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THE EFFECT OF CONSONANT TYPE ON FUNDAMENTAL FREQUENCY AND LARYNX HEIGHT IN DANISH

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Fundamental frequency (Fo) and larynx height were measured in words of the type 'CV:fi *where the initial consonant varied in both manner and place of articulation. The main findings were a clear effect of voicing in the obstruents* [f] *and* [v] *on both Fo and larynx height in the following vowel, a small but consistent effect of aspiration on Fo but not on larynx height in the following vowel, and an effect of place of articulation on larynx height which was not, however, reflected in Fo.*

I. INTRODUCTION

In recent years the vertical movements of the larynx during speech have been playing an increasing role in the discussion of possible explanations for the segmentally conditioned fundamental frequency (Fo) variation, particularly the Fo perturbation in vowels after different consonant types. The basis for taking the vertical larynx movements into consideration in this discussion is the observation that - everything else being equal - Fo and larynx height are positively correlated (see e.g. Shipp 1975, Ohala 1973, Ewan 1979).

Greatest attention has perhaps been given to the effect of the voicing distinction in obstruents on the fundamental frequency in the following vowel. It is commonly observed that due to the reduction of the pressure differential across the glottis during the closure/constriction of voiced obstruents Fo is lowered locally in voiced obstruents, and is lower in the following vowel in comparison with Fo after voiceless obstruents (Di Cristo et Chafkouloff 1977, Fischer-Jørgensen 1972, House and Fairbanks 1953, Johansson 1976, Lea 1973, Lehiste and Peterson 1961, Löfqvist 1975, Mohr 1971, Jeel 1975, Hombert, Ohala and Ewan 1976).

The difference is largest at the beginning of the vowel but can also be observed even at the end of the vowel (Löfqvist 1975). It is also a common finding that the larynx is lower in voiced than in voiceless obstruents (Lindqvist, Sawashima and Hirose 1973, Ewan and Krones 1974, Riordan 1980, Westbury 1983). The low larynx position can be assumed to be the result of an active lowering (Kent and Moll 1969, Bell-Berti 1975, Westbury 1983), which contributes to an increase of the volume of the oral cavities, and consequently to the preservation of a sufficient pressure drop across the glottis for voicing to be maintained during the closure/constriction. The low larynx - like the low fundamental frequency - is preserved well into the following vowel. On the basis of this finding in conjunction with the commonly observed tendency for Fo and larynx height to be positively correlated, Hombert, Ohala and Ewan (1976) and Ewan (1979) suggest that the difference in larynx height after voiced versus voiceless obstruents causes (or is an indicator of) a difference in the vertical tension of the vocal chords, which in turn is responsible for the observed fundamental frequency difference.

This explanation, however, meets with difficulties (which the authors are fully aware of) when the relation between Fo and larynx height in and after nasal consonants is taken into consideration. Hombert, Ohala and Ewan (1976) report data indicating that the fundamental frequency course after [m] corresponds very closely to that found after voiced obstruents. This is surprising, since the free passage through the nose in nasal consonants should not neccessitate a larynx lowering and, therefore, a higher Fo should be expected after nasal consonants than after voiced obstruents. Similarly, Lea (1973) reports that while Fo in nasals does not display the local Fo drop characteristic of the voiced obstruents there is no essential Fo difference in the following vowel after the two consonant types. As for the vertical position of the larynx, Ewan (1979) reports that the larynx height of nasals corresponds more closely to that of voiceless obstruents than to that of voiced obstruents; this is true in the consonant as well as in the following vowel (unfortunately the larynx height data are not accompanied by simultaneous Fo data). Thus, there seems to be a discrepancy between the effect of nasal consonants on Fo and their effect on larynx height in the following vowel: Fo behaves like in voiced obstruents, and larynx height behaves like in voiceless obstruents. There are, however, some divergencies among the - rather few - investigations of larynx height in nasal consonants. Lindqvist, Sawashima and Hirose (1973) found like Ewan (1979) a high larynx position in nasals, while Perkell (1969), Bothorel (1979), Riordan (1980) and Westbury (1983) have found larynx heights in nasals similar to those of voiced obstruents. This last is what should be expected on the basis of the low fundamental frequency in and after nasals, but then, of course, the problem is to explain the low larynx position in the nasals. In view of the importance of the Fo- and larynx height conditions associated with nasals for the evaluation of the vertical tension hypothesis outlined above, and considering the divergencies of previous investigations, one purpose of the experiments reported below was to obtain additional data on Fo and larynx height in nasal consonants.

A point, where data from Danish will be of particular interest, is the relation between Fo and larynx height after aspirated versus unaspirated stops. In Danish the two series of stops, *ptk* and *bdg*, are both voiceless, and are differentiated only by the aspirated/unaspirated distinction (the pair *t-d* also by the presence/absence of affrication). This distinction seems to give rise to a fundamental frequency difference in the following vowel, which approaches the magnitude of the voiced/voiceless Fo difference (Jeel 1975, Reinholt Petersen 1978). The effect of aspiration, however, seems not to be universally agreed upon to the same degree as does the effect of voicing. Fischer-Jørgensen (1968) found no Fo difference after Danish aspirated versus unaspirated stops, and data from other languages having an aspirated/unaspirated distinction show no consistent trend for the effect of aspiration on Fo. Now, in the cases where Fo is higher after aspirated than after unaspirated stops, the difference can hardly be accounted for by Hombert, Ohala and Ewan's (1976) vertical tension hypothesis, and it will therefore be of interest to obtain Fo and larynx height data for these types of stops, and consider them together with data for other consonant types in the discussion of the hypothesis.

Although the present study will focus upon the effect of manner of articulation in consonants on fundamental frequency and larynx height, and the relation between the two, the role of place of articulation will also be taken into consideration. The reason for including this feature is that there seems to be a tendency for larynx height to be influenced by place of articulation. Ewan and Krones (1974) and Ewan (1979) have found the larynx to be higher in dental stops than in labial stops, Westbury (1983) reports a high larynx position in velars, lower in dentals and still lower in labials, and Lindqvist, Sawashima and Hirose (1973) have found that the larynx is higher in velars than in dentals. This pattern of variation (viz. labial<dental<velar) does not seem to be reflected in the fundamental frequency of the following vowel.

II. METHOD

A. MATERIAL

The material consisted of test words of the type [CV:fi], where C represents the consonants [b̥ʰ, d̥ˢʰ, g̊ʰ, b̥, d̥, g̊, f, v, m, n] and V: the long vowels [i:], [u:], and [ɑ:][1]. The test words were inserted in the frame sentence *"Vokalen i ... forkortes"*. [voˈg̊ʰæ:ˀln̩ i .. fʌˈg̊ʰɒ:d̥əs] "The vowel of ... is shortened". The 30 sentences were arranged in four different randomizations in a reading list.

B. RECORDING

The recording equipment consisted of a television camera (Sony AVC-3250 CES) and a video-recorder (Sony U-Matic type 2630). The frame frequency of the equipment was the normal 50 frames per second. The speech signal was recorded on the sound track of the video-tape via a Sennheiser MD 21 microphone placed about 15 cm from the subject's mouth. In order to synchronize speech and video signals a timer signal was recorded on the video-tape using a timing device (FOR-A CO. type VTG 33). On playing back the tape, the timer signal was displayed on the monitor screen in minutes, seconds and centiseconds, and could be registered together with the speech signal on an ink writer as pulses for seconds and centiseconds. In this manner it was possible to relate each TV-frame to the speech signal.

During recording the subject was seated in a dentist's chair with a fixed head-rest. The camera was placed at the level of the subject's thyroid prominence and at right angles to his mid-sagittal plane at a distance which allowed the area between the subject's chin and sternum to be covered by the field of vision. For calibration purposes each recording of the speech material was immediately preceded by a short recording of a millimeter scale placed in front of the subject's thyroid prominence in his mid-sagittal plane. Each subject produced 2 recordings of the list, so that altogether 8 repetitions of each test word were obtained.

C. SUBJECTS

Recordings were made of three male speakers, PD, PM, and NR (the author). PM and NR are phoneticians, and PD is an engineer and member of the technical staff of the Institute. They are all speakers of Standard Danish, although PM, who has grown up in Jutland, has some dialectal influence.

D. REGISTRATION AND MEASUREMENTS

The following acoustic curves were made: duplex oscillogram, two intensity curves, and an Fo curve. The timer signal was also registered on the mingograph. On the basis of the acoustic curves the following reference points were determined: 1) the midpoint in time of the pretonic [i] immediately preceding the test word, 2) the beginning of the test consonant, 3) the beginning of the stressed vowel, 4) the midpoint of the stressed vowel, 5) the end of the stressed vowel, and 5) the midpoint of the first posttonic [i].

On the basis of the timer signal and the acoustic curves the locations on the video-tape of the frames or sequences of frames to be measured were determined. Since the interval between frames was 2 cs (the frame frequency being 50 Hz), the temporal inaccuracy of a frame in relation to the corresponding point of reference was ± 1 cs. The video recorder was equipped with a step function which made it possible during playback to "freeze" the picture and step forward frame by frame and read off larynx height in the frames selected for measurement. Larynx height was determined from a scale drawn on the monitor screen on the basis of the millimeter scale which had been recorded on the tape prior to the reading of the material. The vertical position of the larynx could be measured with an accuracy of ± 0.5 mm. Larynx height measurements were made at the first reference point, in all frames between the beginning of the test consonant and the end of the stressed vowel, and at the sixth reference point. Similarly, Fo was measured at the first and last reference points and at 2 cs intervals during the voiced portion of the [ˈCVː] sequence.

III. RESULTS

A. STATISTICAL TREATMENT

In order to eliminate a systematic influence on the larynx height measurements, deriving from the fact that it had not been possible to place the millimeter scale in exactly the same position in the two recordings, the larynx height measurements in each of the 8 randomizations were converted into deviations from the mean of all measurements in that randomization, before being submitted to further statistical treatment. After this normalization procedure, means and standard deviations for each test word were computed at reference points 1, 2, 5, and 6. In the [ˈCVː] sequence means and standard deviations were computed continuously throughout the sequence (i.e. at 2 cs intervals) using the beginning of the vowel as a line-up point.

For the further statistical analysis a series of one-way analyses of variance was carried out at each of the 6 reference points.

Figure 1 displays the between group variance estimates (s_b^2) at the reference points. It is seen that the maximum consonantal influence on both Fo and larynx height occurs at the onset of the vowel following the test consonant, and although it decays through the vowel the effect is still significant at the 5 per cent level or better at the end of the vowel in about 50 per cent of the cases.

Fo shows only few cases of a significant effect at points earlier than stressed vowel onset, whereas the significant effects of consonants on the vertical position of the larynx tend to be dispersed over all reference points in the measured sequence, although they occur most frequently at the beginning and at the middle of the stressed vowel.

