ARIPUC 19, 1985, p. 95-141

FUNDAMENTAL FREQUENCY AND LARYNX HEIGHT IN SENTENCES AND STRESS GROUPS

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The paper reports experiments investigating a) the relation between larynx height and the slow overall fundamental frequency movement (declination) in sentences of varying length and type, and b) the relation between larynx height and Fo in the prosodic stress group. The aim of the experiments was to see in general to what extent the extrinsic laryngeal muscles could be assumed to be involved in the production of Fo, and as part of this to consider more specifically the question whether the fundamental frequency declination is actively controlled by the speaker in a linguistically purposeful manner, or whether - as has been suggested - it is an automatic consequence of the functioning of the pulmonic system. The results can be summarized as follows: In declarative sentences an overall decline was observed for Fo as well as for larynx height, and for both the slope of declination varied with sentence length, being steeper in short than in long sentences. In interrogative sentences Fo as well as larynx height showed either no decline or a slight rise over the sentence. These results are taken to indicate that Fo declination is actively controlled by the speaker, and it is suggested that it may be attributed primarily to the activity of the extrinsic laryngeal muscles. In the stress group the relation between larynx height and Fo seems to be far more complex, showing patterns which vary both among speakers and (to a lesser degree) within the individual speaker, and which have to be explained as the result of an intricate interaction of the activity of both intrinsic and extrinsic laryngeal muscles.

I. INTRODUCTION

One way of describing the fundamental frequency (Fo) variation in speech is to regard it as the composite result of the superposition of several components related to units of varying temporal scope, ranging from the text, through the utterance, sentence and phrase to the prosodic stress group. In addition to these components a microprosodic component will have to be specified, taking care of the segmentally conditioned Fo variation, such as inherent Fo levels of vowels and (voiced) consonants and effects exerted by consonants on the Fo of adjacent vowels.

The present paper will examine the association between fundamental frequency and larynx height in a Danish material as seen in relation to two of the above mentioned components, namely the sentence component and the stress group component. The basis for taking larynx height into consideration is the existence of a statistical relationship between LH and Fo (see e.g. Shipp 1975, Ohala 1973 and 1978, Ewan 1979) and the ability of the extrinsic laryngeal muscles to affect the vertical position of the larynx in the neck.

Apart from segmentally conditioned effects, the fundamental frequency variation associated with units of short temporal scope, such as the stress group, is generally believed to be caused by the activity of the intrinsic laryngeal muscles, particularly the cricothyroid muscle (see e.g. Collier 1975, Atkinson 1978, Honda 1983, Gelfer, Harris, Collier, and Baer 1983, and Ohala 1978, who gives an extensive review of the literature). But there is also evidence, although less consistent, perhaps, that the extrinsic laryngeal muscles take part in the control of local Fo movements. (See further Ohala 1970, Sawashima, Kakita, and Hiki 1973, Collier 1975, Erickson and Atkinson 1976, Atkinson and Erickson 1977, Erickson, Liberman, and Niimi 1977, Atkinson 1978, Honda 1983.) In an earlier paper (Reinholt Petersen 1984), I presented data showing that for two of the three subjects examined, a larynx rise accompanied the Fo rise from stressed to first posttonic syllable which is found in Standard Copenhagen Danish (see Thorsen 1979). The third subject had the opposite pattern, his Fo rise being accompanied by a larynx lowering. I shall not here enter into a detailed interpretation of these results, since they were essentially similar to those of the present study, which will be discussed below. Suffice it here to say that it was assumed that the extrinsic laryngeal muscles had been involved in the control of local Fo movements, and that the speakers had used two different strategies producing identical Fo movements.

In units of greater temporal scope, such as the sentence, there seems to be a universal tendency for the fundamental frequency in declaratives to fall gradually as a function of time. One of the central issues concerning this phenomenon, which has been termed Fo declination or downdrift, is whether it is to be explained as an automatic, i.e. not actively controlled, consequence of constraints in the speech production apparatus, or whether it is under active speaker control and part of the linguistic system.

The explanations adhering to the former view are based upon the fact that the lung volume gradually decreases as a function of time during speech. One such hypothesis takes its point of departure in Lieberman's (1967) theory which claims subglottal pressure to be the major source of Fo variation. The theory in its general form is hardly tenable (see e.g. Ohala 1978), but Collier 1975, and Gelfer, Harris, Collier, and Baer 1983, who investigated the EMG activity of various laryngeal muscles together with subglottal pressure, present data suggesting that in their material Fo declination could be accounted for by the gradually declining subglottal pressure which they observed, and which was assumed to be related to decreasing lung volume (see also Cohen, Collier, and 't Hart 1982).

Another explanation referring to the pulmonic system has been advanced by Maeda (1974). On the basis of the observation that the vertical position of the larynx - like Fo - shows an overall decline over the utterance, it is hypothesized that the decreasing lung volume causes a continuous lowering of the sternum, which via ligaments and muscular tissue pulls the larynx downwards with a fundamental frequency decline as the result. Other researchers, however, have not found the larynx lowering reported by Maeda; on the contrary, Gandour and Maddieson (1976) and Ewan (1979) report that - if anything - the larynx rises during the utterance.

Maeda (1979) gives a modified version of the hypothesis. In the material presented he also fails to find the Fo decline to be consistently accompanied by a larynx height decline, but he finds that the laryngeal ventricle shows an overall tendency to shorten during the utterance. Under the assumption that ventricle length can be used as an estimator of vocal fold length, the following mechanism is hypothesized: The decreasing lung volume exerts a pull upon the trachea. This pull is transferred to the cricoid cartilage and - if the thyroid cartilage is fixed - is thought to tilt the cricoid cartilage in relation to the thyroid cartilage, whereby the vocal folds are shortened and, consequently, Fo lowered.

The mere fact that fundamental frequency declination is so widespread in terminal declaratives among the languages of the world could be taken to speak in favour of the 'automatic' hypotheses outlined above. However, observation of Fo declination under various linguistic conditions provide strong evidence in support of the view that declination is under active speaker control as part of the linguistic system: Fo declination can convey information about sentence type and function as is the case in Danish (Thorsen 1979 and 1980a), where terminal declarative sentences have the steepest declination, syntactically and lexically unmarked questions have no declination, and non-final periods and interrogative sentences with word-order inversion and/or interrogative particle have intermediate degrees of declination. Furthermore, the slope of declination seems to vary with sentence length, being steeper in short than in long sentences (see e.g. Maeda 1974, Sorensen and Cooper 1980, Thorsen 1980b, 1981, and 1983). And as a final example, resetting (partial or complete) of the declination line has been shown to take place without intervening inhalation (Sorensen and Cooper, 1980, Thorsen 1980b, 1981, and 1983). Data of this kind are not easily accounted for by explanations basing themselves upon physiological constraints in the pulmonic system (or in any other part of the speech production apparatus for that matter).

In the study referred to above on Fo and larynx height (Reinholt Petersen 1984), results were reported indicating that Fo declination is somehow related to larynx height, the larynx as well as the fundamental frequency showing a gradual decline as a function of time through the sentence. But since sentence length and type were not varied (only declarative sentences of three stress groups were examined), these findings cannot be taken to support either of the views on fundamental frequency declination outlined above.

Therefore, the purpose of the experiments reported below was to investigate the relationship between Fo declination and larynx height variation in sentences of varying length and type in an attempt to gain information relevant to the question whether Fo declination is actively controlled or not, and to the discussion of the physiological mechanisms underlying it. Another purpose was to examine the Fo and larynx height variation attributable to the stress group component in a greater number of speakers, with the particular aim of looking for different strategies and, further, to expand the scope of investigation to include not only the relation between stressed and first posttonic syllables (as was done in Reinholt Petersen 1984) but the entire stress group, i.e. up to the next stressed syllable.

II. METHOD

A. MATERIAL

Two types of speech material were employed in the investigation. One (henceforth referred to as material A) was primarily designed with the purpose of examining overall Fo and LH variation in sentences of varying length and type (declarative versus interrogative). It consisted of the nonsense word ['fi:fi] which was inserted in carrier sentences containing from two to five stress groups as follows:

2.1 gi ['fi:fi] forklaring
2.2 forløbet i ['fi:fi]

3.1 i ['fi:fi] forkortes vokalen
3.2 vokalen i ['fi:fi] forkortes
3.3 vokalen forkortes i ['fi:fi]

4.1 i ['fi:fi] forkortes vokalen i starten
4.2 vokalen i ['fi:fi] forkortes i starten
4.3 vokalen forkortes i ['fi:fi] i starten
4.4 vokalen forkortes i starten i ['fi:fi]

5.1 i ['fi:fi] forkortes vokalen for meget i starten
5.2 vokalen i ['fi:fi] forkortes for meget i starten
5.3 vokalen i starten i ['fi:fi] forkortes for meget
5.4 vokalen forkortes i starten i ['fi:fi] for meget
5.5 vokalen i starten forkortes for meget i ['fi:fi]

The sentences have numbers indicating the number of stress groups in a sentence and the the position of the test word, e.g. 5.3 is the 5-stress-group-sentence where the test word occurs in the 3rd stress group. All sentences have an initial unstressed syllable followed by the appropriate number of stress groups, each consisting of a stressed syllable with a long vowel plus two unstressed syllables, except for the last stress group, which contains only one unstressed syllable. This design of the material made it possible, for each sentence length, to treat the measurements as if they had been extracted from only one sentence with that length. (It would have been asking too much of the speakers to have them read e.g. one five-stress-group sentence with five repetitions of ['fi:fi] in it.) All sentences were to be rendered with a neutral declarative intonation, but in order to obtain information about the effect of sentence type on Fo and larynx height the three-stress-group-sentences were also to be spoken on an interrogative intonation. Material A could also, of course, be used for looking into the relation between Fo and larynx height in stressed versus unstressed (1st posttonic) syllables. The material was spoken by three subjects.

The second material (henceforth material B), which was to be spoken by a larger group of subjects, was made up by the following sentences:

2.1 gi ['fi:fi] forklaring
2.2 forløbet i ['fi:fi]

5.1 i ['fi:fi] forkortes vokalen for meget i starten
5.5 vokalen forkortes for meget i starten i ['fi:fi]

4.1/4 { ['fi:fifi] er kortere i starten end ['fi:fi]
['fi:fifi] er kortere i starten end ['fi:fi]

4.2 vokalen i ['fi:fifi 'fi:fəs] i starten

The numbering of the sentences follows the same rules as in material A (note that the two identical 4-stress-group-sentences are both called 4.1/4, meaning that test words occur in the first and in the fourth stress group).

Material B was designed with three objects in mind: 1) As a supplement to material A, it was to give information about Fo declination and larynx height in sentences of varying length.

This requirement was met by the sentences 2.1, 2.2, 5.1, and 5.5, which were identical to the shortest and the longest sentences of material A, and also in essentials by the two identical sentences 4.1/4, although they have a slightly different rhythmical structure compared to the 2- and 5-stress-group-sentences.

2) It was intended to make it possible to observe Fo and larynx movements over the entire stress group. This could be done in the nonsense word portions of sentence 4.2, and in addition stressed and first posttonic syllables could be observed in all ['fi:fi] words in the material and second posttonics in the ['fi:fifi] words in the type 4.1/4 sentences.

3) The third object of the material was to gain information about larynx height in pauses in order to see whether it would differ from the larynx height observed during speech. Since it was considered desirable to have identical sentences adjacent to the pauses in which larynx height was to be observed, the two type 4.1/4 sentences, which always occurred in succession during recording, were included in the material.

The two materials were arranged in eight random orders in two separate reading lists.

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 it could, moreover, 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. The subject was wearing a light but firmly fitting headgear to which a measurement scale was attached in such a manner that it formed the background of the front of the neck and the laryngeal prominence on the TV picture. The scale was divided into units which corresponded to millimetre units at the subject's midsagittal plane. The two materials were recorded at separate recording sessions.

C. SUBJECTS

Recordings were made of altogether nine male speakers. Three of them (PD, PM, and NR, the author) read both materials. The other six speakers (CH, JB, JR, ND, OB, and PH) read material B only. All subjects were speakers of Standard Danish, but with varying degrees of dialectal and/or regional 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. Fo and larynx height were measured at the midpoint of all vowels in the test words (except for the vowel [ə] in ['fi:fəs] in material B, sentence 4.2). Together with Fo and larynx height the distance in time from the beginning of the sentence was also recorded for all points of measurement. The beginning of the sentence was defined as the onset of the first vowel in the sentence. In the pause between the two identical sentences (4.1/4) in material B larynx height was measured at points 4, 6, and 10 cs apart, depending on the distance from the sentences, so that measurements were more closely spaced near the sentences. Furthermore, for the purpose of comparison the larynx height (but not Fo) was measured in all vowels in the two sentences. The locations on the video-tape of the frames in which larynx height was to be measured were determined from the acoustic curves and the timer curve. 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 measurement as determined from the acoustic curves was ± 1 cs. The video recorder was equipped with a step function which made it possible during play-back to "freeze" the picture and step forward frame by frame and read off larynx height in the frames selected for measurement. The vertical position of the larynx could be measured with an accuracy of ± 0.5 mm.

III. RESULTS

Mean values for fundamental frequency and larynx height in material A and B are given in appendix I together with standard deviations and number of observations. Note that in material B the measurements for the two identical sentences (4.1/4) have been pooled, so that the maximum number of observations is 16 instead of 8. The means are displayed graphically as a function of time (i.e. the distance from the onset of the first vowel in the sentence) in figs. 1 to 3 (material A) and figs. 4 to 10 (material B).

