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COARTICULATION OF INHERENT FUNDAMENTAL FREQUENCY LEVELS BETWEEN SYLLABLES

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Abstract: In Advanced Standard Copenhagen (ASC) Danish the inherent Fo level differences between high and low vowels are of an order of magnitude comparable to that of the Fo deflection in the stress groups. In theory, this could imply that the intended stress distribution in an utterance might be perceived incorrectly, since the inherent Fo level variation could distort the linguistically relevant Fo pattern in the stress groups. It was hypothesized that such distortion is compensated for by coarticulation of inherent Fo levels between syllables. Experiments carried out to test this hypothesis showed that Fo level in one vowel is consistently influenced by vowel height in the preceding syllable, being higher after a high than after a low vowel. There seems to be no consistent influence from the succeeding vowel. The greatest amount of compensation is found in the first posttonic vowel in the stress group, and it occurs whether the consonant between the two vowels is a sonorant (m) or a voiceless fricative (f). Formant measurements of first posttonic ɑ showed that the formant frequencies are influenced (although slightly) by both the preceding and the following vowels. An explanation of the discrepancy between the manner in which vowel quality (and hence tongue body position) and the manner in which Fo is influenced by adjacent vowels is attempted in terms of a spring-mass model describing the relation between the tongue body and the laryngeal structures.

1. Introduction

The observed course of fundamental frequency in an utterance can be viewed as the result of contributions from several simultaneous components. In a non-tonal language such as Advanced Standard Copenhagen (ASC) Danish four components have to be considered (Thorsen 1979): (1) a sentence component which gives the intonation contour of the sentence, (2) a stress group component which supplies the Fo patterns of the stress groups (a stress group in ASC Danish is constituted by a stressed syllable plus the following unstressed ones, irrespective of intervening syntactic boundaries on the same intonation contour, cf. Thorsen 1980b), (3) - in words with stød - a stød component which yields Fo movements characteristic of the stød, and (4) a segmental (or microprosodic) component which renders the Fo variation attributable to the segments constituting the utterance, such as intrinsic Fo level differences between segments and coarticulatory effects on Fo at and across segment boundaries. Since it is a consequence of inherent properties of the speech production system, and cannot be voluntarily controlled by the speaker[1], the segmentally determined Fo variation cannot - unlike the contributions from components 1, 2, and 3 - carry linguistically relevant prosodic information. On the contrary, if sufficiently large, the segmentally determined Fo variation could be expected to interfere with and possibly distort the contributions to the fundamental frequency course from the linguistically relevant components.

The present paper examines the interaction between the segmental component (with the emphasis on inherent Fo level differences between vowels) and one of the linguistically relevant components, viz. the stress group component.

The Fo pattern of the ASC stress group can be described as a relatively low stressed syllable followed by a high-falling tail of unstressed syllables (Thorsen 1979, 1980b). The Fo rise from the stressed to the first posttonic syllable varies (with position in time and in the intonation contour) between 3 and 0.5 semitones. These values are very similar to the inherent Fo level differences between high and low vowels, which have been found by Reinholt Petersen (1978, 1979) to vary between 1 and 3 semitones. In theory this might imply that the segmental composition of an utterance could distort the Fo pattern in such a manner that - assumed that Fo is a cue to the perception of stress - the perceived stress pattern of an utterance would differ from that intended by the speaker due to the qualities of the vowels in the utterance.

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1) This applies to non-tonal languages. In Yoruba, a tone language, Hombert (1976) has found a tendency for speakers to actively minimize the effect of initial consonants on Fo in vowels.

Now, apparently this does not happen. People normally perceive the stress patterns as intended by the speaker. One explanation for this could be that the listener perceptually compensates for inherent Fo differences, and thus reconstructs the intended Fo contour and patterns. A similar perceptual compensation seems to take place as far as intrinsic durational differences between high and low vowels are concerned (Reinholt Petersen 1974). However, the inherent Fo level differences are considerably larger in stressed than in unstressed syllables (Reinholt Petersen 1979), and this means that the perceptual system would have to know the stress distribution in order to be able to select the appropriate correction factor for the reconstruction of the intended stress group pattern. Another possibility, which is the one under investigation here, could be hypothesized, namely that the compensation takes place in the speech production system as coarticulation of inherent Fo levels between syllables. A coarticulatory effect of this kind would more or less eliminate the Fo distortion introduced by the segmental component, and thus preserve the intended fundamental frequency course. For example, in a sequence of high stressed vowel plus low first posttonic, where the distortion due to vowel height could reduce the intended fundamental frequency rise from the stressed to the first posttonic syllable, the inherently high Fo level of the stressed vowel could be hypothesized to be carried over to the first posttonic vowel, raising its Fo, or (less likely, perhaps) the inherently low Fo level in the first posttonic could be anticipated in the stressed vowel, lowering the Fo of that vowel. In both cases the distortion introduced by the vowels in the sequence would be smoothed out and the intended Fo pattern preserved (to a greater or lesser extent depending on the magnitude of the coarticulation effect).

