Journal of Phonetics (1979) 7, 357–373

Voicing in intervocalic stops and fricatives in Dutch

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Received 28 *March* 1978

Abstract: This study represents an addition to the literature describing the role of the larynx in the production of voiced and voiceless stop and fricative consonants. Electromyographic recordings from the intrinsic laryngeal musculature and measurements of sub- and supraglottal air pressures were obtained from a speaker of Standard Dutch, who produced nonsense forms preceded by a short carrier Dutch phrase. The forms included intervocalic voiced and voiceless stops and fricatives, as well as certain combinations of these consonants. The data obtained are in general conformity with previous studies of larynx management in consonant voicing, indicating systematic differences for voiced vs voiceless and for stop vs fricative categories. The different EMG patterns suggest that the voicing dimension involves primarily the varying adjustment of static glottal width by means of the adductor-abductor muscles, while the stop-fricative difference involves both this variable and a feature of longitudinal vocal fold tensioning. The evidence is negative so far as providing support for a view that this latter feature plays a significant role in the voicing distinction.

Introduction

This study constitutes one more effort to describe some systematic differences and correspondences in the activity of certain intrinsic laryngeal muscles and in the variation of subglottal and intraoral air pressure that characterize the realization of the "voiced/voiceless" and "stop/fricative" distinctions in consonants.

We have been encouraged in the pursuit of this aim by the growing evidence, offered in previous studies, that the analysis of these variables can reveal important aspects of the speech production process in general and of the physiological implementation of phonologically relevant distinctions in particular.

It has been our intention to duplicate certain electromyographic and air pressure observations of the past, but now based on still another language, viz. Dutch, while extending the range of such observations by investigating both single consonants and consonant clusters, and combining EMG and air pressure data for the same subject.

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0095–4470/79/040357+17 $02.00/0

Experimental set-up

Data collection and processing

In a first experiment we have attempted to record the EMG signals in the following muscles: the interarytenoid (INT), the vocalis (VOC), the lateral cricoarytenoid (LCA), the posterior cricoarytenoid (PCA), and the cricothyroid (CT). The preparation of the hooked-wire electrodes and the techniques of their insertion have been explained by Hirose (1971*a*), and Hirose & Gay (1972).

In a second experiment the air pressure data were recorded. Subglottal air pressure (P_{sg}) was measured immediately below the glottis by means of a flexible plastic tube inserted through the cricothyroid membrane. Intraoral air pressure (P_{io}) was measured in the pharyngeal cavity by means of a catheter inserted through the nose. The two pressure recording tubes were coupled to two pressure transducers (Setra Systems, model 236L). In the second experiment we have again measured the EMG activity in the VOC and CT muscles. This partial repetition of the EMG recordings was done in order to compare the pattern of muscle activity and its timing across the two experiments, so as to be able to decide whether the EMG data of the first experiment could indeed be combined with the pressure data of the second.

The physiological signals, the audio signal, and timing pulses were recorded on a 14-channel instrumentation recorder (Consolidated Electro-dynamics VR-3300). The visual editing of the raw data and their computer processing were performed on the Haskins Laboratories' EMG data processing system. Details of the successive procedures have been explained by Port (1971) and Kewley-Port (1973, 1974). The EMG and pressure signals have been integrated with a time constant of 50 and 25 ms, respectively. The comparison of the VOC and CT data of the two experiments revealed very similar patterns of activity in the respective muscles; the timing of the activity patterns was nearly identical. The data of the two experiments can therefore indeed be combined in the presentation of the results below. Reliable data could be obtained for all the variables under investigation, except for the PCA muscle.

Speech materials and subject

Dutch has the following stop and fricative phonemes: /p,b,t,d,k,f,v,s,z,x,ɣ,H/. There is no phoneme /g/ in Dutch, but [g] can occur as an allophone of /k/. Also lacking in the phoneme inventory is any voiceless glottal fricative in contrast with /H/. To this set of consonants we have added the glottal stop [ʔ], which can occur as the nondistinctive "hard attack" of a word-initial vowel or between adjacent vowel sounds.

In order to study the same consonants as elements in clusters of two consonants we have also included the following intervocalic combinations: [pt, tp, kp, fp, sp, xp, bd, db, gb, vb, zb, ɣb]. It should be noted that in these clusters the two consonants are the same with regard to the feature "voice". Indeed, Dutch phonology has a rule to the effect that in combinations of two consonants (stops or fricatives) both segments become voiceless, except where the second element is /b/ or /d/, in which case both segments become voiced. For example, /pv/ is realized as [pf], /zp/ as [sp], /tb/ as [db], /kd/ as [gd], and so on. The consonants under study were embedded in nonsense words of the form /'bɑC(C)ɑt/. The test words were preceded by the carrier phrase "Waar ligt ——?" (wa:rlɪxt ——), meaning "Where is —— located?".

The complete list of test words is given in Table I. It should be noted that the second column in Table I does not contain all possible combinations of two stops or fricatives in Dutch. We have limited the list to those C_1C_2-combinations in which C_2 is a stop.

Table I List of test words containing one and two intervocalic consonants as used in the experiment

['bapat	'babdat
'batat	'badbat
'bakat	'bagbat
'bafat	'bavbat
'basat	'bazbat
'baxat	'baɣbat
'ba?at	'baptat
'babat	'batpat
'badat	'bakpat
'bagat	'bafpat
'bavat	'baspat
'bazat	'baxpat]
'baɣat	
'baHat	

The order of the test sentences was randomized. The speech materials were read by one subject, the first author, who is a native speaker of the variety of Standard Dutch spoken in the northern part of Belgium.