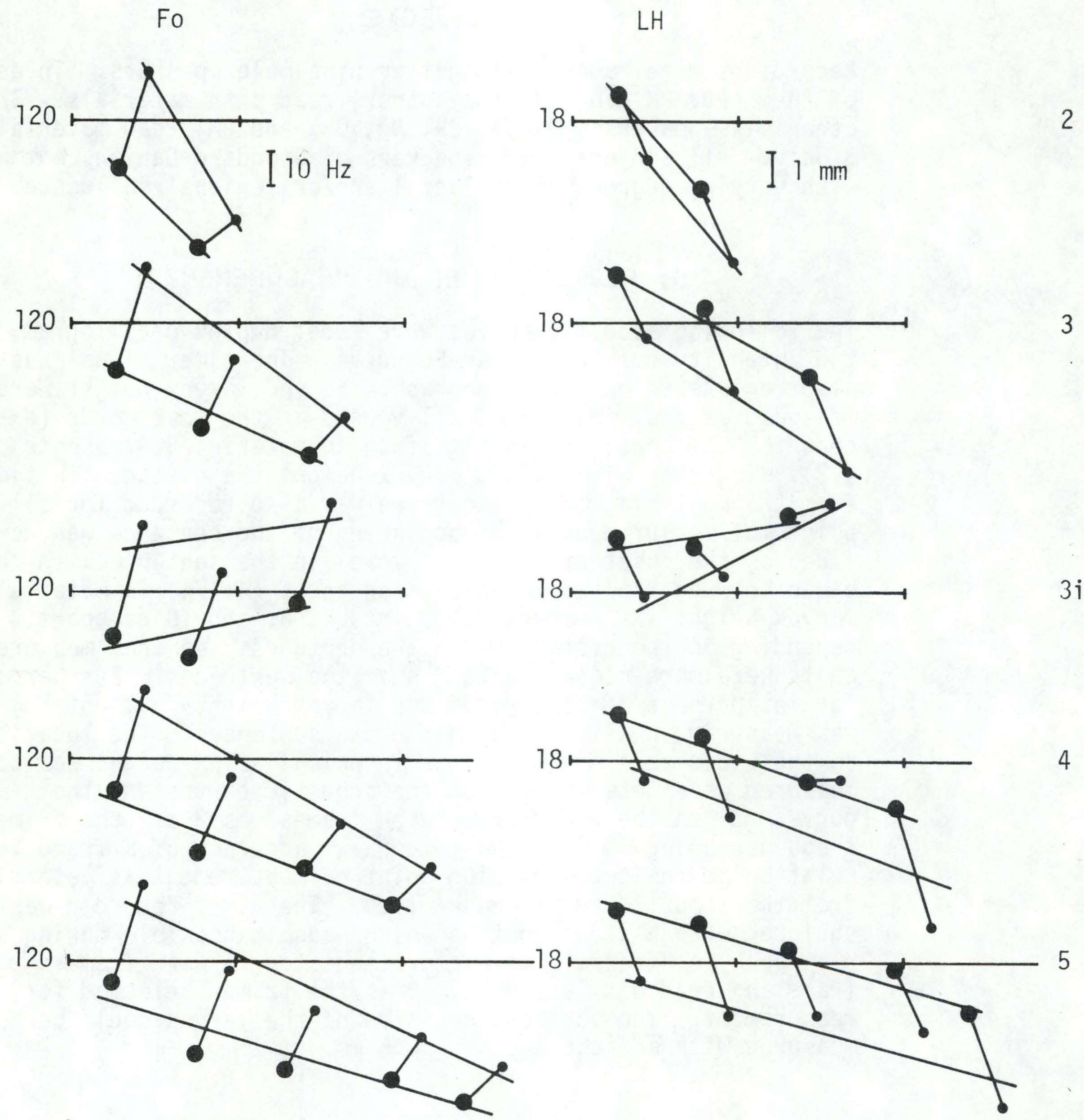

Figure 1

Material A, subject NR. Fundamental frequency (Fo) and larynx height (LH) as a function of time in sentences consisting of 2 through 5 stress groups (3i indicates the 3 stress group sentence spoken in an interrogative intonation). The level of the horizontal reference line is given in Hz and mm, respectively, using an arbitrary zero for larynx height. Large dots indicate stressed syllables, small dots unstressed ones. The lines through the data points are regression lines fitted to stressed and unstressed syllables separately using the method of least squares.

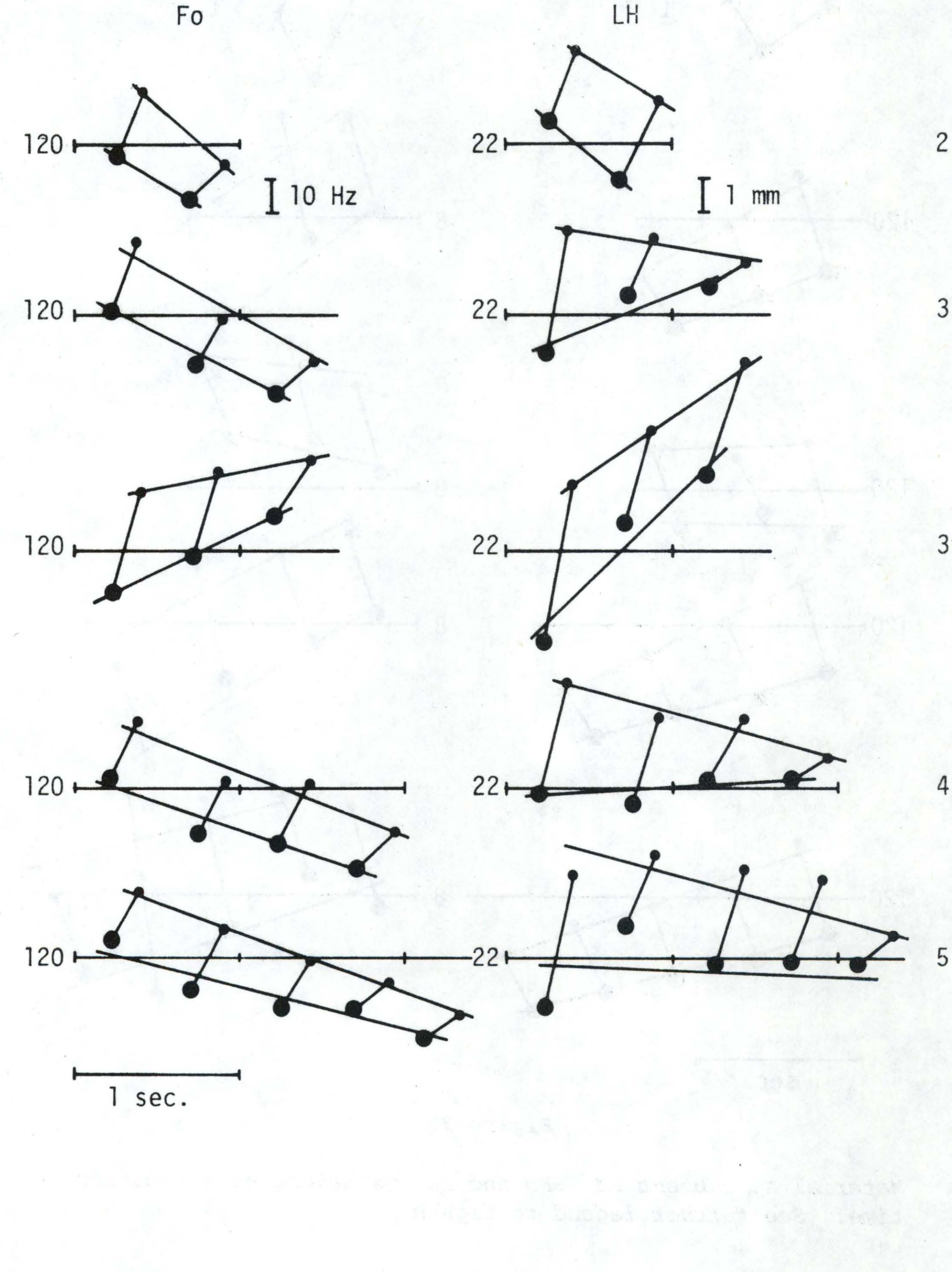

Figure 2

Material A, subject PD. Fo and larynx height as a function of time. See further legend to figure 1.

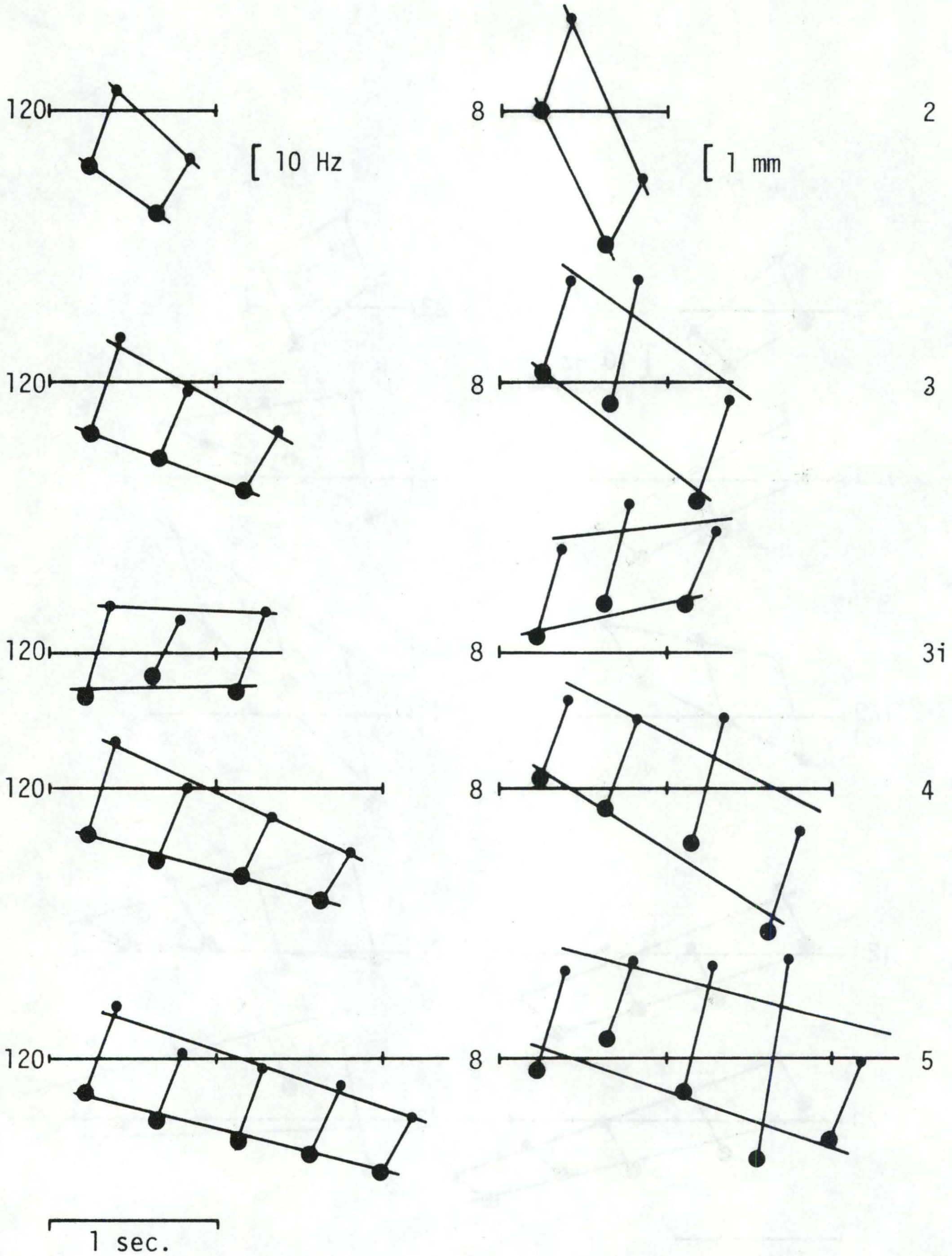

Figure 3

Material A, subject PM. Fo and larynx height as a function of time. See further legend to figure 1.

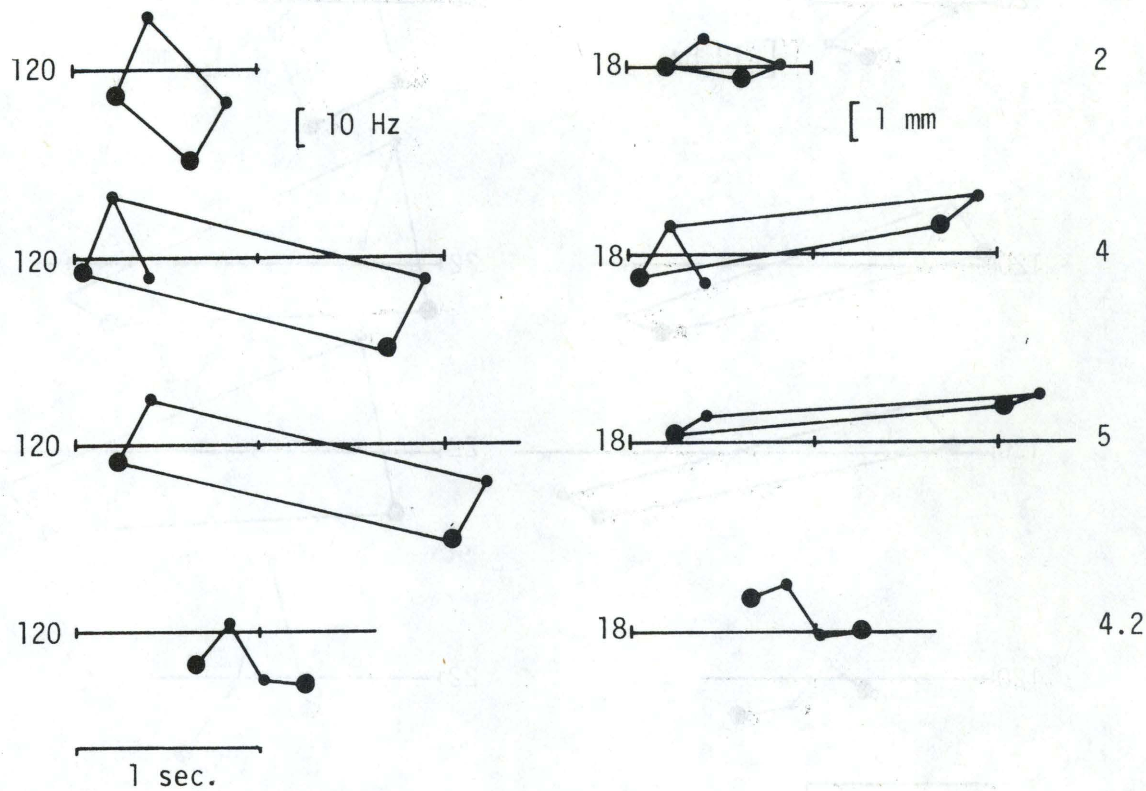

Figure 4

Material B, subject CH. Fo and larynx height in first and last stress groups in sentences of 2, 4, and 5 stress group sentences (upper 3 rows) and in the 2nd stress group in a 4 stress group sentence. The level of the horizontal reference line is given in Hz and mm, respectively, using an arbitrary zero for larynx height. Large dots indicate stressed and small dots unstressed syllables.

A. FUNDAMENTAL FREQUENCY DECLINATION AND LARYNX HEIGHT

1. MATERIAL A

In order to obtain a quantitative estimate of the overall Fo and larynx height variation over the sentence, regression lines and correlation coefficients of these variables versus time were computed. The computations were made on the basis of the raw data, and stressed and first posttonic syllables were treated separately. The regression lines are inserted in the data plots in figures 1 to 3, and slopes (in Hz and mm per second) and correlation coefficients are given in table I.