2. Experiment I

Experiment I concentrated on the inherent Fo level differences between vowels and their influence on Fo in adjacent syllables. More specifically, the following questions were considered:
(1) Can Fo in one syllable be influenced by a high vs. low vowel (i.e. a vowel with high vs. low inherent Fo level) in adjacent

syllables? (2) Is the effect, if any, directional (i.e. is it the preceding or the following syllable which has the stronger effect)? (3) Are there differences between syllables in different positions in the stress group as to how strongly Fo is influenced?

2.1 Method

2.1.1 Material

The test material consisted of nonsense words of the structure mVmVmV with the vowels i, u and ɑ[1] alternating within the words as described below. The test words were embedded in carrier sentences where the word immediately following the test word could be either markeres [mɑˈg̊ʰeˀʌs] 'is/are marked', muteres [muˈd̥ˢeˀʌs] 'is/are mutated', or miteres [miˈd̥ˢeˀʌs] a non-existing, but possible word in Danish. By having i, u, or ɑ in the first syllable of the word following the test word, the sequence within which the vowels could be systematically varied could be extended from three to four syllables. This was considered justified, since word boundaries do not seem to have any influence on the Fo pattern in ASC Danish (Thorsen 1980a). The frame preceding the test word was Stavelserne i ... [ˈsd̥æw̩sʌnə i] 'The syllables of ...".

The vowels examined for effects on Fo from preceding and following high and low vowels occurred in stressed, first posttonic, and second posttonic position. In addition to this, vowels in first pretonic position (i.e. vowels in the last unstressed syllable in the preceding stress group) were examined, in order to see whether stressed vowels might produce a stronger effect on the preceding vowel than do unstressed vowels. (It should be noted that the effect (if any) of stressed vowels on first pretonic vowels operate across the stress group boundary, whereas effects of first and second posttonic vowels on preceding vowels operate within the stress group.) The material consisted of the following 46 test sequences (henceforth a test sequence, i.e. the three-syllable test word plus the first syllable of the following words, will also be referred to as a test word):

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1) The symbol ɑ is used in this paper to denote a low, unrounded mid vowel [ɑ̄-] or [ɑ+].

1	ˈmimimi mi-	24	mimiˈmi mi-
2	ˈmimimi ma-	25	mimiˈmi ma-
3	ˈmimima ma-	26	mimiˈma ma-
4	ˈmimama ma-	27	mimaˈma ma-
5	ˈmamama ma-	28	mamaˈma ma-
6	ˈmamama mi-	29	mamaˈma mi-
7	ˈmamami mi-	30	mamaˈmi mi-
8	ˈmamimi mi-	31	mamiˈmi mi-
9	ˈmimima mi-	32	mimiˈma mi-
10	ˈmimami mi-	33	mimaˈmi mi-
11	ˈmamami ma-	34	mamaˈmi ma-
12	ˈmamima ma-	35	mamiˈma ma-
13	ˈmumumu mu-	36	mumuˈmu mu-
14	ˈmumumu ma-	37	mumuˈmu ma-
15	ˈmumuma ma-	38	mumuˈma ma-
16	ˈmumama ma-	39	mumaˈma ma-
17	ˈmamama mu-	40	mamaˈma mu-
18	ˈmamamu mu-	41	mamaˈmu mu-
19	ˈmamumu mu-	42	mamuˈmu mu-
20	ˈmumuma mu-	43	mumuˈma mu-
21	ˈmumamu mu-	44	mumaˈmu mu-
22	ˈmamamu ma-	45	mamaˈmu ma-
23	ˈmamuma ma-	46	mamuˈma ma-

The vowels underlined in the list are those which were to be examined for effects on the fundamental frequency from vowel height variation in adjacent syllables. In words 1-23 first and second posttonic vowels were examined and in words 24-46 first pretonic and stressed vowels were examined. To give an example: first posttonic i could be measured in i-i environments in word 1, in i-a environments in word 3, in a-i environments in word 8, and in a-a environments in word 12.

2.1.2 Recordings and speakers

The reading list consisted of 46 test sentences and 14 distractor sentences arranged in six different random orders. The recordings took place in a sound treated room in the Institute of Phonetics by means of a REVOX A700 professional tape recorder and a Sennheiser MD21 microphone.

