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CLOSURE DURATION AND ASPIRATION FOR SWEDISH STOPS

Anders Löfqvist

This report deals with closure duration, voicing and aspiration and their interrelations in the production of Swedish stop consonants in various positions and under different stress conditions. The first two parts present data on closure duration and aspiration, respectively. These findings are then used for the development of a working model for the control of aspiration in Swedish. In the third part this model is tested empirically and further revised on the basis of the experimental findings.

I. Closure duration

The complex differentiating voiced and unvoiced sound segments comprises the following features according to Slis and Cohen (1968): acoustical duration of the consonant, acoustical duration of the vowel, duration and spectral extensiveness of the vowel formant transitions, presence or absence of vocal vibrations during the consonant, acoustical duration of the noise burst of plosives and friction noise of fricatives, sound pressure of the adjoining vowels, peak value of the fundamental frequency of the surrounding vowels and the contour of the fundamental frequency during the following vowel.

One thing that Slis and Cohen did not take to be different for voiced and unvoiced sounds was the duration of the oral constriction, a view that was later changed in Slis (1970). Other studies of this particular parameter for plosives do not show a complete agreement in that some state that no difference is found whereas others maintain that it only occurs in some positions and not in others; if a difference is reported to exist it is usually the voiced stops that have the shorter duration of the oral closure. Some of these varying opinions may be due to differences between the languages under investigation as well as to variations in the importance of closure duration for the distinction between voiced and unvoiced stops in different positions within a language. It would thus seem to be of some interest to determine its role in the system of phonological distinctions in a language and how it is related to other phenomena, specifically voicing and the presence or absence of aspiration after the stop release.

Procedure

Measurements of the duration of the articulatory closure for the stops under investigation were made from registrations of supraglottal air pressure and acoustic records. The signals were recorded on a Mingograph at a paper speed of 100 mm/sec and measured by hand; a detailed description of the instrumentation is given in Löfqvist (1976).

The determination of closure duration from records of oral air pressure presents some problems, however, since it is not possible to tell exactly when complete closure is attained. Presumably, oral pressure begins to rise before complete closure has occurred due to the increasing resistance to the air flow at the place of articulation as the articulators are narrowed towards each other; furthermore, for voiceless stops the glottis often begins to open before the oral closure and the increased rate of air flow through the glottis would cause an increase in supraglottal air pressure.

In spite of these caveats it was still felt that the moment of oral closure could be established with some accuracy. The values for closure duration presented by Lubker and Parris (1970), who used both a labial pressure transducer and the oral air pressure trace for their measurements, do not differ too much with respect to which method was used. Furthermore, Shipp (1973) reports that the rise in oral pressure at the implosion for stops corresponds within plus or minus 4 milliseconds to the moment of articulatory closure as determined from simultaneous high speed motion picture films.

Thus, the following convention was adopted for the measurements: the point at which oral pressure began to rise was taken as the instant of articulatory closure.

For the identification of the release of the oral closure the microphone signal was used. One might suppose that the same point could be identified by the drop in oral pressure associated with the release but this is not necessarily so. Due to aerodynamic factors the drop in oral pressure would seem to occur slightly after the release, especially for voiceless aspirated stops and Shipp (1973) reports a time difference of ca 15 milliseconds between the two events for this very stop category. Another factor which could possibly play a role in the present investigation was the position of the tube which sensed oral pressure; it was positioned in the pharynx with the plane of its opening perpendicular to the air flow. With this placement the air flow could impinge on the tube and cause too high pressure readings, cf. Hardy (1965). Since the highest rate of air flow for stop consonants occurs immediately after the release one could assume that pressure would stay at a too high level at this point. According to this line of reasoning one would expect that a comparison between measurements of oral closure for stops based on oral pressure alone and those based on both pressure and speech signal would show the former to give longer values than the latter, which is indeed the case, Löfqvist (1973). It should be added that the position of the microphone was ca 10 cm from the speaker's mouth ensuring that the release burst would be picked up without any significant delay.

Material and subjects

The speech material consisted of nonsense words constructed to contain different stops under different stress conditions and in various positions; they also conformed to common Swedish stress patterns. The following words were used:

1. 'Cɑ:C – where $C_1 = C_2$ = /p, t, k, b, d, g/;
2. Ca'Cɑ: – with the same consonants as above and stress on the last syllable;
3. 'Cɑ́:Cən – with consonants as before and stress on the first syllable; the word carried tonal accent 1;
4. 'Cɑ̀:Cən – as above but the word had tonal accent 2;
5. 'CáC:ən – as above with tonal accent 1 but with short stressed vowel followed by long consonant;
6. 'CàC:ən – as above but with tonal accent 2.

The words were placed in the carrier phrase "Ja sa ... igen" (I said ... again) except for those of type 1 which were produced in the frame "Ja sa ..." and thus occurred in utterance final position.

The same vowels were chosen to minimize coarticulatory effects and the use of a carrier phrase seemed advisable to keep tempo and level as equal as possible although no specific measures were taken to strictly control these factors for the individual speakers.

Table I Closure duration in msec for different stops in # 'CV: position, n = 144.

	p	t	k	b	d	g
$\bar{x}$	143	137	134	123	117	122
s	25.4	31.9	37.6	17.7	23.4	21.7

Table II Means and standard deviations of closure duration for voiced and unvoiced stops in different positions, n = 144 except for # 'CV: where n = 432.

Position		# 'CV:	# CV	V'CV:	'V́:CV	'V̀:CV	V:C#
Sound							
ptk	$\bar{x}$	138	127	111	171	188	216
	s	32.2	37.1	15.6	22.6	23.9	44.8
bdg	$\bar{x}$	121	105	107	91	100	123
	s	21.2	27.3	14.3	13.3	16.1	27.8

The voiced stops were generally produced with vibrations of the vocal folds. In some cases a break in the voicing occurred and then mostly towards the end of the closure period. Thus the terms "voiced" and "voiceless" in the following refer to two sets of sounds differentiated inter alia by their respective modes of glottal activity.

All words were produced in random fashion twelve times by four native Swedish speakers with varying degrees of phonetic training. The speakers were:

1. a male speaker of Southern Swedish;
2. a male speaker of Southwestern Swedish;
3. a male speaker of Southern Swedish;
4. a female speaker from the island of Gotland on the Swedish east coast.

Speaker 4 did not read the words of types 5 and 6.

Results

In one sense all the stops in the study, except those in final position, occurred medially since a carrier phrase was used; the terms "initial" and "medial" therefore in the following refer to positions within the testword.

Although the absolute values for closure duration did show some intersubject variability the relative durations for various positions did not, with a few exceptions; thus, the pooled data for all subjects will be discussed and the individual differences commented upon in the appropriate places.

Table I presents closure duration for stops with different places of articulation in #'CV: position. The effect of place of articulation is rather small and the range of variation is ca 10 msec for the voiceless set and ca 5 msec for the voiced set. One tendency that can be observed is that labials have longer closure duration than dentals and velars; the order between the latter two is not clear. The difference within the unvoiced set is, however, not statistically significant, $F = 1.01$, $P > 5$, whereas the difference in the voiced set is, $F = 8.34$, $P < 0.05$. It should also be noted that there are fairly large interindividual differences in this specific case and thus a great deal of caution is warranted in the interpretation of the relation between place of articulation and closure duration.

Since the influence of the place of articulation seems to be negligible we shall in the following only discuss the two sets, voiced and unvoiced. The relevant material is summarized in Table II. Before we discuss it we should note that the column headed # 'CV: contains measurements of stops in initial stressed position in words of type 1, 3 and 4. Since the number of syllables differs in type 1 compared with types 3 and 4 we would expect the well-known shortening of segment duration in words with increasing number of segments. This is the case in the present material but the variation is only ca 10 msec, the shorter duration to be found in words of type 1; besides, the tonal accent of the word had no discernible influence on closure duration in the initial stop.

Let us first consider the voiceless stops. They have by far the longest closure in final position which in this case is equal to utterance final position. In decreasing order we then find medial unstressed position, where we also can see the influence of the tonal accent on segment duration: the closure is longer if the word has tonal accent 2 than if it has tonal accent 1. Here speaker 4 is an exception in that closure duration in her case is the same in this position irrespective of the tonal accent.

Of the remaining positions initial stressed stops have longer closure than their unstressed counterparts and in medial stressed position we find the shortest closure duration.

If we compare stressed versus unstressed positions we see that the stressed one shows longer closure than the unstressed one initially; medially the situation is the reverse as here the unstressed stops have much longer duration than their stressed counterparts.

We shall next turn to the voiced stops. Their closure durations seem to fall into three categories as far as stress and position are concerned. The longest closure is found in final and initial stressed positions. Next come initial unstressed and medial stressed positions. In medial unstressed position the voiced stops present the shortest closure duration and tonal accent 2 has a lengthening influence; again, speaker 4 does not show any variations due to tonal accent.

Comparing stressed versus unstressed positions we note that the stressed voiced stops have longer closure duration than the unstressed ones both initially and medially.

Generally voiceless stops have longer closure duration than their voiced cognates. This is the case for all speakers and positions with only one single exception. The difference between the two sets is statistically highly significant - $P < 0.0001$, two-tailed test - in all positions except medial stressed position where it is not significant.

In absolute values the difference between the two sets is greatest finally and medially in unstressed position where it is 80-90 msec. Initially it is ca 20 msec and medially in stressed position it is insignificant.

Looking at closure duration for stops in bisyllabic words with stress on the first syllable we see that the initial and medial stops behave differently depending on whether they are voiced or unvoiced. Voiceless stops have longer closure medially than initially but the voiced ones show the inverse pattern, i.e. longer initially than medially.

Another phenomenon that is apparent in Table II is that the closure durations associated with different stress conditions do not span the same range of values for the voiced and voiceless sets. The mean values of closure duration for voiceless stops range from 111 to 216 msec and the same values for the voiced set go from 91 to 123 msec. Thus, the voiced ones do not differ as much as the voiceless stops in closure duration as a function of stress and position.

Table III Closure duration for long stops in medial unstressed position, n = 36.