It is seen that in all declarative sentences there is a clear fundamental frequency decline over the sentence. The correlation of Fo versus time is significantly negative in all cases ($p<0.01$). In interrogative sentences, on the other hand, Fo shows either no decline (subject PM), or it has a slightly rising slope (NR and PD). It is also apparent from table I and

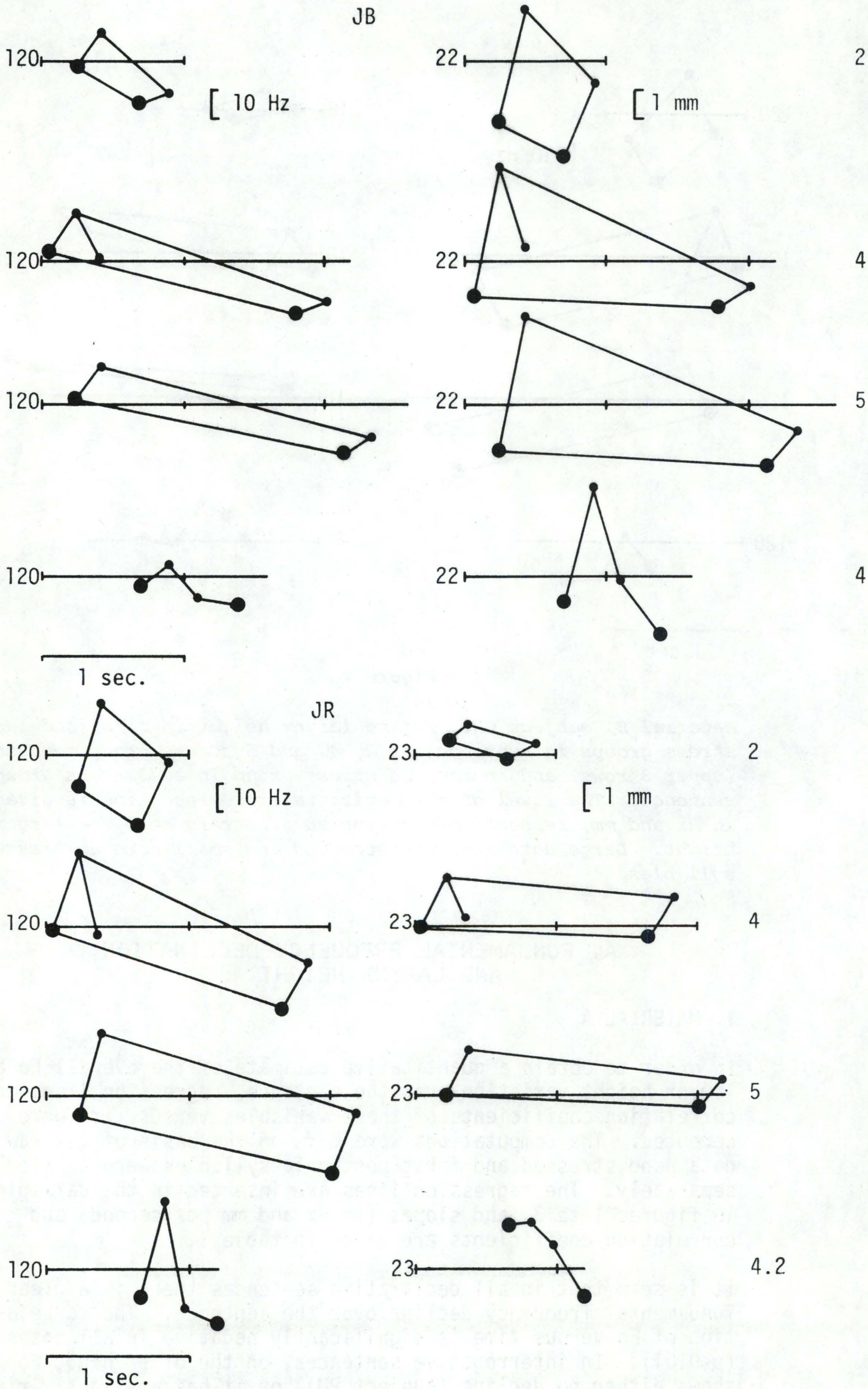

Figure 5

Material B, subjects JB and JR. See further legend to figure 4.

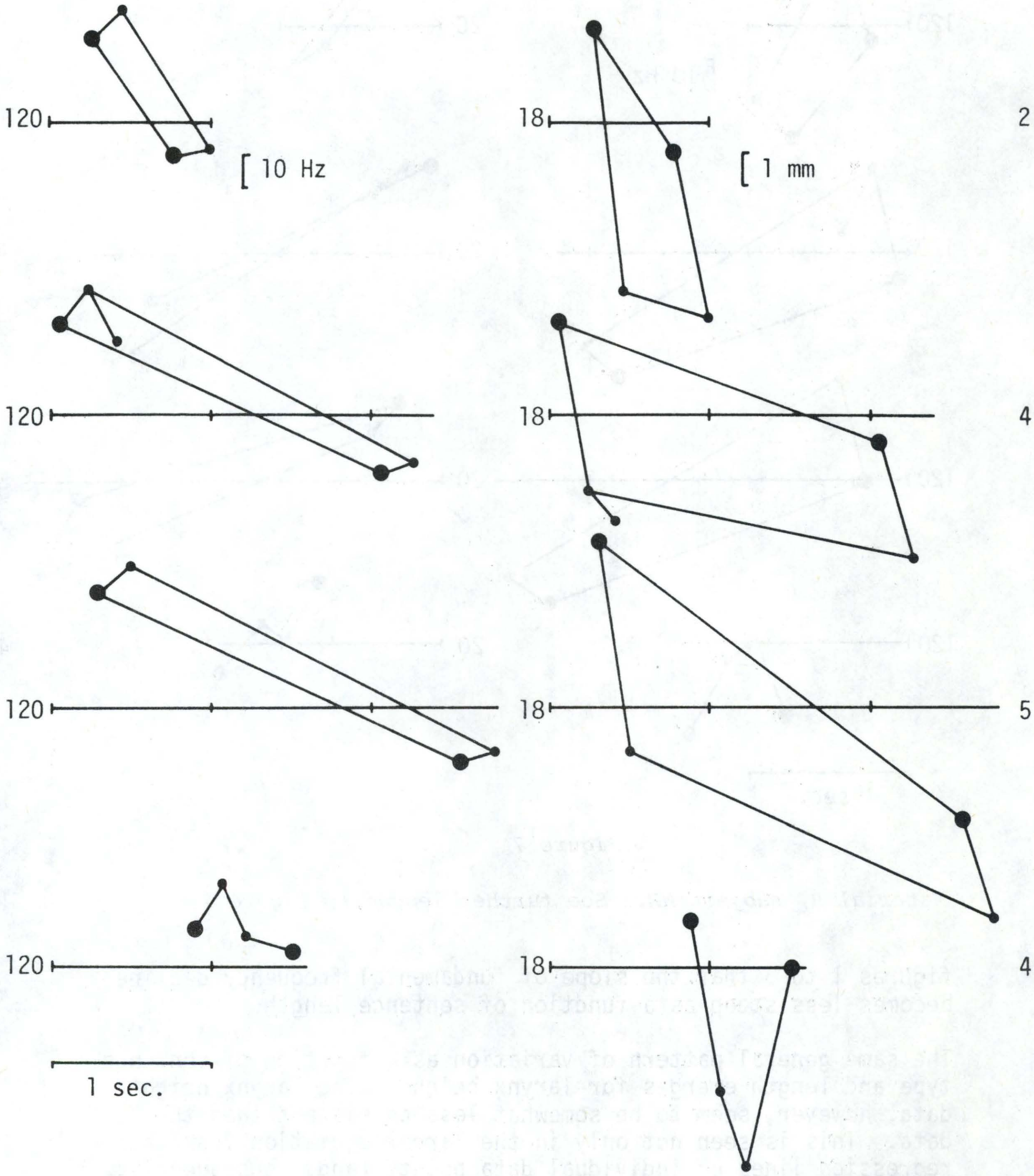

Figure 6.

Material B, subject ND. See further legend to figure 4.

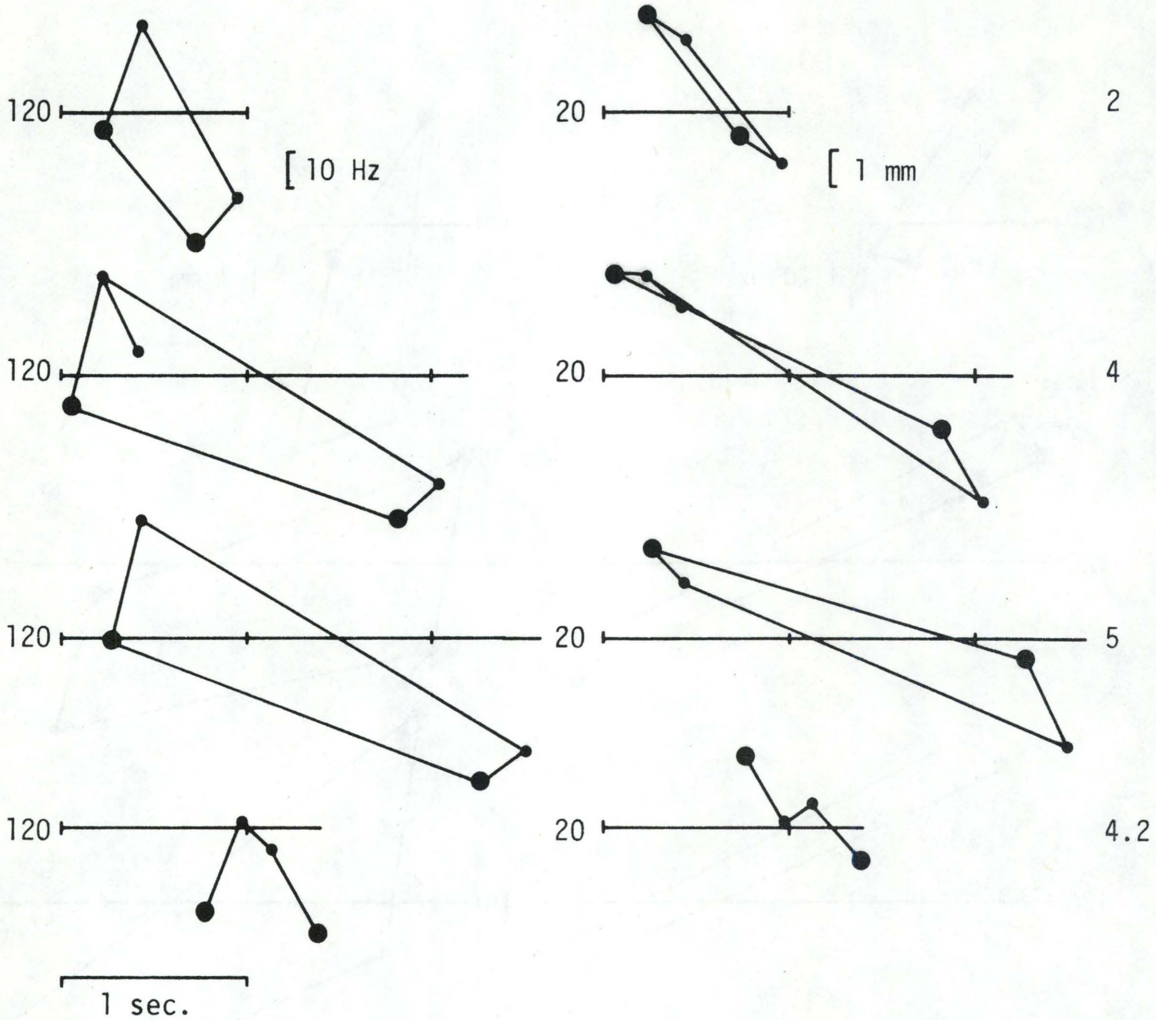

Figure 7

Material B, subject NR. See further legend to figure 4.

figures 1 to 3 that the slope of fundamental frequency decline becomes less steep as a function of sentence length.

The same general pattern of variation as a function of sentence type and length emerges for larynx height. The larynx height data, however, seem to be somewhat less consistent than the Fo data. This is seen not only in the larger deviation from the regression lines of individual data points (and, consequently, in lower correlation coefficients), but also in the instances of gross deviations of slopes from the general pattern. It should be noted, however, that the latter type of deviation is found only with PD (in his 3- and 4-stress-group declarative sentences). PD was also the less consistent speaker in the experiment reported in Reinholt Petersen 1984.

The results are summarized in figure 11, where Fo slopes have been plotted against larynx height slopes. The correlation is positive and statistically significant ($p<0.01$) for all three subjects (NR: $r=0.917$, PD: $r=0.856$, and PM: $r=0.926$). Thus, on the basis of material A, it seems justified to conclude that,

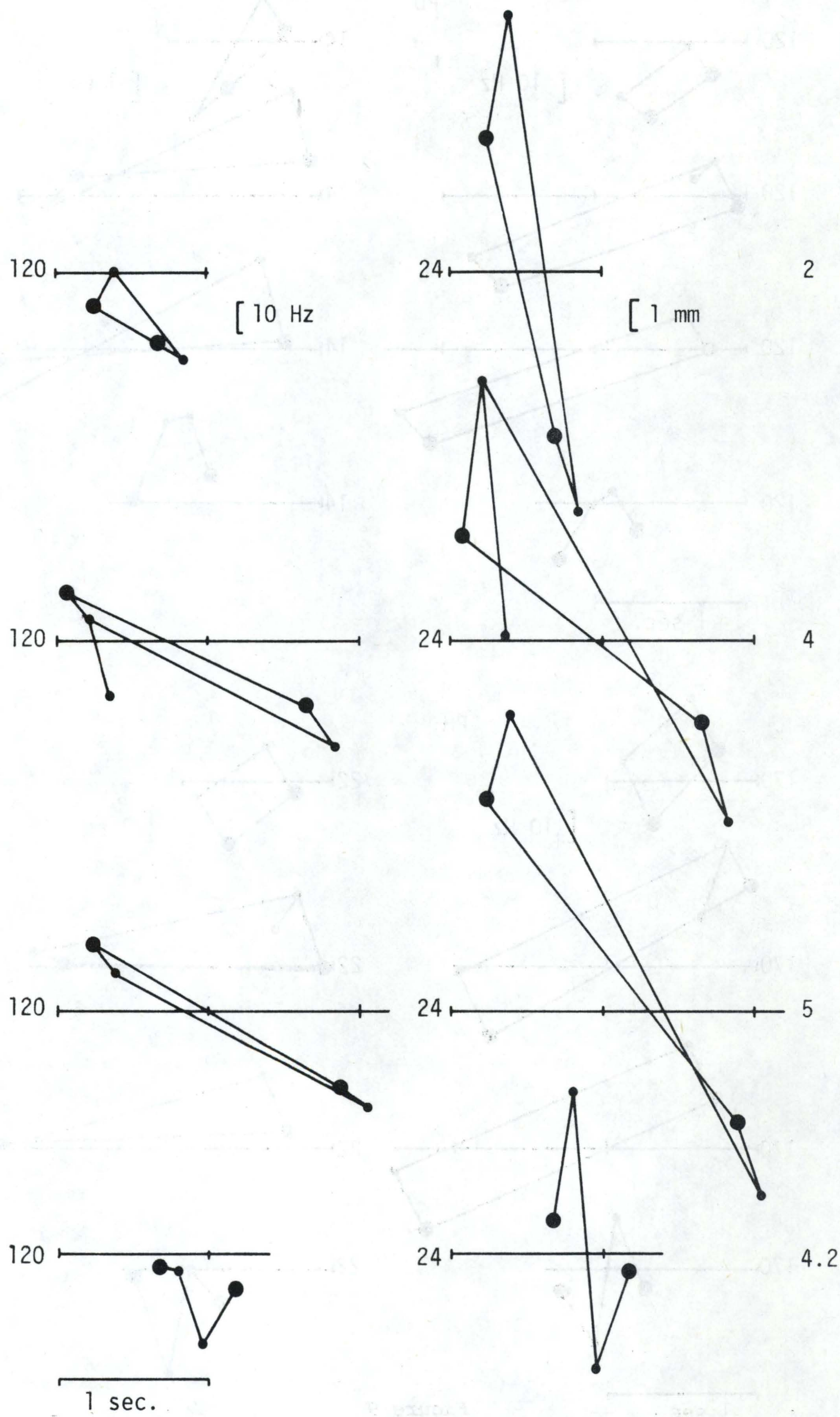

Figure 8

Material B, subject OB. See further legend to figure 4.

