows an opposite downdrift, and a comparison between groups A and B in table 12 seems to indicate a general tendency for those subjects who have long aspirations in ptk to shorten the closure more (in relation to bdg), although the shortening does not fully make up for the longer aspiration, the differences in total consonant length and in CV length between ptk- and bdg-sequences being somewhat larger in group C. It is, however, not a very regular phenomenon in individual averages. Subject 17 has, e.g., very large closure differences, No. 15 and No. 18 only in t-d, No. 13 not in t-d.

There is no tendency to shorten long vowels more than short vowels.

The difference in closure duration between ptk and bdg never reaches the difference in open interval, except for subject 9 in the case of k and g before open vowels. This means that the total duration of the consonants ptk is consistently longer than the total duration of bdg. When the shortening of the vowel is also taken into account, it turns out that the shortening of closure and vowel may make up for the lengthening of the open interval for some subjects (5, 9, and 16). But for most subjects the ptk sequences are clearly longer. The individual differences for total consonant length and CV-length are shown in table 14.

When averages of individual consonants before a and i in list M2 and before high, mid, and low vowels in list S3 are taken separately, the difference between CV-sequences with ptk and with bdg can be compared in 72 pairs. The ptk-sequences are longer in 62 pairs. This means that the difference is significant, although it is not very large (it is less than 1.5 cs in 35 out of the 72 cases).

Table 14

Differences in total consonant duration (closure + open interval) and in CV duration between ptk and bdg for individual subjects (cs).

S	2	3	4	5	7	9
tot.cons. ptk > bdg	+4.1	+2.9	+4.3	+2.6	+4.2	+1.3
CV ptk > bdg	+2.5	+2.6	+2.0	+0.7	+2.8	0

S	13	14	15	16	17	18
tot.cons. ptk > bdg	+4.9	+4.6	+5.8	+5.0	+3.6	+4.0
CV ptk > bdg	+3.3	+3.5	+3.9	+0.6	+1.1	+2.3

The longer closure in bdg than in ptk and the longer overall length of ptk compared to bdg is also found as consistent features in the material investigated by Hutters (1979), and I have found the same relation in an older kymographic material and in a material used for air pressure measurements.

The shorter vowel after ptk was also found for 7 out of 8 subjects in list S1. The same relation for the vowels was found by Hutters (1979) and by Holtse (1977) (two of Holtse's three subjects and four of Hutters' five subjects are identical to subjects used in the present investigation).

It may be of interest to compare the duration of vowels after ptk and bdg with vowel duration after other consonants. This has been done for list M1B (see Fischer-Jørgensen 1964, p. 187). The averages for seven subjects (6 examples of each) are for the short vowels i u after ptk 9.5 cs, after fsh 9.8, after bdg 10.7, and after mnlv 10.0 cs. In list M2 it is possible to compare palə, balə, falə, valə and pi:lə, bi:lə, fi:lə, vi:lə and ta:lə, da:lə, sa:lə. The total consonant durations and the vowel durations are shown in table 15.

It appears from table 15 that f is shorter than p but longer than b, and that the vowel after f is longer than after p and shorter than after b, i.e. there seems to be compensation. But there is only very slight compensation in the vowel for the difference of duration between f and v, and none between the vowels

Table 15

Averages of total consonant duration and duration of following vowel in cs for labial and alveolar consonants in list M2 (10 subjects).

N = 76	p	f	b	v	f>p	f>b	f>v	b>v
cons.	18.5	15.8	13.8	10.7	-2.7	+2.0	+5.1	+3.1
vowel a	15.2	17.2	17.6	17.5	+2.0	-0.4	-0.3	+0.1
cons.	19.1	17.9	15.1	11.6	-1.2	+2.8	+6.3	+3.5
vowel i:	18.9	19.8	20.6	20.6	+0.9	-0.8	-0.8	0

N = 38	t	s	d	s>t	s>d
cons.	17.0	16.1	13.1	-0.9	+3.0
vowel a:	23.0	25.3	24.3	+2.3	+1.0

after b and v. The inverse relation between consonant and vowel duration holds for 14 out of 20 individual averages for f-p and for 13 out of 20 for f-b; for s-t and s-d it holds for 9 and 6 averages, respectively, out of 10. This is not statistically significant, but the tendency is clear.

One of the two subjects in list S3 shows the same relations for p-f-b, but none of them for t-s-d, both consonant and vowel being longer in s + V than in t + V.

Hutters (1979) has found the same inverse relations between consonant and vowel duration for f-p and f-b before i for four out of five subjects, i.e. pi>fi>bi for the consonant and bi>fi>pi for the vowel. For the alveolars the order of the consonant durations is correspondingly ti>si>di, but the order for the vowels is si>di>ti for four out of five subjects (the same subjects have a longer vowel after d than after s in the present material). The relations thus seem to be less stable for the alveolars than for the labials.

Holtse (1977) found vowels after f and s to be of approximately the same duration as after bdg. He did not measure the consonants.

In list M2 it is also possible to compare f and h + vowel for three subjects and in list S5 f s h + vowel for two subjects.

In list M2 both consonant and vowel are longer in fa than in ha. In S3 the consonants f and s are considerably longer than h (by 4.8 and 6.4 cs, respectively), but the following vowels are only very slightly (and insignificantly) shorter (by 0.5 and 1.1 cs, respectively). There is thus hardly any compensation in this case.

5.3.2 Differences between labials, alveolars, and velars

The duration of both closure and open interval differs according to place of articulation.

For bdg the closure durations can be compared on the basis of list S3 and list M2 (subjects 2-5, 7, 9, and 13-18), the open interval, moreover, on the basis of S6, M1B and M1A (all subjects). For ptk the closure durations can be compared on the basis of lists S3, M2, and S5 (subjects 1-9 and 13-18), and the open interval, moreover, on the basis of lists S4, S6, and M1B (all subjects). The durations have been compared by means of individual averages for different subjects and consonants before i a and u, taken separately for lists S5, M1B and M2, and consonants before high, mid, and low vowels, taken separately for lists S3, S4, and S6. As for M1A, bdg before i, y, and u have been combined. Table 16 contains a survey of the results.

Table 16

Differences between labials, alveolars, and velars in the duration of closure and open interval, indicated as the absolute and relative number of averages showing the difference.

closure (28 aver.)	b > d		b > g		d > g	
	23/28	82%	25/28	89%	15/28	54%
open interval (61 aver.)	d > b		g > b		g > d	
	47/61	77%	60/61	98%	57/61	93%
closure (58 aver.)	p > t		p > k		k > t	
	57/58	98%	47/58	81%	53/58	91%
open interval (93 aver.)	t > p		k > p		t > k	
	86/93	92%	75/93	81%	62/93	67%

Except for d > g the differences are all significant at the 0.1 or 1% level. It appears from table 16 that the order for the closure of bdg is b > (d > g) (where the order d > g is unstable) and the order for the open interval is the opposite: g > d > b. Here, d > b has more exceptions than g > d and g > b, but a closer inspection of the material shows that in almost all cases where b has a longer interval than d, the following vowel is rounded (see section 5.3.5). The order for ptk is different. For the closure it is p > k > t, and for the open interval the opposite: (t > k) > p. t > k is only valid in 67% of the averages and, whereas the other cases do not show any differences for lists or subjects, there is a difference between lists for t > k. There is majority for t > k in all lists except list M1B, which has only one case of t > k out of 14. Without list M1B the percentage would have been 77%. As mentioned in section 5.1, the open intervals of ptk are relatively short in this list, and a comparison of list M1B with the other lists for those subjects who have spoken other lists as well (i.e. Nos. 1, 2, 5, 7) shows that in six out of seven cases the shortening of the open interval of t in list M1B is more pronounced than that of k, and in five cases more pronounced than that of p. This may perhaps be due to the fact that in list M1B the consonant following the vowel was also an alveolar (the word type is: pudə, tudə); in list S4, where the same consonant is found before and after the vowel in all cases, there was a general shortening of the open interval. Or the quick tempo of list M1 might shorten the affrication of t. This is, however, pure guesswork.

If the subjects are considered separately (cp. table 6), 11 out of 18 (or 61%) have a longer open interval in t than in k, but if M1B is left out, it will be 13 out of 15 (or 87%).