The analyses of variance, of course, give no detailed information on the pattern of influence of the various consonant types on Fo and larynx height. Therefore an a posteriori multiple comparison procedure had to be applied in order to detect which consonant distinctions were responsible for the observed effects

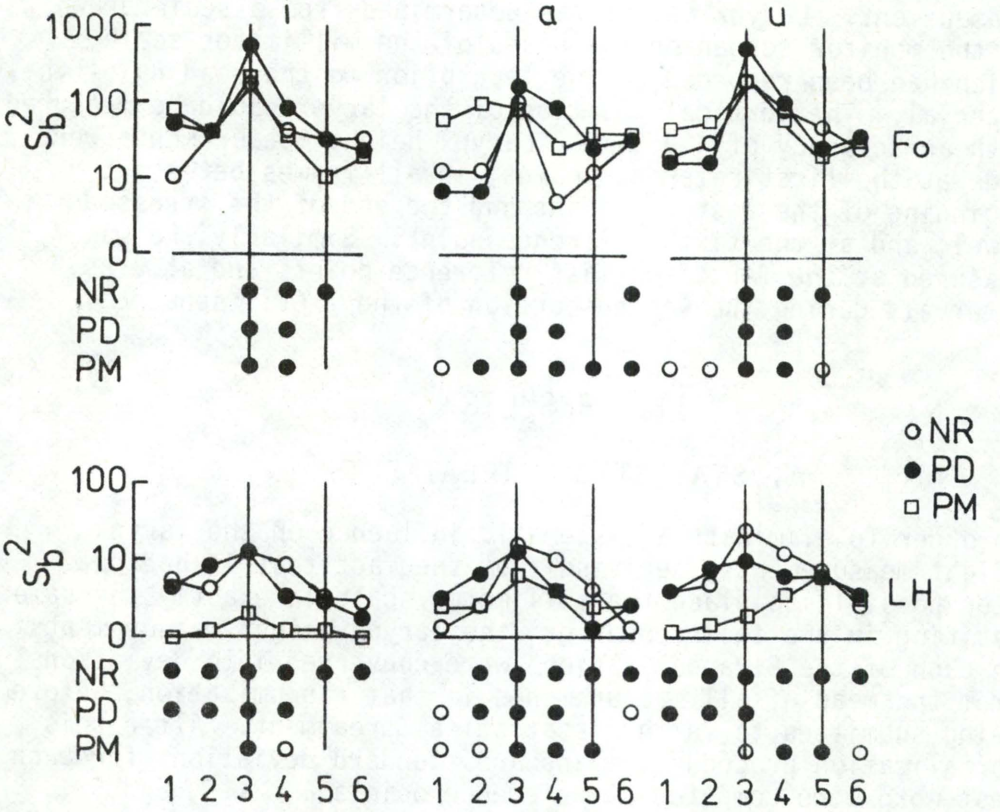

Figure 1

The effect of consonants (expressed in terms of between-group variance estimates) on fundamental frequency and larynx height at the six reference points in [i]-, [ɑ]-, *and* [u]-*words. (Note that a logarithmic scale is used.) Data from three subjects. The circles under the graphs indicate that the effect is statistically significant at the 5 per cent level (open circles), or at the 1 per cent level (filled circles).*

and which were not. The procedure employed in the present study was the Scheffé procedure, which has the advantage that it does not require an equal number of observations in the groups to be compared as do other methods like the Newman-Keuls and the Duncan methods (Ferguson 1976). The demand for an equal number in the groups could not be met in all cases since a number of measurements had to be discarded for various reasons (but no mean represents less than 5 observations and in the vast majority of cases the number of observations is 8). The drawback of the Scheffé procedure is, however, that it focuses on minimizing the probability of Type One errors, i.e. the risk of accepting H_1 (there is a difference) when H_0 (there is no difference) is in fact true. This means that it will lead to fewer significant differences than the other methods. To overcome this bias Ferguson (1976) suggests that a lower level of significance be used, e.g. the 10 per cent instead of the 5 or 1 per cent level. In the treatment of the present data the 10 per cent level was used, but still very few differences were shown to be significant. This does not, per se, discredit the method, but it means that differences which, although they were small, were consistent throughout the material, were obscured by the multiple comparison procedure. An example will illustrate this point: At the midpoint of the vowel the fundamental frequency is higher after aspirated than after unaspirated stops. The difference is quite small, 3 Hz on the average and varying between 0 and 8 Hz, and can be proved statistically significant in only 4 cases out of 27 (3 places of articulation x 3 vowels x 3 subjects). On the other hand, the difference is consistent in the sense that Fo is higher after aspirated stop in 21 cases, in 6 cases there is no difference, and in no cases is Fo lower after aspirated than after unaspirated stop. So, in this instance the multiple comparison procedure has failed to reveal a general and consistent tendency in the data. Because of this, for each pair of consonantal conditions compared, a count was made at each reference point over subjects and vowels (3x3) of the number and directions of the differences between the means of the members in the pair. The results of these counts were taken into consideration in the evaluation of the tendencies in the material.

B. THE INFLUENCE OF MANNER OF ARTICULATION ON THE FUNDAMENTAL FREQUENCY AND ON THE VERTICAL POSITION OF THE LARYNX

Figures 2, 3, and 4 show mean fundamental frequencies, and figures 5, 6, and 7 mean larynx heights at the 6 reference points, cf. above. The data are plotted in such a manner that the effect of the manner of articulation of the test consonants may be readily evaluated. The results of the counts of differences are given in tables 1 and 2.

1. FUNDAMENTAL FREQUENCY

Apart from the local fundamental frequency drop during the [v] which is not found in the nasal consonants (see figure 8), it seems that the effect on Fo exerted by the manner of articulation is confined to the following vowel. There are, of course, differences at the midpoint of the first pre-tonic, at the onset of the consonant, and at the first post-tonic. But these differences do not appear to constitute any systematic pattern.

The consonants can be very clearly divided into two groups according to their influence on Fo at the onset of the following vowel. One group includes the stops and [f], after which Fo is high, and the other consists of the nasal consonants and [v], after which it is low. Within each of the groups, however,

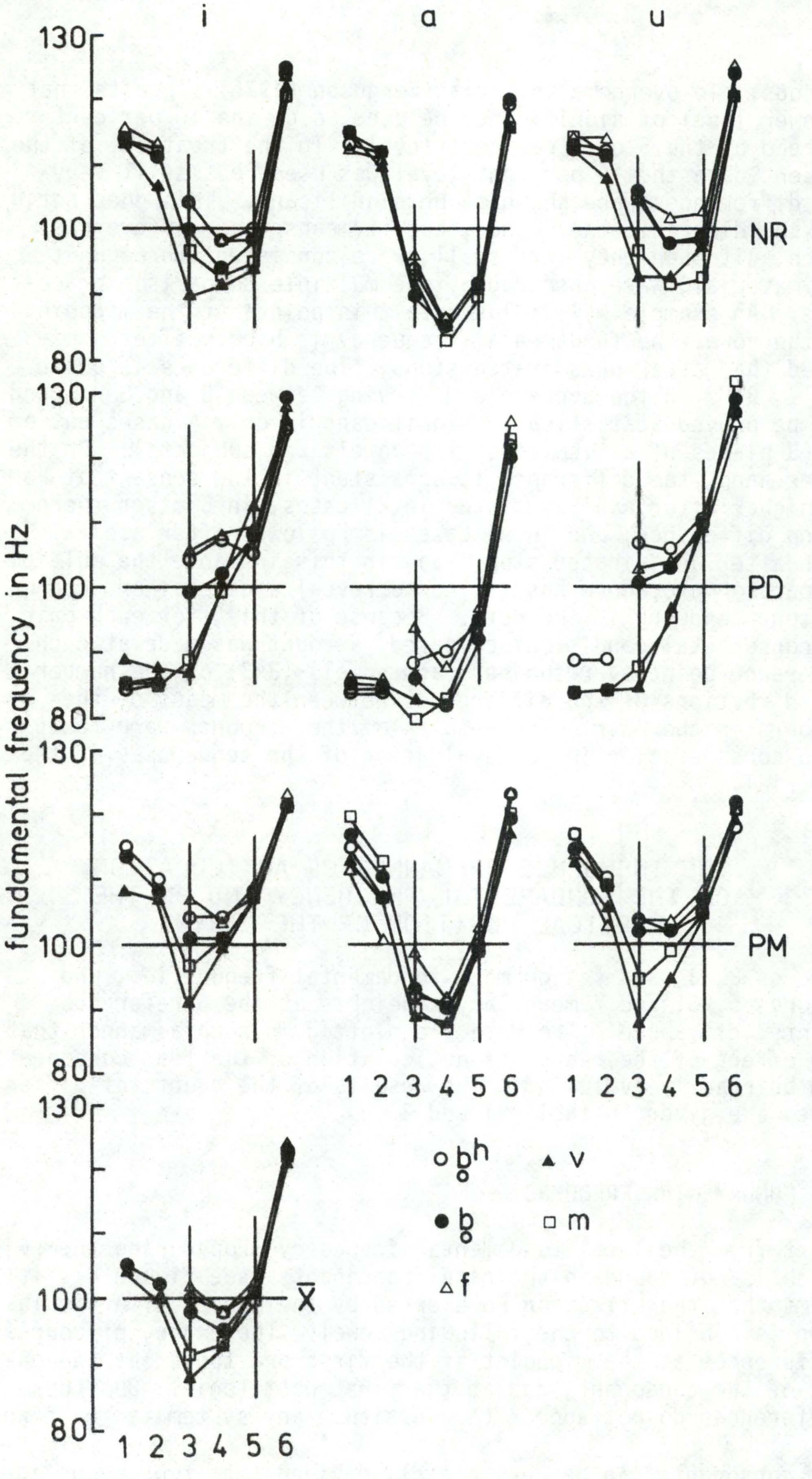

Figure 2

Mean fundamental frequency at six reference points in ['CV:fi] *words with initial labial consonants varying in manner of articulation. The vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and speakers.*

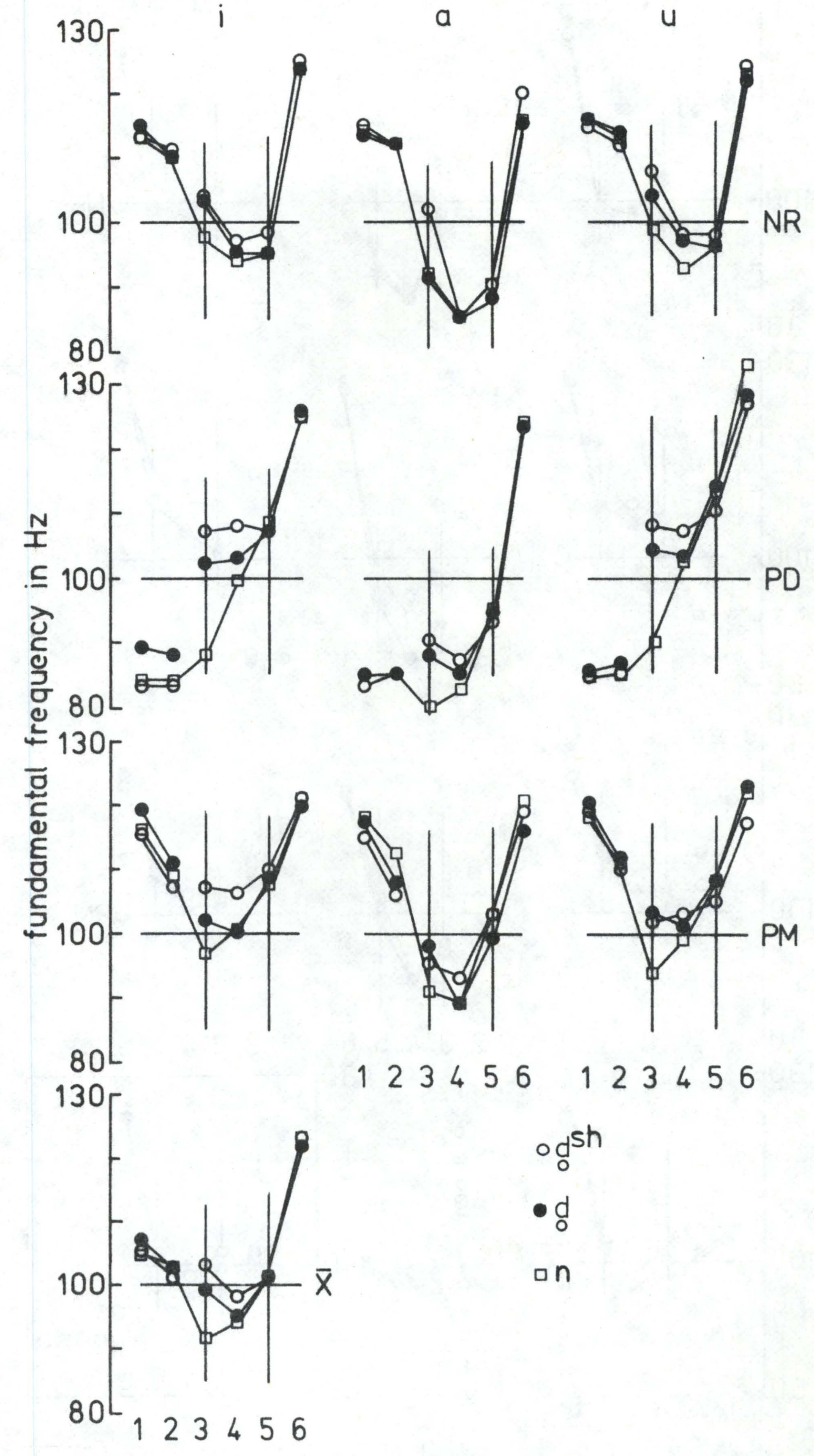

Figure 3

Mean fundamental frequency at six reference points in [ˈCV:fi] *words with initial alveolar consonants varying in manner of articulation. The vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and speakers.*