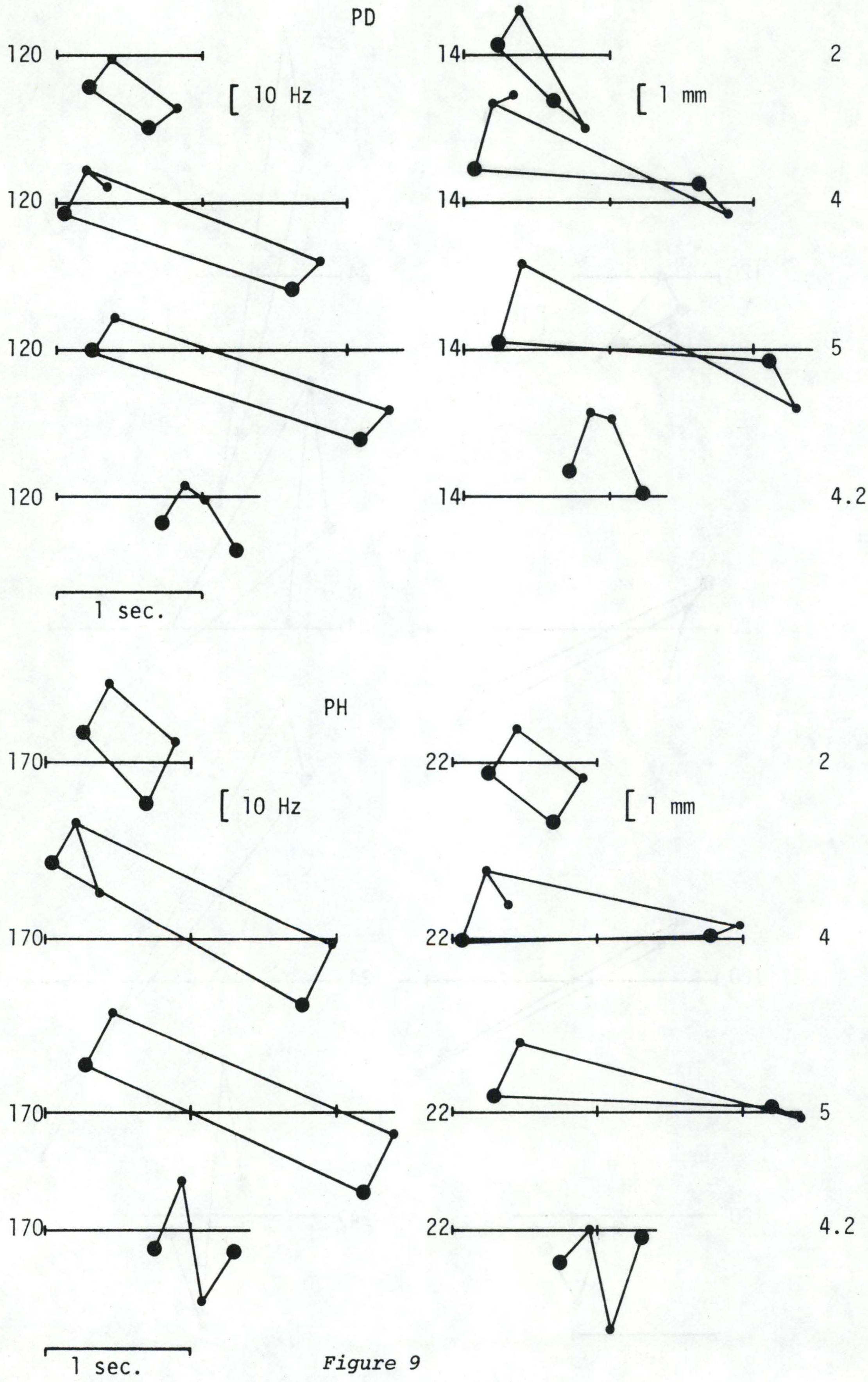

Figure 9

Material B, subjects PD and PH. See further legend to figure 4.

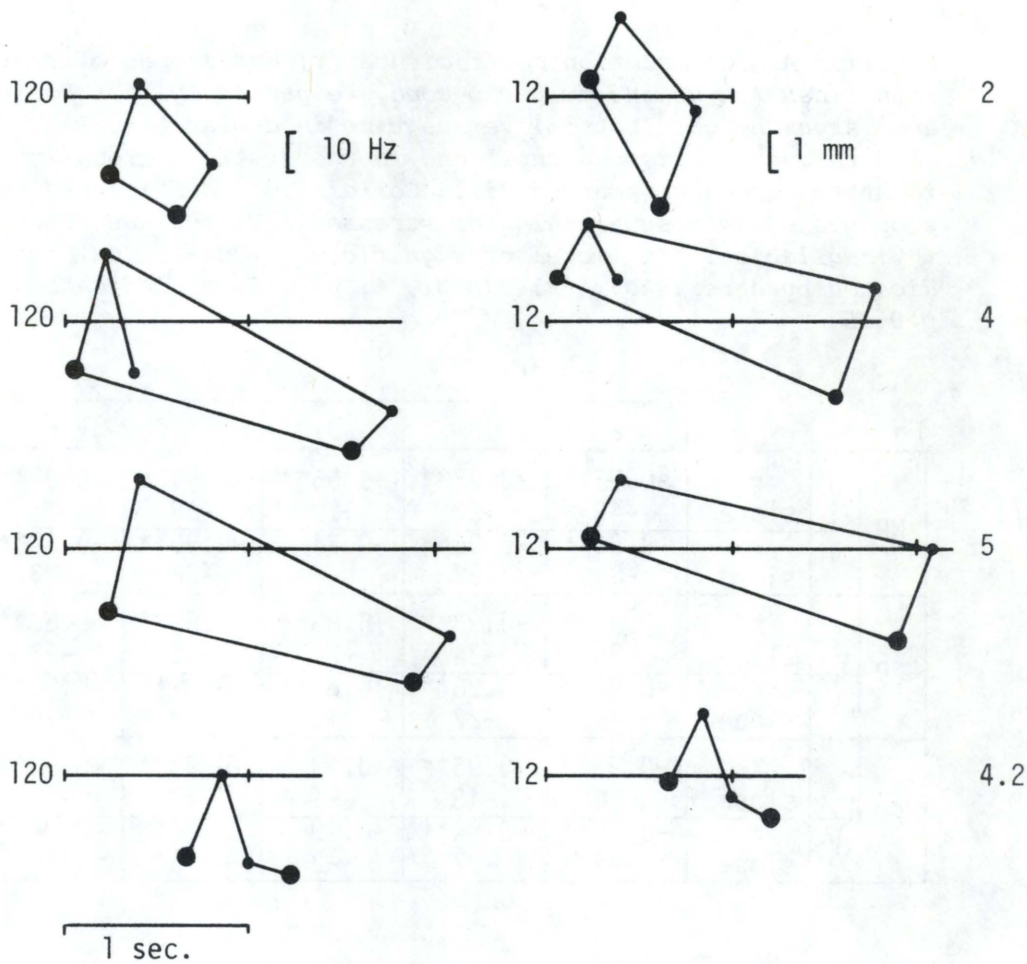

Figure 10

Material B, subject PM. See further legend to figure 4.

on the whole, varying sentence type and length influence fundamental frequency and larynx height in very much the same way.

2. MATERIAL B

In material B Fo and larynx height declination in declarative sentences could be observed by comparing the first and last stress group in sentences containing 2, 4, and 5 stress groups (cf. section III.A above). As is seen from table II Fo is always lower in the last than in the first stress group, this being true for stressed and first posttonic syllables alike. The differences were statistically significant ($p<0.01$) in all cases. Table II also gives the 'slopes' of declination. 'Slope' is here to be understood as the slope (in Hz or mm per second) of the line connecting data points of the first and the last stress group in the sentence, as is seen in figures 4 to 10.

TABLE I

*Material A. Correlation coefficients (r) and slopes of regression lines (in Hz and mm per second, respectively) for Fo (top) and larynx height (bottom) versus time in declarative sentences of 2 through 5 stress groups, and in the 3 stress group interrogative sentences (marked 3i). Correlation coefficients and slopes are given separately for stressed ('V) and unstressed ($_{\circ}$V) syllables. The level of significance (one-tailed) is indicated by asterisks: **: p<0.01, *: p<0.05, no indication: p>0.05.*

F0			2	3	3i	4	5
NR	'V	r	-0.93**	-0.92**	+0.55**	-0.94**	-0.90**
		slope	-49	-22	+10	-18	-15
	$_{\circ}$V	r	-0.96**	-0.94**	+0.34	-0.95**	-0.92**
		slope	-84	-37	+7	-28	-23
PD	'V	r	-0.84**	-0.93**	+0.83**	-0.89**	-0.88**
		slope	-29	-24	+24	-16	-13
	$_{\circ}$V	r	-0.96**	-0.86**	+0.64**	-0.91**	-0.92**
		slope	-43	-27	+9	-19	-18
PM	'V	r	-0.95**	-0.95**	+0.13	-0.92**	-0.93**
		slope	-34	-18	+1	-13	-12
	$_{\circ}$V	r	-0.88**	-0.94**	-0.19	-0.96**	-0.94**
		slope	-44	-27	-2	-23	-17

LH			2	3	3i	4	5
NR	'V	r	-0.85**	-0.84**	+0.38	-0.79**	-0.79**
		slope	-5.7	-2.7	+0.7	-1.7	-1.5
	$_{\circ}$V	r	-0.87**	-0.81**	+0.70**	-0.99**	-0.68**
		slope	-5.8	-3.2	+2.6	-1.8	-1.3
PD	'V	r	-0.63**	+0.42*	+0.85**	+0.09	-0.07
		slope	-4.0	+2.0	+4.8	+0.3	-0.2
	$_{\circ}$V	r	-0.54*	-0.28	+0.80**	-0.44*	-0.45**
		slope	-2.9	-0.8	+3.3	-1.4	-1.4
PM	'V	r	-0.92**	-0.81**	+0.33	-0.83**	-0.63**
		slope	-9.6	-3.8	+1.1	-3.1	-1.7
	$_{\circ}$V	r	-0.89**	-0.69**	+0.23	-0.69**	-0.43**
		slope	-10.3	-3.5	+0.6	-2.5	-1.2

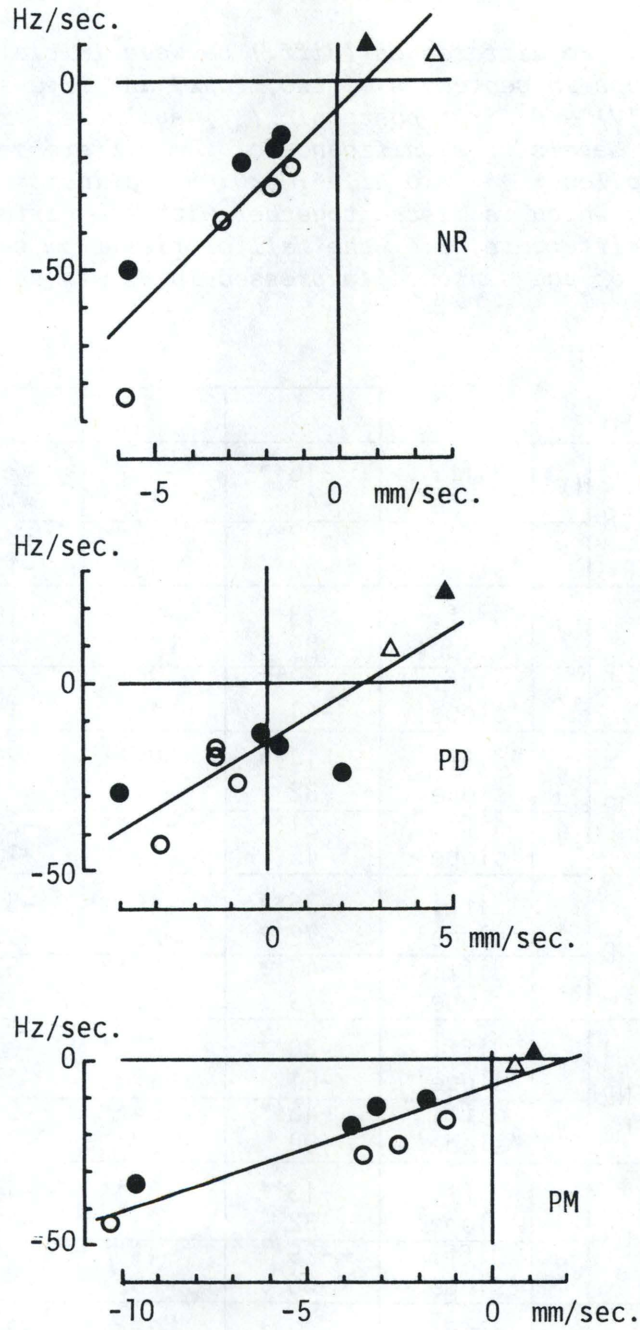

Figure 11

Material A. Overall Fo slopes (in Hz/sec.) versus overall larynx height slopes (in mm/sec.) in sentences of varying length and type. Circles indicate declarative, and triangles interrogative sentences. Filled signs indicate stressed, open signs unstressed syllables.