Results

In presenting the results we will show the data for selected voiceless/voiced and stop/fricative oppositions with single consonants and clusters of two. The figures show the EMG activity in the INT, LCA, and VOC muscles, as well as the P_{io} and P_{sg} variations. The data on PCA activity deteriorated in the course of the experimental session. The activity of CT appeared not to be relevant to the consonant distinctions under investigation, at least not in our subject. Therefore the PCA and CT data will not appear in the figures below.

It can be seen in those figures that, during the production of vowels, P_{io} remains at *ca.* 1 cm aq above atmospheric pressure, rather than being equal to it as one would expect. We have attempted to simulate, post factum, the conditions under which this phenomenon may occur. We have found that it may be caused by a small degree of clogging in the catheter that picks up the pressure in the pharyngeal cavity. It appeared that if the clogging is not too severe, the peak P_{io} values are not significantly affected. The reliability of these peak values remains questionable, but since our P_{io} data are in good agreement with those that have been published by other researchers, we have decided to present and discuss them, be it with some caution.

a. Single stops and fricatives

(a) *The voiceless/voiced contrast in stops*

Figure 1 exemplifies the voiceless/voiced opposition as it is found in the /t-d/ contrast. Table II, a and b, presents the exact numerical values for the physiological variables at selected points in time. In Table II it can also be checked to what extent the /t-d/ opposition is typical of the voicing contrast between Dutch stops in general.

INT: At about 100 ms before the line-up point, INT activity starts to decrease for the following /t/, but not for the following /d/. The lowest level of activity around the line-up point is 97 microvolts for /t/ and 121 microvolts for /d/. There is a high peak of INT activity after /t/, but not after /d/.

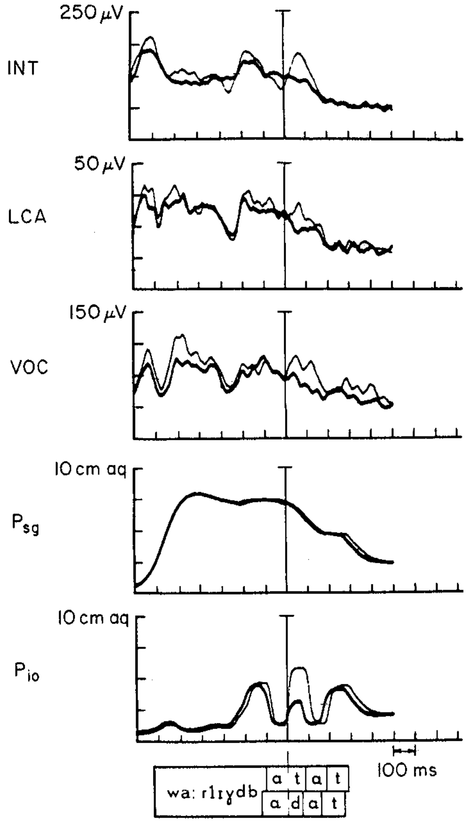

Figure 1 Averaged EMG and pressure data for Dutch /t/ (thin line) and /d/ (thick line).

LCA: During the last 50 ms before the line-up point there is a small decrease in LCA activity for the following /t/, but not for /d/. At the line-up point the level of LCA activity is 27 microvolts for /t/ and 30 for /d/. Following /t/ there is a small peak in LCA activity; after /d/ there is no such peak, but rather a decrease (which, however, is not to be found after /b/ or /g/).

VOC: At about 100 ms before the line-up point VOC activity starts to decrease for both the following /t/ and /d/. At the line-up point the level of VOC activity is 72 microvolts for /t/ and 70 for /d/. After /t/ there is strong increase of VOC activity, but not after /d/.

P_{io}: Intraoral air pressure rises to a maximum of 5·83 cm aq during the closure of /t/, and 3·15 cm aq during that of /d/. The pressure curves also reflect the durational difference between the voiceless and the voiced stop.

P_{sg}: Measured at the moment of maximum P_{io}, the level of P_{sg} is 6·74 cm aq for /t/ and 6·84 cm aq for /d/. The pressure drop across the glottis, ΔP (viz. $P_{sg} - P_{io}$), measured at the moment of maximum P_{io}, is 0·91 cm aq for /t/ and 3·69 cm aq for /d/.

As far as the carrier phrase itself is concerned, it can be observed that the adductor muscles show a momentary burst of activity before the onset of phonation. At about 200 ms before the line-up point there is a drop in the activity of INT, VOC and LCA that can be associated with the cluster /ɣdb/. This cluster results in a first increase of P_{io}. The

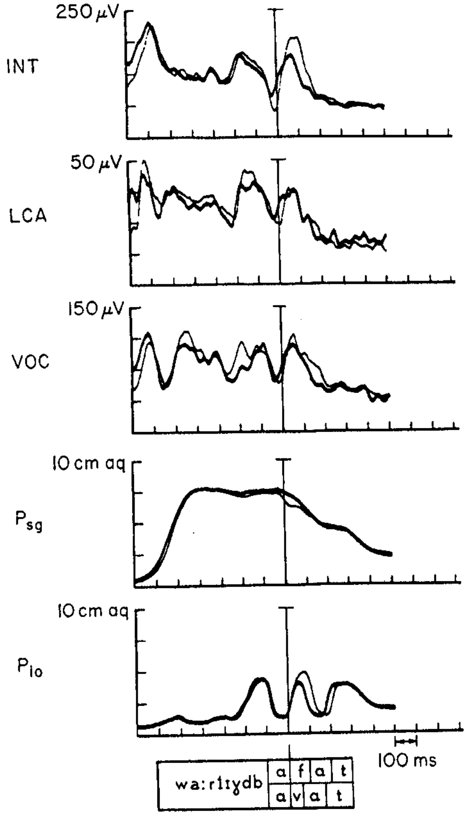

Figure 2 Averaged EMG and pressure data for Dutch /f/ (thin line) and /v/ (thick line).