Position		'V́C:V	'V̀C:V
Sound			
ptk	$\bar{x}$	203	215
	s	35.7	34.9
bdg	$\bar{x}$	139	149
	s	18.3	25.2

Table III presents the values of closure duration for long stops. The same tendencies can be noted as before, viz. closure is longer in words with tonal accent 2 and the voiceless set has longer closure; the difference between the two sets is statistically highly significant.

A comparison of closure duration for long and short stops in the same position reveals that the difference tend to be greater in words with tonal accent 1 and that it also is larger for the voiced than for the unvoiced plosives.

Discussion

In her chapter on the intrinsic duration of consonants Lehiste writes: "Most investigators agree that labials are longer than alveolars and velars, other factors being kept constant", (Lehiste, 1970, p. 27). This statement is at least superficially substantiated in the present material although the difference is statistically significant only for the voiced stops and in this case it seems to be the dental place of articulation that has a very short duration of the oral closure compared to the labials and velars. In view of the interindividual differences it seems hard to draw any valid conclusions for the relative duration of stop consonants produced with different articulators. The small variations that can be found probably play no role in normal production and perception of speech. Considerations of the mobility of a particular articulator might be invoked but the various constraints on the movements of different articulators are not sufficiently known at present.

Another thing to be noted is that there might well be coarticulatory effects such that these differences may show up more clearly if more vocalic contexts had been used, cf. Fischer-Jørgensen (1964), Kim and MacNeilage (1972) and the discussion below of the influence of different vowel contexts on aspiration for different stops.

If we look at the duration of voiced and unvoiced stops we see that the voiceless set has longer closure duration than the voiced set.

This is in accordance with another study of the same parameter for Swedish stops by Karlsson and Nord (1970). They also found that the difference was greatest in medial position after a stressed vowel, which agrees with our findings, if we disregard final position which they did not include. The lengthening that occurs in medial unstressed position is not a particular feature of the grave tonal accent since it also takes place in words with tonal accent 1. At the same time tonal accent 2 obviously contributes an extra lengthening of the medial consonant which was also found by Elert (1964) who studied speakers from Stockholm. The only case where this extra lengthening does not take place is for the speaker from Gotland and this might be a particular feature of that dialect.

The relations between long and short stops presented here are in good agreement with those given by Elert (1964).

The same difference between voiced and unvoiced stops was also found for Dutch by Slis (1971), but only for embedded stops where it was of the order of 15-24 msec. He also found that the length of the preceding vowel influenced the duration of /p/ so that it was longer after short than after long vowels; the lengthening of voiceless stops after stressed vowels that has been noted for Swedish did not take place in Dutch.

For French stops the same relations have been reported, e.g. Thorsen (1966), Fischer-Jørgensen (1972). Thorsen found, furthermore, that the difference between the two sets of stops was greatest in final position which, incidentally, coincides with the results for Swedish reported here.

Bothorel-Witz and Pétursson (1972) and Goudaillier (1974) present the same trends for German. Again the difference seems to be stable across positions in absolute values.

For American English no difference was found between the two stop categories by Kent and Moll (1969). The data given by Lubker and Parris (1970) go in the same direction in that they do not reveal any consistent trends.

About the same conclusions can be drawn from the results presented by Lisker (1967, 1969). He says that the difference in closure duration is negligible except in medial poststress position. In this case the difference seems to be due to the fact that the voiced stops are shorter after a stressed vowel than before it whereas the unvoiced plosives remain the same.

Obviously differences in experimental design and methods of measurement can account for some of the variability in the data from various investigations but language specific variations seem to occur, in the case of Swedish especially the lengthening of voiceless stops after stressed vowels.

Stress is usually considered to lengthen segments and this is what we have found except for the unvoiced stops in medial position. Our material did not include stops medially between unstressed vowels but according to Karlsson and Nord (1970) very short closure durations are found there for the voiceless category so it is obviously a preceding stressed vowel that causes its special behavior. For the stops in utterance final position in the present investigation two factors thus would seem to contribute to their long values of closure duration: prepausal lengthening of segments and also the increase in closure duration for the voiceless stops when they occur after a stressed vowel.

The fact that voiced stops show shorter closure duration can presumably be related to the necessity of maintaining a pressure drop across the glottis to keep the vocal folds vibrating. If the articulatory closure was too long the pressure drop and the transglottal air flow would decrease and the vibrations cease, cf. Rothenberg (1968), Ohala (1971). If this is true one might expect an inverse relation between degree of voicing and closure duration. This is to some extent the case as voiced stops tend to be voiced all through in medial position and here we have the shortest duration of the oral closure. At the same time it is well known that voiced stops often become devoiced in final position and the data in Table II show that closure duration is rather long in that position.

Long durations are also found for the voiced stops in initial stressed position and the material presented in Löfqvist (1975b) shows that a voice break was rather common in this position. On the other hand, closure duration is certainly not the only determinant of voicing in stops as other factors also play a role, specifically subglottal pressure and various mechanisms to increase the volume of the supraglottal cavities, cf. Rothenberg (1968), Löfqvist (1975b). Furthermore, the role of voicing in the sound system must also be taken into account since that would set the limits within which devoicing is allowed to occur.

One thing to note in connection with the lengthening of the Swedish unvoiced stops medially after a stressed vowel is that this is the very position where they also are unaspirated, cf. below, – we shall neglect final position for the moment as this is a special case. This gives us a neat inverse relationship between closure duration and aspiration for Swedish unvoiced stops.

One might speculate whether this is related to the necessary time required for the glottis to go from a voiced to an open and back to a voiced position for intervocalic unvoiced stops. If the articulatory closure is long the gestures of the glottis will be executed while the closure is maintained; if on the other hand the oral closure is shorter than the time required for the glottis to make its adjustments it will not return to the voiced position till after the oral release and the result is an aspirated stop.

Figures on the time required for various glottal movements can be found in the literature. Klatt et al. (1968) state that "the process of separating the vocal cords in anticipation of a voiceless consonant (...) requires a time interval in the order of 100 msec." Kim (1970) found that it took 100-200 msec for the glottis to close before the beginning of an utterance. In Rothenberg (1968) the time for a complete "cyclic" movement of the glottis is found to vary between 80-150 msec and the values given in Lindqvist (1972) are about the same.

The hypothesis that the duration of the articulatory closure in part or wholly determines whether a voiceless stop is aspirated or not would seem to require that the glottal gestures are the same for aspirated and unaspirated unvoiced stops. Fiberoptic data on Swedish presented by Lindqvist (1972) would support such an assumption as far as the size of the glottal opening is concerned, but this might be a peculiarity of Swedish which does not have any phonemic opposition between aspirated and unaspirated voiceless stops.

In fact, cineradiographic evidence for Korean in Kim (1970) shows that there is a difference in the degree of glottal opening between the three different voiceless stops in that language, the heavily aspirated series having greater glottal opening than the other two. At the same time the duration of the oral closure also differs in that the unaspirated stops have the longest closure and the slightly aspirated ones the shortest closure with the heavily aspirated ones falling in between. The same relations between aspiration, closure duration and glottal opening also hold in the material on Korean stops presented by Kagaya (1974).

Similar variations in the magnitude of the glottal opening area related to aspiration occur for Hindi stops, Kagaya and Hirose (1975); again, closure duration is shorter for the voiced than for the voiceless stops and within each category longer for the unaspirated than for the aspirated type. Also in Danish, Fischer-Jørgensen (1968), and Icelandic, Pétursson (1974), where aspiration is phonemic, somewhat longer closure durations are found for the unaspirated than for the aspirated voiceless stops in addition to differences in glottal opening area. Thus, there exists some evidence that closure duration is longer for unaspirated than for aspirated stops although the difference seems to be greater in Swedish than in other languages. At the same time differences in glottal opening area and timing of glottal movements also occur.

From a perceptual point of view aspiration is obviously a strong cue for the distinction between voiced and unvoiced stops, cf. Reeds and Wang (1961), and similar experiments with Swedish subjects and speech material confirm their findings. If aspiration is lost and cannot serve as a cue closure duration is another parameter that can serve the same function, cf. Lisker (1957). In the case of the Swedish stops analyzed here we find in fact that in the very position where aspiration is lost and cannot serve as a cue the two stop categories show greatest difference in the other parameter, closure duration.

We shall return to these questions below in part III after a presentation of some data on aspiration for Swedish stops.

II. Aspiration

The same material was also used for a study of the period of aspiration for the unvoiced stops. Aspiration will in the following be taken as identical to voice onset time (VOT) as defined by Lisker and Abramson (1964), i.e. the time from explosion to onset of vocal fold vibrations for a following segment.

Results

Table IV presents the results of the measurements for different stops.

The decreasing order of the aspiration is k > p > t and the difference is highly significant (F = 64.68).

The influence of stress and position can be seen in Table V.

Two groups can be distinguished in Table V according to the length of the aspiration. One group has a very short aspiration and contains the stops after a stressed vowel and the other comprises the rest of the positions; among them a further subdivision can be made according to whether the following vowel is stressed or not; aspiration is longer in the former case.

Table IV Aspiration in msec for different stops in # 'CV: position, n = 144.

	p	t	k
$\bar{x}$	46	39	55
s	13.5	9.9	13.3

Table V Aspiration for voiceless stops in various positions, n = 144 except for # 'CV: where n = 432.

Position	# 'CV:	# CV	V'CV:	'V́:CV	'V̀:CV
$\bar{x}$	47	32	44	16	15
s	14.1	12.9	13.8	6.7	6.4

Discussion

The results for the aspiration of the different stops are in agreement with those reported in Lehiste (1970) as far as the velars are concerned in that they have the longest aspiration; the order for dentals and labials found here is, however, the reverse compared to that given by other investigators.

In trying to explain the inherent aspiration associated with a particular place of articulation one can presumably view the variations as a result of the functioning of the peripheral speech apparatus and not as an independently controlled feature. What seems to be involved is the time needed for the pressure drop across the glottis to reach a level suitable for voicing to start. This time interval could be related to the pressure buildup during the stop occlusion and to the flow resistance in the vocal tract after the release, other things being equal, i.e. if we assume similar laryngeal adjustments and respiratory activity for all voiceless stops irrespective of their place of articulation.