It may be of interest to see whether the inverse relation between closure and open interval in the differences between labials, alveolars and velars holds in the cases where closure and open interval can be compared directly within individual averages, - not only when they are examined separately on the basis of the whole material as in table 16 (in many cases only the open interval, not the closure, could be measured). This can be investigated for ptk in lists M2, S3 and S5 (i.e. for subjects 1-9 and 13-18) and for bdg in lists M2 and S3 (i.e. for subjects 2-5, 7, 9, and 13-18), where closure and open interval for the same examples

can be measured. The results are shown in table 17. For bdg there is good agreement between tables 17 and 16. The relation between d and g does not show any inverse relation, since the closure difference between d and g is unstable as shown in table 16, whereas the relations between g and b and between b and d do show this inverse relation.

For ptk the inverse relation of t-p is very stable, as should be expected from table 16. But t-k should not be expected to show a higher percentage of inverse relation than p-k.

Table 17

Occurrence of inverse relation between differences of closure and open interval within the same pairs of averages.

ptk - 58 averages			
closure p > k, open interv.	k > p	40/58	69%
- p > t, -	t > p	50/58	86%
- k > t, -	t > k	42/58	72%
bdg - 28 averages			
closure b > g, open interv.	g > b	27/28	96%
- d > b, -	b > d	24/28	86%
- d > g, -	g > d	15/28	53%

The reason is that the relatively low percentage for the open interval (t > k 67%) in table 16 was due mainly to list M1B, which is not included in table 17, because the closure cannot be measured in this list.[1]

The absolute magnitude of the differences is shown in table 18 for the lists in which both closure and open interval could be measured, i.e. S3 and M2 for bdg and S3, S5 and M2 for ptk.

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1) If the delimitation of the open interval had been determined by the voicing start instead of the vowel start, the open interval of k would have been shorter in some cases, and the percentage t > k would have been still higher. In Fischer-Jørgensen 1979 it was said that there was no consistent relation for t-k and that the relation d-b was not significant. This was not correct. correct.

Table 18

Differences in cs between consonants of different places of articulation (closure, open interval, and total duration), based on lists S3 and M2 (subjects 2-5, 7, 9, 13-18) for bdg and S3, S5 and M2 (subjects 1-5, 7-9 and 13-18) for ptk.

bdg
N = 204

	b > d		b > g		d > g	
	S3	M2	S3	M2	S3	M2
clos.	+0.2	+1.1	+0.9	+1.4	+0.8	+0.3
op.int.	-0.3	-1.1	-0.8	-1.7	-0.6	-0.6
tot.dur.	-0.1	0	+0.1	-0.3	+0.2	-0.3

ptk
N = 354

	p > k			p > t			t > k		
	S3	S5	M2	S3	S5	M2	S3	S5	M2
clos.	+0.7	+1.0	+0.9	+2.1	+2.1	+2.0	+1.3	+1.1	+1.1
op.int.	-0.6	-1.0	-1.4	-2.5	-2.1	-2.1	-1.9	-1.1	-0.7
tot.dur.	+0.1	0	-0.5	-0.4	0	-0.1	-0.6	0	+0.4

Table 18 shows that shortenings and lengthenings counterbalance each other, so that the total duration of the consonants is almost identical. A graphic display of the differences t-p and g-b is given in figs. 4-5. The durations of p and b are given the value zero. Overlapping of single measurements has been examined for list S5. Correlation diagrams were made for the single values of aspiration versus closure for consonant + a (18 examples of each) and consonant + i and u (12 examples) in pairs. In fig. 6 examples are given of ta/pa for subject 5 (hardly any overlapping), ta/ka for subject 9 (somewhat more overlapping), and ka/pa for subject 1 (almost complete overlapping). On the whole, No. 1 shows almost complete overlapping except for ta/pa, whereas Nos. 5, 8, and 9 have very good separation for t-p, somewhat less for t-k (but still very good for No. 5), and rather bad separation for k-p. No. 6 has a small pause before each word, and this pause cannot be delimited from the closure. With the pause included he shows very good separation for t-p and p-k but not for t-k.

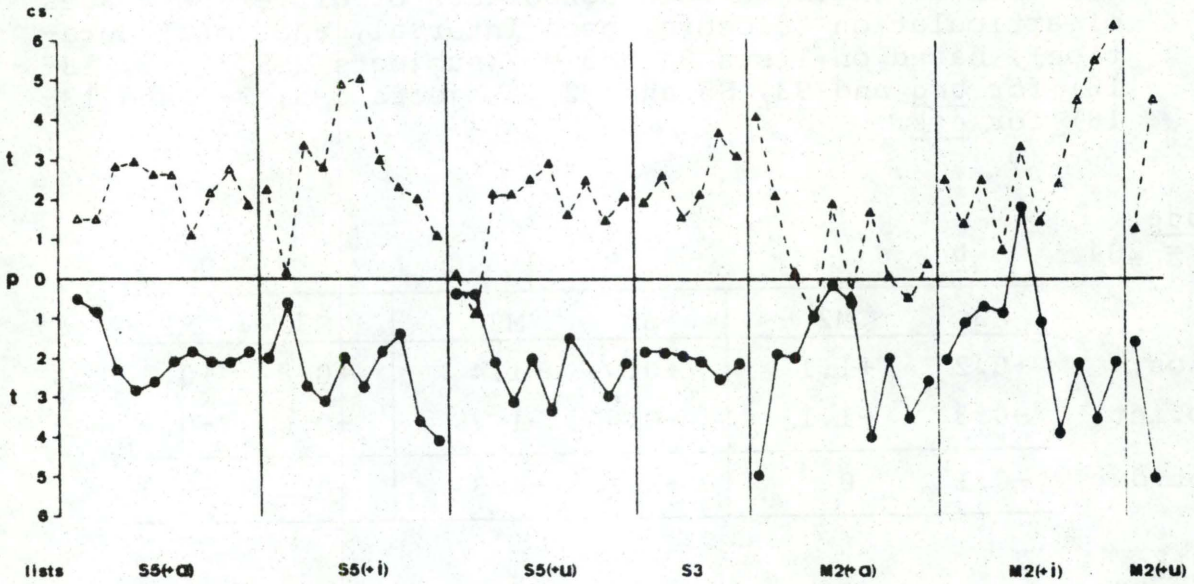

Figure 4

Differences between the durations of the closures (●——●) and open intervals (△----△) for t - p. p is in both cases given the value zero.

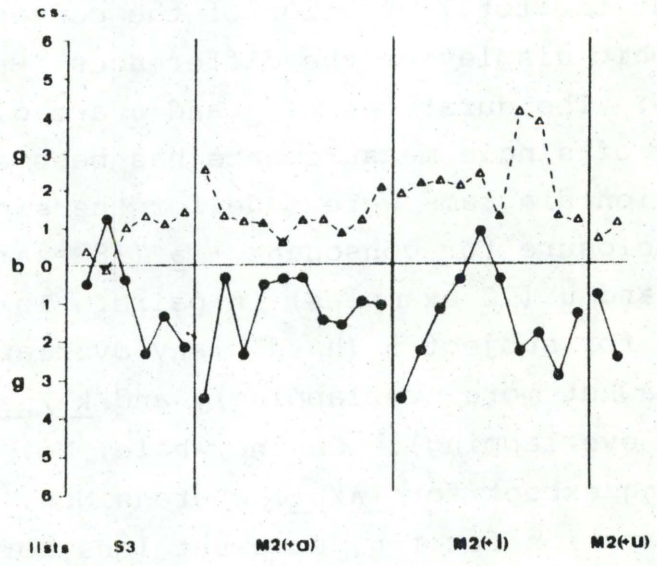

Figure 5

Differences between the durations of the closures (●——●) and open intervals (△----△) for g - b. b is in both cases given the value zero.