TABLE II

*Material B. Fo differences (diff.) between initial and final stress groups in sentences of two, four, and five stress groups. Stressed ('V) and first posttonic ($_{\circ}$V) syllables are listed separately. Levels of significance of the differences are indicated as follows: **: $p<0.01$, *: $p<0.05$, no indication: $p>0.05$. By 'slope', which is listed together with the differences, is meant the difference, i.e. the fall or rise from the beginning to the end of the sentence, expressed in Hz per second.*

Fo			2	4	5
CH	'V	diff.	-16**	-21**	-21**
		'slope'	-41	-13	-12
	$_{\circ}$V	diff.	-22**	-22**	-22**
		'slope'	-52	-13	-12
JB	'V	diff.	-13**	-23**	-19**
		'slope'	-29	-13	-10
	$_{\circ}$V	diff.	-22**	-32**	-25**
		'slope'	-44	-18	-13
JR	'V	diff.	-14**	-28**	-20**
		'slope'	-32	-17	-11
	$_{\circ}$V	diff.	-21**	-31**	-28**
		'slope'	-45	-19	-16
ND	'V	diff.	-36**	-46**	-53**
		'slope'	-72	-23	-23
	$_{\circ}$V	diff.	-43**	-53**	-57**
		'slope'	-79	-26	-25
NR	'V	diff.	-30**	-30**	-37**
		'slope'	-61	-17	-18
	$_{\circ}$V	diff.	-46**	-54**	-51**
		'slope'	-90	-30	-30
OB	'V	diff.	-13**	-36**	-48**
		'slope'	-32	-23	-29
	$_{\circ}$V	diff.	-29**	-41**	-44**
		'slope'	-66	-25	-26
PD	'V	diff.	-13**	-26**	-30**
		'slope'	-32	-17	-16
	$_{\circ}$V	diff.	-17**	-31**	-33**
		'slope'	-38	-19	-18
PH	'V	diff.	-25**	-49**	-43**
		'slope'	-57	-29	-22
	$_{\circ}$V	diff.	-21**	-41**	-41**
		'slope'	-44	-23	-21
PM	'V	diff.	-11**	-23**	-19**
		'slope'	-29	-15	-12
	$_{\circ}$V	diff.	-22**	-32**	-40**
		'slope'	-54	-21	-24

TABLE III

*Material B. Larynx height differences (diff.) between initial and final stress groups in sentences of two, four, and five stress groups. Stressed ('V) and first posttonic ($_{\circ}V$) syllables are listed separately. Levels of significance of the differences are indicated as follows: **: p<0.01, *: p<0.05, no indication: p>0.05. By 'slope', which is listed together with the differences, is meant the difference, i.e. the fall or rise from the beginning to the end of the sentence, expressed in mm per second.*

LH			2	4	5
CH	'V	diff.	-0.3	+1.4**	+0.6
		'slope'	-0.8	+0.8	+0.3
	$_{\circ}V$	diff.	-0.8*	+0.8**	+0.5
		'slope'	-1.9	+0.5	+0.3
JB	'V	diff.	-1.1*	-0.4	-0.5
		'slope'	-2.5	-0.2	-0.3
	$_{\circ}V$	diff.	-2.5**	-4.3**	-4.0**
		'slope'	-5.0	-2.4	-2.1
JR	'V	diff.	-0.6	-0.3	-0.4
		'slope'	-1.4	-0.2	-0.2
	$_{\circ}V$	diff.	-0.8	-0.7	-1.1**
		'slope'	-1.7	-0.4	-0.6
ND	'V	diff.	-3.6*	-3.6**	-5.7**
		'slope'	-7.2	-1.8	-2.5
	$_{\circ}V$	diff.	-0.8	-1.7*	-5.1**
		'slope'	-1.5	-0.8	-2.2
NR	'V	diff.	-3.4**	-4.2**	-3.5**
		'slope'	-6.9	-2.4	-1.7
	$_{\circ}V$	diff.	-3.3**	-6.0**	-4.4**
		'slope'	-6.4	-3.3	-2.1
OB	'V	diff.	-10.0**	-6.8**	-10.5**
		'slope'	-24.3	-4.3	-6.4
	$_{\circ}V$	diff.	-16.2**	-14.4**	-15.8**
		'slope'	-37.0	-8.9	-9.5
PD	'V	diff.	-2.0**	-0.5	-0.6
		'slope'	-5.0	-0.3	-0.3
	$_{\circ}V$	diff.	-4.0**	-3.7**	-4.9**
		'slope'	-9.0	-2.3	-2.6
PH	'V	diff.	-1.8**	+0.3	-0.4
		'slope'	-4.1	+0.2	-0.2
	$_{\circ}V$	diff.	-1.8**	-1.9**	-2.6**
		'slope'	-3.8	-1.1	-1.3
PM	'V	diff.	-3.4**	-3.1**	-2.8**
		'slope'	-9.1	-2.1	-1.7
	$_{\circ}V$	diff.	-2.5**	-1.7**	-1.8**
		'slope'	-6.1	-1.1	-1.1

The slopes are, of course, always negative and, like those of material A, they tend to decrease in steepness with increased sentence length. It is worth noting that the slopes for subjects NR, PD, and PM compare very well with the slopes observed for these subjects in 2-, 4- and 5-stress-group-sentences in material A, even if the 4-stress-group-sentence in the present material has a slightly different rhythmical structure than the 4-stress-group-sentences in material A and the 2- and 5-stress-group-sentences in both materials. Therefore it was considered justified to include that sentence type in the evaluation of the major tendencies in material B.

As was the case for material A, the larynx height data in material B are less consistent than the Fo data, see figures 4 to 10 and table III. There are a few cases where an Fo decline is accompanied by a larynx height rise, such as in CH's 4-stress-group-sentences, where the rise is statistically significant ($p<0.01$), and in his 5-stress-group-sentence, where it is non-significant. Likewise, a non-significant larynx rise is found in PH's 4-stress-group-sentence. In the majority of cases, however, a larynx height decline accompanies the fundamental frequency decline. This is true in 49 out of 54 cases (9 subjects x 2 stress categories x 3 sentence lengths), and out of the 49 cases 37 were statistically significant ($p<0.05$). In 5 cases (of which 2 were significant, $p<0.01$) there was a larynx rise over the sentence; 4 of these cases occurred with one speaker, viz. CH.

Finally, there is a strong tendency for the larynx height slope to be steeper in 2-stress-group-sentences than in 4- and 5-stress-group-sentences. Apart from the few instances of a positive slope, there is only one exception to this tendency, namely ND's first posttonic syllables, where the steepest slope is found in the 5-stress-group-sentences.

Thus, the data derived from material B can be taken to corroborate the conclusions arrived at in section III.A.1 above on the basis of material A, namely that fundamental frequency and larynx height show similar patterns of variation as a function of sentense type and length.

B. FUNDAMENTAL FREQUENCY AND LARYNX HEIGHT IN STRESSED AND UNSTRESSED SYLLABLES

1. MATERIAL A

Table IV gives differences in Fo and larynx height between stressed and first posttonic syllables in the test words in material A (see also figures 1 to 3). It is seen that the three subjects in all cases have significant ($p<0.01$) Fo rises between the two syllables. The rises are accompanied by larynx height rises for two of the subjects, PD and PM, whereas for the third subject, NR, the rises are accompanied by larynx lowering. Thus, there seems to be two distinctly different patterns of larynx movement corresponding to the same pattern of

TABLE IV

*Material A. Fo differences (top) and larynx height differences (bottom) between stressed and first posttonic syllables in first through fifth stress group (columns) in sentences of two through five stress groups (rows). The row marked 3i lists data for the three-stress-group interrogative sentence. Significance levels (one-tailed) are indicated as follows: **: $p<0.01$, *: $p<0.05$, no indication: $p>0.05$.*

Fo		1	2	3	4	5
NR	2	+28**	+8**			
	3	+30**	+19**	+11**		
	3i	+32**	+25**	+29**		
	4	+29**	+21**	+13**	+11**	
	5	+30**	+25**	+16**	+12**	+10**
PD	2	+18**	+11**			
	3	+18**	+13**	+9**		
	3i	+30**	+25**	+16**		
	4	+16**	+15**	+17**	+10**	
	5	+14**	+18**	+13**	+8**	+6**
PM	2	+22**	+17**			
	3	+28**	+20**	+17**		
	3i	+27**	+17**	+23**		
	4	+27**	+22**	+17**	+14**	
	5	+26**	+20**	+21**	+20**	+16**

LH		1	2	3	4	5
NR	2	-2.0**	-2.3**			
	3	-1.8**	-2.4**	-2.5**		
	3i	-1.8**	-0.9*	+0.4		
	4	-1.9**	-2.5**	0.0	-3.6**	
	5	-2.1**	-2.9**	-2.3**	-1.8**	-2.6**
PD	2	+2.0**	+2.3**			
	3	+3.6**	+1.6*	+0.8		
	3i	+4.6**	+2.8**	+3.3**		
	4	+3.3**	+2.5**	+1.8*	+0.6	
	5	+3.9**	+2.0**	+2.9**	+2.4**	+0.8
PM	2	+2.6**	+2.0**			
	3	+2.8**	+3.8**	+3.0**		
	3i	+2.5**	+2.9**	+2.1**		
	4	+2.4**	+2.6**	+3.8**	+2.9**	
	5	+3.0**	+2.4**	+3.6**	+6.0**	+2.3**

fundamental frequency movement. This is in agreement with the results reported in Reinholt Petersen 1984. The larynx movements - whether upward or downward - were statistically significant ($p<0.01$) in the vast majority of cases.

For Fo there is a tendency for the magnitude of the rise to become gradually smaller along the sentence. A similar tendency is seen for larynx height only in speaker PD, whereas in PM and NR there seems to be no correlation between the amount of Fo movement and the amount of larynx movement. This is illustrated in fig. 12, where Fo movements are plotted against larynx movements. The correlation coefficients were for NR 0.301 ($p>0.05$), for PD 0.661 ($p<0.01$), and for PM -0.131 ($p>0.05$).

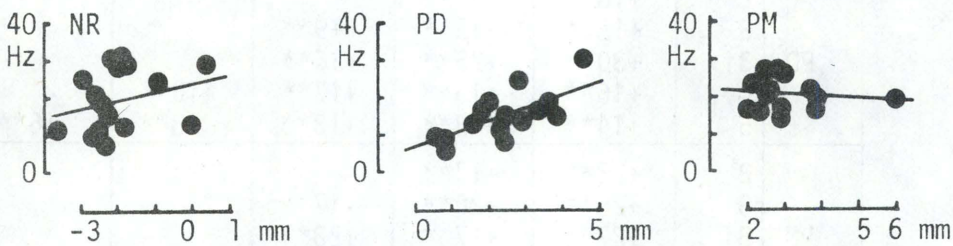

Figure 12

Material A. Fo movement versus vertical larynx movement between stressed and first posttonic syllables.

2. MATERIAL B

In material B it was possible not only to examine stressed and first posttonic syllables but also, in sentence 4.1/4 and 4.2, second posttonic syllables, and in sentence 4.2 the stressed vowel in the following stress group (see section III.4 above). Tables V and VI list the directions and magnitudes of Fo and larynx movements between these syllables (see also figures 4 to 9).

It is seen that all subjects but one (OB) have a fundamental frequency rise from stressed to first posttonic syllable, followed by a fall toward the relatively low level of the next stressed syllable. This pattern of Fo movement in the stress group conforms to the one described by Thorsen (e.g. Thorsen 1979) for Standard Copenhagen Danish. Subject OB, whose speech is appreciably influenced by his dialectal background (Northern Jutland), tends to show the opposite Fo pattern, viz. high stressed and lower unstressed syllables (cf. Thorsen 1982).

In figure 13 fundamental frequency movements have been plotted against larynx movements. Focusing first on the relation between rising fundamental frequency and larynx movement it is clear that, as in material A, the speakers can be divided into

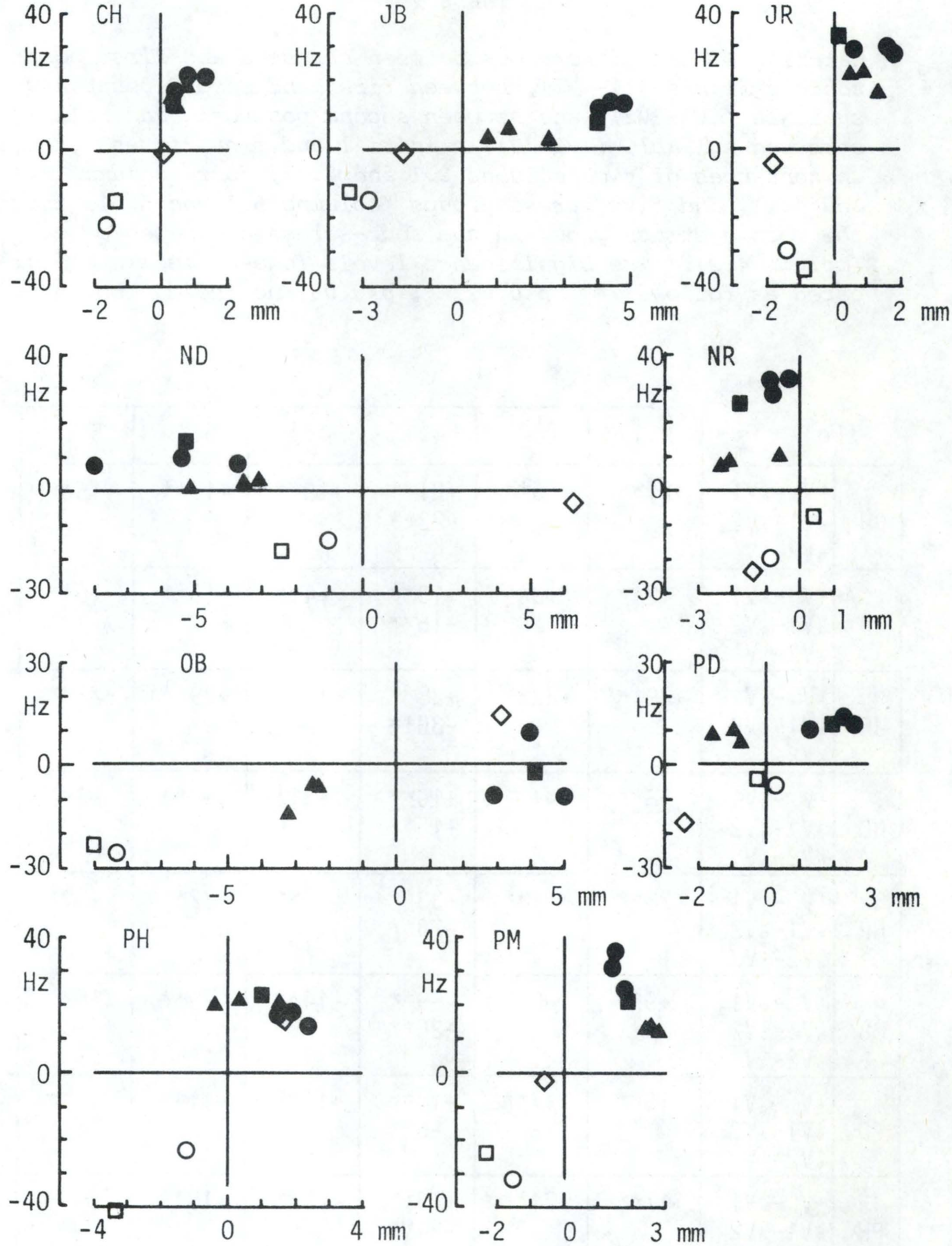

Figure 13

Material B. Fo movement versus larynx height movement between the following syllables:

between stressed and 1st posttonic, initial stress groups (●)
\- - - - - *final* - - (▲)
\- - - - - *2nd stress group sentence 4.2* (■)
\- *1st* - *2nd* - *initial stress group sentence 4.1/4* (○)
\- - - - - *2nd stress group sentence 4.2* (□)
\- *2nd* - *stressed* - - - - - - (◇)