Several factors affect the flow resistance and thus aspiration, e.g. the speed of movement of an articulator and the length of the constriction through which the air has to pass after the release. The former is not too well understood whereas the latter would lead us to predict that aspiration should increase as the length of the constriction increases, i.e. as the place of articulation moves backwards from the lips.

Both of the factors mentioned above are presumably involved and the nature of the following vowel has been found to influence the aspiration so that it is longer before high vowels, Fischer-Jørgensen (1972), Klatt (1973), cf. also Lisker and Abramson (1967) who report no such influence.

In order to find out if such an relation holds true also for Swedish stops and to see if this could explain the order between labials and dentals a small experiment was carried out.

Six native Swedish speakers, three female and three male, read selected 'CV:C syllables in the sentence frame "Ja sa ...". The first and second consonants of the syllables were identical and represented one of the stop consonants /p, t, k/; the stressed vowel was drawn from the set /i, e, ɛ, ɑ, u/. Each syllable was repeated 20 times from randomized lists and recorded on tape under high quality conditions. The measurements of the period of aspiration are summarized in Table VI.

Interestingly, the order most frequently reported holds for the pooled values and for the different vowel contexts except for the low back vowel /ɑ/, the same vowel that was used in the original recordings; here labials and dentals have the same duration of the period of aspiration. This is presumably related to the path the tongue has to travel from the position associated with the dental stop to the one associated with the low back vowel. Furthermore, aspiration tends to be longer before high vowels. An analysis of variance revealed that the effect of place of articulation for the consonant is highly significant, F = 289.4990, and the effect of vowel and the interaction are significant at the 0.5 percent level, F = 8.0295 and 8.1318, respectively. These inherent variations have been shown to have perceptual effects, Summerfield and Haggard (1974).

Table VI Aspiration in msec in stressed CV syllable as a function of consonant and vowel, n = 120.

Vowel		i	e	ɛ	ɑ	u	
Stop							
p	$\bar{x}$	48	47	46	53	55	50
	s	10.7	11.5	11.9	14.2	11.6	12.6
t	$\bar{x}$	63	58	56	52	58	58
	s	9.0	6.9	11.3	11.9	10.4	10.6
k	$\bar{x}$	70	71	66	66	69	68
	s	11.2	31.5	10.4	12.4	9.8	17.4
	$\bar{x}$	60	59	56	57	61	
	s	13.8	22.0	14.5	14.3	12.2	

For the stops in Table V those occurring in poststress position should be regarded as unaspirated even if there is a short period without voicing after the release; a VOT of more than 20 milliseconds would

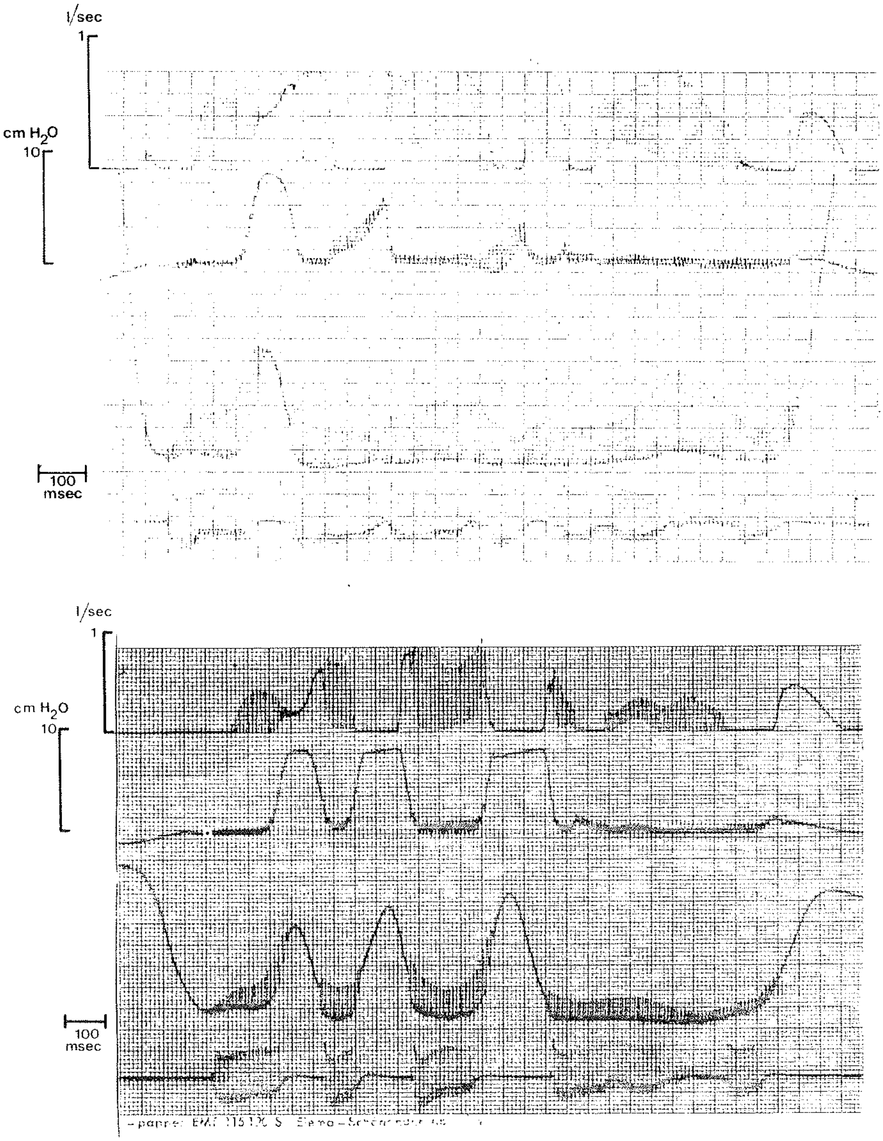


Figure 1 Record of the utterances "Men se 'deden igen", top, and "Men se 'teten igen", bottom. The curves represent from top to bottom, oral air flow, oral pressure, photoglottogram and signal from larynx microphone.

seem to be required for the perception of a stop as aspirated, Stevens and Klatt (1974).

III. On the control of aspiration

The presence or absence of aspiration in stop consonants would seem to depend mainly on the coordination of glottal and supraglottal articulations. The role of the respiratory system in the control of aspiration seems to be limited or none whatsoever, perhaps with the exception of Korean stops. These questions as well as some empirical studies of subglottal pressure in the production of Swedish stops are discussed in Löfqvist (1975b).

In the preceding sections of the present report we saw that in those positions where the Swedish voiceless stops are unaspirated they also have a longer period of articulatory closure than otherwise and, furthermore, that the difference in closure duration between voiced and voiceless stops is greatest in those positions where the latter are unaspirated. On the basis of these findings one might hypothesize that the presence or absence of aspiration in the unvoiced set wholly or in part depends on the duration of the oral closure.

A strong version of such an hypothesis would say that the glottal gestures, abduction and adduction, are the same for voiceless stops in different positions both as far as timing, speed and magnitude are concerned. A weaker version would maintain that closure duration is one factor involved in the control of aspiration, albeit an important one, but that variations in timing, speed of glottal movements and size of glottal opening also play important roles.

Some weaker version clearly receives some support from the study of Lindqvist (1972) where we find that the opening of the glottis occurs earlier when the stop is unaspirated; on the other hand peak glottal opening does not appear to be related to aspiration whereas the size of the glottal opening at the moment of release clearly is. The latter has been claimed by Kim (1970) to be the determining factor for aspiration and results which are consistent with this claim have been reported for Danish, Frøkjær-Jensen et al. (1971), English, Sawashima (1970), Icelandic, Pétursson (1975), Korean, Kagaya (1974), and Swedish, Lindqvist (1972); at the same time findings which are inconsistent with it have been presented for stops in Hindi, Dixit and

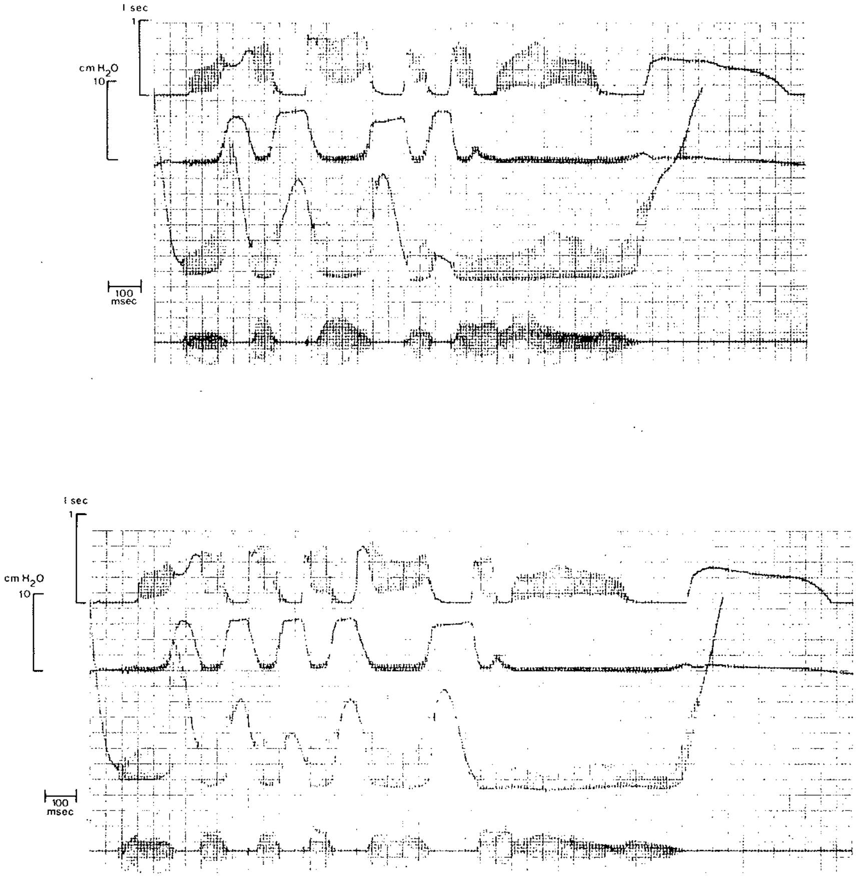


Figure 2 Record of the utterances "Men se 'teteten igen", top, and "Men se tete'teten igen", bottom.