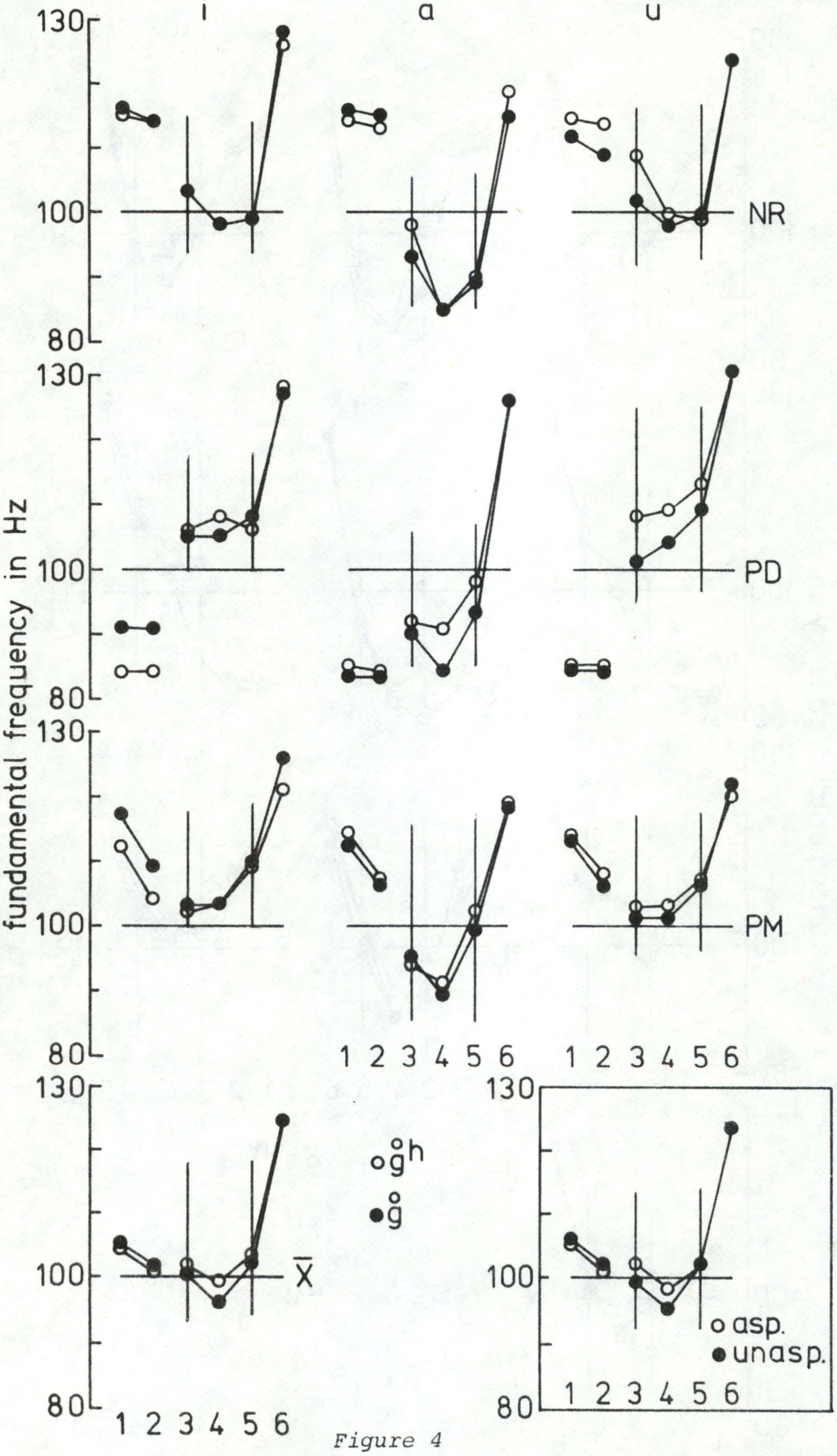

Figure 4

Mean fundamental frequency at six reference points in [ˈCVːfi] *words with initial velar consonants varying in manner of articulation. The vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and subjects. The window in the lower right corner of the figure shows the averages of words with aspirated vs. unaspirated stops for all vowels, speakers, and places of articulation pooled.*

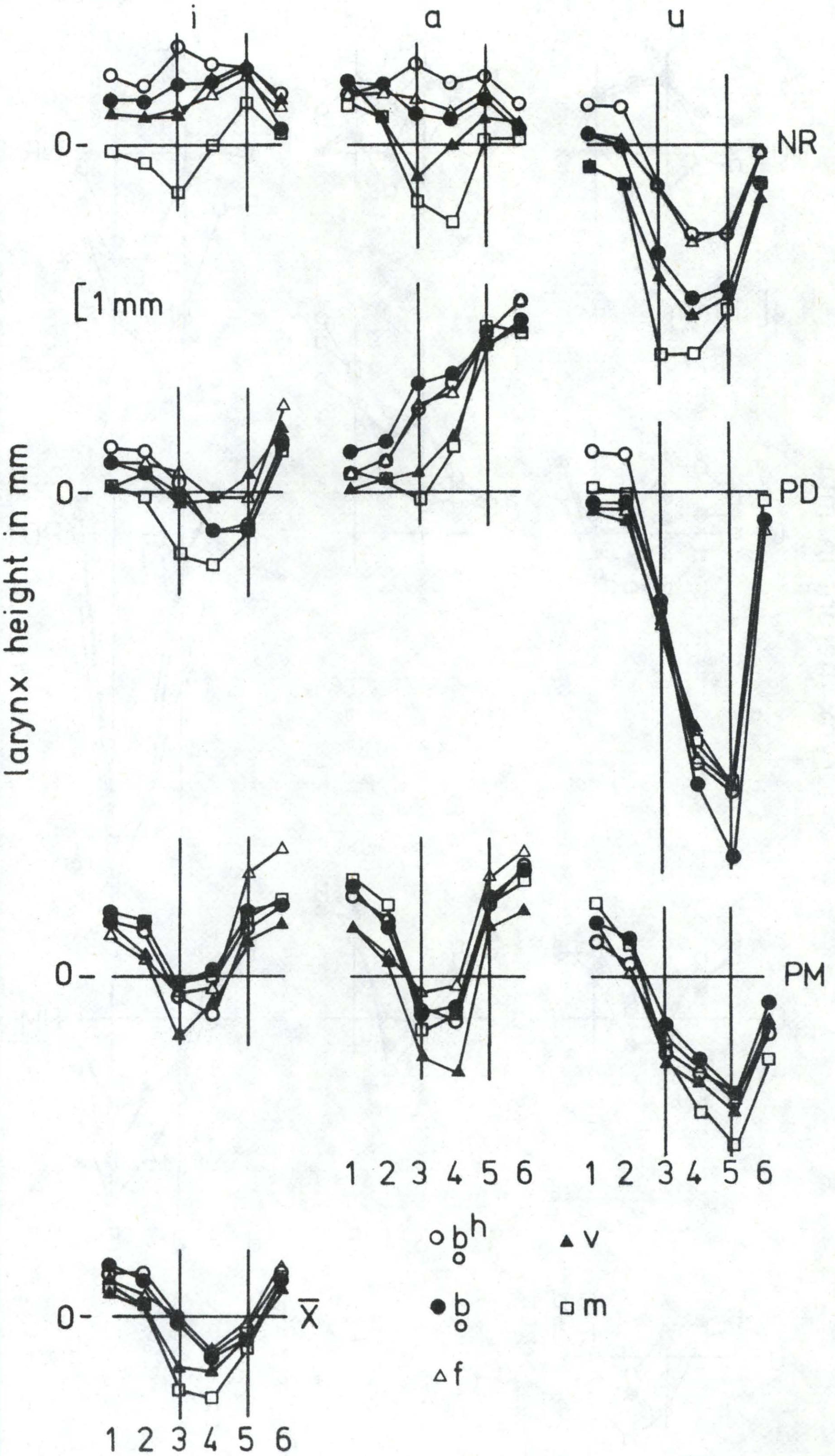

Figure 5

Mean larynx height at six reference points in ['CV:fi]-words with initial labial consonants varying in manner of articulation. The vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and speakers.

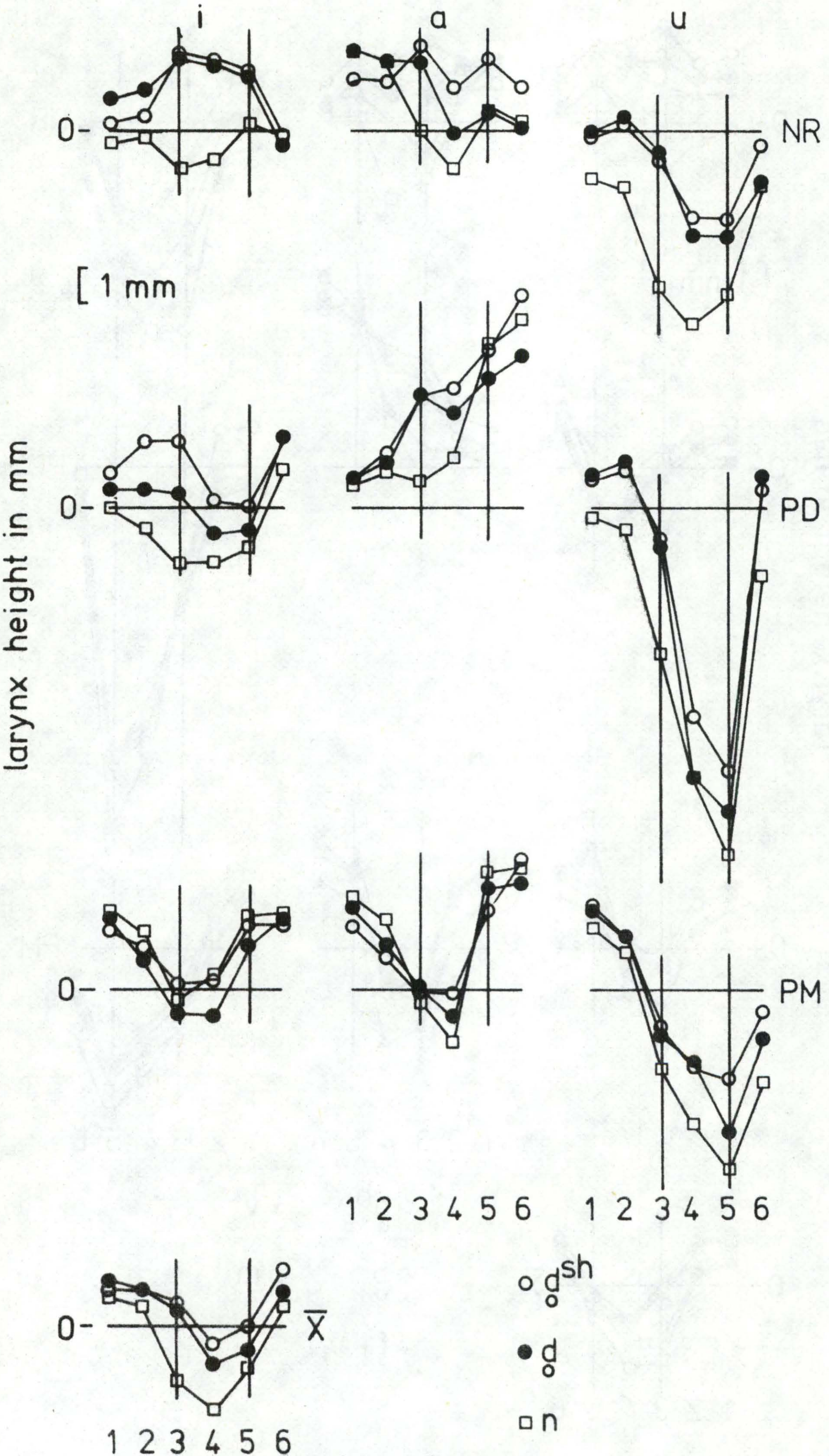

Figure 6

Mean larynx height at six reference points in [ˈCV:fi]-words with initial alveolar consonants varying in manner of articulation. the vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and speakers.