TABLE V

*Material B. Fo differences between stressed and first posttonic syllable ($'V-{}_{\circ}V1$), between first and second posttonic syllable (${}_{\circ}V1-{}_{\circ}V2$), and between second posttonic and following stressed syllable (${}_{\circ}V2-'V$) in initial and final stress groups in sentences of two (columns 2.1 and 2.2), four (columns 4.1 and 4.4), and five stress groups (columns 5.1 and 5.5), and in the second stress group in the four-stress-group-sentences (column 4.2). The significance levels (one-tailed) are indicated as follows: **: $p<0.01$, *: $p<0.05$, no indication: $p>0.05$.*

Fo		2.1	2.2	4.1	4.4	5.1	5.5	4.2
CH	$'V-{}_{\circ}V1$	+21**	+15**	+21**	+19**	+17**	+15**	+12**
	${}_{\circ}V1-{}_{\circ}V2$			-22**				-15**
	${}_{\circ}V2-'V$							-1*
JB	$'V-{}_{\circ}V1$	+12**	+3**	+13**	+4**	+13**	+6**	+8**
	${}_{\circ}V1-{}_{\circ}V2$			-15**				-12**
	${}_{\circ}V2-'V$							-1
JR	$'V-{}_{\circ}V1$	+29**	+22**	+28**	+17**	+29**	+22**	+33**
	${}_{\circ}V1-{}_{\circ}V2$			-30**				-36**
	${}_{\circ}V2-'V$							-4**
ND	$'V-{}_{\circ}V1$	+8**	+1	+10**	+3**	+8**	+3*	+15**
	${}_{\circ}V1-{}_{\circ}V2$			-15**				-18**
	${}_{\circ}V2-'V$							-4
NR	$'V-{}_{\circ}V1$	+28**	+11**	+33**	+9**	+32**	+8**	+25**
	${}_{\circ}V1-{}_{\circ}V2$			-20**				-8**
	${}_{\circ}V2-'V$							-23**
OB	$'V-{}_{\circ}V1$	+9**	-6*	-9**	-14**	-9**	-6*	-2
	${}_{\circ}V1-{}_{\circ}V2$			-26**				-23**
	${}_{\circ}V2-'V$							+17**
PD	$'V-{}_{\circ}V1$	+10**	+7**	+14**	+10**	+11**	+9**	+12**
	${}_{\circ}V1-{}_{\circ}V2$			-6**				-4**
	${}_{\circ}V2-'V$							-17**
PH	$'V-{}_{\circ}V1$	+17**	+21**	+13**	+21**	+18**	+20**	+23**
	${}_{\circ}V1-{}_{\circ}V2$			-24**				-42**
	${}_{\circ}V2-'V$							+17**
PM	$'V-{}_{\circ}V1$	+25**	+14**	+31**	+12**	+35**	+13**	+21**
	${}_{\circ}V1-{}_{\circ}V2$			-32**				-23**
	${}_{\circ}V2-'V$							-3*

TABLE VI

*Material B. Larynx height differences between stressed and first posttonic syllable ('V-$_{\circ}$V1), between first and second posttonic syllable ($_{\circ}$V1-$_{\circ}$V2), and between second posttonic and following stressed syllable ($_{\circ}$V2-'V) in initial and final stress groups in sentences of two (columns 2.1 and 2.2), four (columns 4.1 and 4.4), and five stress groups (columns 5.1 and 5.5), and in the second stress group in the four-stress-group-sentences (column 4.2). The significance levels (one-tailed) are indicated as follows: **: p<0.01, *: p<0.05, no indication: p>0.05.*

LH		2.1	2.2	4.1	4.4	5.1	5.5	4.2
CH	'V -$_{\circ}$V1	+0.8**	+0.3	+1.4**	+0.8**	+0.5	+0.4	+0.4
	$_{\circ}$V1-$_{\circ}$V2			-1.6**				-1.4**
	$_{\circ}$V2-'V							+0.1
JB	'V -$_{\circ}$V1	+4.0**	+2.6**	+4.4**	+0.7*	+4.8**	+1.3*	+4.0**
	$_{\circ}$V1-$_{\circ}$V2			-2.8**				-3.4**
	$_{\circ}$V2-'V							-1.8*
JR	'V -$_{\circ}$V1	+0.6	+0.5	+1.8**	+1.4**	+1.6**	+0.9	+0.1
	$_{\circ}$V1-$_{\circ}$V2			-1.4**				-0.9
	$_{\circ}$V2-'V							-1.8**
ND	'V -$_{\circ}$V1	-8.0**	-5.1**	-5.3**	-3.5**	-3.7**	-3.1**	-5.2**
	$_{\circ}$V1-$_{\circ}$V2			-1.0*				-2.4**
	$_{\circ}$V2-'V							+6.3**
NR	'V -$_{\circ}$V1	-0.8	-0.6	-0.3	-2.1**	-0.9*	-2.3**	-1.8**
	$_{\circ}$V1-$_{\circ}$V2			-0.8**				+0.4
	$_{\circ}$V2-'V							-1.4*
OB	'V -$_{\circ}$V1	+4.0**	-2.5*	+5.0**	-3.2**	+2.9**	-2.4**	+4.1**
	$_{\circ}$V1-$_{\circ}$V2			-8.3**				-9.0**
	$_{\circ}$V2-'V							+3.1**
PD	'V -$_{\circ}$V1	+1.3**	-0.8	+2.3**	-1.0*	+2.6**	-1.6*	+2.0**
	$_{\circ}$V1-$_{\circ}$V2			+0.3				-0.3
	$_{\circ}$V2-'V							-2.5**
PH	'V -$_{\circ}$V1	+1.5**	+1.5**	+2.4**	+0.3	+1.9**	-0.4	+1.0
	$_{\circ}$V1-$_{\circ}$V2			-1.2**				-3.4**
	$_{\circ}$V2-'V							+1.7**
PM	'V -$_{\circ}$V1	+1.8*	+2.6**	+1.4**	+2.9**	+1.5*	+2.5**	+1.9**
	$_{\circ}$V1-$_{\circ}$V2			-1.5**				-2.3**
	$_{\circ}$V2-'V							-0.6

two groups: a smaller one comprising ND and NR, who consistently show downward larynx displacements, and a larger one consisting of the remaining speakers except PD. This group all have upward larynx movements in conjunction with Fo rises. There is one exception: in one case in speaker PH the Fo rise is associated with a (non-significant, $p<0.05$) fall of the larynx.

Speaker PD seems to have a distinction between sentence final and non-final stress groups; in the former the larynx is shifted downwards, in the latter upwards, even if Fo is rising in both cases. This pattern of variation deviates from the findings for PD in material A and in Reinholt Petersen 1984. There, Fo rises were always associated with larynx rises, whether in final or in non-final position. The larynx lowering in final stress groups observed for PD in the present material could perhaps be explained as an anticipation of the low level of the larynx which seems to be characteristic of the pauses between sentences (see section C below). If final stress groups are left out of consideration PD shows a pattern of larynx movement which is essentially congruent with the pattern of the larger group of speakers mentioned above. The question why PD's final stress groups behaved differently in the present material as compared to previous recordings still remains open, of course, and can hardly be addressed on the basis of the available data.

For the group of speakers having larynx rises accompanying Fo rises, it should be noted that only three of them (CH, JB, and PD) have positive correlations between the amount of Fo movement and the amount of larynx movement (CH: $r=0.333$, $p<0.01$, JB: $r=0.492$, $p<0.01$, PD: $r=0.302$, $p<0.05$). The remaining four speakers all have negative correlations (JR: $r=-0.064$, $p>0.05$, OB: $r=-0.160$, $p>0.05$, PH: $r=-0.099$, $p>0.05$, PM: $r=-0.560$, $p<0.01$), but only for PM the correlation can be shown to be statistically significant.

The patterns of larynx movement associated with fundamental frequency lowering seem to be less consistent with respect to their distribution among subjects. Four out of the nine subjects (ND, NR, OB, and PD) have larynx falls as well as larynx rises in such cases. The remaining five subjects always have downward larynx displacements in conjunction with a falling Fo. In the former group it should be noted, however, that the cases in which the greatest downward Fo movements are observed are also those in which the larynx is lowered. This point may, in fact, be generalized to the latter group mentioned above. Even if, in this group, Fo lowering is in all cases accompanied by larynx lowering, there is a tendency for the larynx lowering to be greater in the cases of more extreme Fo fall than in cases of a moderate one. The only exception to this general tendency is subject JR.

With respect to speaker OB it should be pointed out that there seems to be a systematic trend in the direction of larynx displacement associated with his more moderate Fo falls. In sentence final position the larynx is shifted downwards, in non-final position upwards. This distribution of larynx movements may be taken to indicate that the larynx lowering found in final position has the same explanation as was suggested for subject PD, namely an anticipation of the low level of the larynx during pauses.

C. LARYNX HEIGHT IN PAUSES

Figures 14 and 15 display average larynx height traces during the pause between the two identical 4-stress-group sentences. For the sake of comparison mean larynx height in all vowels in the two sentences is also plotted. As is seen there seems to be a clear tendency for the larynx to be lower in the pause than during speech. This tendency is very clear for speakers JR, ND, NR, OB, PD, PH, and PM, less so, perhaps, for CH and JB. For most of the subjects there is a steep fall of the larynx at the beginning of the pause, and a steep rise at or immediately before the beginning of the next sentence. For subjects OB and PD the larynx depression for the pause seems to start already before the end of the sentence.

Thus, the larynx seems to have two general levels, a relatively high speech level and a lower level associated with pauses. It is, of course, a question whether the level observed in pauses corresponds to some sort of relaxation level, since the pauses were relatively short, between one and two seconds, but the levels reached in the pauses between the two sentences compare very well with the levels observed in longer pauses, e.g. before the beginning of the reading of the material.

IV. DISCUSSION

A. FUNDAMENTAL FREQUENCY DECLINATION AND LARYNX HEIGHT

The results presented in section III.A above demonstrate that Fo and larynx height show very similar patterns of variation as a function of sentence length and type. This is in disagreement with what should be expected on the basis of theories of Fo declination which regard it as an automatic consequence of constraints in the speech production apparatus, or more specifically in the pulmonic system. Together with the observations on Fo behaviour referred to in section I, the results of the present study speak strongly in favour of the view that Fo declination is actively controlled by the speaker.

The results also suggest that it is the extrinsic rather than the intrinsic laryngeal muscles that are responsible for the gradual Fo decline over the sentence. Changes in the activity of the vocalis muscle could hardly give rise to changes in larynx height. The cricothyroid muscle could, however, be thought to influence the apparent larynx height. If the activity of that muscle causes the thyroid cartilage to rotate around the cricothyroid joint it would appear, as seen from

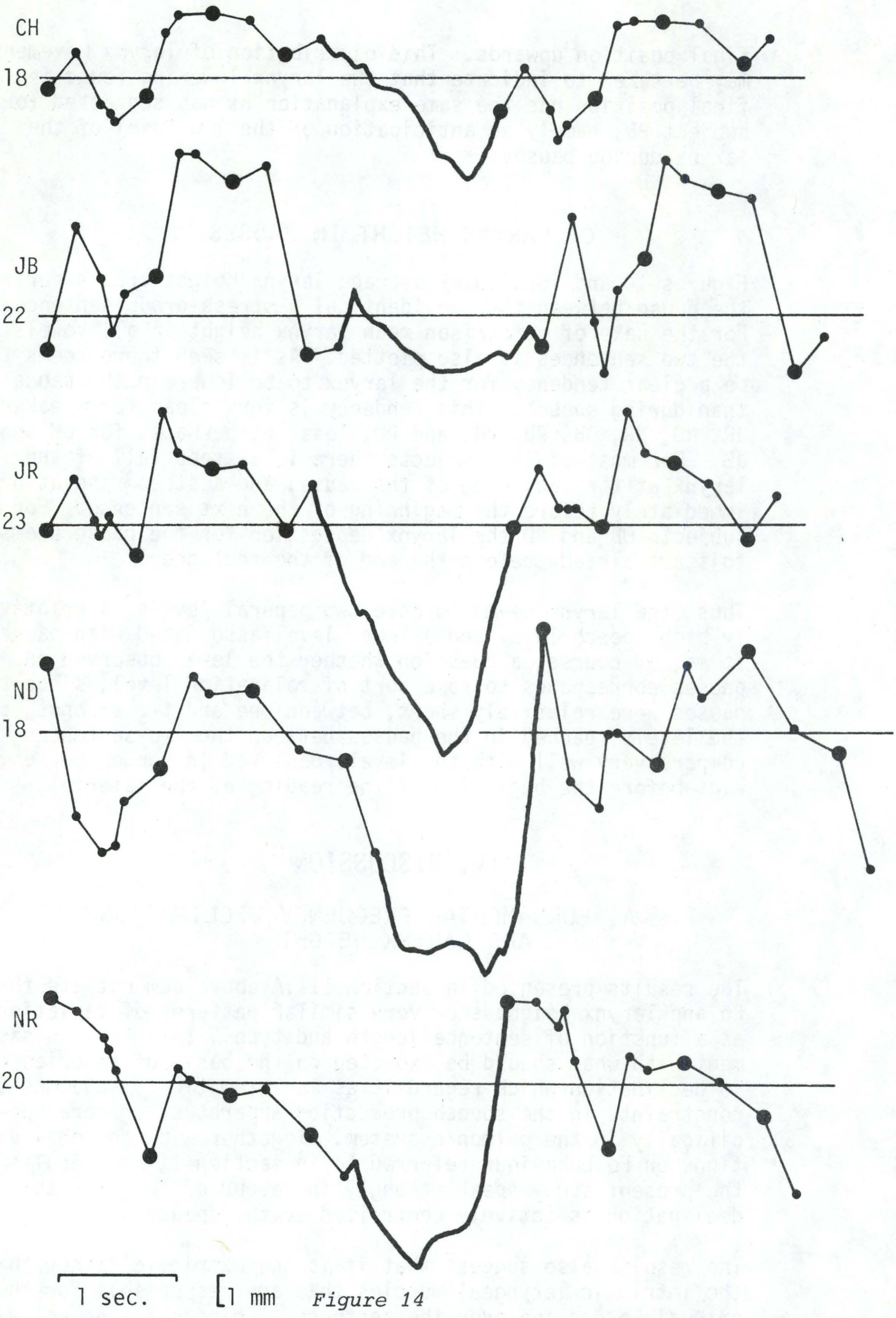

Figure 14

Material B. Subjects CH, JB, JR, ND, and NR. Average larynx height curves (time normalized for each subject) in the two identical sentences, 4.1/4 (thin lines) and in the pause between the sentences (heavy lines). Stressed syllables are indicated by large and unstressed syllables by small dots. The level of the horizontal reference line is given in mm, using an arbitrary zero.