MacNeilage (1974), Kagaya and Hirose (1975).

In order to get some information on the coordination of glottal and supraglottal articulations in the production of Swedish stops and relate it to the model for control of aspiration outlined above some glottographic studies were carried out with two of the subjects who participated in the original recordings.

The speech material used for the measurements reported on in the preceding sections was rather limited since it only contained mono- and bisyllabic words. A more extensive speech material was thus constructed to permit an analysis of stop production in more contexts. The results for this more extensive material will be discussed below after a presentation of the procedure and the results of a pilot study designed to clarify certain factors.

Procedure

The information of laryngeal activity was collected by the transillumination technique, or the photoglottographic method. It is based on the principle that light which enters the subglottic space through the skin from an external light source is modulated when it passes the glottis according to variations in glottal opening area and these modulations are picked up by a phototransistor placed in the pharynx and connected to suitable amplifiers and recorders. In some experiments the positions of light source and light sensor have been reversed which may be convenient in some applications, especially if laryngeal activity is simultaneously observed by a fiberscope.

Early descriptions of the transillumination technique can be found in Czermak (1861) and Wullstein (1936). Sonesson (1960) improved the technique and applied it to a systematic study of laryngeal behavior. Discussions of the merits and shortcomings of the method and its applications in phonetic and phoniatric research can be found in Sonesson (1960), Malécot and Pebbles (1965), Ohala (1966), Frøkjær-Jensen (1967, 1968), Slis and Damsté (1967), Colman and Wendahl (1968), Lisker et al. (1969), Frøkjær-Jensen et al. (1971), Lindqvist (1972), Sawashima (1972), Kitzing and Sonesson (1974).

In the present context it is sufficient to note that the relation between glottal opening area and the output from the light sensor can not be calibrated on living subjects and hence one cannot have a quantitative measure of glottal opening. The amplitude of the signal depends, inter alia, on the relative positions of light source and light sensor and their placement is critical if the signal is to give any useful information. The temporal relations in the glottogram appear, however, to remain fairly stable in spite of the variations mentioned above and we shall therefore concentrate mainly on the timing of glottal and supraglottal articulations.

The light source of the glottograph, LG 900 (F-J Electronics), was placed on the skin over the crico-thyroid membrane and the light entered the subglottic space from almost a vertical position. The light sensor was placed in a small transparent plastic catheter and introduced into the pharynx through the nose. The subject swallowed the free end of the catheter into the œsophagus to keep the transistor in the same position irrespective of articulatory movements. The output from the glottograph was monitored on an oscilloscope and checked for variations in signal quality during the recording sessions.

In addition to the glottogram the egressive oral air flow was registered via a 2 channel Electro-aerometer; EA 510/2 (F-J Electronics). Oral air pressure was sampled through a plastic tube in the pharyngeal cavity and coupled to a differential pressure transducer, EMT 33 (Siemens-Elema). All signals were recorded on a Mingograph at a paper speed of 100 mm/sec together with the signal from a larynx microphone.

A pilot study

To get some preliminary notions about the validity of the model for control of aspiration outlined above and certain other factors a pilot study was made with speaker 2. The speech material was of the same type as before except that the vowel in the testword was changed from /ɑ/ to /e/ and the sentence frame to "Men se ... igen"; these modifications were necessary since the transillumination technique can not be used with low back vowels; the tongue movements for their production interfere with the position of the light sensor and may also block the passage of light from the glottis to the sensor.

The testwords mostly contained voiceless stops but a few examples of voiced stops were also included. Each word was repeated several times in random fashion at a comfortable level and rate.

Results and discussion

Before we go to the results for the voiceless stops we can note that the glottis generally was in a voiced position for the voiced stops, Fig. 1; a small opening of the glottis could be seen towards the end of the closure in a few cases and was then accompanied by cessation of voicing.

The measurements made for the voiceless stops included the same parameters as before, i.e. closure duration and aspiration. As a measure of timing the interval from the implosion of the stop, defined by the flow and pressure traces, to peak glottal opening was measured. The latter point is easy to determine whereas it is difficult or impossible to say when the abduction of the vocal folds starts, cf. Figs. 1-2.

The results of the measurements are summarized in Table VII for different stops in # 'CV: position and in Table VIII for voiceless stops in different positions.

For stops with different places of articulation closure duration and the interval from implosion to peak glottal opening proved not to be statistically significant, $F = 4.6137$ and 1.2849, respectively ($P > 1$). The difference in aspiration is, however, significant, $F = 24.0380$ ($P < 0.05$), and shows the common order of increasing aspiration as the place of articulation moves backwards from the lips. At the same time no systematic differences in glottal opening area could be detected. These findings suggest that the glottal articulations are the same irrespective of the place of articulation for voiceless stops and that the relation between aspiration and place of articulation should be explained along the lines given above.

For the stops in utterance final position no measurement of aspiration could be made and from Table VIII peak glottal opening appears to occur close to the release of the articulatory closure; the mean value of T should be taken with some caution, however, since in this position the variation in the individual measurements is very great and range from 100-370 msec. This variation is much larger than that encountered in other positions and is presumably due to less specific requirements on the timing of the glottal articulation in this position

Table VII Results of the pilot study. Closure duration (C), aspiration (A) and the interval from implosion to peak glottal opening (T) for different stops in # 'CV: position, n = 33.

		C	A	T
p	$\bar{x}$	115	32	101
	s	11.1	8.3	7.0
t	$\bar{x}$	119	39	99
	s	6.9	8.5	9.5
k	$\bar{x}$	113	45	98
	s	7.4	6.3	8.0

Table VIII Results of the pilot study. Closure duration (C), aspiration (A) and the interval from implosion to peak glottal opening (T) for voiceless stops in different positions.

		C	A	T
# 'CV:	$\bar{x}$	116	38	99
n = 99	s	9.0	9.4	8.2
# 'CV	$\bar{x}$	122	30	101
n = 70	s	8.8	6.9	12.0
# CV	$\bar{x}$	116	38	96
n = 27	s	9.1	7.1	6.4
V'CV:	$\bar{x}$	101	52	87
n = 27	s	8.7	10.8	7.7
'V́:CV	$\bar{x}$	149	16	70
n = 36	s	10.3	7.0	6.7
'V̀:CV	$\bar{x}$	156	17	78
n = 36	s	10.9	7.2	6.4
'V́C:V	$\bar{x}$	211	8	97
n = 35	s	13.1	4.7	10.3
'V̀C:V	$\bar{x}$	219	8	103
n = 35	s	11.0	6.3	11.2
V:C#	$\bar{x}$	184		184
n = 21	s	16.1		50.6

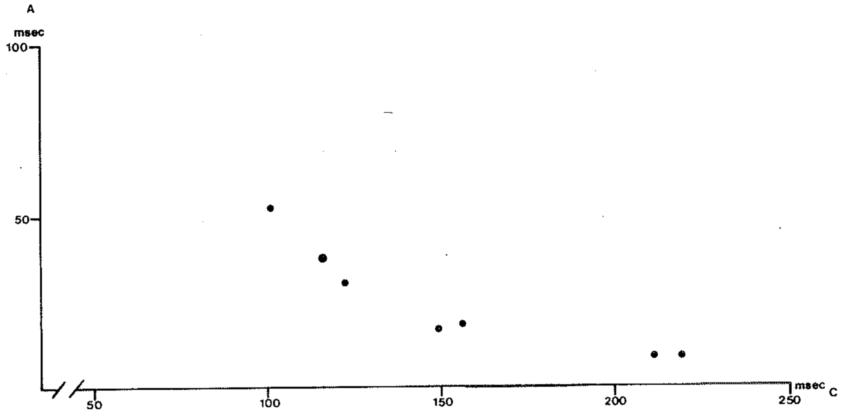


Figure 3 Plot of aspiration (A) versus closure duration (C) for voiceless stops in bisyllabic words.

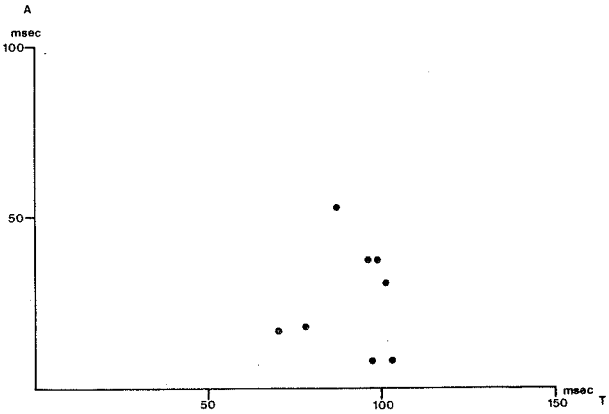


Figure 4 Plot of aspiration (A) versus the interval from implosion to peak glottal opening (T) for voiceless stops in bisyllabic words.

where no othter segement follows and the movements can be executed without the constraints of any tight temporal scheme. For the voiceless stops in utterance final position a "terminating abduction gesture" similar to the one described by Lindqvist (1972) was also found.

To relate the findings to the proposed model we can first turn to Fig. 3 which shows a plot of aspiration versus closure duration for the material in Table VIII. A negative correlation is apparent between these two parameters ($r = -0.9$). On the other hand, an inspection of the relation between aspiration and the interval from implosion to peak glottal opening fails to reveal any systematic relationship ($r = 0.07$), Fig. 4.

The results of the pilot study are thus consistent with the proposed model as far as timing of glottal and supraglottal articulations in the production of voiceless stops in bisyllabic words are concerned. Comparisons of glottal opening for voiceless stops within one and the same test utterance - where one might argue that the external factors influencing the amplitude of the glottogram are fairly constant - failed to show any definite trends apart from the fact that glottal opening at the moment of release is consistent with the theory proposed by Kim (1970).