second increase of P_{io} is associated with the consonants under study, while the third corresponds to the final consonant /t/ of the test word. The utterances were read with a rising-falling intonation on the first word, [wa:r], and on the test word ['baCat]. This variation of F_0 over time is somewhat reflected in the course of the P_{sg} curve. In particular, the falling F_0 on the second syllable of the test word is clearly reflected in the falling P_{sg} during the first 200 ms after the line-up point. In other words, the falling P_{sg} following the line-up point is to be associated with prosodic properties of the utterances, not with the consonants proper.

It can be concluded from the data in Table II, a and b, that the same tendencies also hold for the comparisons /p-b/ and /k-g/.

(b) *The voiceless/voiced contrast in fricatives*

Figure 2 illustrates the opposition between a voiceless and a voiced fricative, as it is found in the /f-v/ contrast. Precise numerical data on these and the other fricatives are to be found in Table II, c and d.

INT: At about 200 ms before the line-up point INT activity begins to decrease for the following consonant. The relaxation in this muscle is greater for /f/ than for /v/: the minimum level of activity is 50 and 80 mV, respectively. There is a higher peak of INT activity after /f/ than after /v/.

Table II Numerical values at selected points in time for EMG and air pressure signals in single stops and fricatives

	Adductor muscles: Minimum values (in microvolts) within 25 ms distance from line-up point			Intraoral and subglottal air pressure (in cm aq)			
	INT	LCA	VOC	Maximum P_{io} during stricture	P_{sg} at moment of maximum P_{io}	$\Delta P (= P_{sg} - P_{io})$	P_{sg} drop/rise during stricture
(a) p	95	28	74	5·81	6·80	0·99	0·18
t	97	27	72	5·83	6·74	0·91	0·08
k	86	30	76	5·81	6·70	0·89	0·22
Average	93	28	74	5·82	6·75	0·93	0·12
(b) b	122	29	64	3·47	6·85	3·38	0·11
d	121	30	70	3·15	6·84	3·69	0·14
g	104	27	78	3·92	6·47	2·55	0·11
Average	116	29	71	3·51	6·72	3·21	0·12
(c) f	50	24	58	4·84	6·09	1·25	1·03/ –
s	69	21	52	5·30	6·49	1·19	0·82/0·25
x	53	25	60	5·22	6·64	1·42	0·96/0·07
Average	57	23	57	5·12	6·40	1·29	0·93/0·10
(d) v	80	26	60	3·99	6·81	2·82	0·21
z	93	23	59	4·72	6·67	1·95	0·32
ɣ	69	21	62	4·56	6·96	2·40	0·38
Average	81	23	60	4·42	6·81	2·39	0·30
(e) H	69	21	62				

LCA: At about 75 ms before the line-up point LCA activity decreases for both /f/ and /v/. The lowest level of LCA activity is 24 mV for /f/ and 26 mV for /v/. There is no difference in LCA activity after the two fricatives.

VOC: At about 75 ms before the line-up point VOC activity decreases to the same extent for the following /f/ and /v/. The lowest level of activity in VOC is 58 mV for /f/ and 60 mV for /v/. The peak in VOC activity is slightly higher after /f/.

P_{io}: Intraoral pressure rises to a maximum of 4·84 cm aq for /f/ and 3·99 cm aq for /v/. The pressure curve also reflects the difference in stricture duration between the two fricatives. This timing difference is also to be found in a slightly later increase of INT and LCA activity after the longer fricative /f/.

P_{sg}: Measured at the moment of maximum P_{io}, the level of P_{sg} is 6·09 cm aq for /f/ and 6·81 cm aq for /v/. During the stricture of /f/ P_{sg} drops by 1·03 cm aq; during /v/ this pressure drop is only 0·21 cm aq. The ΔP value, measured at the moment of maximum P_{io}, is 1·25 cm aq for /f/ and 2·82 cm aq for /v/.

It can be seen in Table II, c and d, that the same tendencies apply to the comparisons /s-z/ and /x-ɣ/. Notice that the degree of INT relaxation is smaller for /s/ and /z/ than for the other fricatives. These two fricatives also have higher P_{io} values than the others. The P_{sg} drop at the beginning of /s/ and /x/ is followed by a small increase.

(c) *Some general comparisons*

Based on a comparison of the data in Figs 1 and 2, and of the averages in Table II we may conclude that:

1. LCA shows almost no reduction of activity for a stop, but it relaxes somewhat for a fricative. There are no major differences in the pattern of (reduced) LCA activity that correspond to the voiceless/voiced distinction in stops and fricatives.
2. VOC shows some reduction of activity for a stop and a much stronger relaxation for a fricative. The degree of relaxation is nearly the same for a voiceless as for a voiced consonant, but the level of VOC activity tends to be somewhat higher after a voiceless consonant.
3. INT shows no significant decrease of activity for a voiced stop. Its activity is clearly reduced for a voiceless stop and even more so for a voiced fricative. INT relaxes most for a voiceless fricative. The degree of INT activity at resumption after a consonant is proportional to the degree of relaxation for that consonant.
4. P_{io} is higher in voiceless stops and fricatives than in their voiced counterparts.
5. P_{sg} decreases momentarily at the beginning of fricatives, especially voiceless ones. In voiceless fricatives the P_{sg} drop may be followed by a slight rise.
6. The pressure drop across the glottis, measured at the moment of maximum P_{io} is greater in voiced consonants than in voiceless ones. It is also greater in voiced stops than in voiced fricatives.