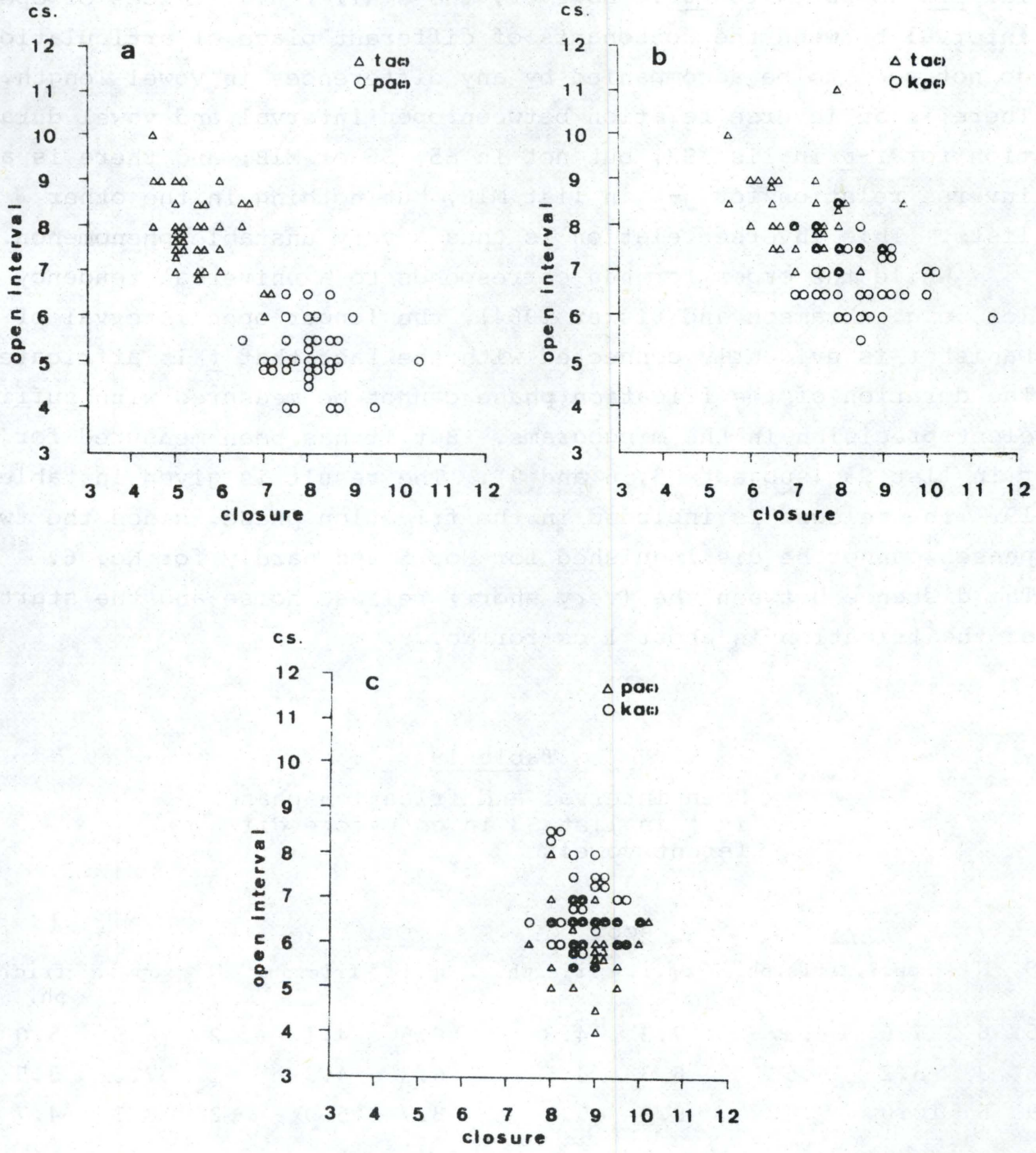

Figure 6

Examples of correlation diagrams of closure and open interval for single tokens (list S5):
(a) tɑ/pɑ (subject 5), (b) tɑ/kɑ (subject 9),
(c) kɑ/pɑ (subject 1).

The material has also been examined in view of a possible compensation between the duration of the open interval and the duration of the following vowel, since a shortening of the vowel was found for ptk compared to bdg. However, the smaller differences of open interval between the consonants of different place of articulation do not seem to be accompanied by any differences in vowel length. There is an inverse relation between open interval and vowel duration for t-p in list S3, but not in S5, S6 or M1B; and there is an inverse relation for g-b in list M1B, but nothing in the other lists. This inverse relation is thus a very unstable phenomenon.

While the order for bdg corresponds to a universal tendency (cf. e.g. Abramson and Lisker 1964), the longer open interval of Danish t is evidently connected with the fact that t is affricated. The duration of the frication phase cannot be measured with sufficient precision in the mingograms. But it has been measured for t in list S3 (subjects 5, 6 and 9). The result is given in table 19. The release is included in the frication phase, since the two phases cannot be distinguished for No. 5 and hardly for No. 6. The distance between the (very short) release noise and the start of the frication is about 1 cs for No. 9.

Table 19

Open interval and frication phase in t in list S3 in cs before different vowels

		iyu		eøo		ɛœɔ		a		
S	N	op.i.	fric.ph.	op.i.	fric.ph.	op.i.	fric.ph.	N	op.i.	fric. ph.
5	6	7.6	6.3	7.3	4.8	6.5	4.1	2	6.5	5.0
6	3	8.2	6.5	6.3	4.5	6.3	4.3	1	7.0	3.5
9	6	10.0	7.0	9.0	5.1	8.7	5.0	2	8.3	4.7

The frication phase is longer before high vowels than before low vowels, and the differences are somewhat larger than for the open interval, so that the frication phase takes up more of the open interval in high vowels. Spectrograms were also taken of some of the examples of S5. The frication phase is approximately of the

same length here as in S3 for subjects 5, 6 and 9, but No. 8, who did not read list S3, has relatively short frications (before i 5.0 cs, before u 4.0 cs, and before a 3.2 cs). Mingograms of the other subjects seem to indicate that the frication phase generally takes up most of the open interval before high vowels, also when the open interval is very long, whereas this is generally not the case before a, and spectrograms of subject No. 16 show frication phases of 9-10 cs before i, but only 3-4 cs before a. Thus, it cannot be maintained for Danish (as it can for English, according to Klatt (1975) and Zue (1976) that when the frication phase is subtracted, the aspiration is approximately of the same length for p, t and k.

5.3.3 Influence of phonological vowel length

The main purpose of list S5 was to investigate the influence of long and short vowels on preceding /ptk/. In table 20 the five subjects are listed separately.

Table 20

Relations of duration between CV- and CV:- sequences (list S5).

CV: > CV					
Subjects	1	5	6	8	9
vowel	+8.4	+4.8	+6.1	+7.6	+9.8
clos.	-0.1	0	-0.6	-0.4	-0.7
op. int.	-0.3	-0.3	+0.4	-0.2	+0.2

It appears from the table that subjects 6 and 9 have no inverse relation between open interval and vowel, and subject 5 no inverse relation between closure and vowel, and for the other subjects the differences are very small compared to the large vowel differences; moreover, they are based on varying single averages and are not statistically significant.

The following consonant has not been measured, but earlier investigations (Fischer-Jørgensen 1955 and 1964) have shown that there is no significant difference in consonant duration after long and short vowels.

5.3.4 Influence of vowel height

It is well known that there is a general tendency for high vowels to be shorter than low vowels, and this relation has also been found for Danish (Fischer-Jørgensen 1955 and Holtse 1977). The material of my 1955 paper was identical with S3 and S4 of the present investigation; but the same relations are found in S5, S6 and M2, which were recorded later. In the whole material high vowels are shorter than low vowels in all 123 comparable pairs of averages. This difference has relation to differences in the preceding consonants.

Table 21 shows the differences between high and low vowels and the corresponding differences in the duration of closure and open interval, based on the lists which permit a measurement of the closure, i.e. lists S3, S5 and M2. Table 22 shows the difference between high and low vowels and the corresponding differences in open interval of the preceding consonants for lists S4 and S6. S3, S4 and S6 contain examples of all Danish vowels (long in S3 and S6, short in S4), but here only the high vowels i y u and the low vowels ɛ œ ɔ are compared. In S5 i and u are compared to a, separately for long and short vowels, and in M2 i is compared to a. In M2 only the vowels i-a after velars have the same phonological length. After alveolars the length is undetermined (tiː)ə diː)ə tuː)ə duː)ə), but the speakers have all pronounced them as long vowels, and the same is the case for /uː)/ after labials. /iː-a/ after labials and /uː-a/ after velars have different phonological length. In the cases where the vowels differ in phonological or intended length, the vowel durations have been put in parentheses. (i after alveolars could only be measured for four subjects; uː after velars was only spoken by two subjects.) A graphical display is given in figs. 7-9.

Tables 21 and 22 and figs. 7-9 show that there is a consistent inverse relation between vowel duration and duration of the open interval of the preceding consonant, but the difference in open interval is considerably smaller than the difference in vowel duration, so that sequences with low vowels remain longer. The difference in open interval is, however, highly significant. For p t k it is valid in 92 out of 103 individual averages with comparable vowels (89%), and for b d g in 32 out of 34 averages (94%). It appears from table 21 that the consonants are also lengthened in

Table 21

Differences (in cs) of vowel, closure and open interval between CV-sequences with high and low vowels (subjects 1-9, 13-18).