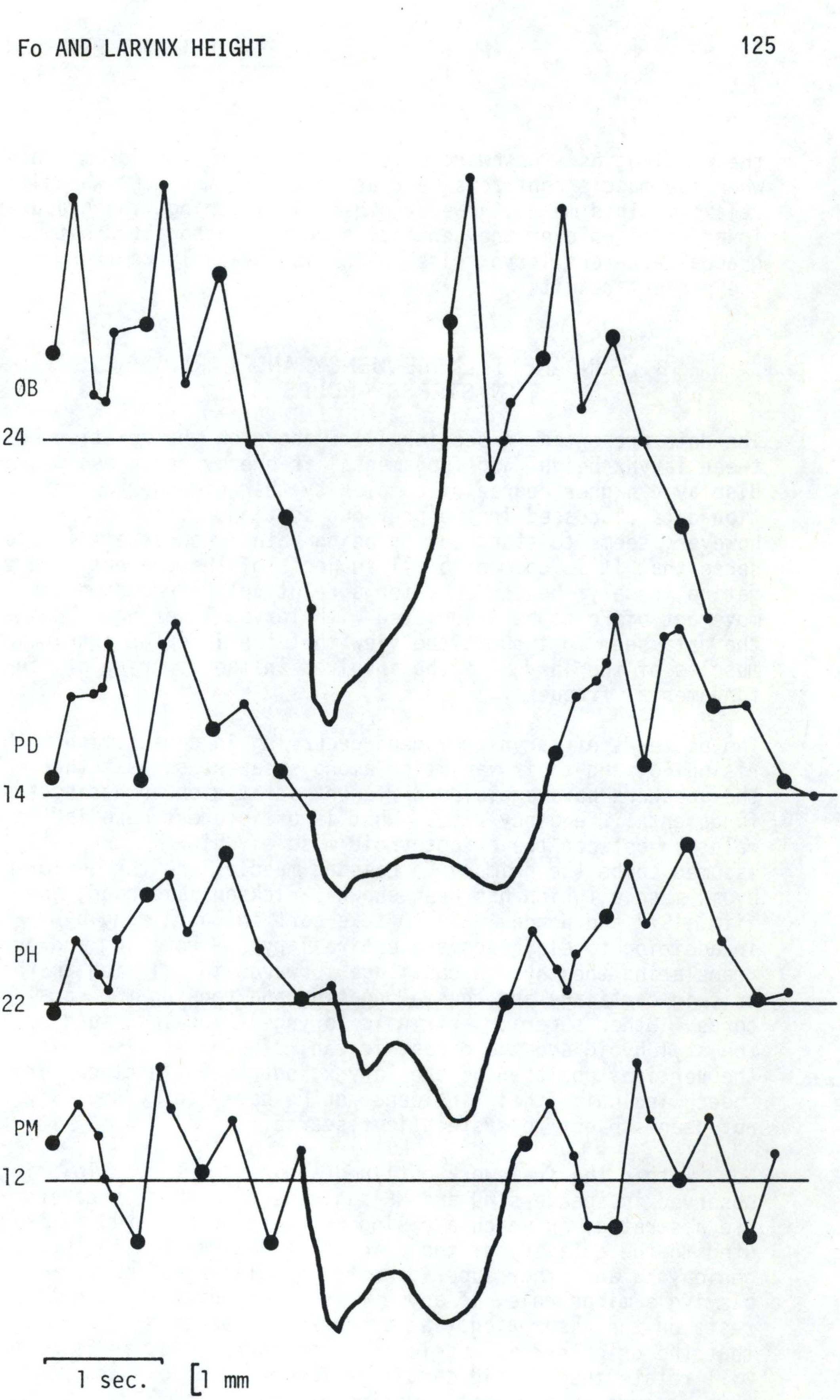

Figure 15

Material B. Subjects OB, PD, PH, and PM. See further legend to figure 14.

the outside, as a downward movement of the thyroid prominence when the muscle contracts, and as an upward movement when it relaxes. This means, however, that, if anything, the gradual lowering of Fo over the sentence should be associated with a gradual apparent larynx rise, which is obviously contrary to the present results.

B. FUNDAMENTAL FREQUENCY AND LARYNX HEIGHT IN STRESS GROUPS

The data presented in section III.B above on the relation between larynx height and fundamental frequency in stress groups display a higher degree of complexity than did the Fo declination data discussed in the previous section. One feature, however, seems to stand out as being rather consistent in the sense that it is common to all subjects of the present investigation, namely the tendency for a relatively large downward movement of Fo to be associated with larynx lowering. Thus, the data seem to support the view that the inferior extrinsic muscles of the larynx may be involved in the lowering of the fundamental frequency.

The patterns of larynx movement occurring in conjunction with rising Fo, and their variation among speakers suggest that the speakers have employed different strategies producing the fundamental frequency rise. What is of interest here is the relation between the cricothyroid muscle, which is generally assumed to be the primary Fo raising muscle, and the geniohyoid muscle, which has been shown (Erickson, Liberman, and Niimi 1977 and Honda 1983) to take part in Fo raising by - in addition to elevating the entire larynx - rotating and/or translating the thyroid cartilage forwards in relation to the cricoid cartilage and thus elongating and tensing the vocal cords. Other superior extrinsic laryngeal muscles, such as the stylohyoid and the digastric can, of course, also shift the vertical position of the larynx, but their function during speech including their influence on Fo has - to my knowledge - not been subject to systematic research.

Now, within the framework outlined above, the larynx lowering observed in speakers ND and NR suggests that these speakers use a strategy in which a rising Fo is to be primarily attributed to the activity of the cricothyroid muscle, with the geniohyoid and other superior extrinsic laryngeal muscles playing a minor role, if any. This interpretation of data rests on the assumption - as discussed in section IV.A above - that the cricothyroid muscle when contracting for an Fo rise will rotate the thyroid cartilage forward and downward, and thus produce an apparent lowering of the larynx.

The larynx elevation observed in the remaining speakers (CH, JB, JR, OB, PD, PH, and PM) suggests that these speakers employ a strategy for raising Fo which involves also the activity of the superior extrinsic laryngeal muscles. And further, it may be ventured that the differences observed within this group in regard to the correlation between larynx and Fo movement (cf. section III.B.1 above) may reflect different degrees of relative importance of intrinsic and extrinsic muscles in increasing the fundamental frequency. The positive correlation between larynx and Fo movement displayed by CH, JB, and PD may be the result of a relatively great and direct effect of the extrinsic muscles on Fo - the higher the Fo rise the more the extrinsic muscles will have to pull on the larynx. The opposite tendency is seen in speaker PM, who has a strong negative correlation between larynx rise and Fo rise. Here the extrinsic muscles can be assumed to pull upon the larynx by some force which is independent of the magnitude of the Fo rise to be produced. The cricothyroid will then be the muscle which directly controls the actual amount of Fo rise. The activity of that muscle will produce a downward (and forward) movement of the laryngeal prominence the magnitude of which will depend on the magnitude of the Fo rise, and this movement together with the upward displacement caused by the activity of the extrinsic muscles will, as observed from the outside, bring about an upward larynx movement which is inversely proportional to the Fo rise produced. The speakers JR, OB, and PH, who have non-significant (negative) correlations between larynx rise and Fo rise, may be assumed to represent degrees of relative activity of intrinsic and extrinsic laryngeal muscles which are intermediate between the patterns observed in CH, JB, and PD on one side, and PM on the other.

In addition to the differences in strategies between speakers discussed so far, different strategies for Fo control in stress groups can also be observed within the individual speaker, as is the case in sentence final position, where the deviating pattern presumably can be seen as an anticipation of the low level of the larynx generally observed in pauses.

The interpretation attempted here to account for the major trends in the data on Fo and larynx height in sentences and stress groups in terms of patterns of activity of extrinsic and intrinsic laryngeal muscles is, of course, highly speculative and needs further substantiation, preferably using EMG techniques, but to the extent that vertical larynx movements can be assumed to reflect muscular activity which may also influence Fo it seems justified to conclude from the data that while the overall Fo variation characterizing units of sentence size can be attributed to extrinsic laryngeal muscle activity alone, the more localized Fo variation of the stress group can only be accounted for by an intricate pattern of interaction between extrinsic and intrinsic laryngeal muscles.

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APPENDIX I

Material A. The following tables list means ($\overline{X}$), standard deviations (s), and number of observations (n)' for fundamental frequency (Fo) and larynx height (LH) for each of the three speakers NR, PD, and PM. Data are arranged according to sentence length (rows) and stress group number (columns). Within each column data for stressed ('V) and first posttonic ($_{\circ}$V) syllables are listed separately. The row marked 3i gives data for the three-stress-group interrogative sentence.

Fo			.1		.2		.3		.4		.5	
			'V	$_{\circ}$V	'V	$_{\circ}$V	'V	$_{\circ}$V	'V	$_{\circ}$V	'V	$_{\circ}$V
	2	$\overline{X}$	106	134	82	90						
		s	6.453	9.150	2.167	4.274						
		n	8	8	8	8						
	3	$\overline{X}$	107	137	90	109	81	92				
		s	5.605	6.341	2.850	7.100	2.642	3.615				
		n	8	8	8	8	8	8				
		$\overline{X}$	107	140	101	126	117	146				
NR	3i	s	6.143	6.209	3.271	4.534	3.962	3.546				
		n	8	8	8	8	8	8				
	4	$\overline{X}$	111	140	93	114	88	101	78	88		
		s	3.998	4.912	1.959	5.120	2.212	5.120	2.360	2.605		
		n	8	8	8	8	8	8	7	7		
	5	$\overline{X}$	113	143	92	117	89	105	85	97	78	88
		s	6.296	5.460	4.033	7.760	2.435	4.464	1.982	3.703	3.237	4.796
		n	8	7	7	7	8	8	8	8	7	7

LH			.1		.2		.3		.4		.5	
			'V	$_{\circ}$V	'V	$_{\circ}$V	'V	$_{\circ}$V	'V	$_{\circ}$V	'V	$_{\circ}$V
	2	$\overline{X}$	18.8	16.8	16.0	13.8						
		s	1.165	1.035	0.535	0.886						
		n	8	8	8	8						
	3	$\overline{X}$	19.3	17.5	18.4	16.0	16.1	13.6				
		s	0.707	1.512	0.744	0.926	0.991	1.188				
		n	8	8	8	8	8	8				
		$\overline{X}$	19.5	17.8	19.3	18.4	20.3	20.6				
NR	3i	s	0.926	1.581	0.886	1.188	0.463	0.916				
		n	8	8	8	8	8	8				
	4	$\overline{X}$	19.3	17.4	18.8	16.3	17.4	17.4	16.6	13.0		
		s	0.886	1.408	0.886	1.035	0.916	1.061	0.787	1.506		
		n	8	8	8	8	8	8	7	7		
	5	$\overline{X}$	19.5	17.4	19.1	16.3	18.4	16.1	17.6	15.9	16.1	13.6
		s	1.195	1.188	0.690	0.488	0.744	0.354	0.744	1.356	0.900	1.133
		n	8	7	7	7	8	8	8	8	7	7

Fo			1		2		3		4		5	
			'V	∘V	'V	∘V	'V	∘V	'V	∘V	'V	∘V
	2	$\overline{X}$	117	135	104	114						
		s	5.418	2.748	3.464	3.927						
		n	8	8	8	8						
	3	$\overline{X}$	122	141	106	119	97	106				
		s	4.173	5.574	2.900	3.739	2.850	3.196				
		n	8	8	8	8	8	8				
	3i	$\overline{X}$	108	137	119	144	131	147				
PD		s	8.700	4.566	5.064	5.318	7.220	5.416				
		n	8	8	8	8	8	7				
	4	$\overline{X}$	123	139	107	122	103	121	97	107		
		s	6.413	4.713	2.375	4.051	2.062	6.952	2.748	5.148		
		n	8	8	8	8	4	4	8	8		
	5	$\overline{X}$	125	139	110	128	105	118	104	112	96	102
		s	3.295	8.734	2.619	4.121	3.059	4.743	4.998	2.964	2.866	3.643
		n	8	8	8	8	8	8	8	8	8	8

LH			1		2		3		4		5	
			'V	∘V	'V	∘V	'V	∘V	'V	∘V	'V	∘V
	2	$\overline{X}$	22.8	24.8	21.0	23.3						
		s	1.035	1.389	1.246	0.886						
		n	8	8	8	8						
	3	$\overline{X}$	20.9	24.5	22.6	24.3	22.8	23.5				
		s	1.808	1.195	2.326	1.282	1.389	1.512				
		n	8	8	8	8	8	8				
	3i	$\overline{X}$	19.4	24.0	22.9	25.6	24.3	27.6				
PD		s	1.302	0.926	0.835	1.302	1.035	0.976				
		n	8	8	8	8	7	7				
	4	$\overline{X}$	21.9	25.1	21.6	24.1	22.3	24.0	22.3	22.9		
		s	1.356	0.991	2.200	1.885	0.500	0.816	1.982	2.800		
		n	8	8	8	8	4	4	8	8		
	5	$\overline{X}$	20.5	24.4	23.0	25.0	21.8	24.6	21.9	24.3	21.9	22.6
		s	2.777	1.408	2.070	1.604	2.315	1.408	1.246	1.035	2.800	3.292
		n	8	8	8	8	8	8	8	8	8	8

Fo			1		2		3		4		5	
			'V	°V	'V	°V	'V	°V	'V	°V	'V	°V
PM	2	$\bar{X}$	104	126	90	106						
		s	2.504	7.329	1.982	2.659						
		n	8	8	8	8						
	3	$\bar{X}$	105	133	97	117	88	105				
		s	3.682	3.682	2.138	2.659	1.356	2.828				
		n	8	8	8	8	8	8				
	3i	$\bar{X}$	107	134	113	130	109	132				
		s	3.454	4.504	2.726	2.816	3.871	5.249				
		n	8	8	8	8	8	8				
	4	$\bar{X}$	107	134	98	120	95	112	87	101		
		s	4.438	3.314	2.188	4.027	2.453	3.295	1.832	2.696		
		n	8	8	8	8	8	8	8	8		
	5	$\bar{X}$	110	136	101	121	96	117	92	112	86	102
		s	2.928	3.091	5.014	2.774	2.252	3.338	1.885	2.696	2.387	4.000
		n	8	8	8	8	8	8	8	8	8	8

LH			1		2		3		4		5	
			'V	°V	'V	°V	'V	°V	'V	°V	'V	°V
PM	2	$\bar{X}$	8.1	10.8	4.1	6.1						
		s	1.126	1.035	0.354	1.356						
		n	8	8	8	8						
	3	$\bar{X}$	8.3	11.0	7.3	11.0	4.5	7.5				
		s	1.035	1.069	1.165	1.069	0.926	1.852				
		n	8	8	8	8	8	8				
	3i	$\bar{X}$	8.5	11.0	9.5	12.4	9.5	11.6				
		s	0.756	0.756	1.069	0.518	1.690	1.061				
		n	8	8	8	8	8	8				
	4	$\bar{X}$	8.3	10.6	7.5	10.1	6.4	10.1	3.9	6.8		
		s	0.866	0.916	1.414	0.991	1.188	1.553	0.354	1.165		
		n	8	8	8	8	8	8	8	8		
	5	$\bar{X}$	7.6	10.6	8.5	10.9	7.1	10.8	5.0	11.0	5.6	7.9
		s	0.916	1.685	0.926	0.835	1.640	1.165	0.926	1.690	1.598	1.808
		n	8	8	8	8	8	8	8	8	8	8

<u>Material B.</u> The following tables list means ($\bar{X}$), standard deviations (s), and number of observations (n) for fundamental frequency (Fo) and larynx height (LH) for the nine speakers CH, JB, JR, ND, NR, OB, PD, PH, and PM. The data are arranged according to sentence length and stress group number (rows) and position within the stress group (columns) ordered consecutively, i.e. stressed syllable ('V column 1), first posttonic (∘V column 2), second posttonic (∘V column 3), and stressed syllable in the following stress group ('V column 4).