(*d*) *Discussion*

The difference between voiceless and voiced stops is most clearly reflected in the pattern of INT activity (and, presumably, in the converse pattern of its antagonist, PCA): voiceless stops are characterized by partially suppressed INT activity, whereas for voiced stops there is practically no INT suppression. The voiced/voiceless distinction is only indirectly reflected in a difference in VOC activity: this muscle tends to be somewhat more active after a voiceless stop than after a voiced one. There is only a small difference between voiceless and voiced stops as far as P_{sg} is concerned: the former may have a small drop in P_{sg} at the beginning of occlusion. P_{io} is higher in voiceless than in voiced stops.

The difference between voiceless and voiced fricatives is also most readily accounted for in terms of differences in INT activity: this muscle shows more relaxation in the voiceless than in the voiced case. VOC activity is related only indirectly to the voicing distinction in fricatives, in that the level of VOC activity tends to be higher after a voiceless than after a voiced fricative. P_{io} is higher in voiceless fricatives than in voiced ones, and the momentary P_{sg} drop is more pronounced with the former than with the latter.

An overall comparison of stops and fricatives indicates that, on the whole, there is less adductor muscle activity in fricatives than in stops. It may also be observed that voiceless stops and voiced fricatives have a fairly similar pattern of INT activity, but that they differ more strongly in terms of LCA and VOC activity. From this we may infer that voiceless stops and voiced fricatives differ in glottal width and/or glottal shape. The unaspirated voiceless stop may be produced with a glottis that is generally closed, but with a small degree of opening at the posterior end, a configuration effected by relaxation of INT, with LCA (and VOC) contracted. When both INT and LCA relax for a voiced fricative we should then have a slightly larger opening that involves also a separation at the level of the vocal processes (assuming that the degree of PCA activity is not widely different in both cases). Voiced stops show practically no relaxation in the adductor muscles and may have the same degree of glottal width as vowels. Finally, voiceless fricatives show the strongest degree of adductor muscle relaxation and, presumably, have the largest degree of glottal opening.

Stops show less VOC relaxation than fricatives, suggesting that the vocal folds are slacker in the latter case. Possibly, the slackening of the vocal folds in fricatives also contributes to their abduction. In the case of voiced fricatives the slackening might be said to facilitate the maintenance of vocal fold vibration during the constriction. Unfortunately for this view, since VOC relaxation also characterizes voiceless fricatives, we should have to admit that slackening of the folds is not incompatible with voicelessness.

Let us now turn to a comparison of the findings described above and some available data on the articulation of consonants other than Dutch. Hirose *et al.* (1972) have examined laryngeal muscle activity in the five types of bilabial stops that are common in Sindhi (as produced by a phonetician who was not a native speaker). They observed no INT or LCA relaxation for [b], but some for [p]. Our observations are in good agreement with their findings. Hirose & Gay (1972) mention that for the articulation of both voiceless and voiced English stops (in intervocalic, post-stressed position) there is a slight decrease of VOC activity. In our data we observe the same tendency. On the other hand, in the data of these authors there is the same degree of VOC relaxation in fricatives as in stops, whereas our results show more VOC relaxation in the case of fricatives. The conclusion would then be that, at least in the present data, VOC activity differentiates very little between voiced and voiceless consonants, but that it clearly correlates with the stop/fricative distinction. This would be in agreement with the results of an EMG study involving Danish consonants (Fischer-Jørgensen & Hirose 1974*a*). These authors have found that in their data the activity pattern of VOC seems more complex than what has been described by Hirose (1971b), viz. as being active in vowels and suppressed in consonants, irrespective of the type of consonant. Our data are in agreement with those of Hirose & Gay (1972) in that they show that LCA and VOC have very similar patterns of activity. Also in agreement with the observations of Hirose & Gay (1972) and of Hirose *et al.* (1972) is that INT (and PCA for that matter) does not show an activity pattern of an all-or-none type, but rather one of fine adjustment. Indeed, our data indicate that in the activity of INT several (at least three) levels can be distinguished: one for vowels and voiced stops, one for voiceless unaspirated stops and voiced fricatives, and one for voiceless fricatives. This three-level distinction in the pattern of INT (and PCA) activity suggests that the corresponding three classes of Dutch speech sounds also differ in their degree of glottal width. Fiberoptics high-speed cinefilms of, among others, Sawashima *et al.* (1970) indicate that there are at least three, possibly as many as five, distinct degrees of glottal aperture in the production of English consonants and vowels in running speech.

The outcome of our experiment can also be related and compared to the hypotheses put forward by Halle & Stevens (1967, 1971) and Stevens (1975).

Halle & Stevens (1967) assume that in both voiced stops and fricatives the glottis remains open during the entire vibratory cycle and that this overt adjustment in vocal fold position toward a more open state is necessary in order to maintain vocal fold vibration with a reduced pressure drop across the glottis. They also assume that the degree of glottal opening is larger in voiceless consonants than in voiced ones.