S3 /i: y: u:/ > /ɛ: œ: ɔ: a:/

N = 15/20	p	t	k	b	d	g
vowel	-2.9	-3.2	-3.6	-3.0	-3.3	-3.5
closure	0	+1.0	+0.3	-0.2	-0.3	-0.7
open int.	+1.1	+1.3	+0.6	+0.7	+0.7	+0.6
CV	-1.8	-0.9	-2.7	-2.5	-2.9	-3.6

S5 /i u/ > /a/ (short and long)

	short			long		
N = 120	p	t	k	p	t	k
vowel	-5.7	-5.1	-5.0	-4.7	-4.0	-6.8
closure	+1.1	+0.4	+0.2	+0.5	+0.6	+0.5
open int.	+1.3	+0.7	+1.3	+1.4	+1.4	+1.6
CV	-3.3	-4.0	-3.5	-2.8	-2.0	-4.7

M2	p	t	k	b	d	g
	i:>a	i:>a:	i>a	i:>a	i:>a:	i>a
	N=76	N=32	N=76	N=76	N=32	N=76
vowel	(+3.5)	-4.7	-5.6	(+3.7)	-4.8	-5.9
closure	+0.4	+0.8	+1.0	+0.9	+1.0	+0.8
open int.	+0.2	+3.2	+0.8	+0.4	+1.6	+1.4
	(+4.1)	-0.7	-3.8	(+5.0)	-2.2	-3.7

N = 12	p	t	k	b	d	g
	u:>a	u:>a:	u:>a	u:>a	u:>a:	u:>a
vowel	(+6.6)	-2.6	(+3.2)	(+4.3)	-4.4	(+4.4)
closure	+2.9	+1.8	+0.5	+2.3	+1.1	+1.4
open int.	-1.2	+2.8	+0.1	+0.7	+0.7	+0.3
CV	(+8.3)	+2.0	(+3.8)	(+7.3)	-2.6	(+6.1)

Table 22

Differences (in cs) of vowel and open interval between CV-sequences with high and low vowels (subjects 1, 5, 9).

S4 /i u y/ > /ɛ œ ɔ a/

N = 15/20	p	t	k
vowel	-2.3	-2.9	-1.8
open int.	+0.8	+0.6	+0.9

S6 /i: y: u:/ > /ɛ: œ: ɔ: a:/

N = 0/12	p	t	k	b	d	g
vowel	-2.1	-1.9	-2.6	-3.9	-2.4	-2.9
open int.	+1.4	+0.6	+0.7	+0.7	+0.9	+0.9

cases where the vowels are of phonologically different length (we shall come back to this in the discussion), so that these cases can be included, but the percentages will be only slightly changed (85 and 94%, respectively). Most exceptions are due to 9 cases of pi-pa in M2 and S5 in which pa has the longer aspiration.[1] The percentage for pi-pa is 75%.

As for the lengthening of the closure before high vowels, table 21 shows no consistent difference in S3, but a consistent difference in S5 and M2. Comparison of individual averages shows that the difference is significant for ptk (52 out of 75 averages or 69%) but not for bdg (27 out of 45 averages or 60%). There are, however, individual differences among the subjects. Some have no exceptions, and two have the opposite relation, i.e. shorter closure before high vowels, viz. No. 9 and No. 13. Apparently, younger Copenhageners tend to lengthen the closure more before high vowels than do older subjects. At any rate, there is a striking difference between the subjects of list S3 (Nos. 5, 6, 9), list S5 (Nos. 1, 5, 6, 8, 9) and list M2 (Nos. 2, 3, 4, 7, 13-18). The percentage of averages showing a longer closure before high vowels than before low vowels is for S3 33%, for S5 66%, and for M2 80% (and for the five youngest Copenhageners of M2 it is 92%).

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1) These exceptions would be reduced if voicing start were taken as marking the end of the open interval.

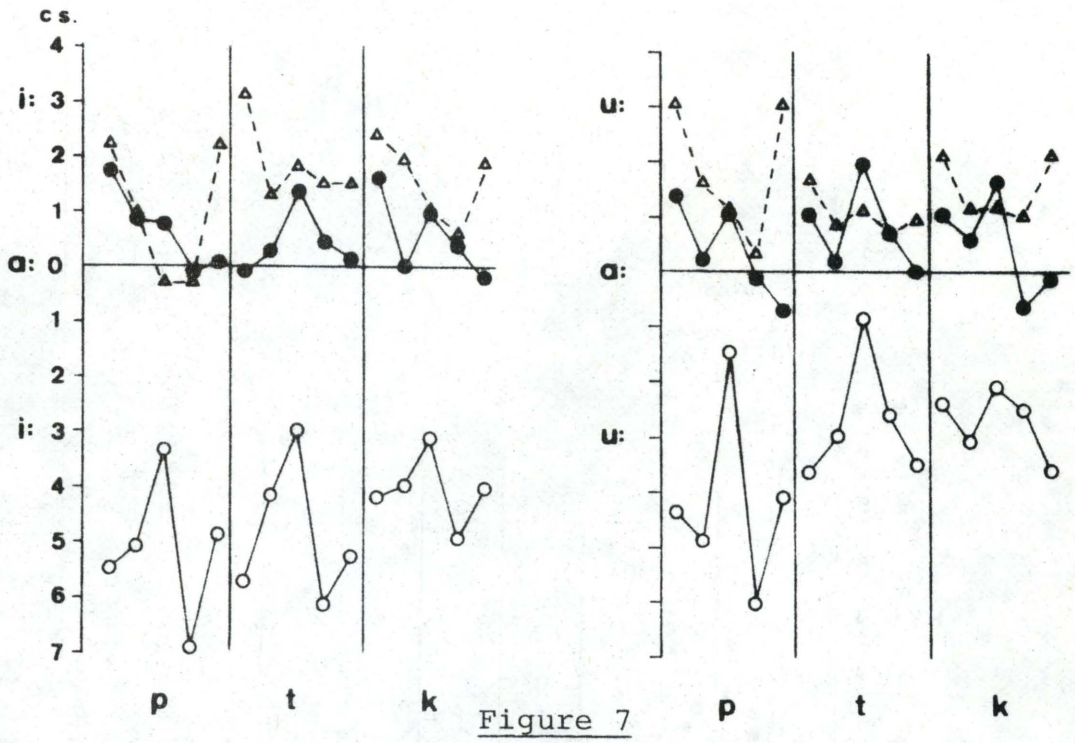

Figure 7

Differences between the durations of the closures (●——●), open intervals (△----△) and following vowels (o——o) for ptk + i: u: - ptk + ɑ: (list S5). The durations of ptk + ɑ: have been given the value zero.