There were four subjects, two females (KM and SI) and two males (PA and NR (the author)), who were all phoneticians and all speakers of ASC Danish. The subjects were instructed to read the list with a neutral declarative intonation at a comfortable speech rate.

As the list was long and proved rather difficult to read, the recordings were divided into readings of one or two randomizations at a time. As it turned out, this caused the overall Fo levels for the individual speakers to vary between readings (see further section 2.2 below). Altogether, six repetitions of each test word were obtained.

2.1.3 Registrations and measurements

The apparatus for registration was a REVOX A77 tape recorder, two intensity meters, a fundamental frequency meter (F-J Electronics), and a Mingograph (Elema 800). The following acoustic curves were made: duplex oscillogram, linear HiFi intensity curve (integration time 2.5 ms), two logarithmic intensity curves (integration time 2.5 ms) HP-filtered at 500 and 2000 Hz, respectively, and a fundamental frequency curve. The paper speed of the Mingograph was 100mm/sec. The duplex oscillogram and the intensity curves were used for segmentation purposes only. The accuracy of segmentation was ± 0.5 cs. The fundamental frequency of the vowels was measured at a point in time two thirds from the vowel onset (cf. Rossi 1976 and 1978). The scale of the Fo curve varied between 1 and 3 Hz/mm depending on the speaker, i.e. an accuracy of measurement of 1 Hz or less was achieved.

2.2 Results

As mentioned in section 2.1.2 above, the recording of the material was divided in several readings of one or two randomizations at a time. This meant a risk for differences in overall Fo level between readings to add unduly to the statistical variability of the measurements. A Friedman two-way analysis of variance by ranks (Siegel 1956) applied to the data showed a statistically significant effect of reading (randomization) on the overall Fo level for all subjects (KM: $\chi_r^2 = 12.39$, $p < 0.05$; SI: $\chi_r^2 = 112.21$, $p < 0.001$; PA: $\chi_r^2 = 63.88$, $p < 0.001$; NR: $\chi_r^2 = 121.06$, $p < 0.001$). Therefore, a normalization procedure was employed in which each of the measurements in one randomization was converted into the deviation from the mean of all measurements in that randomization. This procedure reduced the variation among the six repetitions of the test vowels, and the original means could be restored by adding the mean deviations over the six repetitions to the grand mean, i.e. the mean of all measurements in all randomizations.

The means and standard deviations computed on the basis of the normalized data are listed in tables 1 to 4 for i and ɑ in i/ɑ-words and u and ɑ in u/ɑ-words in each of the four stress group positions examined, viz. first pretonic, stressed, first posttonic, and second posttonic positions. In figs. 1 to 4 the mean Fo values for the individual subjects are plotted as a function of the tongue heights of the preceding and following vowels, respectively (i.e. the data points in the figures represent the row ($\overline{X}_{r.}$) and column ($\overline{X}_{c.}$) means given in tables 1 to 4). Fig. 5 shows the means over all subjects expressed in semitones derived by converting the normalized measurements for each subject into semitone deviations from that subject's grand mean, and then averaging the deviations over the subjects.

In the evaluation of the data as presented in tables 1 - 4 and figs. 1 - 5 it should be kept in mind that the material was organized in such a manner that first posttonic and second posttonic vowels (indicated by +1 and +2 in the figures) appeared in syllables number two and three (i.e. consecutively) in words with the stress on the first syllable (words 1-23), and that first pretonic and stressed vowels (indicated by -1 and 0 in the figures) appeared in syllables number two and three in words with the stress on the third syllable (words 24-46) (see section 2.1.1 above). This means that, apart from comparisons within stress group positions (which was the object of the design of the material), the Fo levels measured can only be compared between the first and second posttonic syllables, and between the first pretonic and stressed syllables. Comparing the Fo levels of stressed and first posttonic vowels, on the other hand, in order to derive the Fo rises from stressed to first posttonic syllables would lead to an overestimation (although not very great) of the rises, because the

Table 1

Mean fundamental frequencies (in Hz) and standard deviations for the vowels i, u, and a in first pretonic, stressed, first post-tonic, and second posttonic syllables before and after high vs. low vowels. Speaker KM.