Fo			'V	∘V	∘V	'V
CH	2.1	$\bar{X}$	113	134		
		s	4.809	7.689		
		n	8	8		
	2.2	$\bar{X}$	96	111		
		s	2.605	1.874		
		n	8	8		
	4.1	$\bar{X}$	116	136	114	
		s	7.145	14.511	6.742	
		n	16	16	16	
	4.4	$\bar{X}$	95	114		
		s	5.310	7.016		
		n	16	16		
	5.1	$\bar{X}$	115	132		
		s	6.739	10.575		
		n	8	8		
	5.5	$\bar{X}$	94	110		
		s	3.623	2.712		
		n	8	8		
	4.2	$\bar{X}$	111	122	107	106
		s	4.892	6.163	4.534	3.739
		n	8	8	8	8

LH			'V	∘V	∘V	'V
CH	2.1	$\bar{X}$	17.9	18.6		
		s	0.354	0.518		
		n	8	8		
	2.2	$\bar{X}$	17.6	17.9		
		s	0.518	0.835		
		n	8	8		
	4.1	$\bar{X}$	17.3	18.7	17.1	
		s	0.794	0.794	0.885	
		n	16	16	16	
	4.4	$\bar{X}$	18.7	19.4		
		s	0.479	0.727		
		n	16	16		
	5.1	$\bar{X}$	18.1	18.6		
		s	0.835	0.916		
		n	8	8		
	5.5	$\bar{X}$	18.8	19.1		
		s	0.707	0.354		
		n	8	8		
	4.2	$\bar{X}$	18.8	19.1	17.8	17.9
		s	0.463	0.835	0.463	0.641
		n	8	8	8	8

Fo			'V	∘V	∘V	'V
JB	2.1	$\overline{X}$	118	130		
		s	2.976	3.137		
		n	8	8		
	2.2	$\overline{X}$	105	108		
		s	1.309	2.816		
		n	8	8		
	4.1	$\overline{X}$	124	137	121	
		s	3.907	3.722	2.626	
		n	16	16	16	
	4.4	$\overline{X}$	101	106		
		s	2.330	4.147		
		n	16	16		
	5.1	$\overline{X}$	121	133		
		s	6.232	6.163		
		n	8	8		
	5.5	$\overline{X}$	102	109		
		s	2.588	4.658		
		n	8	8		
	4.2	$\overline{X}$	117	124	112	111
		s	2.976	4.899	1.642	3.137
		n	8	8	8	8

LH			'V	∘V	∘V	'V
JB	2.1	$\overline{X}$	19.8	23.8		
		s	1.035	1.669		
		n	8	8		
	2.2	$\overline{X}$	18.6	21.3		
		s	0.774	1.581		
		n	8	8		
	4.1	$\overline{X}$	20.8	25.3	22.5	
		s	1.276	1.571	1.592	
		n	16	16	16	
	4.4	$\overline{X}$	20.4	21.1		
		s	1.360	0.771		
		n	16	16		
	5.1	$\overline{X}$	20.4	25.1		
		s	1.923	1.727		
		n	8	8		
	5.5	$\overline{X}$	19.9	21.1		
		s	0.991	0.991		
		n	8	8		
	4.2	$\overline{X}$	21.1	25.1	21.8	20.0
		s	0.835	1.356	1.165	0.956
		n	8	8	8	8

Fo			'V	˳V	˳V	'V
JR	2.1	$\overline{X}$	109	138		
		s	5.148	7.846		
		n	8	8		
	2.2	$\overline{X}$	95	117		
		s	4.534	6.906		
		n	8	8		
	4.1	$\overline{X}$	118	146	117	
		s	5.899	7.949	6.407	
		n	16	16	16	
	4.4	$\overline{X}$	91	107		
		s	2.750	5.013		
		n	16	16		
	5.1	$\overline{X}$	113	142		
		s	4.342	6.266		
		n	8	8		
	5.5	$\overline{X}$	93	114		
		s	4.375	4.224		
		n	8	8		
	4.2	$\overline{X}$	110	143	106	101
		s	3.871	6.198	3.071	3.068
		n	8	8	8	8

LH			'V	˳V	˳V	'V
JR	2.1	$\overline{X}$	23.5	24.1		
		s	1.195	0.835		
		n	8	8		
	2.2	$\overline{X}$	22.9	23.4		
		s	0.835	1.188		
		n	8	8		
	4.1	$\overline{X}$	22.9	24.7	23.3	
		s	1.928	1.852	1.447	
		n	16	16	16	
	4.4	$\overline{X}$	22.6	24.0		
		s	1.204	0.966		
		n	16	16		
	5.1	$\overline{X}$	23.0	24.6		
		s	1.414	0.744		
		n	8	8		
	5.5	$\overline{X}$	22.6	23.5		
		s	1.061	0.926		
		n	8	8		
	4.2	$\overline{X}$	24.5	24.6	23.8	22.0
		s	1.069	1.506	1.165	0.756
		n	8	8	8	8

Fo			'V	°V	°V	'V
ND	2.1	$\overline{X}$	146	154		
		s	7.764	9.568		
		n	8	8		
	2.2	$\overline{X}$	110	111		
		s	5.793	6.341		
		n	8	8		
	4.1	$\overline{X}$	148	158	142	
		s	7.898	8.229	10.353	
		n	14	14	14	
	4.4	$\overline{X}$	102	105		
		s	4.266	4.334		
		n	16	16		
	5.1	$\overline{X}$	155	163		
		s	7.254	5.908		
		n	7	7		
	5.5	$\overline{X}$	103	106		
		s	3.105	5.139		
		n	8	8		
	4.2	$\overline{X}$	132	146	129	125
		s	7.833	11.250	9.418	8.812
		n	8	8	8	8

LH			'V	°V	°V	'V
ND	2.1	$\overline{X}$	20.8	12.8		
		s	4.097	2.503		
		n	8	8		
	2.2	$\overline{X}$	17.1	12.0		
		s	1.727	2.507		
		n	8	8		
	4.1	$\overline{X}$	20.9	15.7	14.7	
		s	2.119	2.277	2.440	
		n	15	15	15	
	4.4	$\overline{X}$	17.1	13.6		
		s	1.408	1.454		
		n	15	15		
	5.1	$\overline{X}$	23.1	16.6		
		s	4.811	2.828		
		n	7	7		
	5.5	$\overline{X}$	14.6	11.5		
		s	1.302	1.195		
		n	8	8		
	4.2	$\overline{X}$	19.3	14.1	11.9	18.0
		s	2.984	1.773	1.113	2.380
		n	7	7	7	7

Fo			'V	˳V	˳V	'V
NR	2.1	$\overline{X}$	115	143		
		s	7.434	3.742		
		n	8	8		
	2.2	$\overline{X}$	85	97		
		s	2.964	3.536		
		n	8	8		
	4.1	$\overline{X}$	112	146	126	
		s	5.095	7.881	5.196	
		n	16	16	16	
	4.4	$\overline{X}$	82	91		
		s	3.633	1.962		
		n	16	16		
	5.1	$\overline{X}$	119	151		
		s	2.900	3.852		
		n	8	8		
	5.5	$\overline{X}$	82	90		
		s	3.615	2.167		
		n	8	8		
	4.2	$\overline{X}$	97	121	114	92
		s	4.504	3.335	6.563	2.875
		n	8	8	8	8

LH			'V	˳V	˳V	'V
NR	2.1	$\overline{X}$	22.6	21.9		
		s	0.518	1.126		
		n	8	8		
	2.2	$\overline{X}$	19.3	18.6		
		s	0.886	1.302		
		n	8	8		
	4.1	$\overline{X}$	22.8	22.6	21.8	
		s	0.750	1.030	0.856	
		n	16	16	16	
	4.4	$\overline{X}$	18.6	16.6		
		s	1.628	1.210		
		n	16	16		
	5.1	$\overline{X}$	22.4	21.5		
		s	0.744	0.926		
		n	8	8		
	5.5	$\overline{X}$	19.4	17.1		
		s	1.302	0.991		
		n	8	8		
	4.2	$\overline{X}$	21.9	20.1	20.5	19.1
		s	0.835	1.246	0.926	1.246
		n	8	8	8	8

Fo			'V	∘V	∘V	'V
OB	2.1	$\overline{X}$	109	120		
		s	4.243	4.435		
		n	4	4		
	2.2	$\overline{X}$	97	91		
		s	8.435	6.081		
		n	8	8		
	4.1	$\overline{X}$	135	127	102	
		s	7.220	5.357	4.241	
		n	16	16	16	
	4.4	$\overline{X}$	99	86		
		s	4.993	4.367		
		n	16	16		
	5.1	$\overline{X}$	141	132		
		s	12.487	7.704		
		n	8	8		
	5.5	$\overline{X}$	93	88		
		s	2.964	4.359		
		n	8	7		
	4.2	$\overline{X}$	116	114	91	109
		s	7.690	7.323	4.685	5.159
		n	7	7	7	7

LH			'V	∘V	∘V	'V
OB	2.1	$\overline{X}$	28.3	32.3		
		s	3.500	2.062		
		n	4	4		
	2.2	$\overline{X}$	18.6	16.1		
		s	1.923	2.696		
		n	8	8		
	4.1	$\overline{X}$	27.4	32.4	24.1	
		s	3.240	2.128	3.052	
		n	16	16	16	
	4.4	$\overline{X}$	21.3	18.1		
		s	2.236	2.670		
		n	16	16		
	5.1	$\overline{X}$	30.8	33.6		
		s	1.488	2.234		
		n	8	8		
	5.5	$\overline{X}$	20.3	17.9		
		s	0.707	2.167		
		n	8	8		
	4.2	$\overline{X}$	25.1	29.3	20.3	23.4
		s	1.959	1.832	0.707	1.768
		n	8	8	8	8

Fo			'V	∘V	∘V	'V
		$\bar{X}$	109	119		
	2.1	s	2.673	4.830		
		n	8	7		
		$\bar{X}$	95	102		
	2.2	s	3.357	3.182		
		n	8	8		
		$\bar{X}$	116	131	125	
	4.1	s	3.864	5.241	7.070	
		n	16	16	16	
		$\bar{X}$	90	100		
PD	4.4	s	2.828	3.071		
		n	16	16		
		$\bar{X}$	119	131		
	5.1	s	5.436	6.022		
		n	8	8		
		$\bar{X}$	89	99		
	5.5	s	2.532	5.153		
		n	8	8		
		$\bar{X}$	112	124	119	102
	4.2	s	3.295	8.464	5.502	3.412
		n	8	8	8	8

LH			'V	∘V	∘V	'V
		$\bar{X}$	14.3	15.5		
	2.1	s	0.707	1.069		
		n	8	8		
		$\bar{X}$	12.3	11.5		
	2.2	s	1.581	1.414		
		n	8	8		
		$\bar{X}$	15.1	17.3	17.6	
	4.1	s	0.927	0.874	1.408	
		n	16	16	16	
		$\bar{X}$	14.6	13.6		
PD	4.4	s	0.886	1.360		
		n	16	16		
		$\bar{X}$	14.3	16.9		
	5.1	s	0.886	1.458		
		n	8	8		
		$\bar{X}$	13.6	12.0		
	5.5	s	1.408	1.309		
		n	8	8		
		$\bar{X}$	14.9	16.9	16.6	14.1
	4.2	s	0.835	0.835	1.061	0.835
		n	8	8	8	8

Fo			'V	∘V	∘V	'V
PH	2.1	$\overline{X}$	180	197		
		s	7.200	4.259		
		n	8	8		
	2.2	$\overline{X}$	156	177		
		s	8.450	7.633		
		n	8	8		
	4.1	$\overline{X}$	196	209	185	
		s	5.690	7.101	7.693	
		n	14	14	14	
	4.4	$\overline{X}$	147	168		
		s	4.879	4.863		
		n	14	14		
	5.1	$\overline{X}$	186	204		
		s	10.650	8.271		
		n	8	8		
	5.5	$\overline{X}$	143	163		
		s	6.289	5.445		
		n	8	8		
	4.2	$\overline{X}$	164	187	146	163
		s	6.813	6.698	7.230	7.308
		n	8	8	8	8

LH			'V	∘V	∘V	'V
PH	2.1	$\overline{X}$	21.6	23.1		
		s	0.744	0.835		
		n	8	8		
	2.2	$\overline{X}$	19.9	21.4		
		s	0.835	1.061		
		n	8	8		
	4.1	$\overline{X}$	21.9	24.3	23.1	
		s	1.232	1.031	1.207	
		n	14	14	14	
	4.4	$\overline{X}$	22.1	22.4		
		s	0.864	1.089		
		n	14	14		
	5.1	$\overline{X}$	22.5	24.4		
		s	0.926	1.061		
		n	8	8		
	5.5	$\overline{X}$	22.1	21.8		
		s	0.354	1.282		
		n	8	8		
	4.2	$\overline{X}$	21.0	22.0	18.6	20.3
		s	1.512	1.414	0.916	1.669
		n	8	8	8	8

Fo			'V	∘V	∘V	'V
PM	2.1	$\bar{X}$	99	123		
		s	3.117	5.222		
		n	8	8		
	2.2	$\bar{X}$	88	102		
		s	4.373	1.852		
		n	8	8		
	4.1	$\bar{X}$	107	138	106	
		s	3.557	4.266	3.575	
		n	16	16	16	
	4.4	$\bar{X}$	85	96		
		s	2.366	2.128		
		n	16	16		
	5.1	$\bar{X}$	103	138		
		s	3.012	7.111		
		n	8	8		
	5.5	$\bar{X}$	84	97		
		s	1.506	3.068		
		n	8	8		
	4.2	$\bar{X}$	98	119	96	93
		s	2.357	5.548	3.583	2.357
		n	8	8	8	8

LH			'V	∘V	∘V	'V
PM	2.1	$\bar{X}$	12.4	14.1		
		s	1.996	0.991		
		n	8	8		
	2.2	$\bar{X}$	9.0	11.6		
		s	0.926	0.518		
		n	8	8		
	4.1	$\bar{X}$	13.2	14.6	13.1	
		s	1.169	1.087	0.885	
		n	16	16	16	
	4.4	$\bar{X}$	10.0	12.9		
		s	0.895	0.680		
		n	16	16		
	5.1	$\bar{X}$	12.3	13.8		
		s	1.035	1.282		
		n	8	8		
	5.5	$\bar{X}$	9.5	12.0		
		s	0.756	0.926		
		n	8	8		
	4.2	$\bar{X}$	11.8	13.6	11.4	10.8
		s	0.886	0.916	1.302	1.389
		n	8	8	8	8