Further glottographic investigations

Since the results of the pilot study were encouraging the same registrations were made with speakers 1 and 2 using a more comprehensive speech material. As the place of articulation turned out to have no specific influence on the glottal articulation in voiceless plosives the dental stop /t/ was chosen as a representative of the entire voiceless set and placed in various positions in words with 2, 3 and 4 syllables constructed to conform to common Swedish stress patterns. The following words were used:

1. 'teten
2. 'tetten
3. 'teteten
4. te'te
5. te'teten
6. tete'teten

All words were produced with the acute tonal accent except for word no 3 which had tonal accent 2; this was thought not to seriously influence the results since the effect of tonal accent was insignificant in the pilot study. Each word was repeated 20 times from randomized lists and for the purpose of comparing closure durations for voiced and voiceless stops the whole material was read the same number of times with the stop /d/ instead of /t/.

The results of the measurements for the two speakers are given in Tables IX and X. Plots of aspiration versus closure duration are presented in Fig. 5 and of aspiration versus the interval from implosion to peak glottal opening in Fig. 6.

As can be seen in Tables IX and X the interval T could not be measured in two cases since there was no clear peak glottal opening in the glottogram, cf. Fig. 2; we shall return to these cases below.

Aspiration and closure duration

The original model proposed an inverse relationship between aspiration and closure duration and such a relation was found to hold in the pilot study for stops in bisyllabic words. To judge from Fig. 5 this is hardly the case for the more comprehensive speech material. Here it seems more appropriate to identify two different groups in the plots. One shows a positive correlation between aspiration and closure duration whereas in the other aspiration remains about the same irrespective of variations in closure duration; the former group consists of the aspirated and the latter of the unaspirated voiceless stops.

For speaker 1 the relation between aspiration and closure duration is almost linear but for speaker 2 there is considerable scatter in the data. It is unclear what these interspeaker differences mean but it can be seen in Tables IX and X that the difference in closure duration between long and short stops and also between stops in prestress and poststress position is less for speaker 1 than for speaker 2 and this phenomenon is generally considered to be characteristic of southern Swedish, Gårding et al. (1974).

The same kind of positive relation between aspiration and closure duration has been reported for certain allophones of American English stops by Umeda and Coker (1974).

Table IX Closure duration (C), aspiration (A) and the interval from implosion to peak glottal opening (T) for speaker 1, n = 20.

Word	Segment		C	A	T
'teten	C_1	$\bar{x}$	100	48	100
		s	6.9	5.2	5.1
	C_2	$\bar{x}$	131	11	72
		s	6.7	3.4	10.6
'tetten	C_1	$\bar{x}$	97	45	101
		s	7.5	5.3	8.9
	C_2	$\bar{x}$	158	9	85
		s	10.7	2.4	14.8
'teteten	C_1	$\bar{x}$	96	43	94
		s	6.5	4.7	9.4
	C_2	$\bar{x}$	106	12	64
		s	8.7	4.6	9.0
	C_3	$\bar{x}$	76	26	67
		s	9.2	6.3	8.2
te'te	C_1	$\bar{x}$	79	24	67
		s	10.3	5.3	10.3
	C_2	$\bar{x}$	99	51	89
		s	7.7	7.7	7.8
te'teten	C_1	$\bar{x}$	73	22	63
		s	8.8	3.4	7.9
	C_2	$\bar{x}$	100	42	77
		s	8.9	7.5	8.3
	C_3	$\bar{x}$	121	11	59
		s	12.3	4.6	11.4
tete'teten	C_1	$\bar{x}$	78	27	71
		s	8.8	4.7	7.2
	C_2	$\bar{x}$	57	16	
		s	7.7	4.2	
	C_3	$\bar{x}$	92	39	84
		s	7.2	5.9	8.1
	C_4	$\bar{x}$	119	10	61
		s	9.3	4.3	8.8

Table X Closure duration (C), aspiration (A) and the interval from implosion to peak glottal opening (T) for speaker 2, n = 20.

Word	Segment		C	A	T
'teten	C_1	$\bar{x}$	116	39	89
		s	9.3	5.8	9.0
	C_2	$\bar{x}$	159	23	72
		s	9.9	5.3	7.5
'tetten	C_1	$\bar{x}$	112	35	84
		s	6.4	4.3	8.5
	C_2	$\bar{x}$	234	22	86
		s	14.3	3.4	5.5
'teteten	C_1	$\bar{x}$	117	42	97
		s	8.5	6.1	8.8
	C_2	$\bar{x}$	135	20	65
		s	13.7	5.0	9.0
	C_3	$\bar{x}$	79	21	
		s	5.8	3.9	
te'te	C_1	$\bar{x}$	113	38	88
		s	9.3	7.1	9.0
	C_2	$\bar{x}$	105	57	95
		s	8.1	6.8	4.9
te'teten	C_1	$\bar{x}$	113	39	89
		s	9.7	7.5	8.9
	C_2	$\bar{x}$	101	46	86
		s	7.5	7.1	6.8
	C_3	$\bar{x}$	148	23	65
		s	7.2	4.7	5.5
tete'teten	C_1	$\bar{x}$	99	36	78
		s	10.8	5.7	7.7
	C_2	$\bar{x}$	90	30	61
		s	10.1	3.9	7.6
	C_3	$\bar{x}$	98	48	83
		s	7.7	7.0	5.9
	C_4	$\bar{x}$	143	20	65
		s	5.9	4.4	4.4

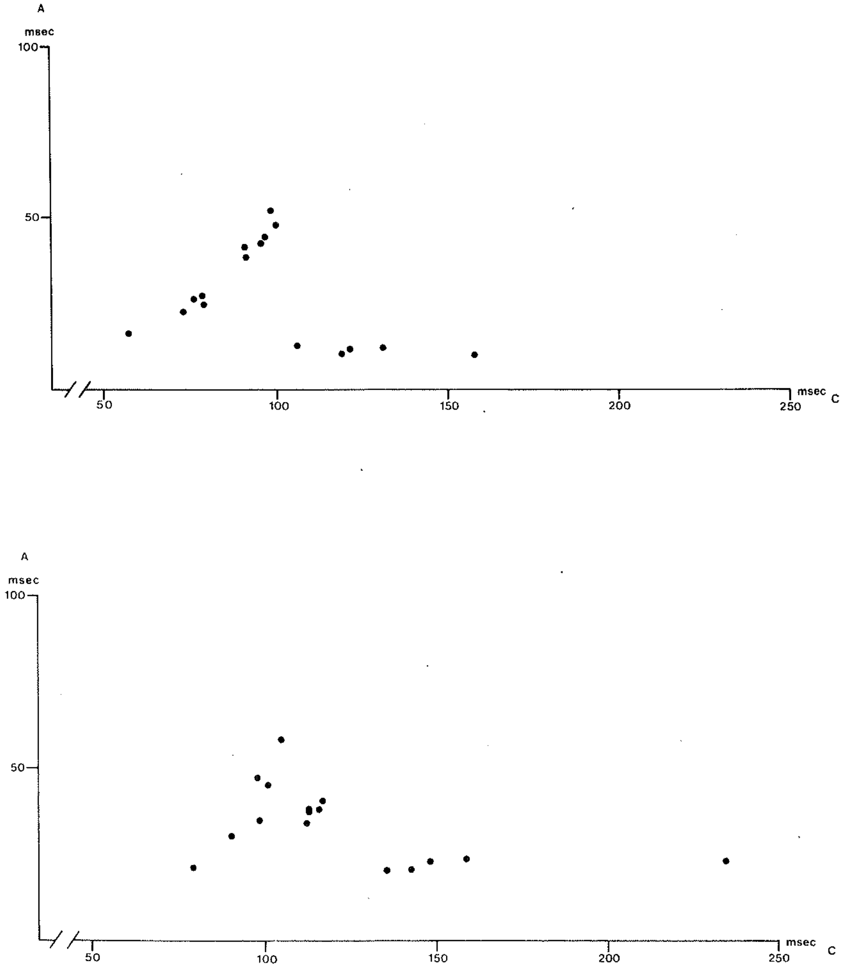


Figure 5 Aspiration (A) plotted against closure duration (C) for speaker 1, top, and speaker 2, bottom.

Aspiration and the interval from implosion to peak glottal opening

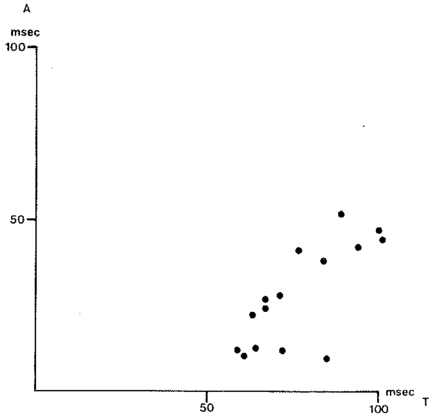
In the pilot study no apparent relation was found between these two parameters. In Fig. 6 we see, however, a positive correlation between them ($r = 0.7$), indicating that the longer the period of aspiration the later peak glottal opening occurs during the occlusion.

A result of these relationships is, of course, that peak glottal opening tends to occur close to the release for the aspirated stops and well ahead of it for the unaspirated ones. For speaker 1 peak glottal opening occurs at the moment of release for the initial stops in the words 'teten and 'tetten and not more than 20 msec before the release for the other aspirated varieties. During the unaspirated stops of the same speaker peak glottal opening occurs 40-70 msec before the release.

In the productions of speaker 2 peak glottal opening generally occurs before the release, 10-30 msec in the aspirated and 70-140 msec in the unaspirated cases.

Even if the original model for the control of aspiration cannot be upheld, at least in its strong version, timing still seems to be an important factor and one can argue that the loss of aspiration in Swedish voiceless stops in certain positions is due to an increase in the duration of the oral closure. This is evident from the fact that closure duration is longer for the unaspirated allophones and also because the interval from implosion to peak glottal opening can vary without any concomitant change in aspiration for these sounds; the glottis is still in a position suitable for voicing to occur at the release since the glottal opening and closing gestures are executed during the occlusion.