		i in i/a-words			a in i/a-words			u in u/a-words			a in u/a-words		
		foll. vowel		$\bar{X}_{r.}$	foll. vowel		$\bar{X}_{r.}$	foll. vowel		$\bar{X}_{r.}$	foll. vowel		$\bar{X}_{r.}$
	prec. vowel	i	a		i	a		u	a		u	a	
1st pretonic	i / u	190 2.2	197 7.5	194	181 2.4	186 7.5	184	195 5.3	190 6.3	193	185 3.9	187 4.0	186
	a	189 4.3	187 2.6	188	187 3.3	188 5.6	188	189 2.4	187 3.9	188	185 4.7	188 5.6	187
	$\bar{X}_{c.}$	190	192		184	187		192	189		185	188	
stressed	i / u	203 5.8	201 4.4	202	187 5.4	186 5.9	187	209 4.6	208 6.2	209	186 5.6	188 5.3	187
	a	204 6.8	203 3.5	204	185 6.6	190 5.2	188	201 4.8	202 7.4	202	186 4.7	190 5.2	188
	$\bar{X}_{c.}$	204	202		186	188		205	205		186	189	
1st posttonic	i / u	226 5.1	229 3.5	228	222 5.5	222 7.1	222	229 9.0	223 2.7	226	219 3.0	216 2.2	218
	a	220 5.2	221 5.5	221	215 2.5	214 5.7	215	218 2.9	220 5.2	219	214 5.1	214 5.7	214
	$\bar{X}_{c.}$	223	225		219	218		224	222		217	215	
2nd posttonic	i / u	207 2.9	206 4.4	207	193 6.2	192 4.7	193	212 11.7	212 8.0	212	185 6.5	182 2.9	184
	a	201 4.8	206 2.9	204	193 4.2	192 5.1	193	200 5.0	203 6.1	202	191 6.2	192 5.1	192
	$\bar{X}_{c.}$	204	206		193	192		206	209		188	187	

Table 2

Mean fundamental frequencies (in Hz) and standard deviations for the vowels i, u, and a in first pretonic, stressed, first posttonic, and second posttonic syllables before and after high vs. low vowels. Speaker SI.

i in i/ɑ-words

Syllable	prec. vowel	foll. vowel i	foll. vowel ɑ	$\overline{X}_{r.}$
1st pretonic	i	236 6.2	240 9.1	238
	ɑ	231 5.8	231 5.8	231
	$\overline{X}_{c.}$	234	236	
stressed	i	255 5.4	248 6.6	252
	ɑ	251 5.7	252 9.4	252
	$\overline{X}_{c.}$	253	250	
1st posttonic	i	278 4.8	276 7.6	277
	ɑ	271 9.4	274 6.3	273
	$\overline{X}_{c.}$	275	275	
2nd posttonic	i	260 4.0	260 3.7	260
	ɑ	253 8.1	258 4.5	256
	$\overline{X}_{c.}$	257	259	

ɑ in i/ɑ-words

Syllable	prec. vowel	foll. vowel i	foll. vowel ɑ	$\overline{X}_{r.}$
1st pretonic	i	234 3.9	226 6.5	230
	ɑ	227 7.4	222 3.8	225
	$\overline{X}_{c.}$	231	224	
stressed	i	222 8.1	225 9.0	224
	ɑ	224 7.5	227 4.8	226
	$\overline{X}_{c.}$	223	226	
1st posttonic	i	276 18.0	277 11.9	277
	ɑ	264 11.3	262 4.4	263
	$\overline{X}_{c.}$	270	270	
2nd posttonic	i	243 4.5	244 5.6	244
	ɑ	241 3.9	240 3.2	241
	$\overline{X}_{c.}$	242	242	

u in u/ɑ-words

Syllable	prec. vowel	foll. vowel u	foll. vowel ɑ	$\overline{X}_{r.}$
1st pretonic	u	241 7.9	240 3.7	241
	ɑ	231 8.6	231 6.1	231
	$\overline{X}_{c.}$	236	236	
stressed	u	258 7.4	256 4.1	257
	ɑ	243 4.2	250 6.6	247
	$\overline{X}_{c.}$	251	253	
1st posttonic	u	277 8.7	284 8.1	281
	ɑ	266 7.4	264 7.2	265
	$\overline{X}_{c.}$	272	274	
2nd posttonic	u	255 5.8	258 3.3	257
	ɑ	253 3.0	254 9.1	254
	$\overline{X}_{c.}$	254	256	

ɑ in u/ɑ-words

Syllable	prec. vowel	foll. vowel u	foll. vowel ɑ	$\overline{X}_{r.}$
1st pretonic	u	238 5.0	226 2.7	232
	ɑ	222 7.2	222 3.8	222
	$\overline{X}_{c.}$	230	224	
stressed	u	224 4.5	226 5.6	225
	ɑ	222 7.5	227 4.8	225
	$\overline{X}_{c.}$	223	227	
1st posttonic	u	274 13.6	269 7.5	272
	ɑ	268 2.5	262 4.4	265
	$\overline{X}_{c.}$	271	266	
2nd posttonic	u	246 4.2	243 5.5	245
	ɑ	241 4.1	240 3.2	241
	$\overline{X}_{c.}$	244	242	