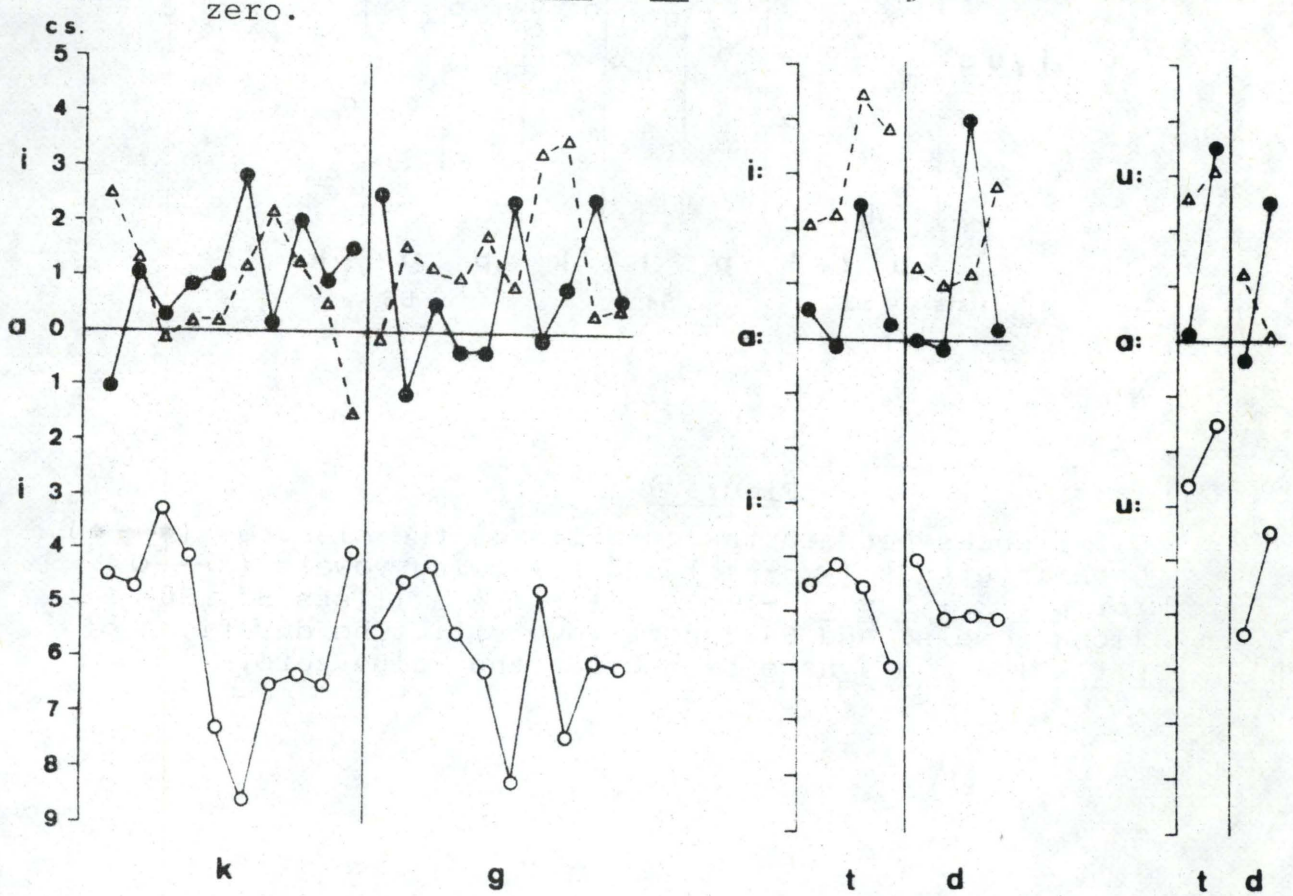

Figure 8

Differences between the durations of the closures (●——●), open intervals (△----△) and following vowels (o——o) for k g t d + i i: u: - kg td + a i: (list M2). The durations of k g t d + a a: have been given the value zero.

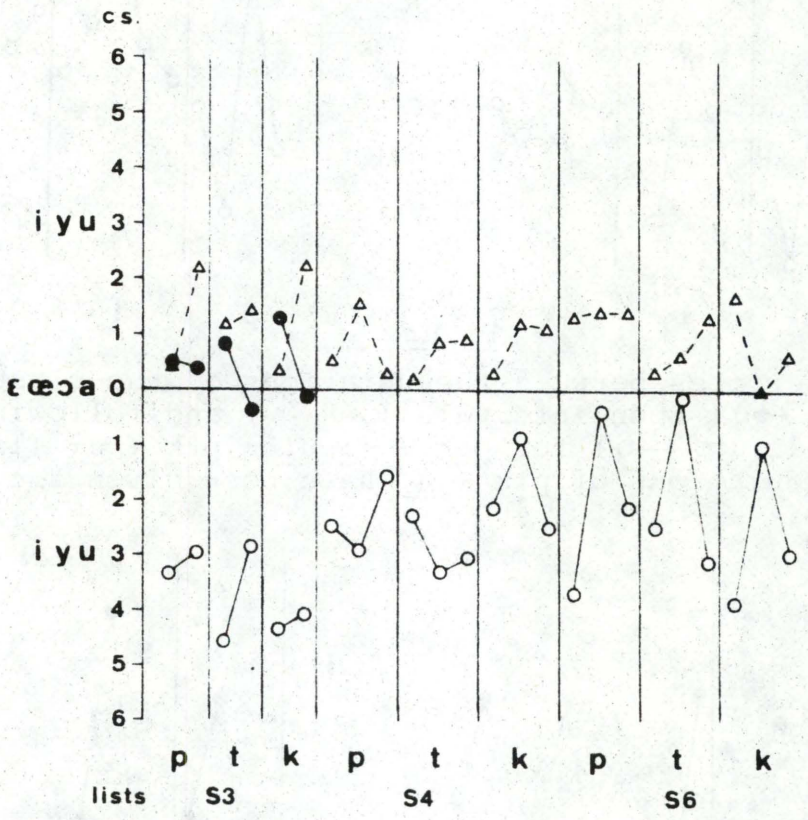

Figure 9

Differences between the duration of the closures (●——●) open intervals (△----△) and following vowels (○——○) for p t k + i y u - p t k + ɛ œ ɔ a (lists S3, S6 (long vowels) and S4 (short vowels)). The durations of p t k + ɛ œ ɔ a have been given the value zero.

And whereas in S5 there are only 5 cases out of 30 (17%) where the lengthening of the closure of ptk exceeds the lengthening of the open interval, the corresponding number in M2 is 16 out of 36 (44%). There is a slight inverse tendency for the open interval, i.e. more lengthening in S3 and S5 than in M2, but this may be due to inconsistencies in the delimitation of open interval and vowel, whereas the delimitation of the closure is pretty safe.

In Hutters 1979 the lengthening of the closure before i compared to a is found in 11 out of 15 averages (73%), whereas her subjects lengthen the open interval before i in only 53% of the averages.

In lists S3 and M2 there are also examples of other consonants. The fricatives f s v show the same lengthening before i and u compared to a as the stops, as seen in table 23.

Table 23

Difference in cs between CV-sequences with f,s,v before high and low vowels (Subjects 2 - 7, 9, 13 - 18).

S3			M2							
N = 15/20			N = 76						N = 12	
/i: y: u: > ɛ: œ: ɔ: a:/			/i:>a/		/i:>a:/		/u:>a/		/u:>a:/	
	f	s	f	v	s		f	v	s	
vowel	-3.7	-3.4	(+2.7)	(+3.1)	-5.0		(+4.2)	(+3.7)	-3.0	
cons.	-0.3	+0.2	+2.0	+0.9	+3.0		+1.9	+2.2	+2.3	

The negative difference for f in S3 is due to subject 6 (5 and 9 have a positive difference). The consonant is longer before high vowels in 33 out of 36 individual averages (91%). There is also a small difference for h in S3, but the delimitation is not too certain, and in M2 h is variable. The same is true of the examples of m and l (spoken by 5 subjects of list M2).

Again it is found that the consonant lengthening is independent of the phonological length of the following vowel (the vowels

of M2 have the same length only after s). In Hutters 1979 all five subjects have longer f and s before i than before ɑ.

5.3.5 Influence of vowel rounding

The relation between vowel rounding and the open interval of the preceding stop is different for labials, alveolars, and velars, and it is only significant for labials. Table 24 shows the differences in open interval and vowel duration for labials.

Table 24

Differences in cs between CV-sequences with labial stop + rounded and unrounded vowel (subjects 1-2, 5-12, 17). S3, S6, M2 long vowels, S4, M1 short vowels, S5 short + long vowels).

	S3 N=15	S4 N=15	S6 N=6	S3 N=15	S6 N=6	M1A N=84
p	yøœ > iɛ			b yøœ > iɛ		y > i
op.int.	+1.5	+0.3	+1.5	+0.5	+1.4	+0.6
vowel	+1.1	-0.2	+1.1	+1.8	+0.8	-0.5
p	uɔ > iɛ			b uɔ > iɛ		
op.int.	+1.5	+0.3	+1.0	+0.4	+0.9	
vowel	+1.4	+0.6	+1.2	+2.4	+0.4	
	M2 N=12	M1B N=42	S5 N=60	M2 N=12	M1B N=42	M1A N=84
p	u > i			b u > i		
op.int.	-0.3	+0.9	+0.7	+0.5	+0.5	+0.5
vowel		+0.6	+1.6		+1.4	-0.3

It appears from table 24 that the open interval of labials is longer before rounded than before unrounded vowels. The difference is significant for both p and b (for p the open interval is longer in 31 out of 37 individual averages (84%) and for b in 30 out of 35 (86%). Rounded vowels are also generally longer than unrounded vowels, but this depends in part on the following consonant. Rounded vowels are longer than unrounded ones in lists S3, S5, S6, M2 and M1B, where the following consonant is alveolar (n, l or d),

but u and y are shorter than i in list M1A and variable in list S4. In these two lists the following consonant was b or p. (This influence has been shown in detail in Fischer-Jørgensen 1964.) The open interval is longer, irrespective of this vowel difference. The closure is not longer before rounded vowels.

As for alveolars, there is an opposite but not significant tendency to have a longer open interval before unrounded vowels. As for velars, the relations are irregular. This explains that although b has generally a shorter open interval than d, this is not always the case in list M1A, because the vowels are i, y and u. It also explains why the open interval was found to be in decreasing order in g>d>b except before rounded vowels, where the order is g>b>d.

The tendency to longer duration of the consonants f s h before rounded than before unrounded vowels mentioned in my 1979 paper is weak and not significant.