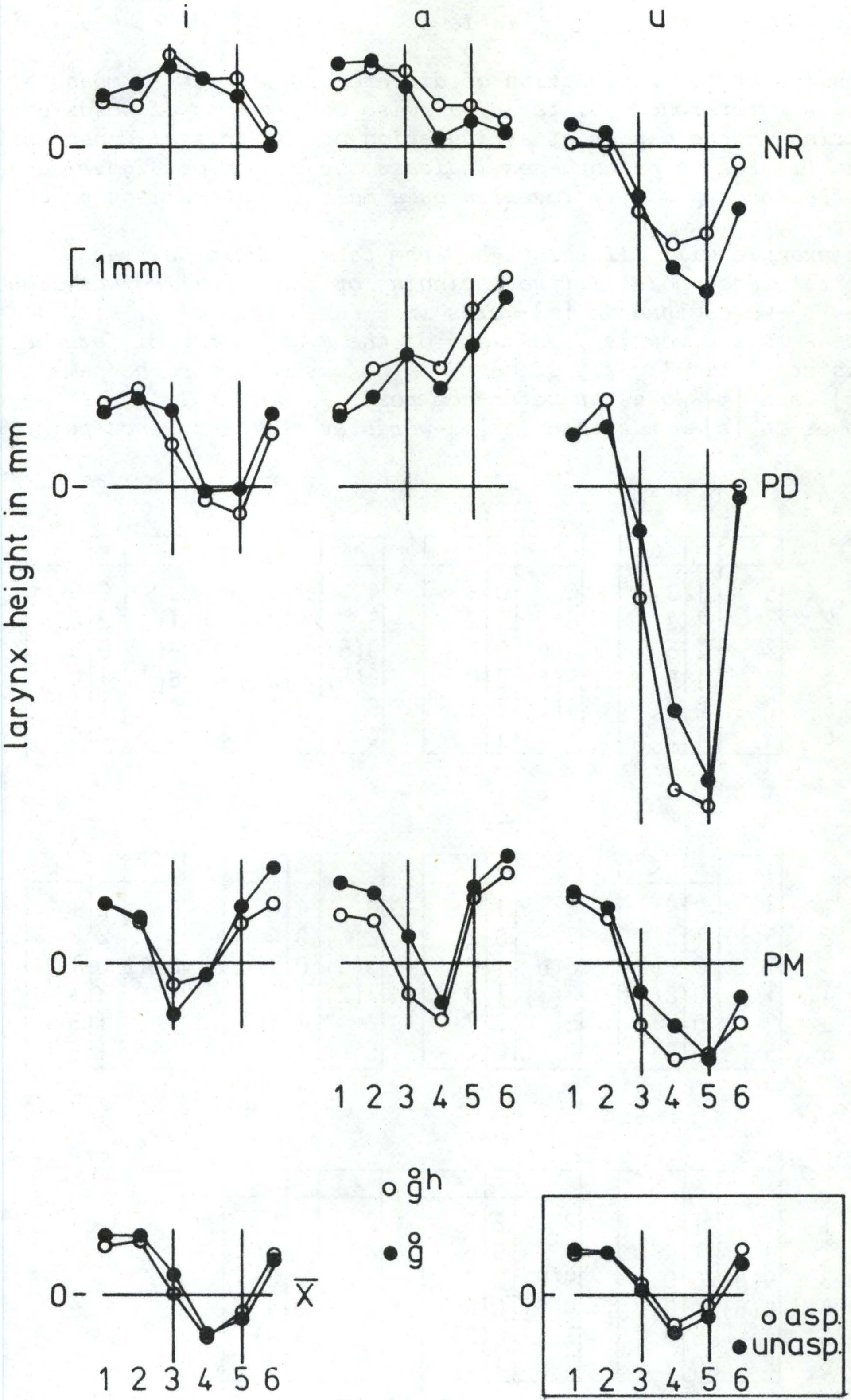

Figure 7

Mean larynx height at six reference points in [ˈCV:fi]-words with initial velar consonants varying in manner of articulation. The vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and subjects. The window in the lower right corner of the figure shows the averages of words with aspirated vs. unaspirated stops for all vowels, speakers, and places of articulation pooled.

Table I

Results of the enumeration of differences between Fo means at the six reference points in pairwise comparisons of words differing in the manner of articulation of the initial consonant. The figures in parentheses indicate the number of significant difference ($p < 0.1$) revealed by a multiple comparison procedure.

An example will illustrate how the table should be read: at reference point 3 (the beginning of the vowel) Fo was higher in [b̥]-words than in [m]-words in 8 cases (out of 9, viz. 3 speakers x 3 vowels), and in 5 of the 8 cases the difference was statistically significant; in no cases Fo was the same in [b̥]- and [m]-words at reference point 3, and in 1 case Fo was lower in [b̥]-words than in [m]-words at that reference point.

b̥ʰ-f

	>	=	<
1	5	1	3
2	5	1	3
3	2	2	5
4	3	1	5
5	2	0	7
6	3	1	5

b̥ʰ-v

	>	=	<
1	6	0	3
2	6	1	2
3	9(6)	0	0
4	9(5)	0	0
5	4(1)	4	1
6	5	1	3

b̥ʰ-m

	>	=	<
1	4	0	5
2	3	4	2
3	9(5)	0	0
4	9(5)	0	0
5	6	2	1
6	4	1	4

d̥ˢʰ-n

	>	=	<
1	2	2	5
2	1	2	6
3	9(7)	0	0
4	8(3)	1	0
5	4	1	4
6	3	2	4

b̥-f

	>	=	<
1	4	2	3
2	5(1)	1	3
3	1	0	8(2)
4	1	0	8(1)
5	2	0	7
6	5	0	4

b̥-v

	>	=	<
1	6	1	2
2	7	0	2
3	8(6)	1	0
4	8(3)	1	0
5	5	2	2
6	7	0	2

b̥-m

	>	=	<
1	0	4	5
2	2	3	4
3	8(5)	0	1
4	7(2)	1	1
5	7	1	1
6	5	1	3

d̥-n

	>	=	<
1	6	2	1
2	5	2	2
3	8(4)	0	1
4	5	3	1
5	3	1	5
6	2	1	6

f-v

	>	=	<
1	5	1	3
2	4	1	4
3	9(8)	0	0
4	8(6)	1	0
5	7	0	2
6	8	0	1

f-m

	>	=	<
1	2	2	5
2	3	0	6
3	9(8)	0	0
4	9(6)	0	0
5	7	0	2
6	7	1	1

v-m

	>	=	<
1	2	1	6
2	2	1	6
3	1	0	8(3)
4	5	0	4
5	1	4	4
6	3	1	5

b̥ʰ-b̥

	>	=	<
1	4	1	4
2	5	2	2
3	7	0	2
4	6(1)	3	0
5	4	1	4
6	2	3	4

d̥ˢʰ-d̥

	>	=	<
1	1	1	7
2	1	3	6
3	7(1)	0	2
4	8(2)	1	0
5	5	0	4
6	5	1	3

g̊ʰ-g̊

	>	=	<
1	5	1	3
2	5	1	3
3	6(1)	1	2
4	7(1)	2	0
5	5	2	2
6	3	3	3

Table II

Results of the enumeration of differences between larynx height means at the six reference points in pairwise comparisons of words differing in manner of articulation of the initial consonant. See further the caption to table I.