In our EMG data we find no clear indication of adductor muscle relaxation for /b/ and /d/. We do find some for /g/, in which stop the ΔP for /g/ is still 2·5 cm aq, and this value is well above the minimum of 1 cm aq that appears to be required for continued vocal fold vibration during obstruents (Lindqvist, 1972). Voiceless stops, on the other hand, appear to be produced with reduced INT muscle activity, indicating some separation of the arytenoids. In a later article Halle & Stevens (1971) make a different proposal.

They now assume that for (unaspirated) voiced and voiceless stops there is on vocal fold separation, and the voicing distinction is brought about by slackening the vocal folds in the voiced case and stiffening them in the voiceless.

Our EMG data suggest that there is no vocal fold separation for voiced stops, but that there is one for voiceless stops. Furthermore we find no evidence in VOC activity for vocal fold stiffening during voiceless stops. As far as fricatives are concerned, Halle & Stevens (1971) do not make explicit claims with regard to their degree of glottal width, but they do hypothesize "stiff" vocal folds for the voiceless fricatives and "slack" vocal folds for the voiced. Our EMG data suggest that the glottis is more open for the voiceless than for the voiced fricatives, but that there is no difference in vocal fold stiffness. In fact, both types of fricative would have to be considered as implying "slack" vocal folds, since there is evidently strong VOC relaxation during their production.

Stevens (1975) elaborates on the physiological characteristics of the different larynx modes. Again it is assumed that the unaspirated voiced and voiceless stops have the same degree of glottal opening, viz. the neutral position of the arytenoid cartilages that is also typical of vowels. Now the "stiffness" of the vocal folds in voiceless stops is no longer sought in their longitudinal tensing, but in their vertical stretching, resulting from larynx raising. Conversely, voiced stops are produced with slack vocal cords resulting from larynx lowering.

Our EMG data do not speak to these hypotheses. However, we would like to point out that Hirose *et al.* (1972) have found EMG evidence for active larynx lowering in the implosive stop [ɓ] only, not in [b] or [bh]. The EMG data on pharyngeal cavity size expansion for voiced stops, presented by Bell-Berti (1975), indicate that not all speakers actively lower their larynx during the articulation of these consonants. Finally, the X-ray analysis of Perkell (1969) shows that "there is little observable effect of the different consonants on the behavior of vertical movement of the hyoid bone and larynx" (p. 42).

We believe that the general picture emerging from the physiological data available so far is, that—at the level of the larynx—the type of voiced/voiceless distinction discussed in this paper correlates more strongly with different degrees of glottal width than with different degrees of vocal fold stiffness. The four classes of (unaspirated) consonants labeled "voiced stop," "voiceless stop," "voiced fricative," and "voiceless fricative" can be separated by unique combinations of a specific degree of glottal width and a specific degree of supraglottal constriction. A model of the voiced/voiceless distinction in consonants may do without an additional parameter of vocal fold stiffness, since, even in the opinion of Halle & Stevens (1971), increased stiffness is only effective in inhibiting vocal fold vibration if there is a sufficient decrease in the pressure drop across the glottis, or if the glottis is either wide open or tightly constricted.

Let us now direct the discussion to a comparison of our air pressure data to those reported by other researchers. Our data indicate that the average peak P_{io} is highest for voiceless stops, somewhat lower for voiceless fricatives, still lower for voiced fricatives and lowest for voiced stops. The same rank order is to be found in the P_{io} data of Prosek & House (1975) for the corresponding classes of speech sounds in English. In particular, our data confirm the earlier observation that voiced fricatives have higher peak P_{io} values than voiced stops. Our data are also in agreement with those presented by, among others, Netsell (1969), Lisker (1970), Slis (1970), and Löfqvist (1974b). Prosek & House (1975) have reported "a tendency for consonants produced in the back of the mouth to have greater peak pressures than consonants produced anteriorly" (p. 140). Table III

Table III Comparison of pooled P_{io} values for consonants, ranked according to their place of articulation

Prosek & House (1975)	Our data
p, b, f, v: 4·5 cm aq	p, b, f, v: 4·52 cm aq
t, d, s, z: 4·9	t, d, s, z: 4·75
k, g: 5·0	k, g, x: 4·87

compares the Prosek and House data to ours. It can be seen that both sets agree in the rank order of P_{io} values as a function of the place of articulation. It should be noted that the agreement between the two sets of data can only be found if, in our data, *all* the homorganic consonants are pooled. However, in any subgroup of consonants the rank order is different, and no single subgroup exhibits the same rank order as the pooled data. Furthermore, the magnitudes of the differences between any two consonants in a subgroup vary widely.