6. Summary and discussion

6.1 Summary

The results of the present investigation of Danish CV-sequences with stop consonants can be summarized as follows:

6.1.1 p t k vs. b d g

CV-sequences with ptk have a much longer open interval than those with bdg, and at the same time a shorter closure and following vowel, but the shortenings of closure and vowel do not generally counterbalance the lengthening of the open interval, so that for almost all subjects, CV-sequences with ptk are longer than those with bdg (grand mean 2.1 cs) (see section 5.3.1 and figs. 1-3).

6.1.2 Place of articulation

Labials, alveolars, and velars differ both in closure and in open interval, the order for the closure being b>d>g and p>k>t and for the open interval g>d>b and t>k>p. The differences are significant with exception of the closure d>g and, consequently,

the inverse relation between closure and open interval for d-g. There is thus an inverse relation between closure and open interval, and it is of almost the same magnitude so that CV-sequences with consonants of different place of articulation are approximately of the same length. There is generally no difference in the following vowel (see section 5.3.2 and figs. 4-5).

6.1.3 Phonological vowel length

There is no consistent compensation in consonant duration in relation to the phonological length of the following vowel (see section 5.3.3).

6.1.4 Vowel height

The open interval - and often the closure - is longer before high vowels than before low vowels. But the differences in vowel duration (the high vowels being longer than the low vowels) are in almost all cases larger than the differences in open interval and closure, so that the CV-sequences with low vowels are normally longer than those with high vowels (grand mean +2.5 cs). (See section 5.3.4 and figs. 7-9). The fricatives f and s are also longer before high vowels, but there is no clear tendency in the case of h m l.

6.1.5 Vowel rounding

Labial stops have a longer open interval before rounded vowels than before unrounded vowels. Since rounded vowels are, on the average, longer than unrounded vowels, the CV-sequences with labials + rounded vowels will be longer than those with unrounded vowels

6.2 Discussion

The problem is now whether the relations which have been found should be explained as compensation, in the sense that the inverse relations are due to a tendency to maintain a constant duration of the CV-sequences, as it has often been proposed for VC-sequences and for larger units, or whether they are due to more specific physiological mechanisms.

Since the relations between ptk and bdg (section 6.1.1 above) and between different places of articulation (section 6.1.2) are the most problematic, I shall treat them at the end and start with a discussion of phonological vowel length, vowel height, and vowel rounding (sections 6.1.3, 6.1.4, and 6.1.5, respectively).

6.2.1 Phonological vowel length and rounding

It is obvious that no compensation takes place between phonological vowel length and preceding consonant (6.1.3). One might set up the hypothesis that programmed phonological differences do not cause compensation within the syllable. This seems to be true of phonological vowel length in Danish, also in relation to the following consonant, but it is not a universally valid rule; it is, e.g., not valid for languages like Swedish and Italian, where long vowels are followed by short consonants and short vowels by long consonants. One might also try the hypothesis that there is no compensation between vowel and preceding consonant. This is valid for phonological vowel length and also for the phonetic difference due to rounding of the following vowel (6.1.5). (Labials before u have longer open interval than before i, although the vowel u is also generally longer than i.)

6.2.2 Vowel height

It might be objected that the hypothesis of no compensation is not valid for differences in consonant duration due to vowel height. Here an inverse relation between vowel and preceding consonant was found. But this may not be a case of compensation but a coincidence due to specific conditions of sound production.

Since, as seen in table 21, the lengthening of the open interval before i and u compared to a is quite independent of the phonological length of the vowel, i.e. the consonant is lengthened before long i: compared to short a, although i: is in fact longer than a, one might even take this as proof that the duration of the consonant has nothing to do with the duration of the following vowel but only with its quality (cf. Klatt, 1975). This is, however, not sufficient proof; it only shows that it is not crude phonetic duration which is at stake. It might be so that phonological length does not cause compensation, as already shown above, but within long and short vowels there could be a compensation for differences of duration due to vowel height.

(Nooteboom (1972) found a difference of duration between words with long and short vowels but not between words with high and low vowels.) There is, however, a further and, as far as I can see, more convincing argument against considering the longer open interval before high vowels as due to compensation, viz. that it is possible to give independent physiological explanations of the durations of consonants and vowels and a common explanation for rounding and vowel height.

The longer duration of the open interval of labials before rounded vowels can be explained by the fact that, particularly in high vowels, where the longer open interval is very clear, the lips are only opened very little from consonant to vowel, consequently the airflow is relatively slow, and the supraglottal pressure goes down slowly, which delays the start of voicing. Similarly, in the case of high vowels, the opening from consonant to vowel is of relatively small extent, and the airflow is delayed. This is particularly evident for the Danish affricated t, but it is also evident for the velars. As for the labials, the degree to which the airflow is delayed may depend on the degree of coarticulation and the relation is, in fact, also found to be more variable, also individually, in labials. In the present material pi has in most cases a longer open interval than pa, but some subjects have the opposite relation.

The difference in duration between high and low vowels has been explained by the extent of the articulatory movement. Jespersen (1932) seems to have been the first to give this explanation (a fact which I had overlooked in earlier papers (1955, 1964), cf. also Maack 1953, Fischer-Jørgensen 1955 and 1972, Kohler and Künzel 1978). The longer distance is partly, but not fully, compensated for by the speed of the movement (Lindblom 1967). The slightly longer duration of rounded vowels can, similarly, be explained by the extra articulation. This means that both the differences in vowel duration and the difference in open interval can be physiologically explained, and their interrelation in the time domain may be accidental and has nothing to do with compensation.

This explanation is corroborated by the fact that neither the difference in vowel length nor in length of open interval are specific Danish phenomena but well documented in a large number of languages (see, for the literature on vowel height, Lehiste 1970

p. 18 and Lindblom 1967, and for the open interval, e.g. for French Fischer-Jørgensen (1968 and 1972), Serniclaes (1974), Wajskop (1979), for German Fischer-Jørgensen (1976) (ti > ta and ki > ka, but pi-pa variable), and Kohler (1978), for English Klatt (1975), Summerfield (1975) (ki > ka, but pa > pi). I have found similar relations in a Dutch material. The dependency of the open interval on vowel height thus seems to be a general, physiologically conditioned tendency.

The lengthening of the fricatives f, v and s before high vowels can be explained in the same way, viz. as a delay of the airflow, and the fact that this lengthening is not consistent for h, m and l, which have a freer air escape, corroborates this assumption.

The physiological explanation is also corroborated by actual measurements of air pressure decay and airflow rise. Fischer-Jørgensen (1968) gives an analysis of the stop consonants of a French-Danish bilingual subject, which shows complete agreement between decay of intra-oral air pressure after the release, rise of airflow and length of open interval before the vowels i, a, u for bdg and ptk in French and Danish (with one exception). There is also agreement between decay of air pressure and length of open interval before i a u for pt (three German subjects) and k (only one subject measured) in Fischer-Jørgensen (1976), again with only one exception (only the air pressure data are given in the paper). Danish material will be published later; it shows a clear correlation between decay of intra-oral air pressure and length of open interval for ptk. The explanation is also supported by the fact that the most consistent lengthening of the open interval before i compared to a is found for the consonant t (also in Hutters 1979), and t is affricated and has a very slow escape of air after the release, particularly before i.

The most serious counter-argument against a purely physiological explanation is the fact that in many cases the closure of the stop consonants is also lengthened before high vowels, although in my material (but not in Hutters 1979) less consistently than the open interval. The German material shows the same very clearly, whereas only a weak tendency is found for the French-Danish bilingual subject. The problem is whether this forces us to recognize a real case of compensation, i.e. to assume that the

lengthening of the closure is due to a tendency to keep Ci- and Ca-sequences at approximately the same length (as mentioned in 5.3.4, the compensation is never complete, so that the goal is not reached).

I do not think that the possibility of compensation can be excluded, but, on the other hand, it is also possible to find a physiological explanation for the closure. Lindblom (1967) has shown that the opening movement of the jaw for the vowel begins during the preceding consonant and that it begins earlier for low than for high vowels. This would favour an earlier release of the consonant and thus shorten it. Lindblom finds that this effect may be prevented by a later opening activity of the lips for low vowels. This turns out to be the case for his subjects A and C, but not for B. Thus, there seems to be different individual strategies. Lindblom has only investigated labials, where a further complication is the possibility of more or less coarticulation with the tongue movements. It might be assumed that in general the jaw movement is dominating, and that the shortening of the consonant is thus not prevented by other factors, but the irregularity of the shortening shows that more factors may be at work.