b̥ʰ-f

	>	=	<
1	6	1	2
2	8	1	0
3	4	0	5
4	4	0	5
5	5	0	4
6	3	2	4

b̥ʰ-v

	>	=	<
1	6(1)	1	2
2	8(1)	0	1
3	9(2)	0	0
4	6(1)	0	3
5	6	0	3
6	7	0	2

b̥ʰ-m

	>	=	<
1	6(2)	0	3
2	6(2)	0	3
3	7(3)	0	2
4	6(3)	0	3
5	5(1)	0	4
6	7	0	2

d̥ˢʰ-n

	>	=	<
1	6	0	3
2	6(2)	0	3
3	9(5)	0	0
4	8(3)	0	1
5	6(3)	0	3
6	7	1	1

b̥-f

	>	=	<
1	5	3	1
2	6	0	3
3	5	0	4
4	4	0	5
5	3	0	6
6	2	0	7

b̥-v

	>	=	<
1	8	0	1
2	8	1	0
3	9(2)	0	0
4	6	0	3
5	5	0	4
6	6	0	3

b̥-m

	>	=	<
1	5	1	3
2	7	0	2
3	8(2)	1	0
4	8(2)	0	1
5	6	0	3
6	5	1	3

d̥-n

	>	=	<
1	6	1	2
2	6(1)	1	2
3	8(3)	0	1
4	8(2)	0	1
5	5	0	4
6	4	0	5

f-v

	>	=	<
1	4	1	4
2	7	0	2
3	8(3)	0	1
4	6(2)	1	2
5	6	1	2
6	7	1	1

f-m

	>	=	<
1	5	0	4
2	5(1)	0	4
3	7(4)	0	2
4	7(2)	0	2
5	6(1)	0	3
6	7	0	2

v-m

	>	=	<
1	4	0	5
2	2	4	3
3	5(1)	0	4
4	7(1)	0	2
5	5	0	4
6	4	1	4

b̥ʰ-b̥

	>	=	<
1	4	0	5
2	5	1	3
3	5(1)	0	4
4	4(1)	1	4
5	5	2	2
6	6	2	1

d̥ˢʰ-d̥

	>	=	<
1	2	0	7
2	3	0	6
3	7	0	2
4	8	0	1
5	8	0	1
6	6	1	2

g̊ʰ-g̊

	>	=	<
1	2	2	5
2	3	0	6
3	3	0	6
4	3	2	4
5	5	0	4
6	5	0	4

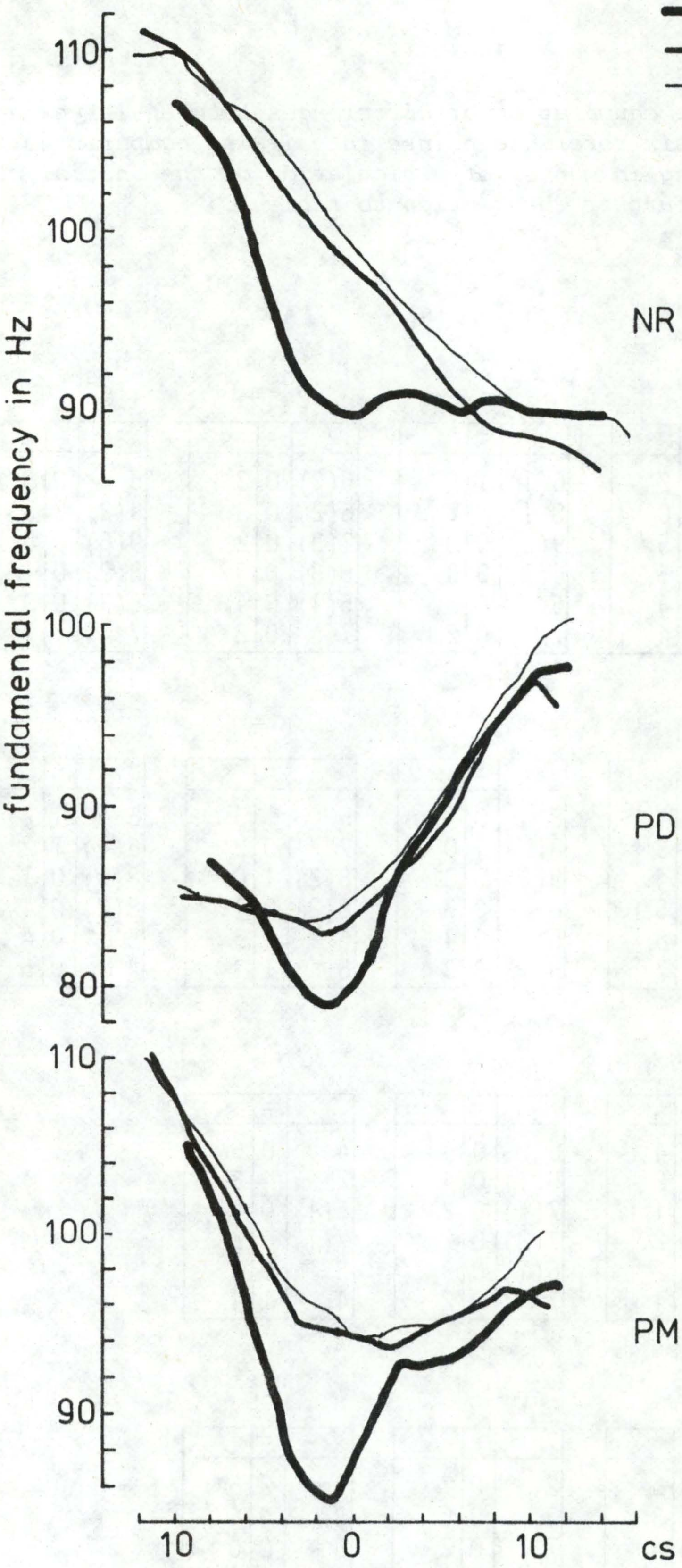

Figure 8

Mean fundamental frequency tracings in sequences of [v], [m], *and* [n] *plus stressed vowel (lined up around the onset of the vowel).* [i]-, [ɑ]-, *and* [u]-*sequences are pooled.*

there are fairly consistent differences to be found. There is a general tendency for Fo to be higher after aspirated than after unaspirated stops. The difference is small, 2 Hz on the average, but the relation holds in 20 out of 27 comparisons (3 vowels x 3 speakers x 3 places of articulation).

The fricative [f] tends to be followed by a higher Fo at the onset of the vowel than does the corresponding stop [b̥ʰ]. The mean difference is 2 Hz, which is the same as the aspirated-unaspirated difference, but referring to table I it is evident that the [b̥ʰ-f] difference is less stable than the [b̥ʰ-b̥] difference. Thus, on the basis of their effect on the fundamental frequency at the onset of the following vowel it seems reasonable to subdivide the voiceless consonants into two groups, [b̥ʰ d̥ˢʰ g̊ʰ f] versus [b̥ d̥ g̊].

Within the group of voiced consonants the fundamental is in most cases lower after [v] than after [m] at the start of the vowel. This difference must be ascribed to the aerodynamic conditions during the [v]-constriction, which are still effective at or immediately after the release.

At the midpoint of the vowel, which lies between 6 and 10 centiseconds after its onset, the effect on Fo exerted by the preceding consonant is considerably smaller than at the beginning of the vowel, but two groups of consonants can still be clearly discerned, namely the aspirated stops and [f], that are accompanied by a relatively high Fo and the nasal consonants and [v], after which Fo is low. Further, the difference between [m] and [v], which was found at the beginning of the vowel, is eliminated at the midpoint of the vowel. The relation of the unaspirated stops to the two groups is less clear. As is seen from table II Fo after [b̥] is higher than after [v] and [m] in 8 and 7 (out of 9 cases), respectively, and after [b̥ʰ] Fo is higher in 6 cases (out of 9) than after [b̥], i.e. the [b̥ʰ-b̥] difference is slightly less consistent than the [b̥-m] and [b̥-v] differences. On the other hand, the [b̥-v] and [b̥-m] differences are slightly smaller (2 Hz on the average) than the [b̥ʰ-b̥] differences (3 Hz on the average). This tendency comes out more markedly in the alveolars, where Fo after [d̥] is only 1 Hz higher than after [n] but is 3 Hz lower than after [d̥ˢʰ]. Furthermore, the [d̥ˢʰ-d̥] difference is consistent to a high degree, whereas the [d̥-n] difference is not. In the velars, no comparison can be made with voiced consonants, of course, but it should be noted that Fo after [g̊ʰ] is 3 Hz higher than after [g̊] which is identical to the corresponding differences in labials and alveolars. Thus, judging from their influence on the fundamental frequency at the midpoint of the following vowel, the unaspirated stops tend to be more similar to the voiced than to the other unvoiced consonants, where, at the beginning of the vowel, they were clearly separated from the voiced consonants.

At the end of the vowel the effect of the manner of articulation of the preceding consonant is very small, and follows no consistent pattern.

2. LARYNX HEIGHT

As mentioned above the consonantal influence on the vertical position of the larynx seems to be more evenly dispersed over the measured sequence than does the influence on the fundamental frequency.

This tendency can also be read from table II where it appears that the degree of consistency of the outcome of a given comparison remains fairly constant over all points of reference. But apart from that the pattern of consonantal influence on larynx height is subject to gross variation between speakers, and also - to a lesser degree - to variation between the vowels following the consonant.

The most consistent feature of the data seems to be the tendency for nasals to be associated with a lower larynx position than the other consonants, particularly at the onset and the midpoint of the following vowel. The tendency is very clear for subject NR, less so for PD, and it is only found for PM in the [u]-words and at the midpoint of [ɑ] after [n].

In the first pretonic vowel, at the beginning of the consonant, and at the beginning of the following vowel the larynx is generally lower in [v]-words than in [bʰ]- [b]- and [f]-words. At the beginning of the vowel this is true in all cases except one (PD's [u]-words). The tendency still remains at the midpoint of the vowel, but the differences are considerably smaller and less consistent than at the beginning. Further, at the midpoint of the vowel the vertical position of the larynx in [v]-words is closer to the position in [b]-, [bʰ]- and [f]-words than to the position in [m]-words, whereas the opposite was true at the beginning of the vowel.

The tendency for Fo to be higher after aspirated than after unaspirated stops is hardly - if at all - reflected in the larynx height data. Although the larynx tends to be higher after aspirated labial and alveolar stops, the difference is consistent for the alveolars only.

C. PLACE OF ARTICULATION

In figures 9 to 14 Fo means and larynx height means at the 6 reference points are plotted in such a manner as to display the effect of place of articulation. The results of the counts of differences and their directions are given in tables III and IV.

1. FUNDAMENTAL FREQUENCY

An effect of place of articulation of the test consonants is only found at the beginning of the following vowel. Here Fo is slightly higher, 3 Hz on the average, after [d^{sh}] than after [b̥ʰ] in 7 out of 9 cases. A similar degree of consistency

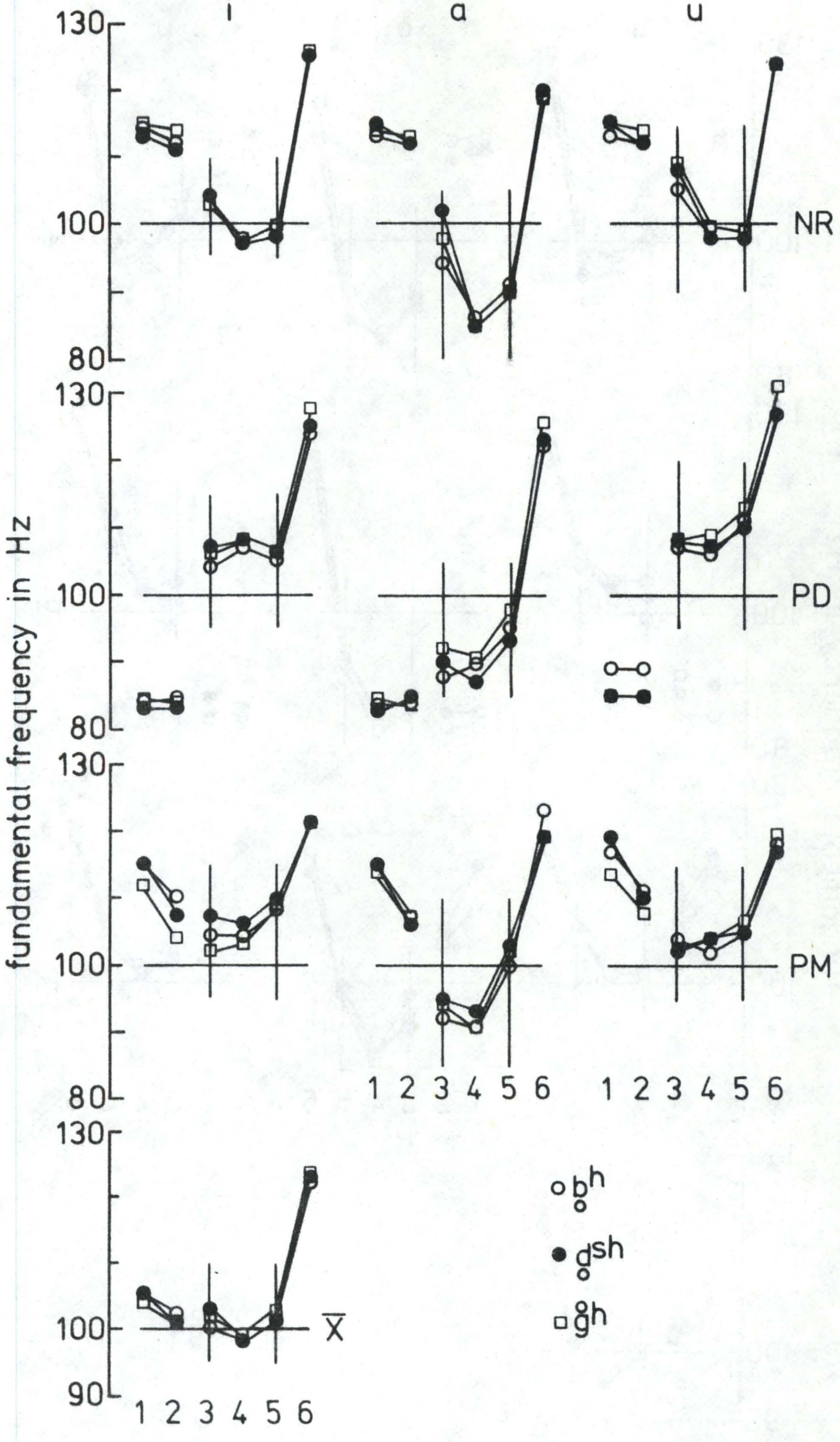

Figure 9

Mean fundamental frequency at the six reference points in [ˈCV:fi]-words with initial aspirated stops varying in place of articulation. The vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and speakers.

