INTRINSIC FUNDAMENTAL FREQUENCY OF DANISH VOWELS

Niels Reinholt Petersen

Abstract: In a number of languages the intrinsic F_o of vowels has been reported to be positively correlated with tongue height.
Measurements of the fundamental frequencies of Danish vowels showed a similar correlation to exist in Danish. The F_o differences between high and low vowels were greatest in long vowels in stressed position, but also short vowels in unstressed position differed with respect to intrinsic F_o, although to a much lesser degree. The hypotheses advanced to account for the intrinsic F_o differences are briefly outlined, and discussed in relation to the results of the present and other similar experiments.

1. Introduction

There seems to be a tendency for the fundamental frequency (F_o) of vowels to be correlated with their quality. Low vowels have - other things being equal - a lower F_o than high vowels. This tendency has been reported e.g. for English by Black (1949), Peterson and Barney (1952), House and Fairbanks (1953), Lehiste and Peterson (1961), Peterson (1961), Mohr (1971), for Korean by Kim (1968) (cited in Mohr 1971), for Serbo-croatian by Ivić and Lehiste (1963) (cited in Lehiste 1970).

Various hypotheses have been advanced to explain the connection between tongue height and intrinsic F_o of vowels. The most recent ones will be briefly outlined below:

Mohr (1971) assumes a pressure of air to be built up behind the supraglottal constriction, which reduces the airflow through the glottis and consequently the rate of vocal fold vibration. According to Mohr's hypothesis it is so that the greater the distance between the constriction and the glottis, the longer it takes for the air pressure to be established behind the constriction and hence for the fundamental frequency to drop. If this explanation were true, a higher F_o should be expected in [i] than in [u]. What is generally found, however, is that the F_o of [u] is equal to or - more often - higher than that of [i]. Furthermore, vowels of medium tongue height in the front series should have a higher F_o than [i], since their constriction is less narrow than that of [i]. This prediction, however, is also contradicted by data.

Another hypothesis rests on the assumption that the glottis impedance is sufficiently low for some coupling to occur between the vocal tract and the glottis (see e.g. Flanagan and Landgraf 1968, Lieberman 1970). If this is so the first resonance of the vocal tract will cause a change, i.e. an increase, of the fundamental frequency. Since such an effect becomes greater the closer the resonance in question is to the F_o range, vowels with low first formants (e.g. [i] and [u]) will have a higher fundamental frequency than low vowels (e.g. [ɑ]), which have high first formants.

The question whether the glottis impedance is sufficiently low for this effect to be active seems still open for discussion.

Contradictory to this hypothesis, however, the findings reported in Beil (1962) indicate that vowels spoken in a mixture of atmospheric air and helium, which raises the formant frequencies of all vowels, have essentially the same F_o relations as vowels spoken in atmospheric air alone, although the coupling hypothesis would predict smaller F_o differences in "helium vowels" than in "normal" vowels.

A third hypothesis which has been forwarded to explain the intrinsic F_o differences assumes that the tongue, when elevated for the production of high vowels, pulls the hyoid bone and the larynx upwards (Ladefoged 1964, Lehiste 1970). This vertical pull is thought to be translated into an increased vocal cord tension, which in turn leads to a higher F_o.

This explanation is contradicted by the fact that the hyoid/larynx position always seems to be lower in [u] (and sometimes in [i] as well) than in [ɑ], although vowels having high tongue positions might be expected to have high larynx positions, since larynx height and F_o are normally positively correlated. Ohala (1973) points out, however, that the negative correlation between tongue height and hyoid/larynx height need not invalidate the tongue pull hypothesis; it merely suggests that the variations in vocal cord tension, which may be assumed to underlie the intrinsic F_o differences are not likely to be due to changes of the larynx/hyoid position. Ohala advances another explanation according to which the increased tongue pull in high vowels gives rise to increased vertical tension in the vocal folds. The vertical tension can be established exclusively through the mucous membrane and other soft tissues without involving the hyoid bone and the hard tissues of the larynx. In support of this explanation Ohala cites data on the size of Morgagni's ventricles (van den Berg 1955, and Shimizu 1961). It appears that there is a positive correlation between ventricle size, which is assumed to reflect vertical tension in the vocal cords, and tongue height and intrinsic F_o of vowels.

The tongue pull hypothesis has been expanded by Ewan (1975). Ewan suggests that in order for a sufficiently low first formant to be produced in the vowel [u], the supralaryngeal cavities are expanded by means of an active downward pull of the larynx. This seems to account for the low larynx position of [u] in spite of its high intrinsic F_o. Furthermore, since it may stretch the soft tissues of the larynx and thus add to the tension created by tongue pull, the active lowering of the larynx in [u] might also explain why the intrinsic F_o of that vowel is often found to be higher than the intrinsic F_o of [i].

In addition to tongue pull - or, rather, lack of tongue pull - Ewan proposes a "tongue retraction/pharyngeal constriction component" to account for the low intrinsic F_o of low vowels. He builds upon data on Arabic, from which it appears that the F_o of a vowel following a pharyngeal consonant (where the retraction/constriction component is effective) is lower than the F_o of a vowel following a stop consonant without any such component. Ewan suggests that the low F_o of low vowels, which are also assumed to involve a tongue retraction or pharyngeal constriction component, is caused by the soft tissues being pressed downwards in the direction of the larynx and thus increasing the vibrating mass of the vocal folds, which results in a decrease in F_o. The pressure of soft tissues behind the hyoid bone may also push the hyoid bone slightly upward and forward and thus explain the relatively high hyoid/larynx position of low vowels.

Although it needs further substantiation, the tongue pull theory as modified by Ohala and Ewan seems to be that one among the current theories advanced to account for the intrinsic F_o differences among vowels which shows the best agreement with available data.

The main purpose of the experiments to be reported below was to investigate whether F_o differences between high and low vowels might also be found to exist in Danish, and to estimate the order of magnitude of these differences. Such information will be relevant to investigations of Danish intonation (cp. Thorsen, this issue), as it may help to separate the F_o variation attributable to the intonation proper from variation conditioned entirely by segmental factors - in this case tongue height.

Thus, although it was not the primary purpose of the present investigation to obtain data to evaluate the hypotheses outlined above, it will, of course, be examined whether or not the results are in agreement with the predictions of the hypotheses.

2. Experimental procedure

2.1 Material

The material consisted of the Danish long vowels [i:, e̞:, ɛ̞:, æ:, ɑ:, y:, ø:, œ̞:, u:, o̞:, ɔ̞+:] (henceforth referred to as [i, e, ɛ, a, ɑ, y, ø, œ, u, o, ɔ]) occurring in nonsense words of the type $p^hV'p^hV{:}p^hV$, the vowel being identical in each of the three syllables. The intention was primarily to carry out measurements of the fundamental frequency of the long, stressed vowels, but the type of words chosen made it possible to obtain measurements from short vowels in pretonic and posttonic position as well. The material also included words of the same type as above, but having [b̥], [f], and [m] instead of [p^h] (combined with the vowels [i, ɑ, u] only), so that the relation between F_o in these vowels and the manner of articulation of the neighbouring consonants might be examined. Thus the material comprised 20 different testwords, i.e. 11 "p-words", 3 "b-words", 3 "f-words", and 3 "m-words". The words were embedded in the carrier sentence "Stavelserne i ...... forkortes." ('The syllables of ...... are shortened.').