6.2.3 Place of articulation

As concerns the difference between labials, alveolars and velars, it may be useful first to examine what is universal in the relations found in Danish and how the deviation from the universal tendencies can be explained. As mentioned above (5.3.2), the order in Danish stops is b>(d>g) and p>k>t for the closure, and the opposite order g>d>b and t>k>p for the open interval.

The relations for bdg correspond to a universal tendency, see Lehiste 1970, p. 27-28, Fischer-Jørgensen (French) 1968 and 1972 (in the latter case only as an average over different speakers). The same relations were found in a Hindi material. For the closure the tendency is rather weak. Kohler (1978) and Mansell (1979) have found the order b>g>d for German. This is also common for Danish subjects, and two of six German subjects in my investigation (1976) deviated in different ways from the normal order b>d>g. For the open interval the order g>d>b is, however, very stable, cf. Lisker and Abramson 1964 and 1965 (various languages), Bothorel-Witz and Pétursson 1972 (Icelandic),

Klatt 1975 and Zue 1976 (English), Löfqvist 1976 (Swedish), and Wajskop 1979 (French).

As concerns ptk, the relations p>k>t for the closure and t>k>p for the open interval are, however, specific for Danish, the normal relations being the same as for bdg, i.e. p>t>k for the closure and k>t>p for the open interval (see the references for bdg above). It is interesting that the deviation in Danish concerns both the closure and the open interval, which means that there is an inverse relation between closure and open interval in all cases.

It was mentioned in 5.3.2 that the reason for the deviating relations for Danish ptk was the strong affrication of t, involving a longer open interval and a shorter closure. French speakers, who have affrication of t before i also have a longer open interval in t than in k in this case, and German affricates compared to plosives are characterized by a shorter closure and a longer open interval and have a slower opening of the articulators, evidenced by a slower decay of the intra-oral pressure and a slower rise of the airflow after the release (Fischer-Jørgensen 1976).

On this background it seems promising to look for similar explanations of the universal relations. The normal short closure and long open interval of velars may be explained by the slow movement of the body of the tongue compared to the tongue tip and the lips. As the closing and opening movement of a stop is regarded as being part of the preceding and following vowel (or the open interval), respectively, velars will have a shorter closure and a longer open interval. In labials, on the other hand, the movement of the lips is independent of the vowel articulation, the closure can therefore start earlier and last longer without hampering the articulation of the vowels, the lips can also move more quickly than the body of the tongue. This explanation has the advantage of being of the same type as that offered for the relations due to vowel height and rounding, and it has the advantage of seeking a common cause for the durations of closure and open interval and their inverse relation, so that it is not necessary to invoke the concept of compensation. The correlation diagrams in fig. 6 also show an inverse relation between the consonants (e.g. t and p), but no inverse relation within the same consonant. It has also been argued that there will be a higher

pressure behind the point of articulation the farther back it is, and that it will take a longer time for this pressure to decrease to a level which permits voicing. But this higher pressure might also be expected to lead to a stronger airflow instead of a slower decay of the pressure. It might, however, contribute to the shortening of the closure.

There may, however, be other factors involved. Hutters (1978 and 1979) has found differences in the glottal activity in Danish stops according to place of articulation, the maximum glottal opening being larger in k than in p, whereas t varies. Moreover, the oral release comes earlier in relation to the glottal movement in the order t>k>p, at least before the vowel i. Similarly, g has a larger maximum glottal opening and an earlier oral release relative to the glottal closing movement than b. A larger glottal opening in k than in p has also been found for other languages, e.g. Japanese (Sawashima and Niimi 1974) and Icelandic (Pétursson 1976). The problem is whether these differences are artefacts of the method, perhaps due to a raising of the larynx in velars and, if they are real, whether the differences are programmed or whether they are due to some sort of reflex mechanism conditioned by aerodynamic factors, e.g. the pharyngeal pressure (Hutters 1979). This needs further investigation.

Klatt (1975) has a different explanation of the longer open interval in k. For bdg he assumes physiological constraints, but for p-k he supposes that there are perceptual reasons. He thinks that a longer VOT is needed in a voiceless plosive with slower formant transitions, such as k, to prevent listeners from hearing the low frequency energy cue that would indicate a g. It does not seem very plausible to explain the parallel order k>t>p and g>d>b in quite different ways. The slower transitions in velars should rather be considered as the acoustic result of the same slower movement which hampers the airflow and consequently the voicing. If these causal relations were disrupted, it would of course cause confusion, but I cannot see that perceptual factors should be more important in this specific case than in other cases.

6.2.4 ptk vs. bdg

Finally, there is the problem of the differences between the CV-sequences with ptk vs. bdg, where it was found that in the ptk -sequences the open interval is longer, but both the closure and the following vowel shorter than in the bdg-sequences. Can these differences be explained by the physiological mechanisms or is it a case of compensation?

It should first be stated that the relations found in Danish are not universal. The symbols "ptk" and "bdg", when used in broad transcription of different languages, cover differences which may have some auditory similarities (although there are overlappings, cf. that the unaspirated voiceless stops in Chinese, Icelandic and Greenlandic are sometimes transcribed as b d g, sometimes as p t k), but which must be described by means of three different oppositions: voicing, aspiration or fortis-lenis, or by various combinations of these oppositions. In Danish the main difference is, as stated earlier, one of aspiration, but there may be a concomitant difference of fortis-lenis, so that the aspirated is more lenis (see below).

The mechanism of aspiration is fairly well understood. In Danish (Frøkjær-Jensen, Ludvigsen and Rischel 1971, Hutters 1979) as well as in Hindi (Kagaya and Hirose 1975) and Icelandic (Pétursson 1976) the difference between aspirated and unaspirated stops is evidently due to a different programming of the glottal gesture: aspirated stops have a wider glottal opening and an approximately symmetric closing-opening movement with its maximum close to the oral release, whereas unaspirated stops have a smaller opening with the maximum opening in the beginning of the closure period so that the glottis is practically closed at the release. These different glottal mechanisms explain the differences in aspiration (cf. also Kim 1970), but the cause of the shortening of the closure is not quite clear. It might be assumed that a stronger intra-oral pressure in the aspirated stops would contribute to weaken and open the oral closure. Two of my Indian subjects have a definitely higher intra-oral pressure in aspirated stops. But one did not have any evident difference. In Danish the difference is very small, and in Icelandic the two types do not show any difference in intra-oral pressure. So this is not a sufficient explanation. It is more probable that a separate timing command of the

release is part of the aspiration feature. A very long closure would prevent aspiration. The French-Danish bilingual subject whose stops I investigated in my 1968-paper had the same duration of French and Danish bdg, but her French ptk had a longer closure and her Danish a shorter closure. Löfqvist 1976 has also drawn attention to the very long closures of the Swedish medial unaspirated stops, which may have a relatively large glottal opening. Generally, however, the differences in the magnitude and particularly the differences in the position of the maximum of the glottal opening are so large that they give room for quite a variation in oral closure duration with preservation of the difference aspirated - unaspirated; and the different timing does not explain the weaker closure in aspirated stops which has been found in several languages (see below), and which must also be the cause of the further development to affricates in Danish t (and in the Old High German consonant shift). It may therefore be assumed that there is a concommittant fortis - lenis feature.

The fortis - lenis opposition, manifested initially by lengthening of the closure, a stronger organic pressure, and, according to Debrock (1977), by a quicker rise of the intensity of the following vowel, only rarely occurs alone. It generally accompanies the voiced - voiceless opposition, so that the voiceless member is more fortis (e.g. in French and Dutch). It may also accompany the opposition of aspiration, but in two different ways:

(1) In languages in which ptk and bdg are distinguished initially by aspiration and voicing (like Swedish) or by aspiration and optional voicing (like English and German), and medially before unstressed vowel by voicing, ptk are often assumed to be more fortis than bdg. This seems to be true for the medial position (cf. Löfqvist 1976 for Swedish and Kohler 1977 for German), but for the initial position one generally finds rather inconsistent indications of duration, organic pressure and EMG-activity (cf. e.g. for English Lisker 1966, Harris, Lysaught and Schvey 1965, Kent and Moll 1969, and Lubker and Parris 1970). Thus, the fortis feature is only evident when combined with obligatory voicing (i.e. medially in German and English).