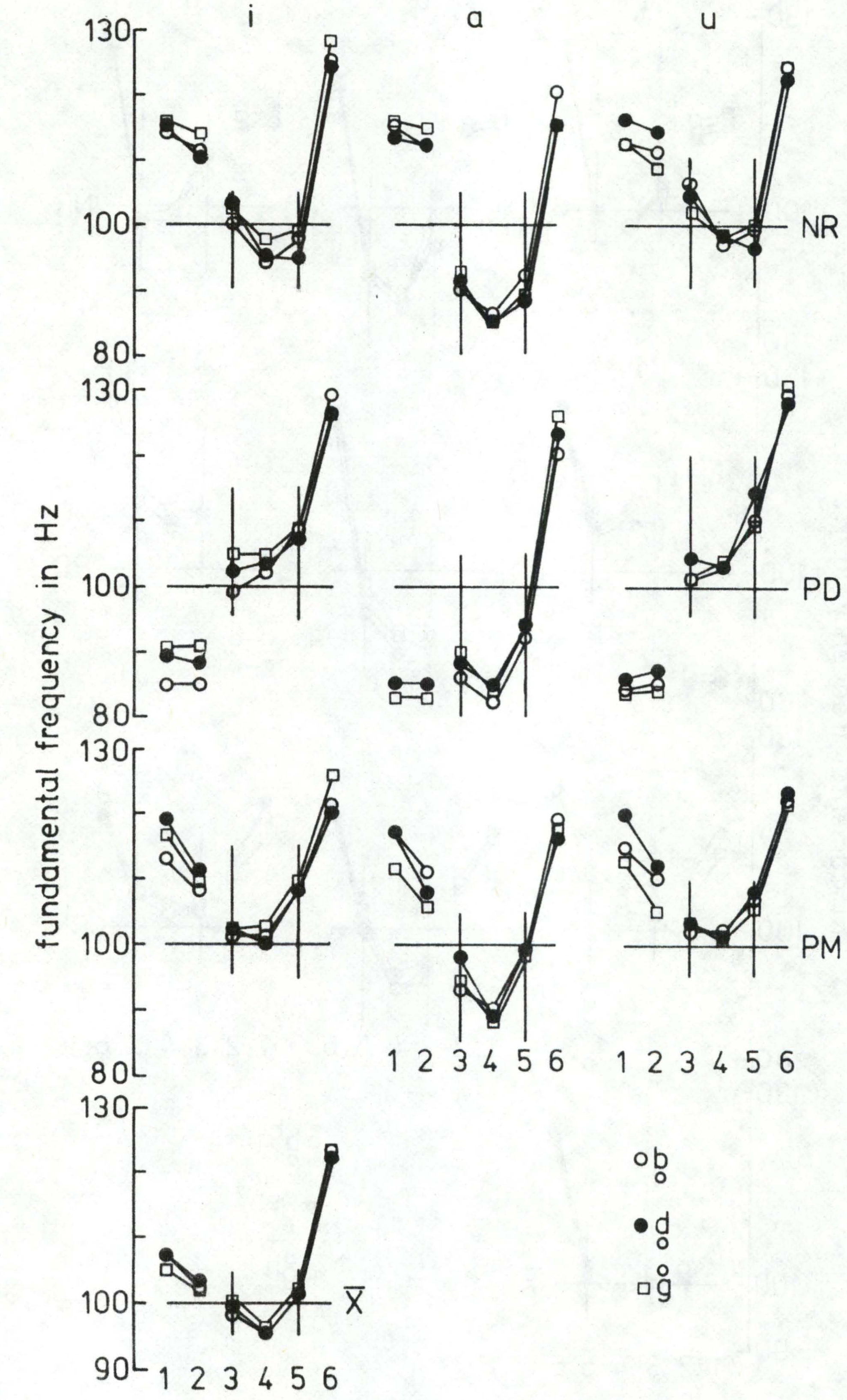

Figure 10

Mean fundamental frequency at the six reference points in ['CV:fi]*-words with initial unaspirated stops varying in place of articulation. The vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and speakers.*

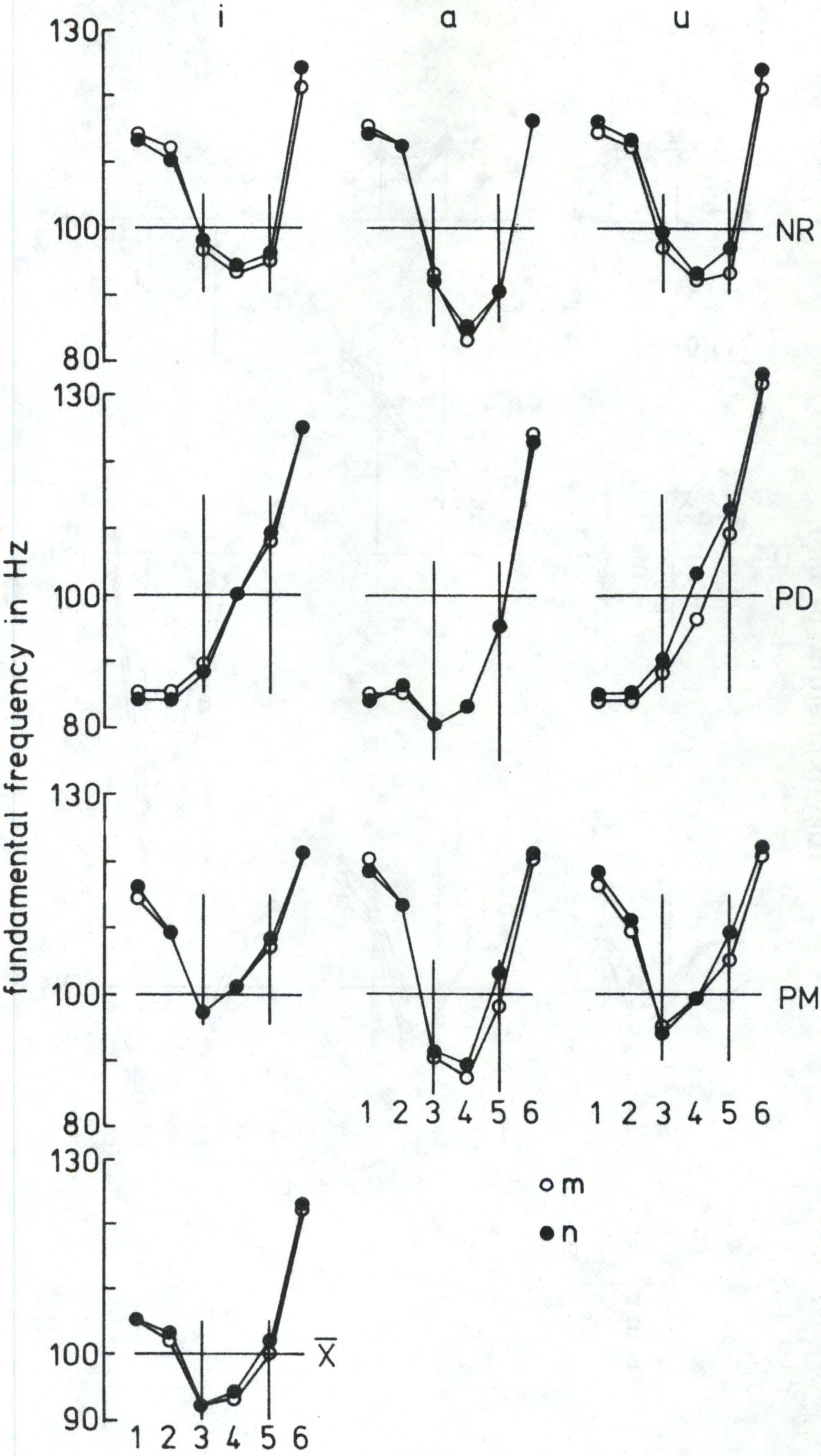

Figure 11

Mean fundamental frequency at the six reference points in ['CV:fi]*-words with initial nasal consonants varying in place of articulation. The vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and speakers.*

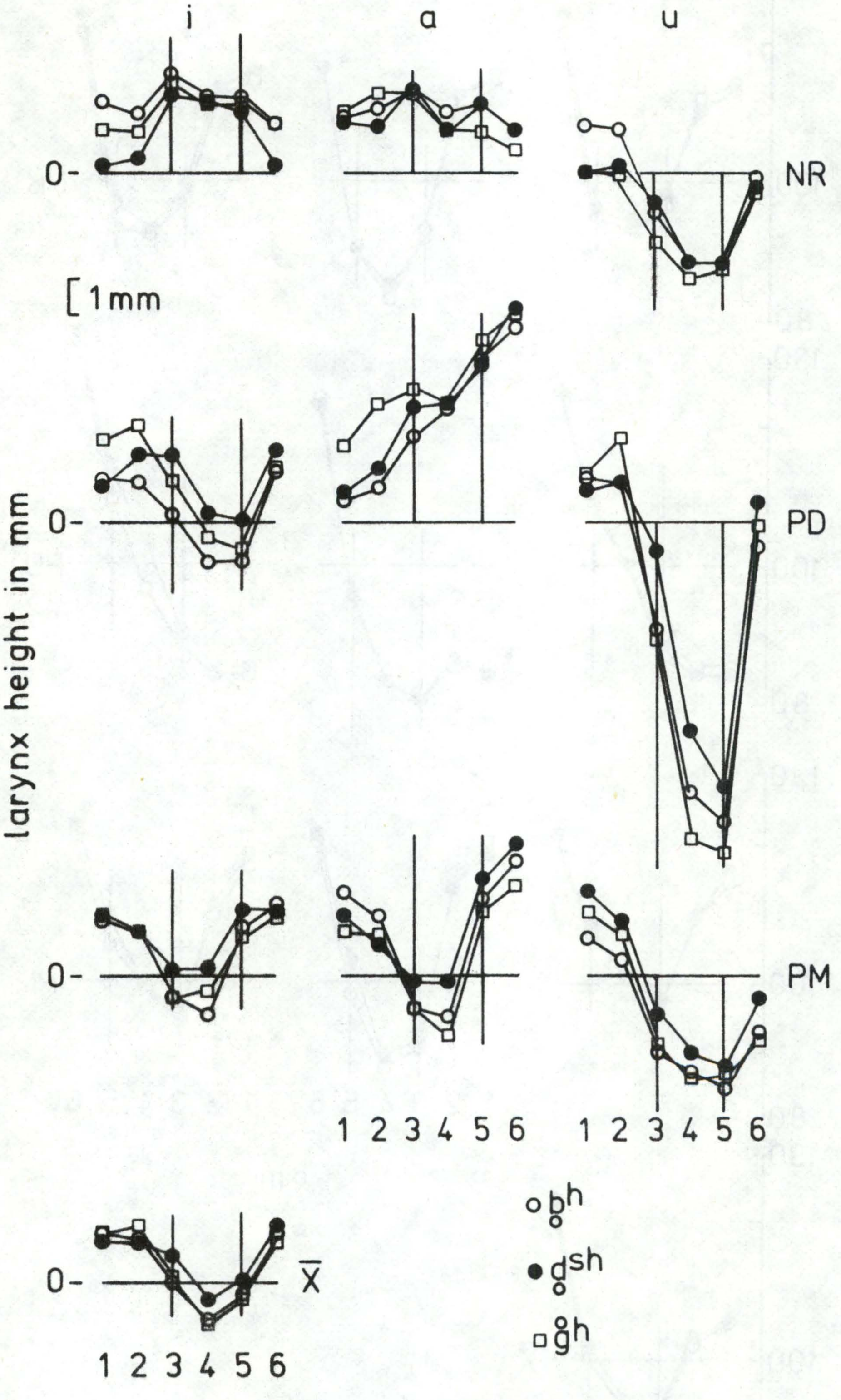

Figure 12

Mean larynx height at the six reference points in [ˈCV:fi]*-words with initial aspirated stops varying in place of articulation. The vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and speakers.*