In order to prevent a tendency towards rhythmicization during the reading of the list, 20 "dummy-sentences" were incorporated in the material. The forty sentences were arranged in five different randomizations in the reading list, the limitations to the random order being, however, that no more than three test sentences or dummy sentences should occur in immediate succession, and that each page of the list should start and end with a dummy sentence.

2.2 Recordings and speakers

The recordings took place in an anechoic chamber by means of professional recording equipment. Two female subjects (BH and JG) and three male subjects (JB, SH, and NRP) acted as speakers.

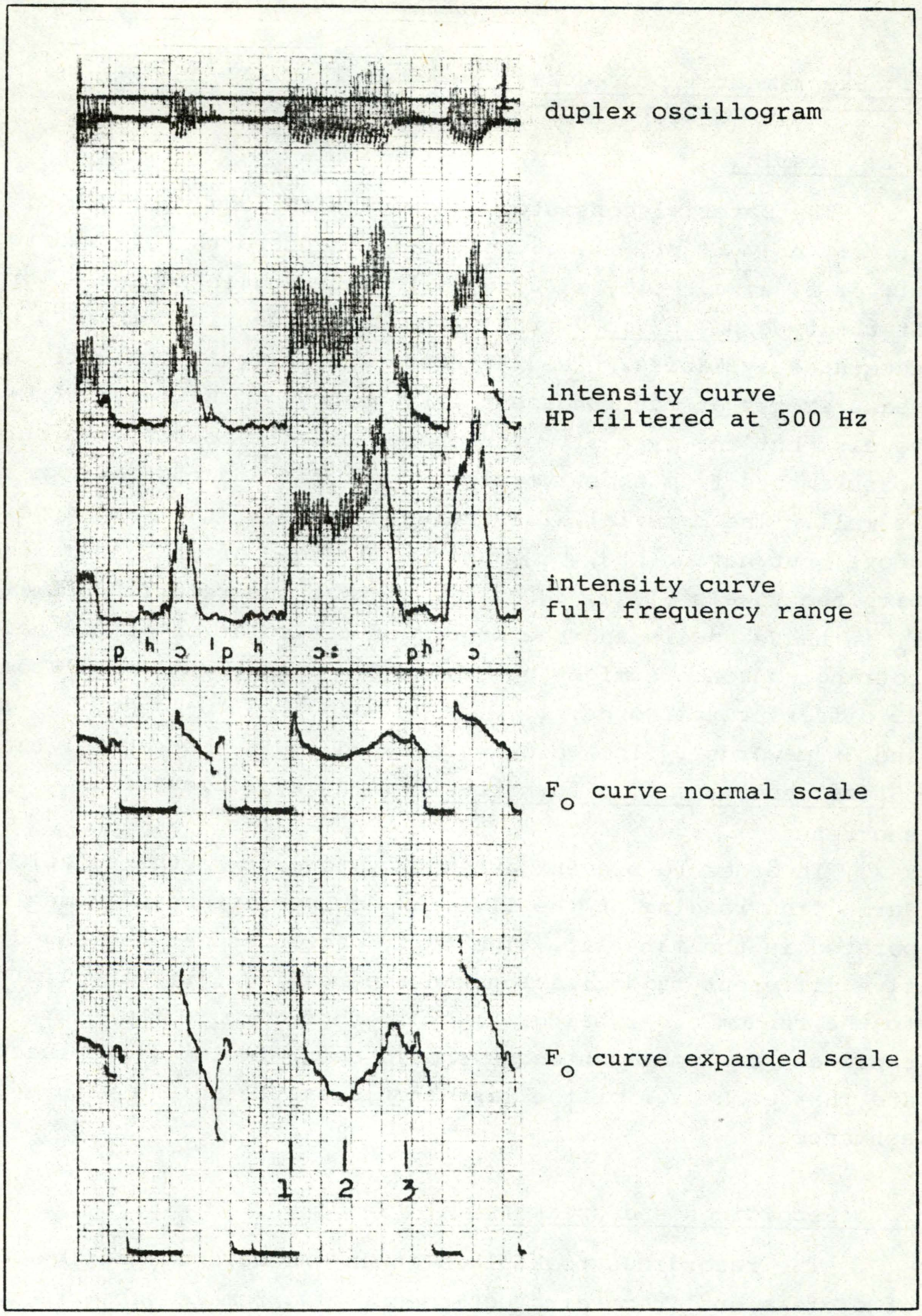


Figure 1

Example of curves of the testword [$p^hV{}^{\prime}p^hV{:}p^hV$]. The figures under the expanded scale F_o curve refer to start of vowel, point of measurement, and end of vowel, respectively.

They were all phoneticians, and all speakers of Advanced Standard Copenhagen Danish (see Basbøll 1968). Each subject read the list twice, at intervals between a few hours and a couple of days.

2.3 Registrations

The apparatus used for registration of the recorded material was a semiprofessional tape recorder, an intensity-meter, a pitch-meter, and a mingograph. The following acoustic curves were obtained:

1) duplex oscillogram
2) intensity curve, full frequency range
3) intensity curve, HP-filtered at 500 Hz.
4) F_o curve, normal scale
5) F_o curve, expanded scale (some 2 Hz per mm)

The oscillogram, the intensity curves and the ordinary F_o curve were used for segmentation, whereas F_o-measurements were made on the expanded F_o curve. The curves of one testword are shown in fig. 1.

2.4 Measurements

A preliminary examination of the F_o curves was made in order to establish a well defined point of measurement. It was found that the long, stressed vowels in the p-, b- and f-words in almost all cases had a falling-rising F_o movement with a minimum in the middle third of the vowel (see fig. 2a). This minimum was chosen as the point of measurement, not only because it was clearly defined but also because it occurred in a portion of the vowel where the influence from surrounding consonants may be considered to be minimal. In a few cases, however, the F_o movement was either monotonically rising (see fig. 2b), or (very rarely) falling during the greater part of the vowel. Under these circumstances the fundamental frequency was measured at a point corresponding

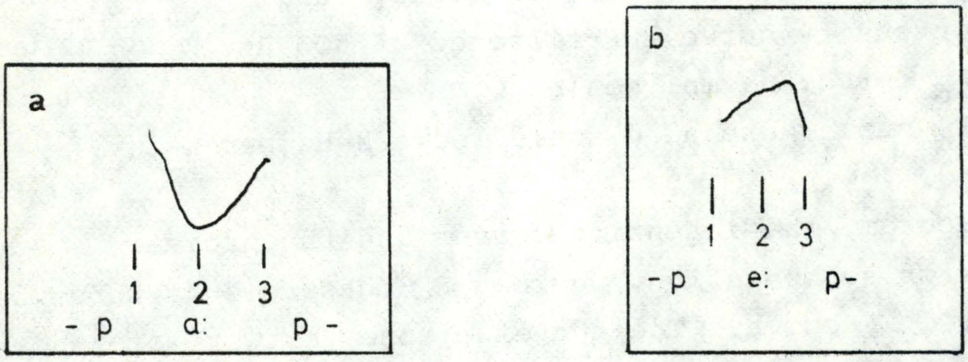


Figure 2

Examples of F_o movements in long stressed vowels. a) movement with a clear minimum point, b) monotonically rising movement. The figures 1, 2, and 3 refer to point of vowel start, point of measurement, and point of vowel end, respectively.

approximately in time to the point chosen in cases where a clear minimum could be seen.