(2) In languages which have a pure opposition of aspiration without a voicing opposition (like Danish and Icelandic) or with the two oppositions clearly independent of each other (like many Indian languages), it is the unaspirated member which seems to be more fortis (thus in Danish and Icelandic the stops that are written bdg in initial position). Danish bdg do not sound as fortis as e.g. French or Indian unaspirated ptk, but they have a longer closure than Danish aspirated ptk and a tendency to higher organic pressure and to stronger EMG activity, at least at the release of b, for some also at the implosion (Fischer-Jørgensen and Hirose 1974). Icelandic bdg sound almost like Danish, but Pétursson transcribes them as [ptk] and considers them as fortes (Bothorel-Witz and Pétursson 1972, Pétursson 1976 and Löfqvist and Pétursson 1976). They normally have a longer closure than the aspirated stops, and more contact on palatograms and a closer jaw distance. As for Indian unaspirated ptk, they have been found to have a longer closure than the aspirated stops (Kagaya and Hirose 1975, Dixit 1975 and Benguerel and Bhatia 1980 (Hindi), and Senn 1935 (Bengali)). I have found the same relations in Hindi, Gujarati and Dogri (unpublished material), and for a Gujarati speaker a lower organic lip pressure in ph than in p. Rousselot (1897-1908) also found a lower lip pressure in Armenian p^h than in p.

I therefore assume that the shorter duration of the closure in Danish aspirated stops is mainly due to weakness of articulation. In any case I do not think it is simply a question of compensation.

As for the shortening of the following vowel after aspirated stops, it is a consistent phenomenon in Danish. I have not found any indications for Icelandic, but I have found the same shortening in Gujarati and Dogri. Peterson and Lehiste (1960) found a slight shortening in American English. As for Swedish, I mentioned in my 1979-paper that Fant (1970) had found a very drastic shortening of the vowel after aspirated stops (6 cs). This quotation was, however, misleading. This large difference was only found in the word type pa'pa:pa vs. ba'ba:ba, where the following consonant is evidently mainly responsible, as Fant also remarks himself. When the following consonant is identical, the shortening is much smaller.

It is evident that the start of voicing is delayed by aspiration, so that the vowel starts later, but it would be possible to delay the end of the vowel correspondingly and thus get the same duration after aspirated and unaspirated stops. The fact that this is not done, is probably due to a tendency to maintain a relatively equal duration of the whole sequence, i.e. to a factor of compensation. This assumption is corroborated by the observation that vowels may also differ in duration after ptk and bdg in languages with unaspirated ptk. Thus in French vowels are shorter after ptk than after bdg, see Wajskop (1979) and Fischer-Jørgensen (1972). In the latter paper it is also shown that the lengthening of vowels after bdg exceeds the small difference in open interval after ptk and bdg in French. In 1972 I proposed that it might be due to the fortis character of ptk, but that is not a good explanation. It is more probable that it is a compensation for the longer closure of ptk. I have found a similar lengthening of vowels after bdg compared to unaspirated ptk in Hindi, Dogri and Gujarati. (But Kozhevnikov and Chistovich (1966) did not find any difference of vowel duration after t and d in Russian.) Moreover, measurements of stops in Gujarati have shown that the affricates č and čh have a longer open interval than k and kh, respectively, but also a longer following vowel, the difference being quite consistent. At the same time, however, the affricates have a shorter closure, so that the total duration of the affricates is shorter than that of the plosives. The difference of the vowels must therefore be explained as a compensation phenomenon. This is not, however, a quite general phenomenon for CV-sequences since the vowel does not seem to be lengthened after h (see 5.3.1 above); but perhaps, as Reinholt Petersen has suggested to me, h may have a special status since it has no supra-laryngeal articulation. The fact that Lehiste (1971) did not find any consistent compensation in CV-sequences does not directly invalidate the assumption made here, since what she measured was the variation of the same word, repeated a large number of times, thus the variation of the same sounds in a single token, whereas what has been discussed here is a problem of inverse relation between sequences containing different consonants or different vowels with different intrinsic duration. Fig. 4a also shows that there may be a clear inverse relation between closure and aspiration in ta and pa (whether due to

real compensation or to physiological factors), whereas there is no inverse relation between the durations of closure and aspiration in single tokens of the two individual words.

However, in Danish it is not so that the vowel stops at the same distance from the release of ptk and bdg, nor is it so in the Indian languages. That would give an acoustic vowel duration after ptk which would probably be below an acceptable minimum. After long aspirations it might even disappear completely. One seems to strike a compromise between equal duration of vowel gesture, and equal duration of perceptible (voiced) vowel, but a compromise which is considerably closer to the acoustic vowel duration after bdg (cf. table 12 in 5.3.1, showing that the vowel is shortened much less than the open interval after ptk is lengthened).

Fant (1969) also emphasized that the temporal organization is not simply a matter of delay of voicing in ptk vs. bdg at the expense of vowel duration, the differences in the (voiced) vowel durations after ptk and bdg being much smaller than the differences in open interval. Moreover, there may be differences in the vowel gesture according to the preceding consonant. Fant quotes Öhman (1965), who has shown that when curves of Swedish words of e.g. the types kà:da and gà:da are lined up in such a way that the tone contours cover each other as exactly as possible, then the start of the vowel after g will not coincide with the start of the vowel after k, but will correspond to a point in the middle of the aspiration interval of k, and the release of k will lie about 4 cs earlier than the release of g. Öhman mentions that exactly the same result will be obtained if the words are lined up according to formant transitions instead of tone contours. Fant has found this assumption corroborated in a number of Swedish spectrograms. He found a displacement of the release of ptk vs. the release of bdg of about 3 cs when the formant transitions are lined up, and he adds that this involves either that the formants start at different frequencies at the release of ptk compared to bdg, i.e. closer to the consonant target, which means that there is less coarticulation with ptk, or they start at the same point but move more slowly in the beginning after ptk. He finds that the former explanation is valid for labials, and probably the latter for palatals and alveolars. Gay (1979) has supported this assumption by means of EMG measurements showing that the muscle

activity for the following vowel starts earlier in bip and bap than in pip and pap, whereas this is not the case for t-d. Fant suggests some rules for the lengthening of the vowel compared to the differences in open interval and in release, but this will probably require further investigations. A preliminary examination of a number of Danish spectrograms has shown a pronounced displacement for t-d, which may be explained by the affrication of Danish t, involving a later start of the vowel movement, and in labials before back vowels, but no displacement of labials before i and hardly any difference in velars. These relations thus seem to be very complicated. A very preliminary examination of some French spectrograms did not show any clear displacements, and I would venture the hypothesis that in so far as the differences are due to a slower vowel gesture after ptk, this may be part of the lenis feature of aspirated stops. It must, however, be mentioned that Kozhevnikov and Chistovich (1965) have found a slower opening also of unaspirated p than of b in Russian.

Since the vowel movement takes place partly during the aspiration after ptk, one might think of considering the aspiration as part of the vowel and not as part of the consonant. This would, however, give absurd vowel durations in Danish. A third possibility is to consider it as a separate element. This would be in agreement with the phonological interpretation of Danish ptk as bdg + h, first proposed by Uldall, and accepted by Hjelmslev (1951) and others. Frøkjær-Jensen, Ludvigsen and Rischel (1971) have also found that glottograms of Danish aspirated p are very similar to glottograms of final b + initial h, and they suggest an interpretation of p as a summation of a b- and an h-gesture. A very similar description is given by Kagaya and Hirose (1975) of Indian aspirated stops. Holtse (1977) has measured the distance from the release of the stop to the end of the vowel in syllables with p and b + V, rV, lV and jV for two subjects. He finds that the duration of pV is approximately the same as that of bjV, brV and blV, whereas pjV, prV and plV have still longer durations. This is in agreement with Lehiste's measurements of English clusters with stop consonants (1972). She found that the duration of aspiration following initial voiceless stops is almost the same as that of resonants following voiced stops. Holtse draws the conclusion that p might be interpreted as b+h, where h is a separate unit in

the programming. The shortening of the vowel (and probably of the closure, which Holtse has not measured) could then be seen as a compensatory shortening due to the larger number of segments in the syllable. This is an interesting suggestion. I am, however, inclined to think that more plausible explanations are reached if the aspiration is considered to be part of the stops, as I have done above.

My main endeavour in the preceding pages has been to try to see how far it is possible to find physiological explanations of the different temporal relations without taking recourse to the concept of compensation, a concept which is certainly important, but which is sometimes too easily advocated and which may sometimes prevent an analysis of the production mechanism. The main result was that physiological production mechanisms may explain the temporal relations in most cases: the longer open interval in labials before rounded vowels, the longer open interval (and perhaps also the closure) before high vowels, the differences according to place of articulation, and the longer open interval and the shorter closure in ptk vs. bdg. - But I found indications of a compensation mechanism for the different vowel durations after ptk vs. bdg.

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