As far as subglottal air pressure in stops is concerned, our data do not show any significant differences in peak pressure between the voiced and voiceless cognates when these are averaged over the three places of articulation. But when we compare stops of the same place of articulation the P_{sg} difference may well be significant. Also note that while /b/ and /d/ show higher P_{sg} than /p/ and /t/, /g/ has a markedly lower P_{sg} than /k/. The absence of a significant difference between the /p, t, k/ and /b, d, g/ groups is in agreement with the findings of Netsell (1969), McGlone & Shipp (1971), Ohala & Ohala (1972), and Löfqvist (1974*a*). The very small drop in P_{sg} that we observed at the beginning of the closure phase of voiceless stops was also observed by Löfqvist (1974*a*), but he showed that the difference in this respect between voiceless and voiced stops was not statistically significant in his data. P_{sg} variation in fricatives is less well documented in the literature. Our data show that in voiced fricatives there is a slight drop in P_{sg} at the very beginning of the supraglottal constriction gesture; this drop is more pronounced with voiceless fricatives and can be of the order of 1 cm aq. The momentary decrease in P_{sg} is in fact already initiated at the end of the preceding vowel, indicating that the glottis is already relatively wide open before the oral constriction (and hence P_{io}) has reached its maximum. As the constriction becomes narrower, P_{sg} may slightly rise again, especially in voiceless fricatives. These characteristic P_{io} and P_{sg} variations are in good agreement with the airflow variations in voiceless fricatives as studied by Klatt and his colleagues (1968). These authors observed that the airflow traces of (English) voiceless fricatives show a characteristic "double peak," which they explain as a consequence of the relative timing of the laryngeal and articulatory gestures. During the vowel that precedes the fricative the glottis begins to open while the vocal cords continue to vibrate; this results in an increase in airflow and a lowering of P_{sg}. As the upper teeth begin to contact the lower lip there is a decrease in airflow, a rise in P_{io} and a rise (or stabilization) of P_{sg}. Then, as the lower lip moves away from the upper teeth, air flow increases and P_{io} decreases. Finally, vocal cord vibration resumes and airflow and pressure return to values that are characteristic of vowel production.

b. Glottal stop [ʔ] *and glottal fricative* /*H*/

The intervocalic stop appears to be produced by the following sequence of laryngeal events [see Fig. 3(c)]: (1) preceding the glottal stop there is no INT relaxation. In fact,

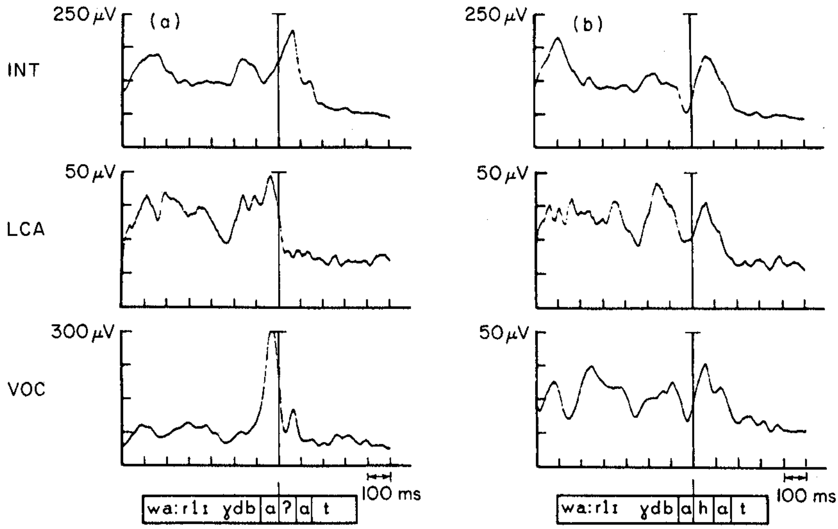

Figure 3 Averaged EMG data: comparison of [ʔ] (a) and Dutch /H/ (b).

the degree of INT activity is the same as for a voiced stop, so that we assume that the vocal folds are loosely adducted; (2) then follows a moment of strong medial compression of the folds by an increase of INT and LCA activity and by unusually strong VOC contraction; (3) the next moment there is a sudden release of the glottal occlusion, brought about by an abrupt, large scale relaxation of VOC and LCA; (4) finally, the vocal folds are adjusted to their normal voicing position, apparently by the continued increase in INT activity and a momentary burst of VOC contraction. As far as the air pressure data are concerned, (not shown in Fig. 3), there is of course no P_{io} increase for [ʔ]; a small decrease of P_{sg} is observed at the end of the preceding vowel. Our EMG data are in agreement with those reported by Hirose & Gay (1973), who studied "hard vocal attack," and by Fischer-Jørgensen & Hirose (1974*b*), dealing with Danish "stød." In these two studies, however, there is no indication of strong INT activity after the release of the glottal stop. The pattern of EMG activity for the production of the voiced glottal fricative /H/ [Fig. 3(b)] shows partial suppression of INT activity and strongly reduced VOC and LCA activity. Since there is no oral constriction there is no increase in P_{io} and the separation of the vocal folds leads to a marked drop in P_{sg} of more than 1 cm aq. As can be seen in Table II, the pattern of EMG activity for /H/ is the same as that for the velar fricative /ɣ/, which accords with its being classified as a "glottal fricative" in the IPA chart.

c. *Stops and fricatives in clusters*

(*a*) *The voiceless/voiced contrast in clusters of two stops*

In intervocalic position Dutch consonants can occur in clusters of two or more. Figure 4 illustrates the intervocalic contrast of /tp/ and /db/. Table IV, a and b, gives numerical values for the various physiological variables at selected points in time.

INT: At about 150 ms before the line-up point INT activity starts to decrease for the following /tp/ cluster, but much less so for following /db/. The lowest level of INT activity for /tp/ is 86 mV and 117 mV for /db/. There is a high peak of INT activity after /tp/ but not after /db/.