In the m-words containing the narrow vowels [i] and [u], it proved difficult, and in numerous cases impossible, to carry out a reliable segmentation, and consequently to determine a point of measurement with reasonable certainty. Therefore, it was decided to exclude the m-words from the material to be measured. Nor was the F_o of pretonic and posttonic vowels submitted to a quantitative treatment, since these vowels showed F_o movements which did not make it possible to determine a reliable point of measurement. Moreover, these F_o movements displayed considerable variation in their position on the frequency scale (see figs. 9 and 10 below).

2.5 Statistical treatment

In the statistical computations the subjects were treated individually, and for each subject the p-, b-, and f-words were kept apart.

A t-test for correlated data was applied in order to determine whether the two readings for each speaker might be pooled. If $p > .05$ the recordings were pooled, otherwise they were treated separately.

By means of a one-way analysis of variance it was examined whether the obtained F_o data for the different vowels might have been drawn from same or different populations. Since, however, the vowels differed not only in tongue height but also in place of articulation and rounding, the analysis of variance had to be supplemented by a multiple comparison procedure (Scheffé's method) in which the mean F_o of every vowel was compared with the mean F_o of every other vowel.

3. Results

3.1 Comparison of the first and second recording

With two of the speakers (BH and JG) the t-test revealed significant differences between the two recordings, the second recording being lower than the first in all cases. The differences were for BH 11.2 Hz in the p-words, 11.6 Hz in the b-words, and 10.5 Hz in the f-words, and for JG 11.6 Hz, 5.6 Hz, and 14.1 Hz, respectively.

The second recording of speaker NRP was slightly higher than the first one for the p-words. Although the difference was only 1.5 Hz it was statistically significant ($p < .01$). For the b- and f-words no significant difference between recordings could be shown with that subject.

The two recordings of the speakers SH and JB were not significantly different ($p > .05$). This applies to all three types of words.

3.2 Fundamental frequency versus vowel quality

3.2.1 p-words

The mean fundamental frequencies for each of the 11 vowels in the p-words are given in table 1 and are shown graphically in fig. 3. The computed F-values (indicating the ratio of the between group variance to the within group variance, s_b^2/s_w^2) shown in the bottom row of table 1 were in all cases statistically significant ($p < .01$).

It becomes evident from the multiple comparison results, as summarized in fig. 4, that the F_o differences between the vowels are due to tongue height rather than to place of articulation or rounding. Here the number of significant differences ($p < .05$) over all subjects are given for every vowel compared with every other vowel. It is obvious that the number of significant differences increases with the difference in tongue height between

Table 1

Average F_o in Hz for each of the 11 vowels in the p-words. Recordings are pooled or kept apart according to the criteria stated in section 2.5. Unless otherwise stated each mean represents 5 observations. In cases of fewer observations, their number is given in brackets after the mean in question. In the bottom line the computed F values are indicated.

	Subject							
	BH		JG		JB	SH	NRP	
	recording 1	recording 2	recording 1	recording 2	recording 1+2	recording 1+2	recording 1	recording 2
i	219.4	212.2	210.8	201.0	141.8	125.7	93.4	95.0
e	211.4	199.6	203.4	189.8	130.7(9)	118.8	91.2	91.6
ɛ	197.0	188.2	195.4	184.0	128.9	113.3	87.6	88.4
a	198.6	185.6	195.2	181.8	125.2	109.9	85.0	87.8
ɑ	188.2	174.8	185.8	176.6	118.3	110.9	83.2	87.2
y	220.0	212.2	219.2	207.8	143.1	123.5	95.8	96.2
ø	215.4	203.6	206.0	194.4	133.6	118.3	89.8	93.2
œ	199.8	188.0	195.2	185.8	132.7	114.2	88.0	87.2
u	225.2	213.0	230.2	213.8	144.5(9)	126.5	95.0	96.6
o	220.0	208.8	307.8	196.4	138.4(9)	121.1	91.8	93.2
ɔ	204.8	190.8	195.6	186.0	133.3	115.7	89.4	90.6
F	11.918	17.916	18.785	26.077	19.350	37.495	17.944	7.296