One can further strengthen this argument by considering the size of the glottal opening. Even if this can not be measured quantitatively with the transillumination technique it seems possible to establish the relative glottal opening for stops in various positions within one and the same testword where one might argue that external factors such as variations in the position of the light sensor are relatively constant. Such comparisons of peak glottal opening reveal different trends for the two speakers. For speaker 1 peak glottal opening appears to be related to stress and increase with it. For speaker 2, on the other hand, peak glottal opening is related to the duration of the occlusion



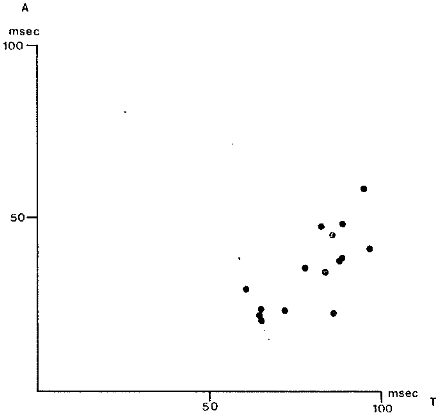


Figure 6 Aspiration (A) plotted against the interval from implosion to peak glottal opening (T) for speaker 1, top, and speaker 2, bottom.

and tends to be larger as the closure gets longer. Thus, no necessary relation was found between peak glottal opening and aspiration which seems to be in agreement with the findings of Lindqvist (1972). This point needs further verification, however, and appears to be specific for Swedish, where aspiration is not phonemic. In American English which also is considered to have non-phonemic aspiration larger peak glottal opening has been reported for aspirated than for unaspirated voiceless stops, Sawashima (1970). This also seems to be the situation in languages where aspiration is phonemic, e.g. Danish, Frøkjær-Jensen et al. (1971), Hindi, Kagaya and Hirose (1975), Icelandic, Pétursson (1975), Korean, Kagaya (1974).

On the other hand, glottal opening at the moment of release was consistent with the theory proposed by Kim (1970) although some clear counterexamples could be found.

In two positions no clear peak glottal opening could be identified, cf. Fig. 2. These are not the same for the two speakers, see Tables IX and X, but in both cases very short closure durations are found together with small values of aspiration, cf. Fig. 5 where the leftmost datapoint in each plot refers to these two positions. It is possible that the short occlusion did not permit any large glottal opening and since these positions are very weakly stressed it is presumably not necessary to maintain all aspects of the distinction between voiced and voiceless stops. It is unclear whether the small glottal opening is an active one and the result of activity in the posterior cricoarytenoid muscle, Hirose (1975), or whether it is a passive response to aerodynamic forces. The latter has been hypothesized for the unaspirated voiceless stops in Danish by Frøkjær-Jensen et al. (1971) and the glottograms presented by them are very similar to the ones found for the stops in the two positions under discussion here. Recent EMG studies of laryngeal muscles during the production of Danish stops do, however, indicate some activity in the posterior cricoarytenoid for the unaspirated stops in the speech of one subject, Fischer-Jørgensen and Hirose (1974).

Closure duration and aspiration in the voiced-voiceless distinction

We noted above that the difference in closure duration between voiced and voiceless Swedish stops is greatest in those positions where the

Table XI Closure duration for voiced stops in different positions, n = 20.

			Speaker	
Word	Segment		1	2
'deden	C_1	$\bar{x}$	92	116
		s	7.1	7.4
	C_2	$\bar{x}$	77	86
		s	6.8	8.6
'dedden	C_1	$\bar{x}$	98	110
		s	4.6	5.7
	C_2	$\bar{x}$	112	181
		s	9.8	8.3
'dededen	C_1	$\bar{x}$	91	115
		s	6.0	7.9
	C_2	$\bar{x}$	60	79
		s	7.2	8.5
	C_3	$\bar{x}$	59	57
		s	5.4	5.0
de'de	C_1	$\bar{x}$	70	93
		s	6.5	7.7
	C_2	$\bar{x}$	94	104
		s	9.1	7.7
de'deden	C_1	$\bar{x}$	68	95
		s	9.1	6.4
	C_2	$\bar{x}$	91	99
		s	8.4	6.6
	C_3	$\bar{x}$	71	76
		s	6.7	5.6
dede'deden	C_1	$\bar{x}$	74	88
		s	7.1	4.4
	C_2	$\bar{x}$	55	68
		s	6.7	8.2
	C_3	$\bar{x}$	82	89
		s	7.1	6.6
	C_4	$\bar{x}$	72	78
		s	6.3	6.2

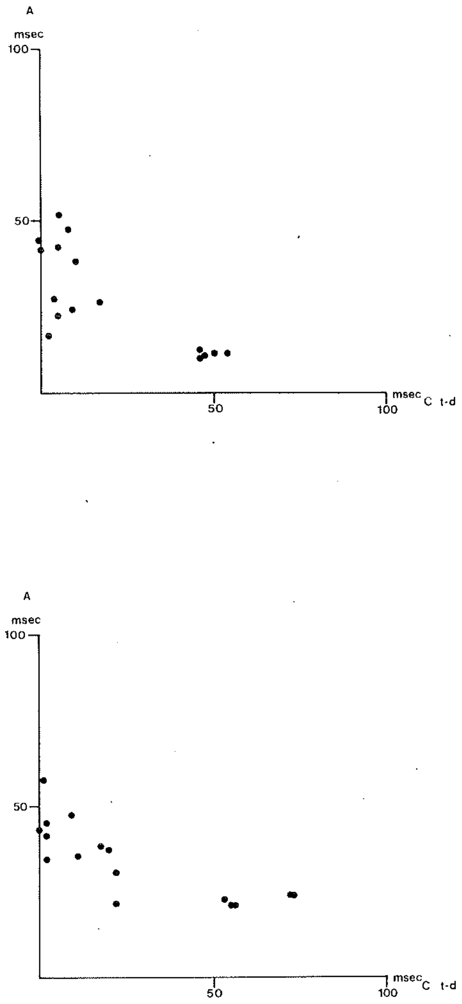


Figure 7 Aspiration (A) plotted against the difference in closure duration between voiceless and voiced stops (C t-d) in different positions for speaker 1, top, and speaker 2, bottom.

latter are unaspirated. This is apparent from Tables IX, X and XI and is due to an increase in closure duration for the voiceless set in certain positions. Since both closure duration and aspiration can serve as perceptual cues for the distinction between voiced and voiceless stops there appears to exist a reciprocal relation between them in the system of Swedish stops. This is further illustrated in Fig. 7 which plots aspiration versus the difference in closure duration between voiceless and voiced stops in different positions for the two speakers. Again, two groups can be distinguished. In one of them, characterized by unaspirated voiceless stops, the difference in closure duration is ca. 50 msec. The other group contains those positions where aspiration occurs in the voiceless set and also the two "exceptional" positions discussed above; here the difference in closure duration is generally less than 20 msec and there is a weak negative correlation between the two parameters.

The importance of these relations for the perception of Swedish stops remains as yet to be clarified and it is also unclear whether there is any causal relation between closure duration and aspiration from a diachronic point of view.

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ORAL AIR PRESSURE IN THE PRODUCTION OF SWEDISH STOPS

Anders Löfqvist

Stops and fricatives are normally produced with an increase in oral air pressure. Several studies have been made of this parameter which in part have examined how pressure in the supraglottal cavities is affected by variations in stress and position and in part have used air pressure as a means for investigating other aspects of speech, e.g. speech production under sensory deprivation, Hutchinson and Putnam (1974). Since the pressure build up behind the place of articulation is especially important for voiceless stops and fricatives these sounds are severely impaired in the speech of individuals with cleft lip and palate, Moll (1968), and aerodynamic techniques have been applied to the assessment of the speech of such patients, see Lubker (1970) for a review and further references.

This paper reports some studies of oral air pressure in the production of Swedish voiced and voiceless stops.

Procedure

Oral pressure was sampled through a plastic tube, 20 cm long and with an inner diameter of 1.9 mm. The tube was introduced into the pharynx through the nose and coupled to a differential pressure transducer EMT 33 (Siemens-Elema); the output from the transducer was amplified by an electromanometer EMT 31 and recorded together with the speech signal on a Mingograph at a paper speed of 100 mm/sec. A simultaneous tape recording was made of the speech signal through a Sennheiser MD 421 dynamic microphone on a Studer A 62 tape recorder at a recording speed of 7.5 ips.

The end of the tube sensing oral pressure was open and the plane of the opening was perpendicular to the air flow which could give rise to spurious pressure records due to air impinging on the open end of the tube, cf. Hardy (1965). One might argue, on the other hand, that air flow for the sounds under investigation is minimal except at the release which would make this problem a less serious one.