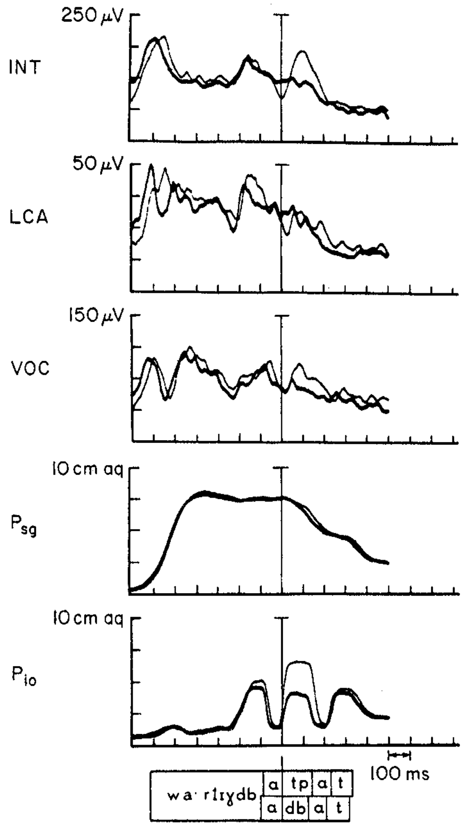

Figure 4 Averaged EMG and pressure data for Dutch sequences /tp/ (thin line) and /db/ (thick line).

LCA: At about 175 ms before the line-up point there is a decrease in LCA activity for /tp/, resulting in a minimum value of 22 mV. For /db/ there is little or no relaxation in LCA, the lowest level of activity being 30 mV.

VOC: At about 50 ms before the line-up point the activity of VOC decreases for both /tp/ and /db/. The lowest level of activity of VOC is 59 mV for /tp/ and 64 mV for /db/. There is a higher peak of VOC after /tp/ than after /db/.

P_{io}: Intraoral air pressure rises to a maximum of 6·56 cm aq in /tp/ and 4·03 cm aq in /db/. The pressure curves also reflect the durational differences between the two clusters.

P_{sg}: Measured at the moment of maximum P_{io} subglottal air pressure is at a level of 7·18 cm aq in /tp/ and at 7·39 cm aq in /db/. The ΔP value at that moment is 0·62 cm aq for /tp/ and 3·36 cm aq for /db/. In /tp/ ΔP gets down to a value of 0·24 cm aq at the end of the /p/-closure. It can be seen in Table IV, a and b, that the same tendencies hold for the comparison of /pt-bd/ and /kp-gb/. The minimum ΔP value during /pt/ and /kp/ (not given in the Table) is 0·24 and 0·12 cm aq, respectively.

(b) The voiceless/voiced contrast in stop + fricative clusters

The voicing distinction in clusters consisting of a stop followed by a fricative is illustrated by the comparison of /fp/ and /vb/ in Fig. 5.

Table IV Numerical values at selected point in time for EMG and air pressure signals in consonant clusters

	Adductor muscles			Intraoral and subglottal air pressure (in cm aq)			
	Minimum values (in microvolts) within 25 ms distance from line-up point						
	INT	LCA	VOC	Maximum P_{io} during stricture	P_{sg} at moment of maximum P_{io}	ΔP	P_{sg} drop/rise
(a) pt	82	20	60	6·70	7·05	0·35	0·07
tp	86	22	59	6·56	7·18	0·62	0·03
kp	84	23	66	6·50	7·03	0·53	0·14
Average	84	22	62	6·58	7·08	0·50	0·08
(b) bd	120	32	70	4·19	7·46	3·27	0·01
db	117	29	63	4·03	7·39	3·36	0·08
gb	112	29	73	4·15	6·79	2·63	0·04
Average	116	30	69	4·12	7·21	3·08	0·04
(c) fp	52	24	53	6·27	6·77	0·50	0·95/0·29
sp	68	21	58	6·03	6·30	0·27	0·84/0·23
xp	56	25	64	5·72	6·18	0·46	1·49/0·28
Average	59	23	58	6·00	6·41	0·41	1·09/0·26
(d) vb	88*/128†	27*/30†	64*/84†	5·08	7·19	2·11	0·01
zb	101/116	24/26	69/77	4·96	6·99	2·03	0·10
ɣb	91/113	25/29	69/83	4·74	6·83	2·09	0·09
Average	93/119	25/29	69/83	4·92	7·00	2·07	0·06

*Measured at 40 ms before line-up.
†Measured at line-up.

INT: At about 150 ms before the line-up point INT activity decreases. This reduction of activity is much more pronounced for /fp/ than for /vb/, the lowest level of INT activity being 52 and 88 mV, respectively. The resumption of INT activity starts earlier in the case of /vb/, so that at the line-up point the level of activity is already 128 mV. This timing difference is not merely the result of the shorter duration of /vb/; it also indicates the glottis being opened for /v/ and closed for /b/. Indeed, comparing INT activity in the sequences /vb/ and /vɑ/, we have found very little difference. In the case of /fp/ the later resumption of INT activity may suggest that the glottis is opened for /f/ and kept open for the following /p/. However, comparing INT activity in the sequences /pɑ/, /fɑ/, and /fp/, we have found that the resumption of INT activity starts at the same moment in the three cases, but that it builds up more slowly in the case of /fp/. This fact might be taken as an indication that in the /fp/ cluster the glottis is being partially closed for /p/. Following /fp/ there is a higher level of INT activity than after /vb/.

LCA: At about 125 ms before the line-up point LCA activity starts to decrease. There is more LCA relaxation for /fp/ than for /vb/, the minimum level of activity being 24 and 27 mV, respectively. The resumption of LCA activity starts later in the case of /fp/, and develops more slowly than after a single /f/.

VOC: At about 100 ms before the line-up point VOC activity starts to decrease. The reduction of VOC activity reaches a minimum level of 53 mV in the case of /fp/ and of 64 mV in the case of /vb/. VOC activity resumes later in the former case than in the latter.