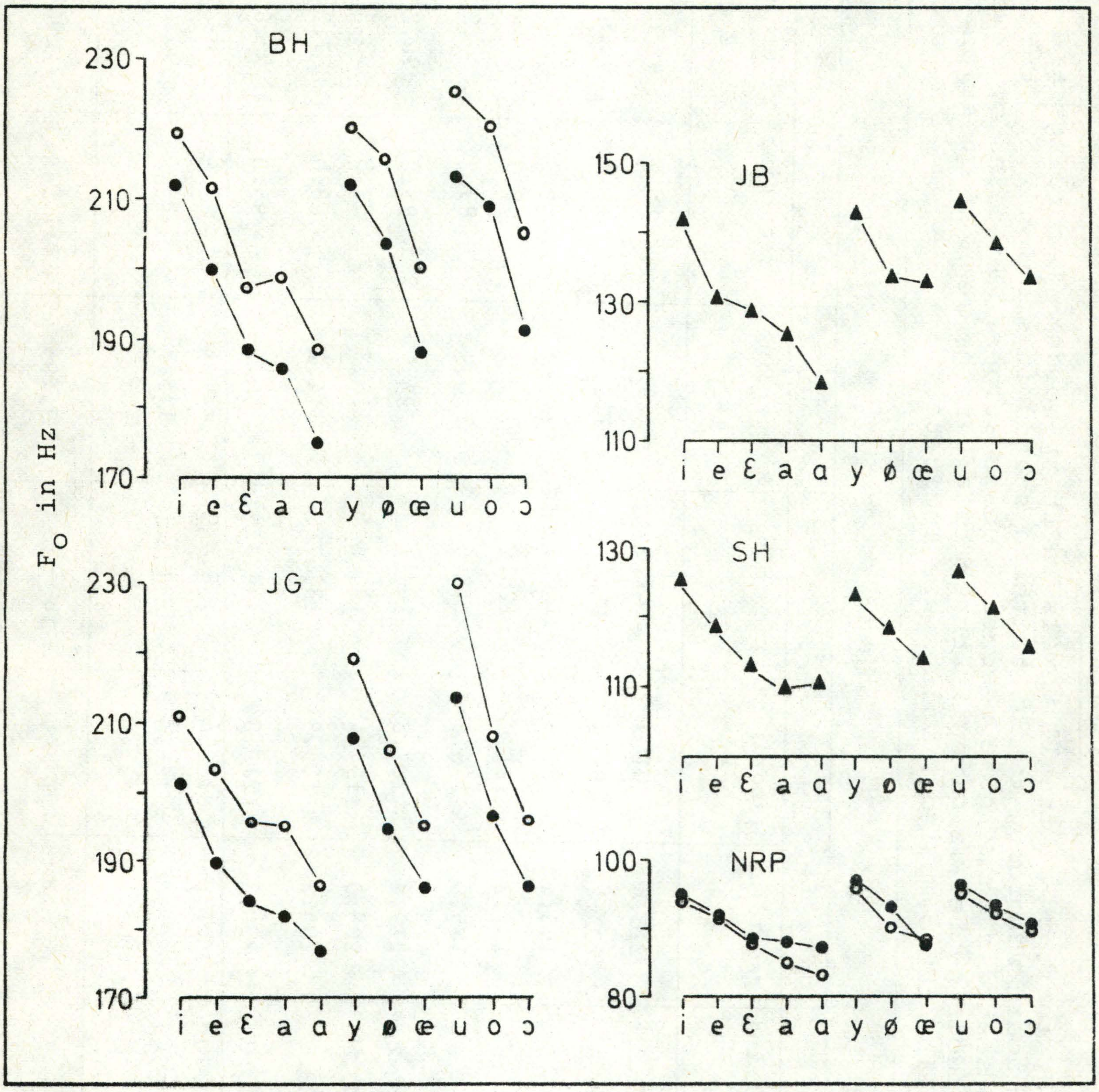


Figure 3

Average F_o in Hz for each of the 11 vowels in the p-words. Open circles refer to the first recording, filled circles to the second recording. Triangles represent the averages over both recordings in the cases where they were pooled.

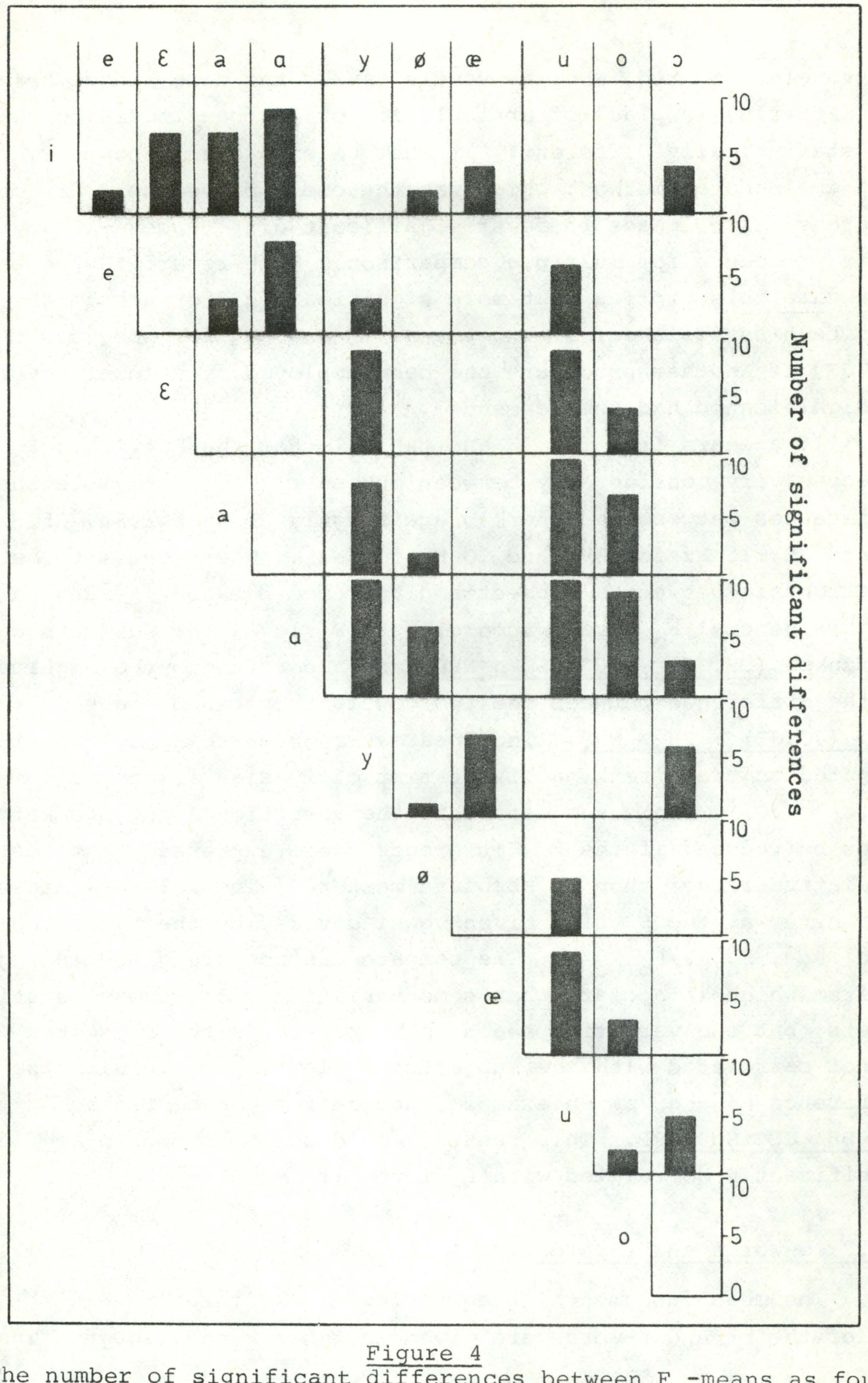


Figure 4

The number of significant differences between F_o-means as found by multiple comparison of all vowels in the p-words. In the cases where the first and second recordings were pooled one significant difference was given value 2, the number of significant differences for a comparison of two vowels thus being 10.

the vowels compared, whereas vowels having the same tongue height but differing in place of articulation or in rounding in no cases are statistically different. It must be emphasized, however, that the Scheffé method, which was the one employed here, is more rigorous - i.e. leads to fewer significant differences - than any other procedure for multiple comparison. With regard to the present data this implies that more significant differences might have been established, e.g. between [i] and [u] for subjects BH and JG, if another procedure had been employed or a lower level of significance had been demanded.

It appears from fig. 3 and table 1 that the intrinsic F_o differences vary considerably between subjects. As an example the differences between [ɑ] and [i] are roughly 35 Hz for BH, 25 Hz for JG and JB, 15 Hz for SH, and 10 Hz for NRP. There seems to be a relationship between a subject's difference between [i] and [ɑ] and his general F_o level: according to F_o level the subjects can be ranked (BH,JG) > JB > SH > NRP, and according to the magnitude of the difference between the two vowels they can be ranked BH > (JG,JB) > SH > NRP. The Spearman rank correlation coefficient computed on these rankings is statistically significant (r_s = .95, $p < .05$). This suggests that the variation among speakers might be reduced if the F_o differences were expressed in terms of a relative rather than an absolute measure. The relative measure used here was the F_o of a given vowel divided by the F_o of the vowel [ɑ], $F_{o(V)}/F_{o([ɑ])}$. The computed ratios are given in fig. 5, from which it appears that some variation among subjects still exists, but the variation seems to be random in the sense that it is not correlated with the subjects' F_o level. Again with the difference [i]-[ɑ] as an example, the ratios can be ranked JB>BH>JG>SH>NRP. This ranking could not be shown to be significantly correlated with F_o level (r_s = .67, $p > .05$).