Table 3

Mean fundamental frequencies (in Hz) and standard deviations for the vowels i, u, and ɑ in first pretonic, stressed, first posttonic, and second posttonic syllables before and after high vs. low vowels. Speaker PA.

i in i/ɑ-words

	prec. vowel	foll. vowel i	foll. vowel ɑ	$\bar{X}_{r.}$
1st pretonic	i	109 3.1	109 1.1	109
	ɑ	111 2.6	110 3.7	111
	$\bar{X}_{c.}$	110	110	
stressed	i	121 5.9	117 3.3	119
	ɑ	113 3.2	120 3.7	117
	$\bar{X}_{c.}$	117	119	
1st posttonic	i	142 4.8	149 7.4	146
	ɑ	140 3.6	143 3.1	142
	$\bar{X}_{c.}$	141	146	
2nd posttonic	i	120 4.6	123 5.4	122
	ɑ	118 3.7	119 5.6	119
	$\bar{X}_{c.}$	119	121	

ɑ in i/ɑ-words

	prec. vowel	foll. vowel i	foll. vowel ɑ	$\bar{X}_{r.}$
1st pretonic	i	105 1.5	104 5.2	105
	ɑ	105 1.6	103 1.4	104
	$\bar{X}_{c.}$	105	104	
stressed	i	109 3.2	106 3.1	108
	ɑ	107 7.1	104 4.9	106
	$\bar{X}_{c.}$	108	105	
1st posttonic	i	141 3.2	143 3.7	142
	ɑ	138 8.2	136 5.9	137
	$\bar{X}_{c.}$	140	140	
2nd posttonic	i	111 6.0	113 8.2	112
	ɑ	114 4.0	112 3.5	113
	$\bar{X}_{c.}$	113	113	

u in u/ɑ-words

	prec. vowel	foll. vowel u	foll. vowel ɑ	$\bar{X}_{r.}$
1st pretonic	u	113 1.4	110 3.3	112
	ɑ	115 4.1	112 2.3	114
	$\bar{X}_{c.}$	114	111	
stressed	u	122 3.9	123 5.0	123
	ɑ	116 4.6	121 3.2	119
	$\bar{X}_{c.}$	119	122	
1st posttonic	u	144 4.2	153 4.9	149
	ɑ	142 6.0	142 8.1	142
	$\bar{X}_{c.}$	143	148	
2nd posttonic	u	124 4.9	124 4.4	124
	ɑ	119 3.9	119 5.2	119
	$\bar{X}_{c.}$	122	122	

ɑ in u/ɑ-words

	prec. vowel	foll. vowel u	foll. vowel ɑ	$\bar{X}_{r.}$
1st pretonic	u	107 2.5	108 2.4	108
	ɑ	109 3.2	103 1.4	106
	$\bar{X}_{c.}$	108	106	
stressed	u	109 3.1	107 4.5	108
	ɑ	108 3.8	104 4.9	106
	$\bar{X}_{c.}$	109	106	
1st posttonic	u	142 3.2	143 6.9	143
	ɑ	137 5.0	136 5.9	137
	$\bar{X}_{c.}$	140	140	
2nd posttonic	u	109 2.2	111 3.5	110
	ɑ	113 3.9	112 3.5	113
	$\bar{X}_{c.}$	111	112	

Table 4

Mean fundamental frequencies (in Hz) and standard deviations for the vowels i, u, and ɑ in first pretonic, stressed, first posttonic, and second posttonic syllables before and after high vs. low vowels. Speaker NR.

i in i/ɑ-words

Syllable	prec. vowel	foll. vowel i	foll. vowel ɑ	$\bar{X}_r$
1st pretonic	i	89 1.5	87 1.8	88
	ɑ	83 4.3	85 1.6	84
	$\bar{X}_c$	86	86	
stressed	i	91 1.4	91 2.5	91
	ɑ	89 3.4	88 1.6	89
	$\bar{X}_c$	90	90	
1st posttonic	i	106 4.5	109 4.3	108
	ɑ	102 3.3	102 5.5	102
	$\bar{X}_c$	104	106	
2nd posttonic	i	102 3.5	102 2.8	102
	ɑ	100 2.2	100 2.8	100
	$\bar{X}_c$	101	101	