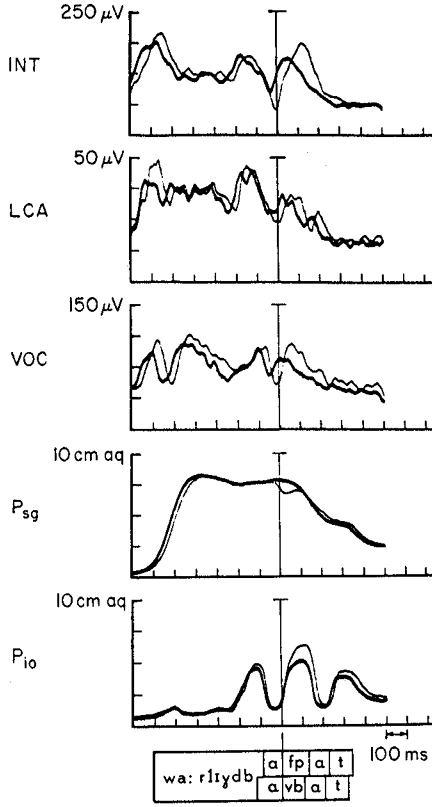

Figure 5 Averaged EMG and pressure data for Dutch sequences /fp/ (thin line) and /vb/ (thick line).

P_{io}: The maximum value of P_{io} during /fp/ is 6·27 cm aq; during /vb/ it is 5·08 cm aq. The pressure curves reflect the durational differences between the two clusters.

P_{sg}: Measured at the moment of maximum P_{io}, P_{sg} attains a value of 6·77 cm aq for /fp/ and 7·19 cm aq for /vb/. With /fp/ there is a drop of 0·95 cm aq from about 50 ms before the line-up point to 30 ms after it. This drop is followed by a slight increase (0·29 cm aq). At the moment of maximum P_{io} the value of ΔP is 0·50 cm aq in /fp/ and 2·11 cm aq in /vb/. The lowest ΔP value during /fp/ is 0·38 cm aq. It can be seen in Table IV, c and d, that the tendencies observed in the /fp-vb/ contrast are also to be found in the oppositions /sp-zb/ and /xp-ɣb/.

(*c*) *Discussion*

Generally speaking, the differences and correspondences between single stops and fricatives in their voiceless and voiced conditions are reproduced in the comparison of the same speech sounds in clusters of two.

Table V presents a more detailed comparison of the EMG data that were sampled for single consonants and for the same consonants occurring in clusters. It can be observed that there is more relaxation in the adductor muscles for clusters of two voiceless stops than for a single voiceless stop in intervocalic position. Specifically, there is evidently more LCA relaxation in the former case than in the latter. On the other hand, the com-

Table V Comparison of minima of activity in the adductor muscles around the line-up point for single consonants and clusters of two.

	INT	LCA	VOC
p, t, k	93	28	74
pt, tp, kp	84	22	62
b, d, g	116	29	71
bd, db, gb	116	30	69
f, s, x	57	23	57
p	95	28	74
fp, sp, xp	59	23	58
v, z	81	23	60
b	121	29	64
vb, zb, ɣb	93/119*	25/29	69/85

*The values to the left of the slash correspond to the fricative, those to the right represent /b/.

parison of single voiced stops and the same stops in clusters of two does not reveal any major differences. As far as the voiceless fricatives are concerned, the degree of adductor muscle relaxation is the same when they occur singly and when they are first members of a fricative + stop combination. However, if a voiced fricative occurs in a fricative + stop cluster there is less adductor muscle relaxation than for the same fricative occurring singly. The level of adductor muscle activity is *ca.* 15% higher in the voiced fricative in the cluster. We have pointed out in the first part of this paper that, in the case of single stops and fricatives, the voicing contrast is not systematically reflected in the degree of LCA and VOC activity, which mainly correlates with the stop/fricative distinction. In a stop + stop cluster, however, the pattern of LCA activity correlates systematically with the voicing distinction, and in a fricative + stop combination the voicing contrast is reflected in both LCA and VOC activity. Therefore it may be concluded that all three adductor muscles, and specifically INT, simultaneously reflect both the voiceless/voiced and the stop/fricative contrast in the particular clusters under investigation.

It is worth noticing that the data on the production of consonant clusters are even more at variance with the claims of Halle & Stevens (1967, 1971), than those on single consonants. For one thing, there is no indication of overt changes in intrinsic laryngeal muscle activity to facilitate the continuation of glottal pulsing in voiced stop + stop clusters, even with increased closure duration. For another, there is more VOC relaxation in the voiceless stop + stop clusters than in single stops, indicating that no stiffening of the vocal folds is required to inhibit their vibration.

Conclusion

Our experiment has confirmed that at the level of laryngeal adjustment systematic differences can be found that correlate with the voiced/voiceless and the stop/fricative contrasts among consonants. Four groups of Dutch consonants can be distinguished along these two dimensions. To separate these four classes in terms of articulatory differences it is of primary importance to specify for each its particular degree of glottal width and of supraglottal constriction. The degree of longitudinal vocal fold stiffness appears not to be a crucial factor in the voicing distinction. Our data also suggest that the degree of glottal aperture as well as the shape of the glottis may vary as a function of the combined difference in voicing and in manner of consonant production. This is to say that static glottal width and glottal shape not only correlate with the positive or negative specification of the phonetic feature [voice], but with that of the feature [sonorant] as well.

This research was supported in part by National Institute of Neurological and Communicative Disorders and Stroke, Grant NS-13870.

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