3.2.2 b-words and f-words

The mean fundamental frequencies of the three vowels ([i, ɑ, u]) of the b- and f-words are given in table 2 and fig. 6. The

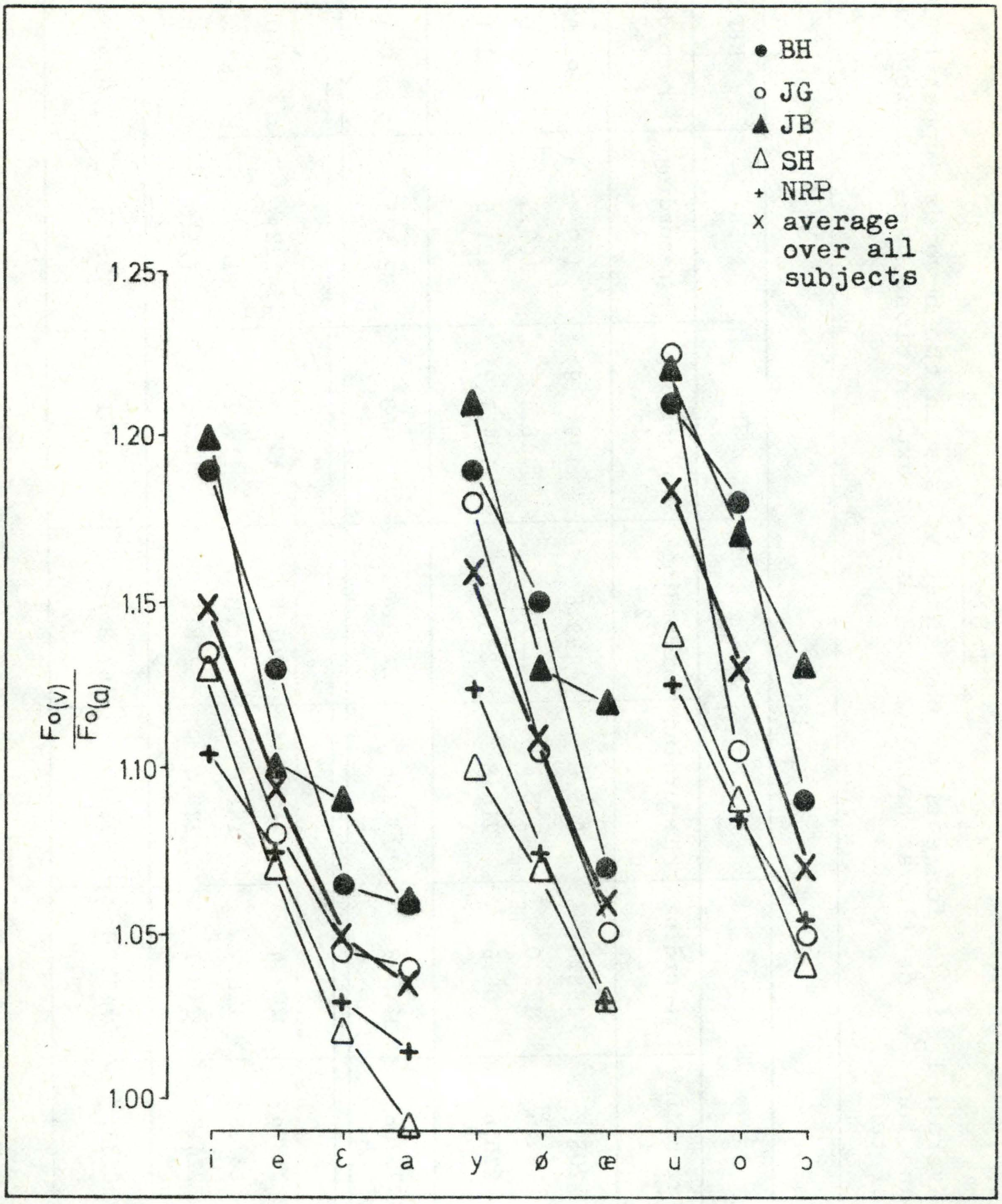


Figure 5

The relative difference between F_o of the vowel [ɑ] and the remaining 10 vowels of the p-words. The first and second recordings are pooled in all cases.

Table 2

Average F_o in Hz for each of the three vowels in the b-words (upper half) and the f-words (lower half). For further explanations, see the legend of table 1.

		Subject						
		BH		JG		JB	SH	NRP
		recording 1	recording 2	recording 1	recording 2	recording 1+2	recording 1+2	recording 1+2
b-words	i	208.8	198.8	205.0	199.8	139.0(9)	119.9	91.5
	ɑ	184.6	172.0	178.4	172.3	118.1	109.5	83.0
	u	220.8	208.6	216.8	210.6	139.7(9)	121.5	92.1
	F	177.708	33.549	173.236	84.514	22.060	32.573	55.094
f-words	i	219.6	209.4	215.0	201.8	142.3(9)	122.7	94.0
	ɑ	187.8	176.4	181.8	170.0	119.2	108.3	82.5
	u	226.2	216.2	225.4	208.2	144.4	124.0	95.1
	F	236.831	107.397	65.640	167.877	124.951	69.208	120.200