ɑ in i/ɑ-words

Syllable	prec. vowel	foll vowel i	foll vowel ɑ	$\bar{X}_r$
1st pretonic	i	83 1.1	84 1.6	84
	ɑ	84 2.4	83 3.0	84
	$\bar{X}_c$	84	84	
stressed	i	83 3.4	82 2.5	83
	ɑ	83 3.5	82 3.9	83
	$\bar{X}_c$	83	82	
1st posttonic	i	110 2.8	106 4.0	108
	ɑ	102 2.6	99 3.2	101
	$\bar{X}_c$	106	103	
2nd posttonic	i	96 3.0	95 6.8	96
	ɑ	96 3.1	96 2.3	96
	$\bar{X}_c$	96	96	

u in u/ɑ-words

Syllable	prec. vowel	foll vowel u	foll vowel ɑ	$\bar{X}_r$
1st pretonic	u	89 2.0	89 1.8	89
	ɑ	86 2.0	85 1.3	86
	$\bar{X}_c$	88	87	
stressed	u	94 2.3	92 1.2	93
	ɑ	89 3.5	89 2.3	89
	$\bar{X}_c$	92	91	
1st posttonic	u	108 3.8	111 6.0	110
	ɑ	105 5.3	106 6.3	106
	$\bar{X}_c$	107	109	
2nd posttonic	u	103 4.6	103 6.0	103
	ɑ	98 3.0	99 2.4	99
	$\bar{X}_c$	101	101	

ɑ in u/ɑ-words

Syllable	prec. vowel	foll vowel u	foll vowel ɑ	$\bar{X}_r$
1st pretonic	u	86 1.4	85 2.4	86
	ɑ	84 0.6	83 3.0	84
	$\bar{X}_c$	85	84	
stressed	u	84 3.7	84 3.2	84
	ɑ	83 4.1	82 3.9	83
	$\bar{X}_c$	84	83	
1st posttonic	u	106 3.3	110 2.1	108
	ɑ	101 3.0	99 3.2	100
	$\bar{X}_c$	104	105	
2nd posttonic	u	96 3.5	95 5.1	96
	ɑ	96 3.4	96 2.3	96
	$\bar{X}_c$	96	96	