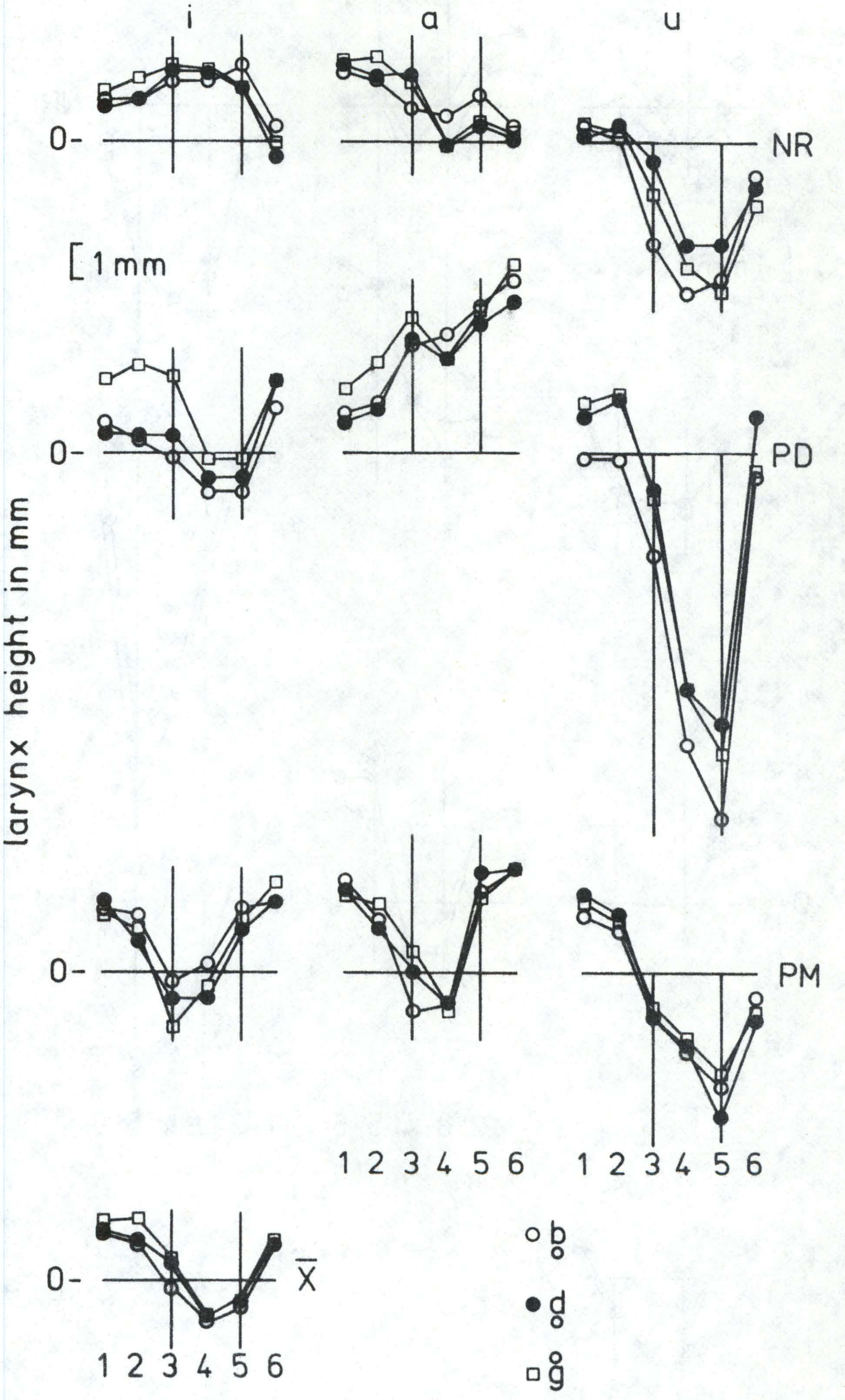

Figure 13

Mean larynx height at the six reference points in ['CV:fi]-*words with initial unaspirated stops varying in place of articulation. The vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and speakers.*

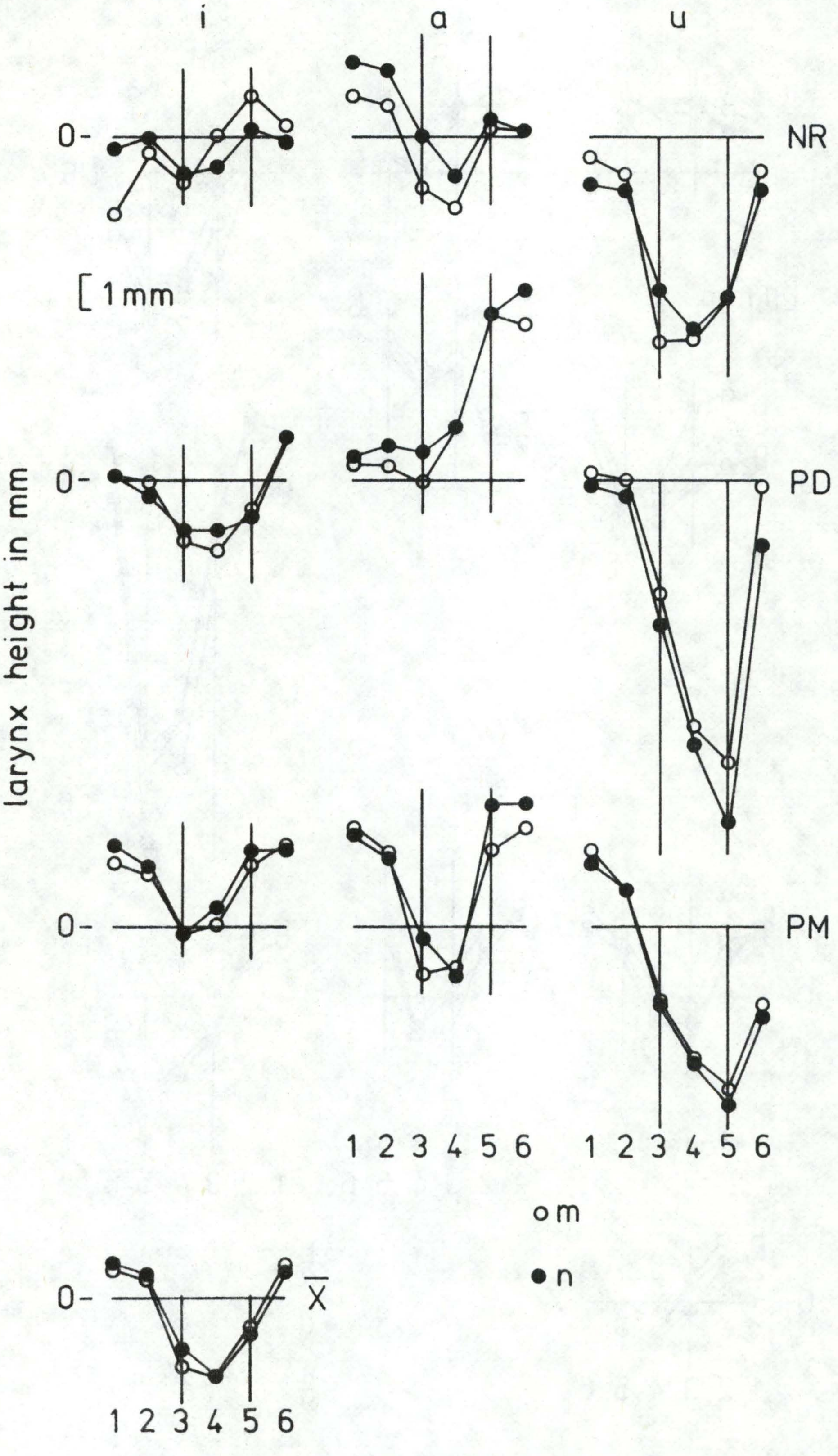

Figure 14

Mean larynx height at the six reference points in [ˈCV:fi]-*words with initial nasal consonants varying in place of articulation. The vertical lines in the graphs indicate the beginning and end of the stressed vowel. The lower left graph displays the average over all vowels and speakers.*

Table III

Results of the enumeration of differences between Fo means at the six reference points in pairwise comparisons of words differing in place of articulation of the initial consonant. See further the caption to table I.

b̥ʰ-d̥ˢʰ

	>	=	<
1	4	2	3
2	6	2	1
3	1	1	7(1)
4	3	1	5
5	4	2	3
6	2	4	3

b̥ʰ-g̊

	>	=	<
1	4	1	4
2	4	2	3
3	3	0	6
4	2	2	5
5	2	0	7
6	1	3	5

d̥ˢʰ-g̊

	>	=	<
1	3	1	5
2	3	1	5
3	5	1	3
4	2	3	4
5	2	2	5
6	1	3	5

b̥-d̥

	>	=	<
1	1	3	5
2	2	2	5
3	2	0	7
4	5	1	3
5	2	2	5
6	7	0	2

b̥-g̊

	>	=	<
1	4	1	4
2	5	0	4
3	2	1	6
4	3	1	5
5	3	2	4
6	3	2	4

d̥-g̊

	>	=	<
1	6	0	3
2	6	0	3
3	4	1	5
4	1	3	5
5	4	2	3
6	1	1	7

m-n

	>	=	<
1	4	1	4
2	2	3	4
3	3	2	4
4	1	3	5(1)
5	1	1	7
6	0	3	6

Table IV

Results of the enumeration of differences between larynx height means at the six reference points in pairwise comparisons of words differing in place of articulation of the initial consonant. See further the caption to table I.

b̥ʰ-d̥ˢʰ

	>	=	<
1	6(1)	0	3
2	4	2	3
3	1	1	7
4	2	1	6
5	2	2	5
6	3	1	5

b̥ʰ-g̊ʰ

	>	=	<
1	3	0	6
2	3	1	5(1)
3	4	2	3
4	6	0	3
5	6	0	3
6	6	0	3

d̥ˢʰ-g̊ʰ

	>	=	<
1	2	0	7
2	2	1	6
3	7	0	2
4	6	3	0
5	7	0	2
6	7	1	1

b̥-d̥

	>	=	<
1	4	0	5
2	3	1	5
3	1	1	7
4	3	1	5
5	5	0	4
6	6	1	2

b̥-g̊

	>	=	<
1	2	0	7
2	1	0	8(1)
3	1	0	8(2)
4	4	0	5
5	6	0	3
6	4	1	4

d̥-g̊

	>	=	<
1	2	1	6
2	2	0	7
3	3	0	6
4	2	0	7
5	2	1	6
6	2	0	7

m-n

	>	=	<
1	4	1	4
2	4	0	5
3	2	1	6
4	4	1	4
5	4	2	3
6	5	2	2

is found for the pair [b̥-d̥], but the average difference is only 1 Hz. Fo after [g̊ʰ] and [g̊] are also slightly higher than after [b̥ʰ] and [b̥] but not very consistently so. After nasals there is no effect of place of articulation on Fo.

2. LARYNX HEIGHT

The larynx tends to be higher for alveolars than for labials, especially at the beginning of the following vowel. This applies to aspirated and unaspirated stops and nasals alike, and the tendency is fairly consistent. At the midpoint of the first pre-tonic and at the beginning of the consonant the velars give rise to a higher larynx position than do labials and alveolars, most markedly so in PD's [i]- and [ɑ]-words. In the following vowel [g̊ʰ] seems to associate with [b̥ʰ] (i.e. to be lower than [d̥ʰ]), whereas [g̊] associates with [d̥] (i.e. is higher than [b̥]).

D. THE ASSOCIATION BETWEEN LARYNX HEIGHT AND FUNDAMENTAL FREQUENCY

In order to assess quantitatively the overall degree of association between larynx height and fundamental frequency, a correlation analysis (Pearson's r) was made. Since Fo and larynx height vary not only as a function of the type of consonant, which is the variation in focus here, but also as a function of time over the reference points and as a function of vowel quality, it was necessary to eliminate these effects by expressing any mean Fo and larynx height as the deviation from the grand mean over the 10 consonants at each reference point and in each vowel. In figure 15 the normalized means are plotted, Fo against larynx height. It is seen that there is some degree of association between the two variables. The correlation coefficient is 0.409. This is not very high, but because of the great number of data points (540 = 3 subjects x 3 vowels x 10 consonants x 6 reference points) it is highly significant, $p < 0.001$. By squaring the correlation coefficient a measure can be derived of that portion of the entire variation in one variable which can be accounted for by the variation in the other ($r^2 = s_{y'}^2/s_y^2$). Thus, in the present material, 17 per cent of the entire Fo variation can be explained by the variation in larynx height.

IV. DISCUSSION

The results of the present study are in good agreement with those of previous investigations in the field. This applies not only to the magnitudes and directions of the main effects of consonants on larynx height and fundamental frequency in the following vowel, but also - and to a higher degree, perhaps - to the tendency for the pattern of influence of consonants on larynx height to be subject to variation between subjects and vowel qualities, whereas Fo shows a considerably more consistent pattern of variation over the entire material.