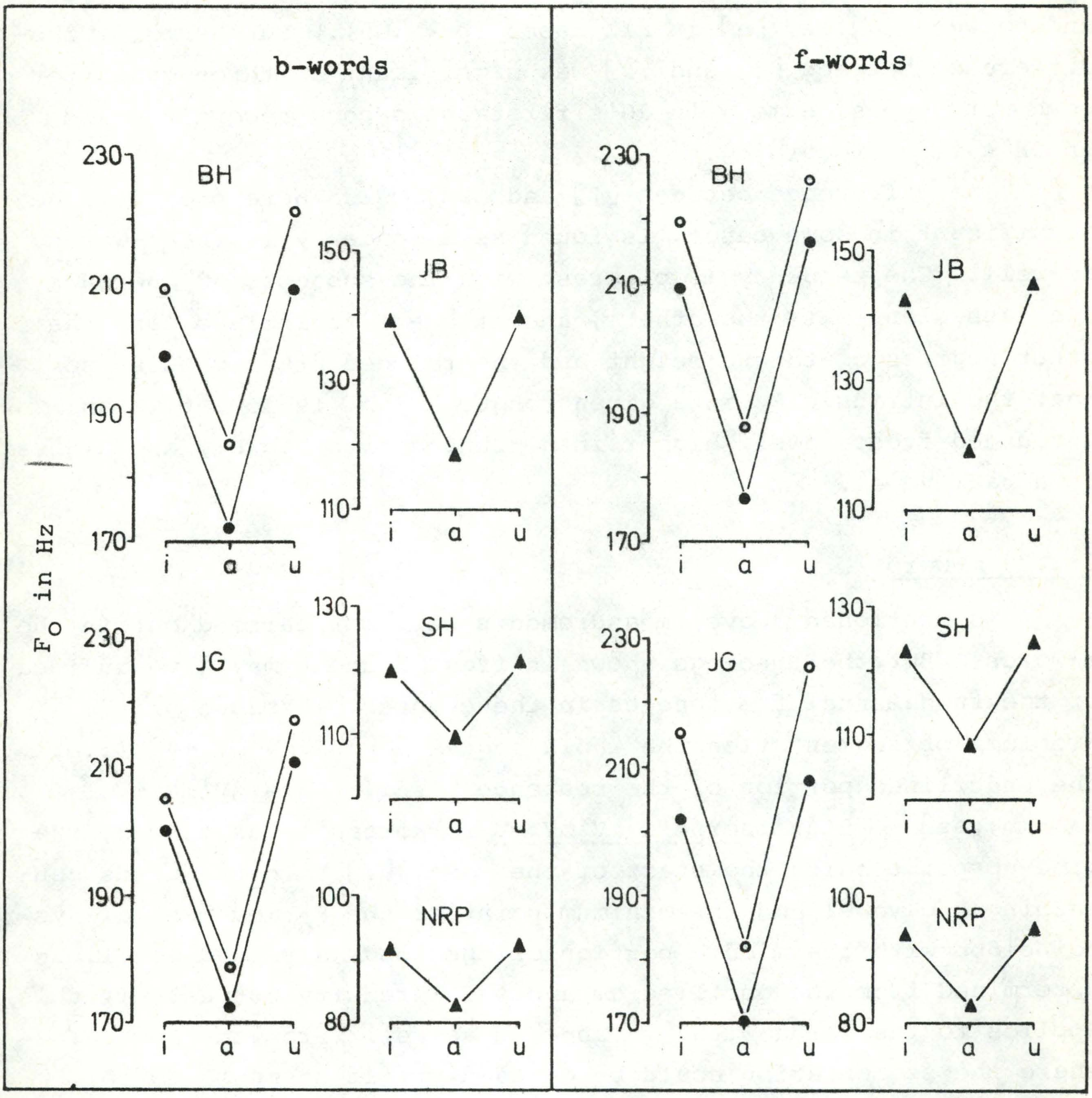


Figure 6

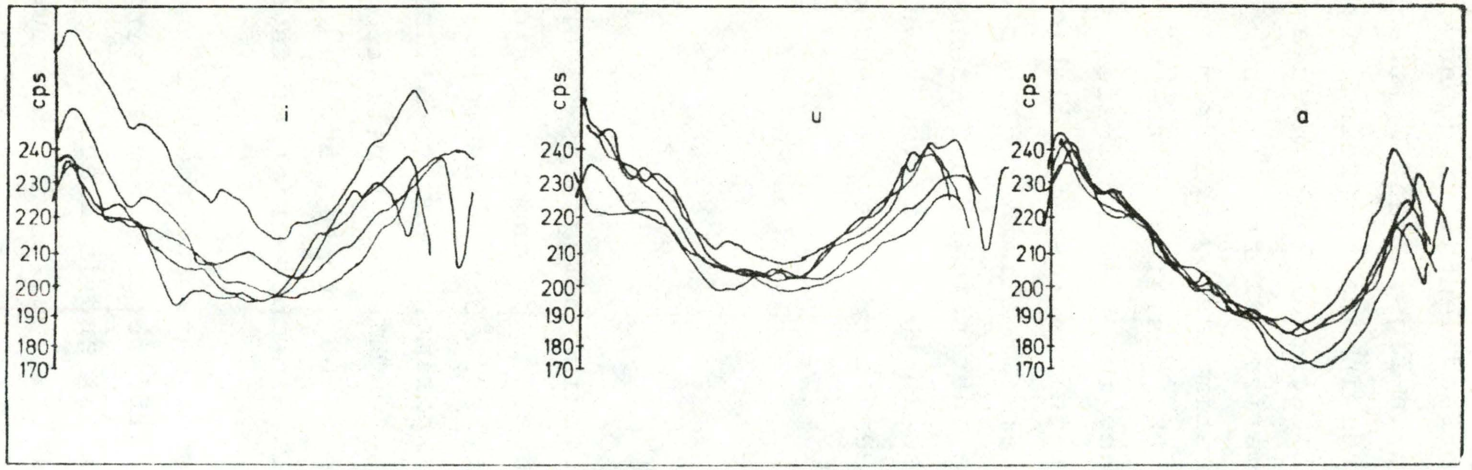
Average F_o in Hz for each of the three vowels in the b-words (left) and f-words (right). For further explanations, see the legend of fig. 3.

computed F-values (bottom row in the table) were all statistically significant ($p < .01$). For both word types the multiple comparison procedure showed significant differences between [i] and [ɑ] and between [u] and [ɑ] in all cases ($p < .05$). Furthermore, the difference between [i] and [u] was significant in three cases for both word types, namely in JG's first and second recordings and in BH's first recording.

The difference between [i] and [u], which here proved to be significant in some cases, is found as a tendency in the p-words as well. The tendency is clearest with the subjects JG and BH and less clear with the others, and it seems to include also the other degrees of tongue height and the rounded front vowels, so that the intrinsic F_o at a given tongue height is lowest in an unrounded front vowel, higher in a rounded front vowel, and highest in a back vowel.

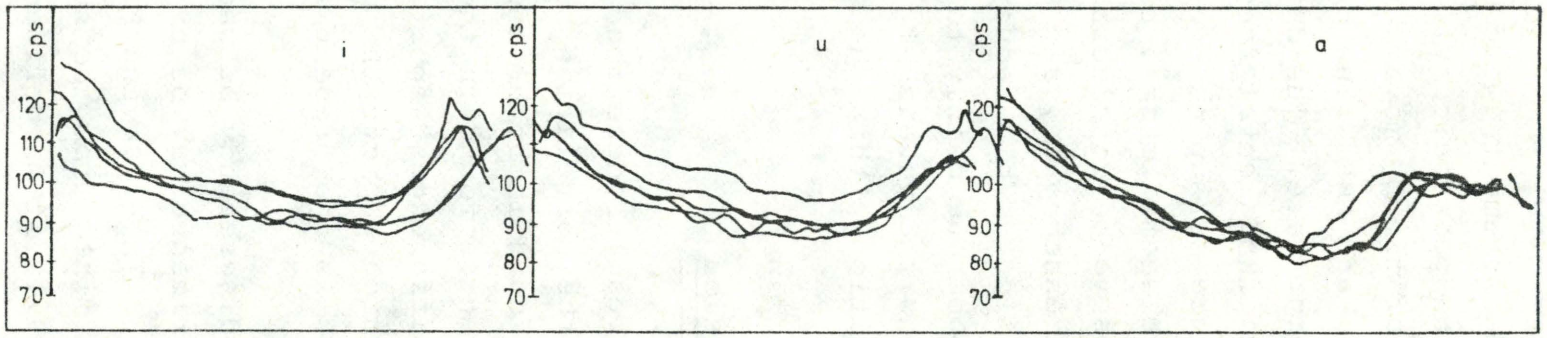
3.2.3 m-words

As mentioned above, measurements were not carried out in the m-words. But the tracings shown in figs. 7 and 8 may give an idea of the fundamental frequencies in these words. Because of the problems of segmentation the whole sequence [ʌnəimV'mV:mV] (i.e. the underlined portion of the sentence ['sg̊æ:ulsʌnəimV'mV:mV fʌ'kʰɒ:g̊əs] - "Stavelserne i mV'mV:mV forkortes") was traced, the line-up point being the start of the vowel [ʌ]. In the words containing the vowel [ɑ] the minimum point of the F_o movement always coincided with the middle portion of the long, stressed vowel, as determined from the oscillogram and the intensity curves. If this applies to the words with [i] and [u] as well (from the few cases where the segmentation could be guessed at, it seems to do so), the F_o movement in the m-words appear to be in good agreement with the movement in the word types where reliable measurements could be carried out. But, of course, a more thorough examination is needed before any safe conclusions can be drawn.