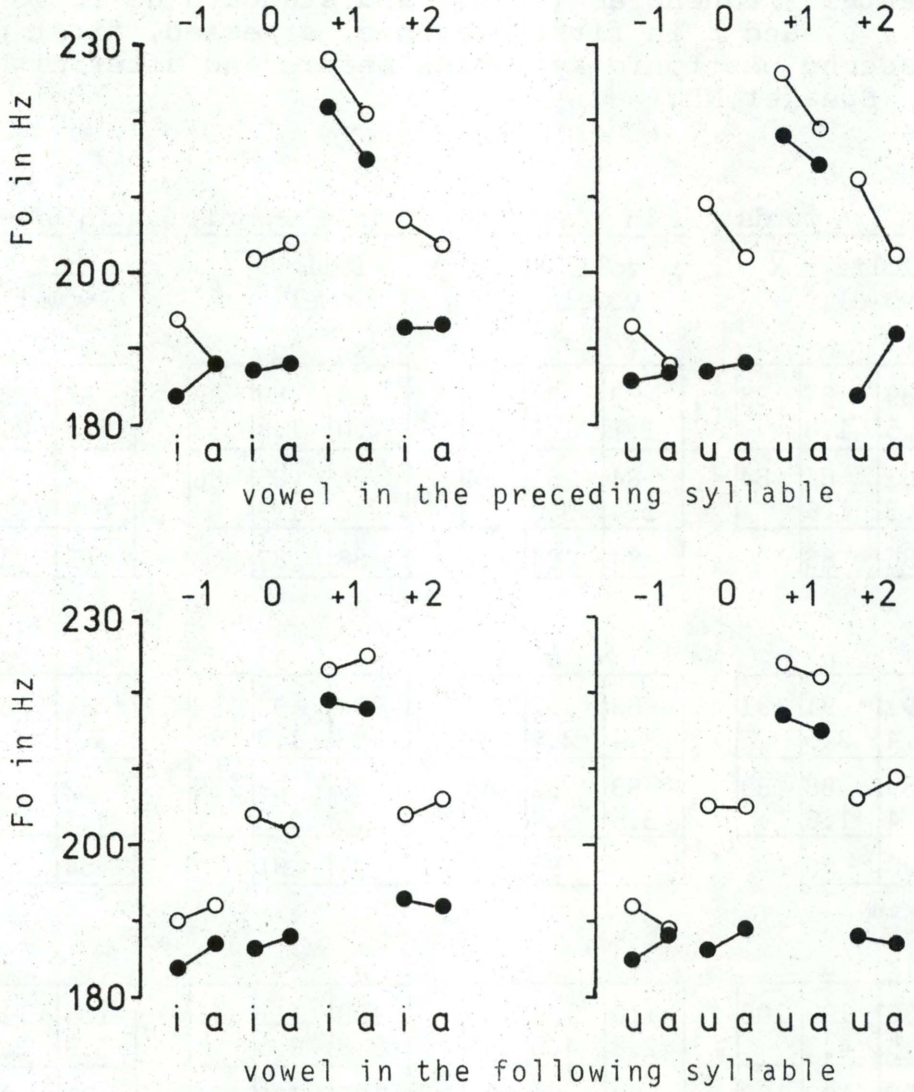

Figure 1

Mean fundamental frequencies in i (o), u (o), and a (•) in first pretonic (-1), stressed (0), first posttonic (+1), and second posttonic (+2) syllables as a function of high and low vowels in the preceding (upper graph) and following (lower graph) syllables. Left: i/a words; right: u/a words. Speaker KM.

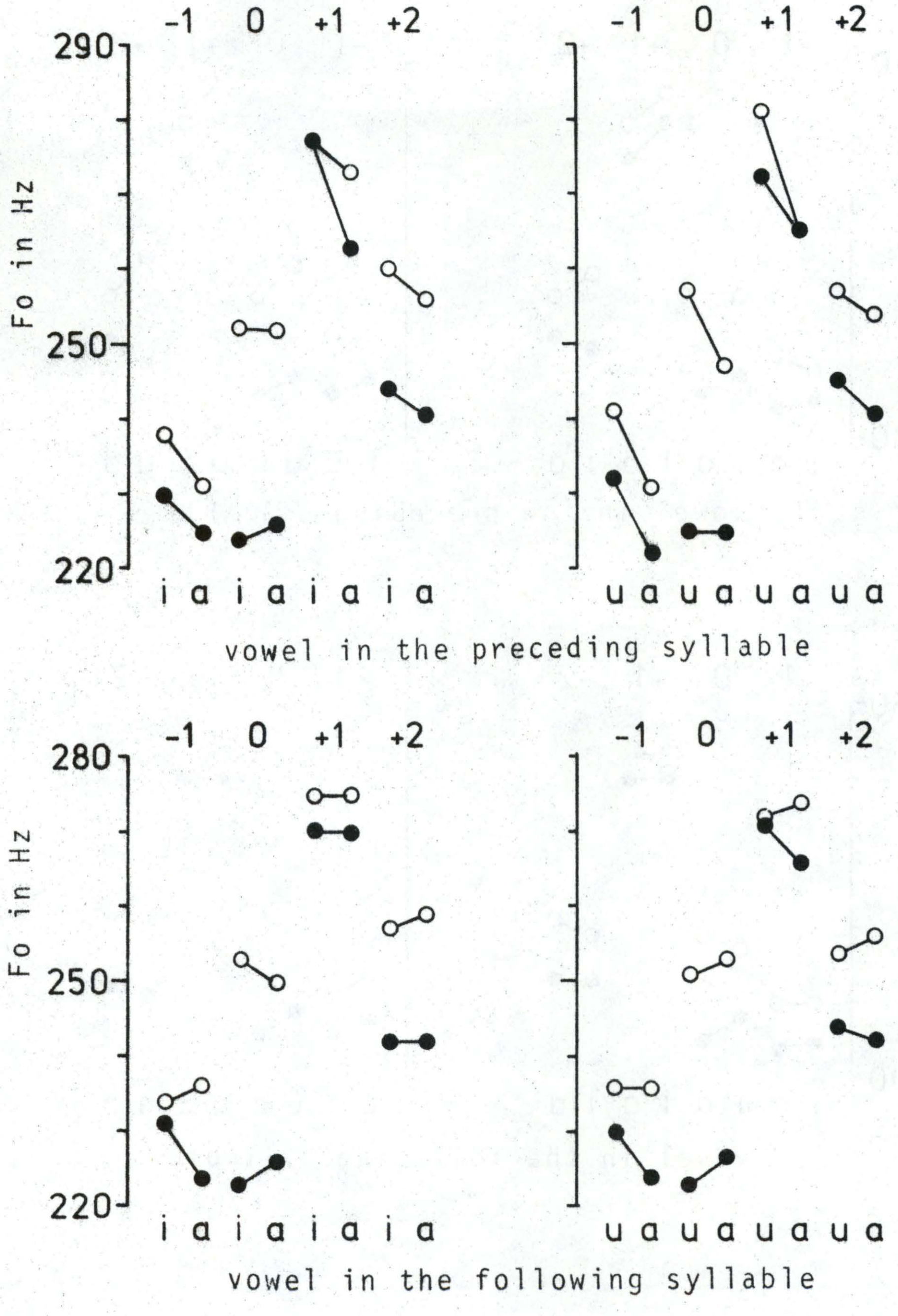

Figure 2

Mean fundamental frequencies in i (o), u (o), and a (•) in first pretonic (-1), stressed (0), first posttonic (+1), and second posttonic (+2) syllables as a function of high and low vowels in preceding (upper graph) and following (lower graph) syllables. Left: i/a words; right: u/a words. Speaker SI.