Before the pressure signal was written out on the Mingograph it was low pass filtered at 80 Hz. In spite of this filtering the fre-

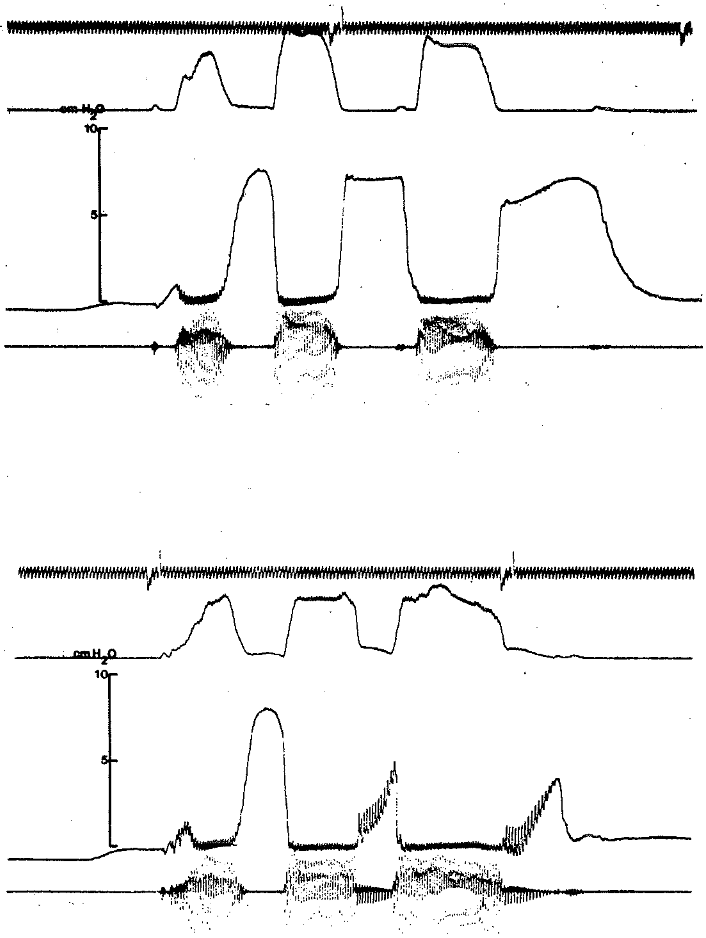

Figure 1 Record of the utterances "Ja sa tat", top, and "Ja sa dad", bottom. The curves represent from top to bottom, time signal, 0.01 sec, intensity, oral air pressure and oscillogram.

quency response of the recording system was judged sufficient for the purpose of the study which was concerned with the rather slow variations in pressure associated with stop production, see further Fry (1960) for a detailed account of technical aspects of pressure recordings.

The recording system was calibrated with a water manometer at regular intervals during the recording sessions to check stability and linearity.

Material

The speech material consisted of voiced and voiceless stops in various positions and under different stress conditions; they occurred in nonsense words of the following types:

1. **'Cɑ:C** – where $C_1 = C_2$ = /p, t, k, b, d, g/;
2. Ca**'Cɑ:** – with the same consonants as before and stress on the second syllable;
3. **'Cá:Cə**n – with consonants as before and stress on the first syllable; the word carried tonal accent 1;
4. **'Cà:Cə**n – as above but the word had tonal accent 2.

The words were embedded in the carrier phrase "Ja sa ... igen" except for those of type 1 which were produced in the frame "Ja sa ..." and thus occurred in utterance final position.

The words were repeated several times in random fashion by the following speakers:

1. male speaker of Southern Swedish;
2. male speaker of Southwestern Swedish;
3. male speaker of Southern Swedish;
4. female speaker of the dialect of the island of Gotland on the Swedish east coast.

During the recordings no attempt was made to strictly control variations in intensity and tempo and each speaker chose the level and rate which seem natural to him/her. All speakers had various degrees of phonetic training.

Inspection of the records revealed that most of the tokens of voiced stops were produced with glottal vibrations during the period of articulatory closure so the terms "voiced" and "unvoiced" in the

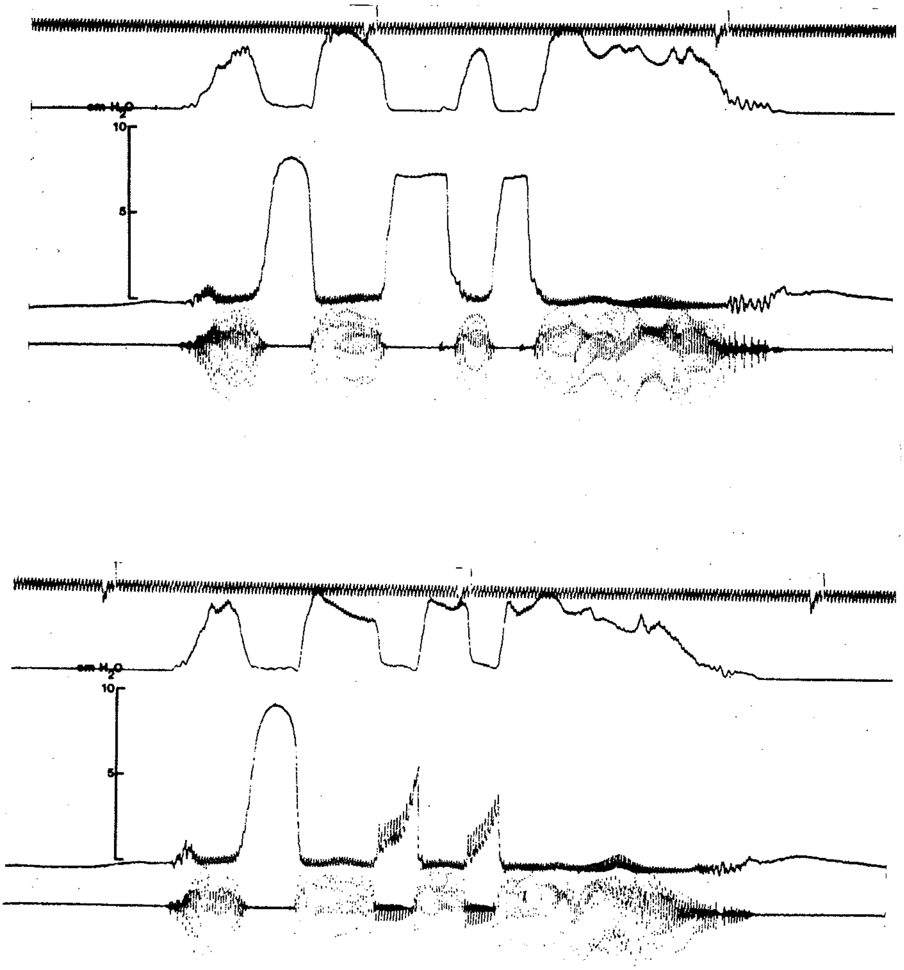

Figure 2 Record of the utterances "Ja sa ta'ta igen", top, and "Ja sa da'da igen", bottom.

following refer to two classes of sounds differentiated inter alia by their respective modes of glottal activity.

Measurements

From the mingographic records the following measurements were made:

1. peak oral pressure;
2. the interval from pressure rise to peak pressure;
3. the interval from pressure rise to the point where oral pressure had reached 85 % of its peak value;
4. the interval from pressure rise to the point where a level of stable elevated pressure occurred; this measurement was only made for the voiceless stops since no corresponding point can be found in pressure curves for voiced stops, cf. Figs. 1-3.

The measurements 2, 3 and 4 all refer to what has usually been called "rise time". This measure has, however, been defined in different ways in various investigations which sometimes makes comparisons difficult. It was thus decided to incorporate various possible ways of measuring rise time to see if and how they relate to each other. Measurement no 2 is essentially the same as the one chosen by Lisker (1970); no 3 is taken from Fischer-Jørgensen (1968) and no 4 follows Subtelny et al. (1966).

All pressure measurements are given in mm of water; whenever voicing occurred the pressure trace was bisected and pressure measured at the midline. The temporal measurements are given in milliseconds.

Results

Before we turn to the presentation of the results a few points should be noted. The absolute values for the various measurements differed for the different speakers but the relations between stops in various positions and between voiced and voiceless stops remained almost the same irrespective of these variations; thus, the pooled results for all speakers will be given below. The variations in absolute values can presumably be explained by differences in speech level and tempo since these factors were not strictly controlled and they have been shown to influence oral pressure, Subtelny et al. (1966), Arkebauer et al. (1967).

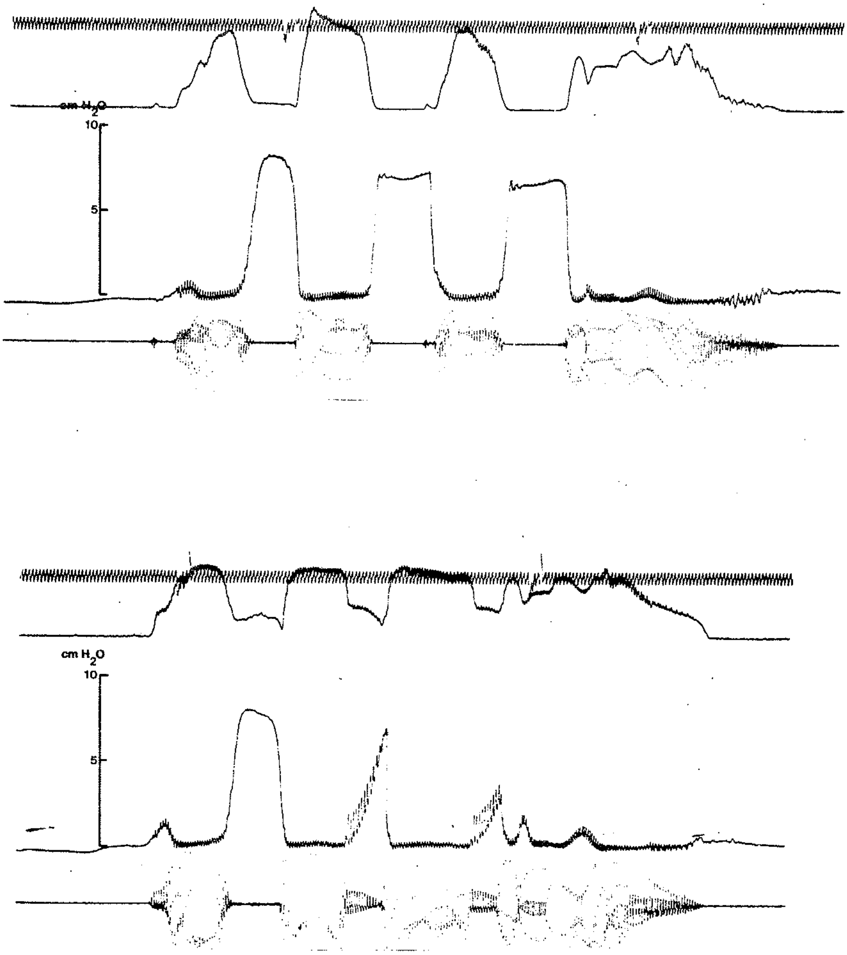

Figure 3 Record of the utterances "Ja sa táten igen", top, and "Ja sa dáden igen", bottom.