<u>Figure 7</u>

F_o tracings of m-words, BH's first recording.



<u>Figure 8</u>

F_o tracings of m-words, NRP's second recording.

3.2.4 Vowels in pretonic and posttonic position

No measurements were made of the fundamental frequency in pretonic and posttonic syllables. But in figs. 9 and 10 tracings are given of the F_o movements in f-words in one recording of the subjects JG and NRP. The beginning of each vowel was used as line-up point here. The data are summarized in fig. 11 where the average fundamental frequencies (estimated by eye from the tracings) are set up as a function of the position in the word.

There seems to be a clear tendency for the intrinsic F_o differences to be considerably smaller in unstressed syllables than in stressed ones, and even to be almost eliminated in pretonic position. This reduction of the intrinsic F_o differences appears to be due mainly to an increase in the F_o of the vowel [ɑ], whereas the vowels [i] and [u] seem to be less influenced by the position within the word.

4. Discussion

The results described in the preceding paragraphs clearly show that the correlation between tongue height and intrinsic F_o of vowels found in other languages exists in Danish as well. The differences found in the present experiment seem to be larger than the differences reported elsewhere. This is illustrated in fig. 12, which depicts the mean ratios of [ɑ] to [i] and [u] as established in the present study and in a number of other investigations.

The discrepancy between the present data and those found in other experiments may be explained by differences in measuring procedures. In House and Fairbanks (1953) and in Black (1949) F_o is determined from the number of glottal pulses in the vowel. In Mohr (1971) it is defined as the mean of the F_o values measured at the beginning, at the minimum point (lowest F_o), and at the end of the vowel.

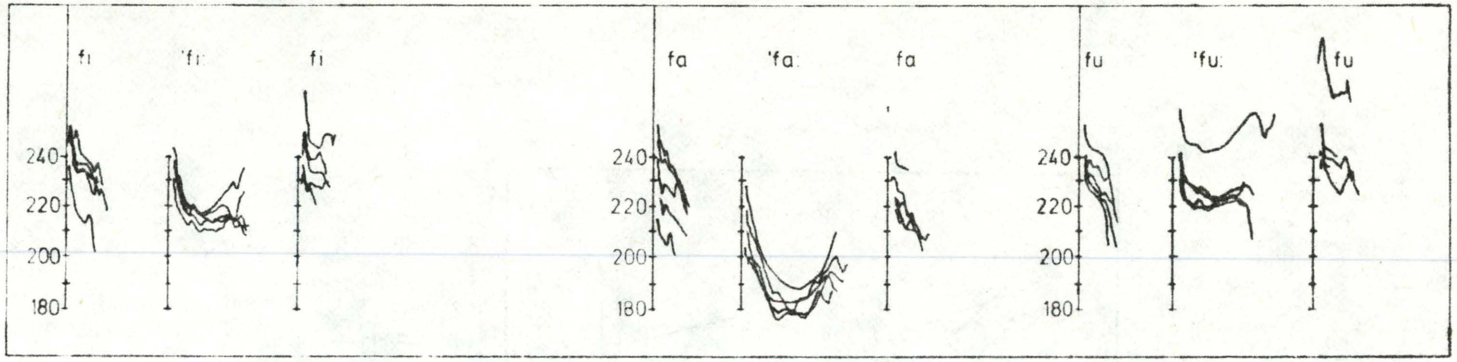


Figure 9

Tracings of F_o in pretonic, tonic, and post-tonic syllables in f-words. JG's first recording.

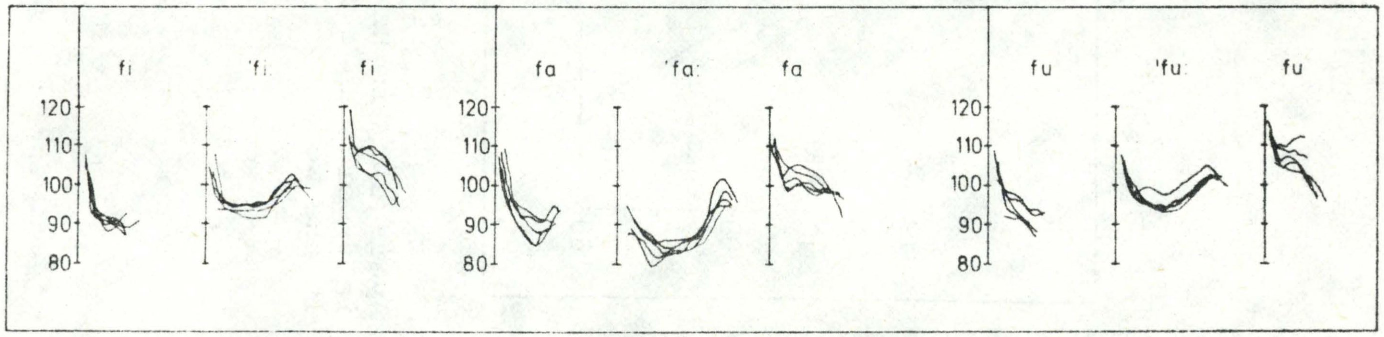


Figure 10

Tracings of F_o in pretonic, tonic, and post-tonic syllables in f-words. NRP's first recording.

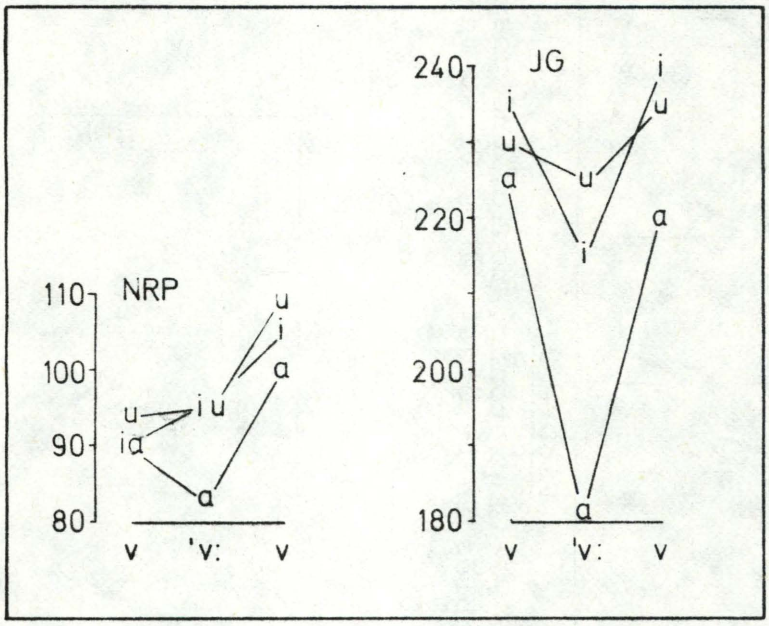


Figure 11

Average F_o in Hz in the vowels [i ɑ u] in f-words as a function of position in the word.