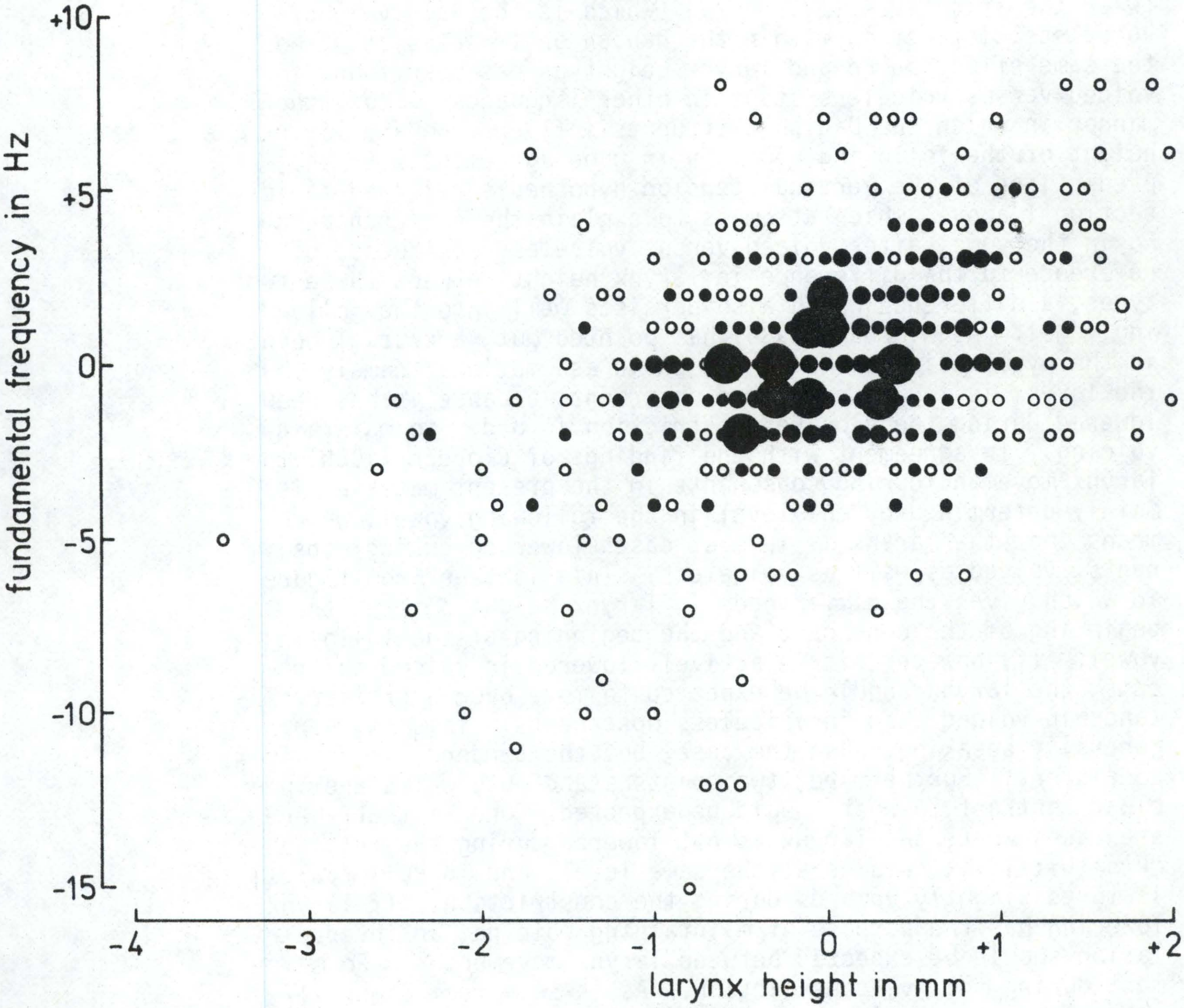

Figure 15

Fo means versus larynx height means. The number of data points at each pair of coordinates is indicated as follows: ○ = 1, • = 2-3, ● = 4-6, and ⬤ = 7 or more data points. The total number of data points is 540, viz. 3 speakers x 3 vowels x 10 consonants x 6 reference points.

One of the main findings of the present experiment is that both Fo and larynx height tend to be low following the voiced obstruent [v] and high following the voiceless obstruents. In this connection it is worth noting that the distinction between the fricatives [f] and [v] (which is the only voiced/voiceless distinction within the Danish obstruent system) has the same effect on Fo and larynx height as has been found for voiced versus voiceless stops in other languages. Thus, the manner in which the Danish obstruents influence Fo and larynx height of the following vowel is in good agreement with the predictions of the vertical tension hypothesis referred to in section I above, which attempts to explain the difference in Fo in the vowel after voiced versus voiceless obstruents by reference to the difference in larynx height between these two types, a difference which also persists well into the following vowel. As Riordan (1980) has pointed out, a crucial point in the hypothesis is one of its basic assumptions, namely that the larynx is low after voiced obstruents because it has been lowered during the closure/constriction in order to maintain voicing. In agreement with the findings of Riordan (1980) the larynx movement during consonants in the present material is mainly determined by the level in the following vowel, which means that the larynx is in most cases lowering during consonants, voiced as well as voiceless. This is seen from figure 16 which gives the differences in larynx height between the beginning of the consonant and the beginning of the following vowel. If, however, it is actively lowered in voiced obstruents, the larynx should be expected to move over a greater distance in voiced than in voiceless obstruents. This is, very generally speaking, also the case, but the tendency is far from consistent. Furthermore, two points stand out, which are in clear contrast to what should be expected. One is that there are cases where the larynx is not lowered during the [v]; in NR's [viːfi] it remains at the same level, and in PD's [vɑːfi] it moves slightly upwards during the constriction. If larynx lowering has the purpose of maintaining voicing, an inverse relation should be expected between larynx movement and Fo movement during the [v]-constriction. As is seen from figure 17, where Fo movement (from the beginning of the consonant to the Fo minimum at or near the end of the consonant) has been plotted against larynx movement, the extent and direction of larynx displacement has no influence on Fo, not even in the cases of no or upward displacement; if anything, the correlation is positive.

The other point which speaks against the assumption that the larynx is lowered in order to maintain voicing is the behaviour of the nasal consonants. Not only is the larynx lower in the vowel after nasals than after [v] but the larynx is also displaced farther downwards during nasals than during [v], although the purpose of the larynx lowering can hardly be to preserve a sufficient pressure drop across the glottis for voicing to be maintained during the nasal consonants. The nasal consonant

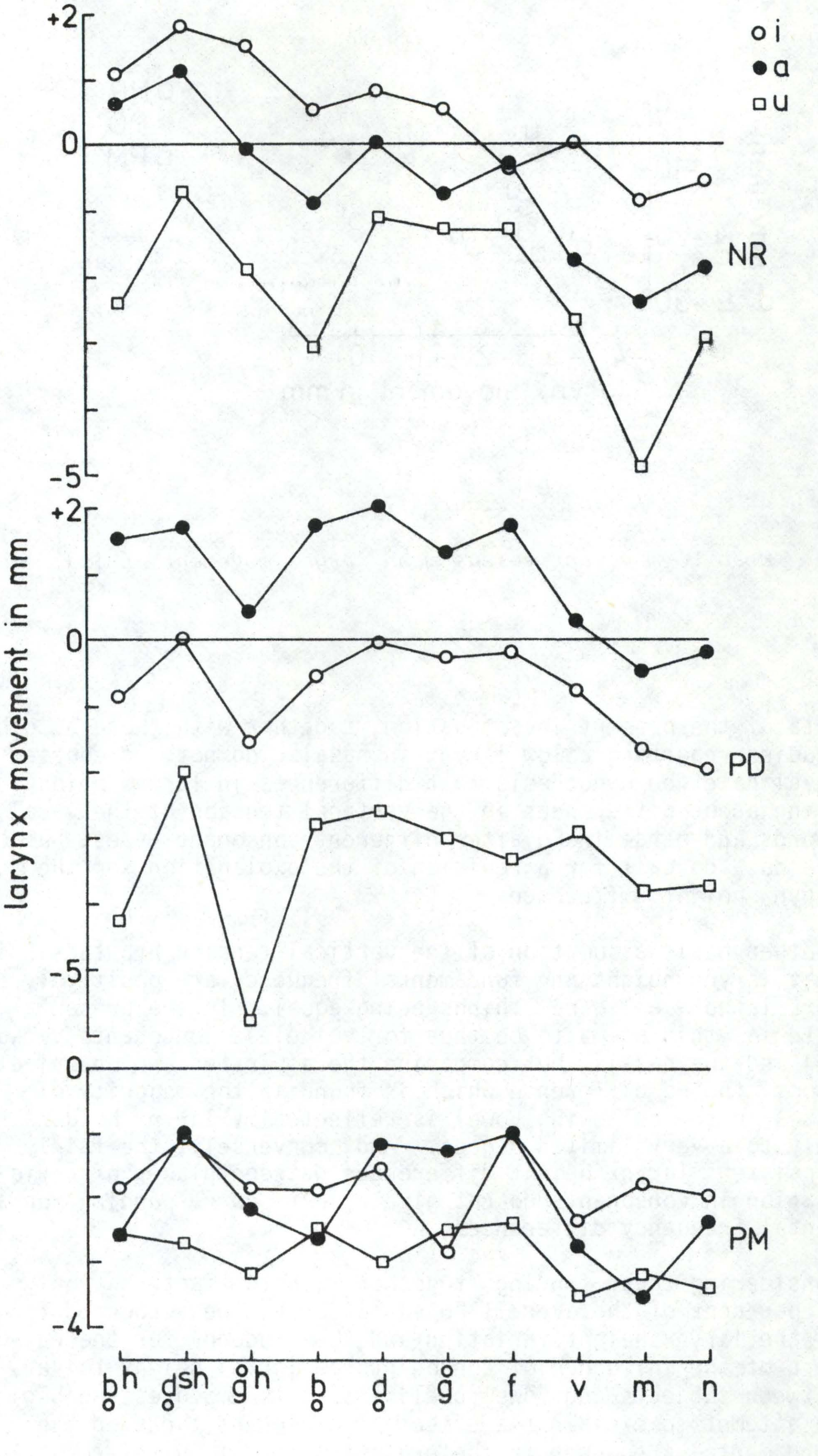

Figure 16

Mean larynx movement in mm during the test consonant. A positive value indicates an elevation of the larynx and a negative value a lowering of the larynx.

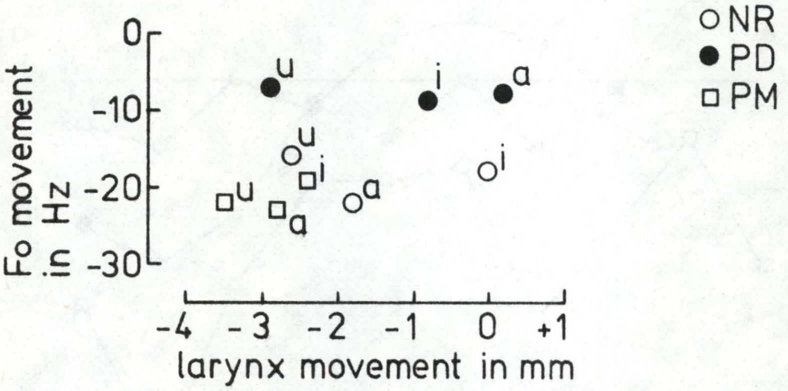

Figure 17

Mean Fo movement versus mean larynx movement in [v].

data of the present investigation, together with those of other studies reporting a low larynx in nasals, do not, of course, invalidate the hypothesis that differences in larynx height bring about differences in the vertical tension of the vocal chords and hence in Fo after different consonant types, but the data do call for a revision of the explanation for the larynx height differences.

Another basic assumption of the vertical tension hypothesis is that larynx height and fundamental frequency are positively correlated - all other things being equal. In the present material this seems to be true for voiceless consonants versus [v] and the nasals, but comparing the aspirated and unaspirated stops, the Fo difference which is found in the majority of cases in the following vowel is reflected by larynx height only to a very limited degree. And, conversely, the fairly consistent larynx height differences between places of articulation in consonants do not give rise to corresponding fundamental frequency differences.

Considering these findings together with the fact that only 17 per cent of the overall Fo variation can be accounted for by the larynx height variation and the tendency for the pattern of the influence of consonants on larynx height to vary between subjects and vowel qualities, it seems questionable to attempt to explain the effect of consonant types on the fundamental frequency in the present material by reference to the vertical position of the larynx.

V. NOTE

1. The material was designed so as to investigate the effect of vowel quality on Fo and larynx height, also. The analysis of the results from that point of view will be dealt with in a later paper.

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