One phenomenon could, however, not be explained in this way, the influence of the tonal accent of the testword on the pressure for the medial stops in words of types 3 and 4. Here, the speaker's dialect appeared to be involved as well as the way the accent distinction is manifested. The pooled results for these positions thus do not give the whole picture in that they reflect the tendency found for three of the speakers, no 1, 3 and 4, whereas speaker 3 had the opposite pattern to the one showed in the Tables below as far as the relations between the medial stops in words with different tonal accents are concerned. These facts have been discussed in detail in Löfqvist (1974) where also some studies of subglottal pressure are reported; in the present context it is sufficient to note that the variations due to tonal accent seem to reflect different respiratory activity and can be related to the F_o variations associated with the particular manifestation of the accents.

If the tonal accents thus were found to influence oral pressure for the medial consonants in the words of types 3 and 4 no such influence could be found for the initial stops in the same words which in their turn proved not to be different from the initial stops in words of type 1; the results for stops in these three positions have thus been pooled.

Peak oral pressure

The measurements of peak oral pressure are summarized for stops with different places of articulation in Table I and for voiced and voiceless stops in different positions in Table II.

From Table I it appears that labials tend to have lower oral pressure than dentals and velars; for the latter two the order is not clear and the difference rather small. The differences within the voiceless set are, however, not statistically significant - $F = 3.526$, $P > 2.5$ - whereas the differences among the voiced stops are - $F = 17.417$, $P < 0.05$.

In Table II we see that stress is an important determinator of oral pressure, as could be expected; pressure is higher in prestress than in poststress position.

There is a significant difference in oral pressure between the voiced and voiceless stops in all positions - $P < 0.001$, two-tailed test.

Table I Peak oral pressure for different stops in # 'CV: position, n = 144.

	p	t	k	b	d	g
$\bar{x}$	85.4	89.6	87.5	62.6	72.6	73.5
s	13.0	13.7	14.2	15.2	17.5	19.6

Table II Peak oral pressure for voiced and unvoiced stops in different positions, n = 144 except for # 'CV: position where n = 432.

Position		# 'CV:	#CV	V'CV:	'V́:CV	'V̀:CV	V:C#
Sound							
ptk	$\bar{x}$	87.5	84.8	90.1	72.8	77.2	64.4
	s	13.8	13.9	14.6	8.6	12.8	7.9
bdg	$\bar{x}$	69.6	66.5	73.2	42.4	51.2	45.8
	s	18.2	19.2	23.6	16.2	20.9	16.2

Table III The interval from pressure rise to peak oral pressure for different stops in # 'CV: position, n = 144.

	p	t	k	b	d	g
$\bar{x}$	117	127	128	116	117	122
s	46.0	42.4	45.5	21.3	23.6	21.7

Table IV The interval from pressure rise to peak oral pressure for voiced and unvoiced stops in different positions, n = 144 except for # 'CV: where n = 432.

Position		# 'CV:	# CV	V'CV:	'V́:CV	'V̀:CV	V:C#
Sound							
ptk	$\bar{x}$	124	103	101	136	149	132
	s	44.7	48.6	25.9	43.7	49.6	68.3
bdg	$\bar{x}$	118	103	105	88	95	120
	s	22.3	27.8	15.1	12.8	19.1	27.1

Table V The interval from pressure rise to the point where oral pressure had reached 85 % of its peak value for different stops in # 'CV: position, n = 144.

	p	t	k	b	d	g
$\bar{x}$	56	47	54	87	99	105
s	31.5	27.6	30.3	19.3	22.0	20.7

Table VI The interval from pressure rise to the point where oral pressure had reached 85 % of its peak value for voiced and unvoiced stops in different positions, n = 144 except for # 'CV: position where n = 432.

Position Sound		# 'CV:	# CV	V'CV:	'V́:CV	'V̀:CV	V:C#
ptk	$\bar{x}$	53	43	41	49	64	48
	s	30.1	17.6	9.3	16.5	26.9	19.8
bdg	$\bar{x}$	97	86	86	70	71	103
	s	21.9	27.1	14.5	14.1	20.4	28.4

Oral pressure for the voiceless set is generally more than 1.5 cm of water higher than that for the voiced set.

The interval from pressure rise to peak oral pressure

The results for this parameter are given in Tables III and IV. For the different places of articulation the differences are very small, especially for the voiced stops, and labials tend to have shorter rise time than dentals and velars. These small differences are not significant, however - F = 1.130 and 2.810 for the voiceless and voiced sets respectively.

Again, stress is one determining factor in that this interval is shorter in prestress than in poststress position for the voiceless stops whereas the opposite seems to be the case for the voiced set. This interval does not show any significant difference for voiced and voiceless stops except in medial unstressed position where the values for the voiced stops are significantly shorter than those associated with their voiceless cognates.

The interval from pressure rise to the point where oral pressure had reached 85 % of its peak value

Tables V and VI present the relevant measurements. Among the voiceless plosives dentals have a quicker rise than labials and velars but the difference is not significant - F = 3.515. For the voiced set there is an increase in rise time as the place of articulation moves backwards from the lips and the difference is, moreover, significant, F = 27.181.

The effects of stress and position are not quite clear, Table VI. For both voiced and voiceless stops long rise times are found for the stressed initial stops in the prestressed category; at the same time the two other members of the prestressed group show lower values. Short rise times are also found in the poststressed group except that the medial voiceless stops have rather long rise time, at least in words with tonal accent 2. Large interspeaker variations preclude any definite conclusions.

Voiceless stops have shorter rise time than their voiced cognates and the difference is significant in all positions except 'V̄:CV.

Table VII The interval from pressure rise to the point where a level of stable elevated pressure occurred for different voiceless stops in # 'CV: position, n = 144.

	p	t	k
$\bar{x}$	55	48	57
s	9.1	7.1	24.6

Table VIII The interval from pressure rise to the point where a level of stable elevated pressure occurred for voiceless stops in different positions, n = 144, except for # 'CV: position where n = 432.

Position	# 'CV:	# CV	V'CV:	'V̂:CV	'V̌:CV	V:C#
$\bar{x}$	53	52	51	60	64	56
s	16.2	8.4	7.0	14.0	15.9	12.2

The interval from pressure rise to the point where a level of stable elevated pressure occurred

This measurement was only made for the voiceless category since no corresponding point is found for the voiced stops, cf. Figs. 1-3, and the results are given in Tables VII and VIII.

Dentals show a faster rise time in this respect than either labials or velars and the difference is significant, F = 14.173.

Stress and position do not appear to affect this measure to any greater extent and the only notable trend is that the medial unstressed stops occurring after a stressed vowel have a somewhat longer rise time than stops in other positions.

Discussion

The results of the present investigation are generally in agreement with other studies of the same parameter and for comparable speech material: voiceless stops are characterized by higher oral pressure and quicker pressure rise than their voiced cognates and stress is an important determinator of oral pressure, cf. the works listed among the references.

Reviews of comparable studies of oral pressure in stop production, cf. Subtelny et al. (1966), Arkebauer et al. (1967), Löfqvist (1971), show considerable variations in the results as far as position is concerned. If, however, the prime role of stress is taken into account much of this variation is resolved and the remaining part would seem to be accounted for by differences in the composition of the test material - specifically the use of a carrier phrase or not - and variations in speech level and tempo.

The relationship between the various measurements used in the present study is generally the following: voiceless stops having higher peak pressure also have shorter rise time; the voiced stops with higher peak pressure, on the other hand, usually have longer rise time.

The higher peak pressure in the voiceless set depends mainly on the lower glottal resistance during their production - the glottis is open - in comparison with the voiced category which was normally produced with glottal vibrations; a close correlation between voicing and oral pressure has been reported by Fischer-Jørgensen (1963). The same explanation also takes care of the shorter rise time in the voiceless set, provided rise time is taken as the interval from pressure rise to the point where oral pressure had reached 85 % of its peak value. Another factor which could play a role is a possible expansion of the supraglottal cavities in the production of voiced stops to maintain a transglottal pressure drop and thus facilitate voicing during the occlusion, see Rothenberg (1968), Minifie et al. (1974), Bell-Berti (1975).

The interval from pressure rise to peak oral pressure is not significantly different for the two sets of stops except in medial unstressed position. This is presumably related to the continous rise in oral pressure that occurs during voiced stops, cf. Figs. 1-3; in this case one would expect that this interval is related to the duration of the oral closure and in the position noted above the voiced stops have very short closure durations, Löfqvist (1976).

Another, more obscure, phenomenon involved here is the behavior of oral pressure for the voiceless stops when a level of stable elevated pressure has occurred. After this oral pressure may either stay at about the same level or rise a little. The latter is the more common case. The mechanisms governing the oral pressure for the voiceless category in these instances are difficult to pin down since no definite trends could be found and there are, moreover, speaker specific tendencies. On the whole, this particular measure of rise time seems to be the least revealing one to judge from the present results.

Labials tend to have lower peak oral pressure than velars and dentals; this is presumably related to differences in the volume of the supraglottal cavities for the three places of articulation and one would expect these variations to show up most clearly among the voiced stops due to the lower transglottal air flow in their case. Studies of both oral and subglottal pressure for voiced stops show the same difference as the one reported here for oral pressure but none that could be related to place of articulation for subglottal pressure, Löfqvist (1975).

For the voiced stops rise time becomes longer as the place of articulation moves backwards from the lips and this is presumably related to the differences in peak pressure noted above. Among the voiceless stops dentals show a quicker rise time than labials and velars, the difference between the latter two being insignificant. The reason for this is unclear, perhaps the greater mobility of the tongue tip is involved, if its greater mobility can be said to be an established fact.

Oral pressure has sometimes been taken as a reflection of the difference between tense and lax stops, the lax ones usually being voiceless and thus having higher oral pressure, cf. Malécot (1955, 1970). The higher oral pressure would, however, seem to depend more on these stops being unvoiced than lax and oral pressure is now not regarded as a correlate of tenseness and laxness, Fischer-Jørgensen (1968).

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