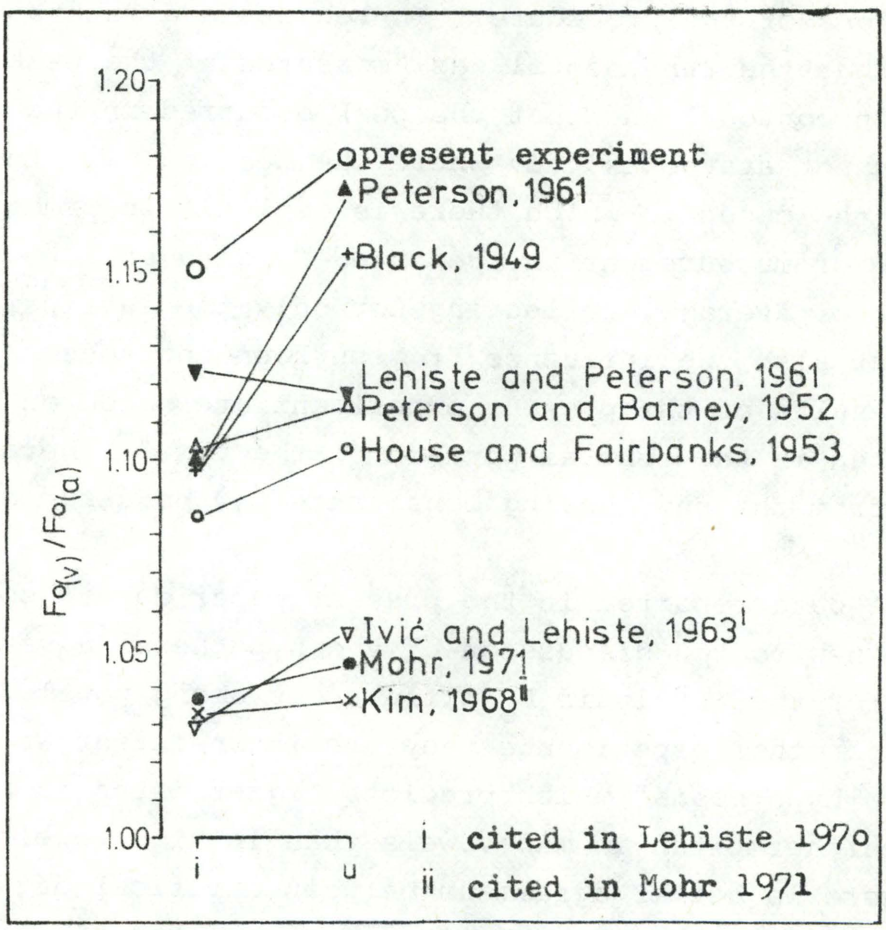


Figure 12

The ratios of [ɑ] to [i] and [ɑ] to [u] computed on the basis of data from the present and a number of other investigations.

The data from Kim (1968) were available to me only in the form of illustrations in Mohr (1971). In that paper (fig. 3) the F_o movements were given as straight lines connecting the F_o values at the beginning and end of the vowels. The points in fig. 12 were computed from the values reached at the mid point of the vowels. In Peterson and Barney (1952), in Peterson (1961), and in Ivič and Lehiste (1963) (cited in Lehiste 1970) there are no descriptions of the procedure. In Lehiste and Peterson (1961) it is said that the fundamental was "measured at the peak of the intonation contour" and that the peak occurred in the testword, but it is not stated exactly where the peak was within that word.

In the cases in which there is explicit information on the procedure of measurement the reported F_o data seem to represent some sort of average, reflecting not only the intrinsic F_o of vowels but also the influence from surrounding consonants, whereas the results of the present experiment are based on measurements taken in the central portion of the vowels where the influence from the surrounding consonants may be assumed to be minimal.

The data reported in the present paper do not contribute anything new to the discussion of the hypotheses advanced to account for the intrinsic F_o differences among vowels. Like the results of other experiments they are inconsistent with Mohr's "pressure hypothesis" which predicts higher pitch in [i] than in [u] and higher pitch in mid vowels than in high vowels.

There is better agreement between empirical data and the source/tract coupling hypothesis. However, the relationship between [i] and [u] stands out as a crux. The intrinsic F_o of [i] is generally lower than that of [u]. Now, since the hypothesis predicts an inverse correlation between F_1 and F_o, [i] should be expected to have higher F_1 than [u]. Nevertheless, we normally find the opposite relation, viz. a higher F_1 in [u] than in [i]. It may be assumed, therefore, that the intrinsic F_o differences cannot be fully accounted for by the source/tract coupling hypothesis alone.

As pointed out in section 1 of this paper, the modified tongue pull hypothesis seems to provide the best explanation of available data on the intrinsic F_o of vowels, particularly of the relation between the vowels [i] and [u]. Since the results of the present investigation are in good agreement with data obtained in other experiments, they may be considered to speak in favour of the tongue pull hypothesis. It must be emphasized, however, that the data reported here do not provide conclusive evidence. Such evidence will have to be based on physiological rather than acoustic data.

References

Basbøll, H. 1968: "The phoneme system of Advanced Standard Copenhagen", ARIPUC 6, p. 33-54

Beil, R.G. 1962: "Frequency analysis of vowels produced in a helium-rich atmosphere", JASA 34, p. 347-49

van den Berg, J. 1955: "On the role of the laryngeal ventricle in voice production", Folia Ph. 7, p. 57-69

Black, J.W. 1949: "Natural frequency, duration, and intensity of vowels in reading", JSHD 14, p. 216-21

Ewan, W.G. 1975: "Explaining the intrinsic pitch of vowels", Paper presented at the Fifth California Linguistics Association Conference, San Jose, May 4, 1975, p. 1-9

Flanagan, J. and L. Landgraf 1968: "Self-oscillating source for vocal-tract synthesizers", IEEE Transactions on Audio and Electroacoustics AU-16, p. 57-64

House, A.S. and G. Fairbanks 1953: "The influence of consonant environment upon the secondary acoustical characteristics of vowels", JASA 35, p. 84-92

Ladefoged, P. 1964: A phonetic study of West African languages: an auditory-instrumental survey (Cambridge)

Lehiste, I. 1970: Suprasegmentals (MIT Press)

Lehiste, I. and G.E. Peterson 1961: "Some basic considerations in the analysis of intonation", JASA 33, p. 419-25

Lieberman, P. 1970: "A study of prosodic features", Haskins SR 23, p. 179-208

Mohr, B. 1971: "Intrinsic variations in the speech signal", Phonetica 23, p. 65-93

Ohala, J.J. 1973: "Explanations for the intrinsic pitch of vowels", Monthly Internal Memorandum, Phonology Laboratory University of California, Berkeley, p. 9-26

Peterson, G.E. 1961: "Parameters of vowel quality", JSHR 4, p. 10-29

Peterson, G.E. and H.L. Barney 1952: "Control methods used in a study of the vowels", JASA 24, p. 118-27

Shimizu, K. 1961: "Experimental studies on movements of the vocal cords during phonation by high voltage radiograph motion pictures", Studia Phonologica 1, p. 111-16

Thorsen, N. 1976: "An acoustical investigation of Danish intonation: preliminary results", <u>this issue</u>.