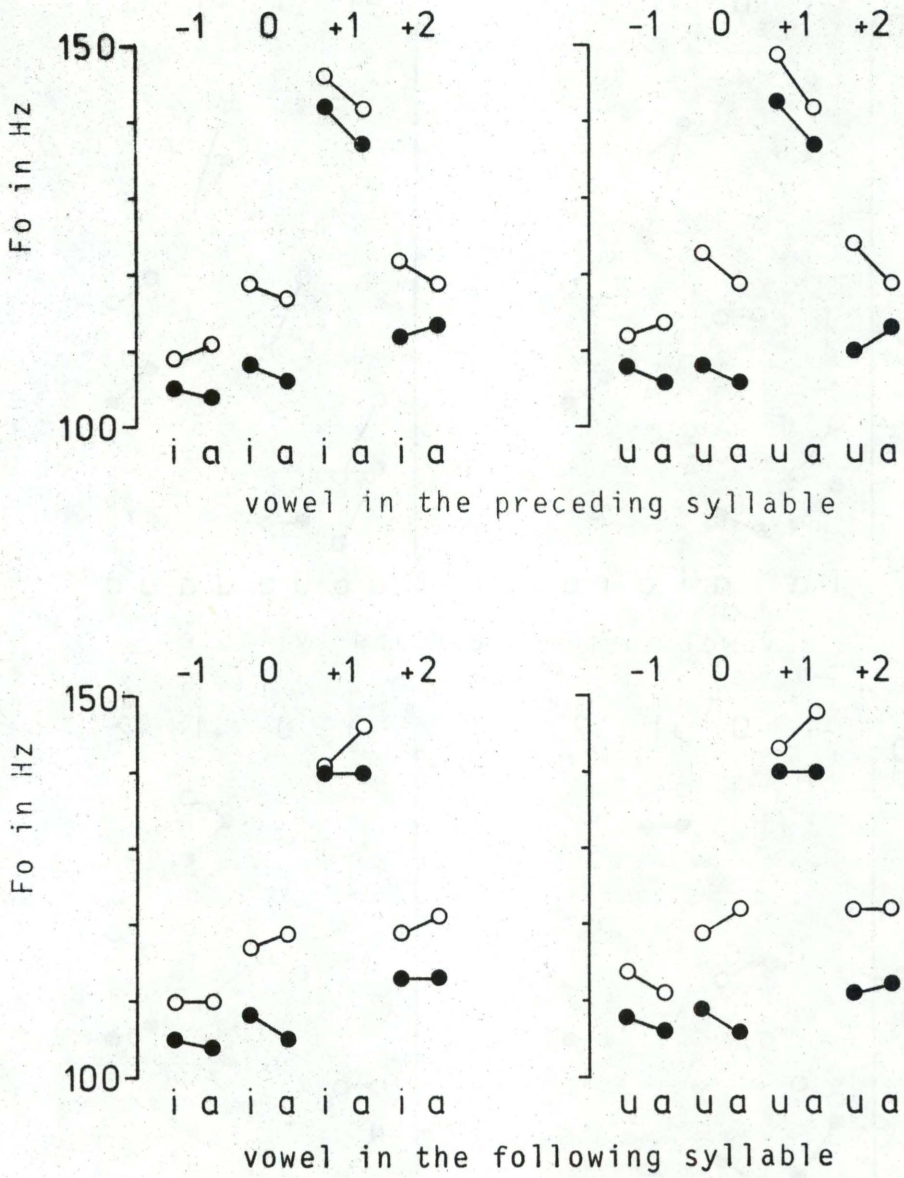

Figure 3

Mean fundamental frequencies in i (o), u (o), and ɑ (•) in first pretonic (-1), stressed (0), first posttonic (+1), and second posttonic (+2) syllables as a function of high and low vowels in the preceding (upper graph) and following (lower graph) syllables. t: Left: i/ɑ words; right: u/ɑ words. Speaker PA.

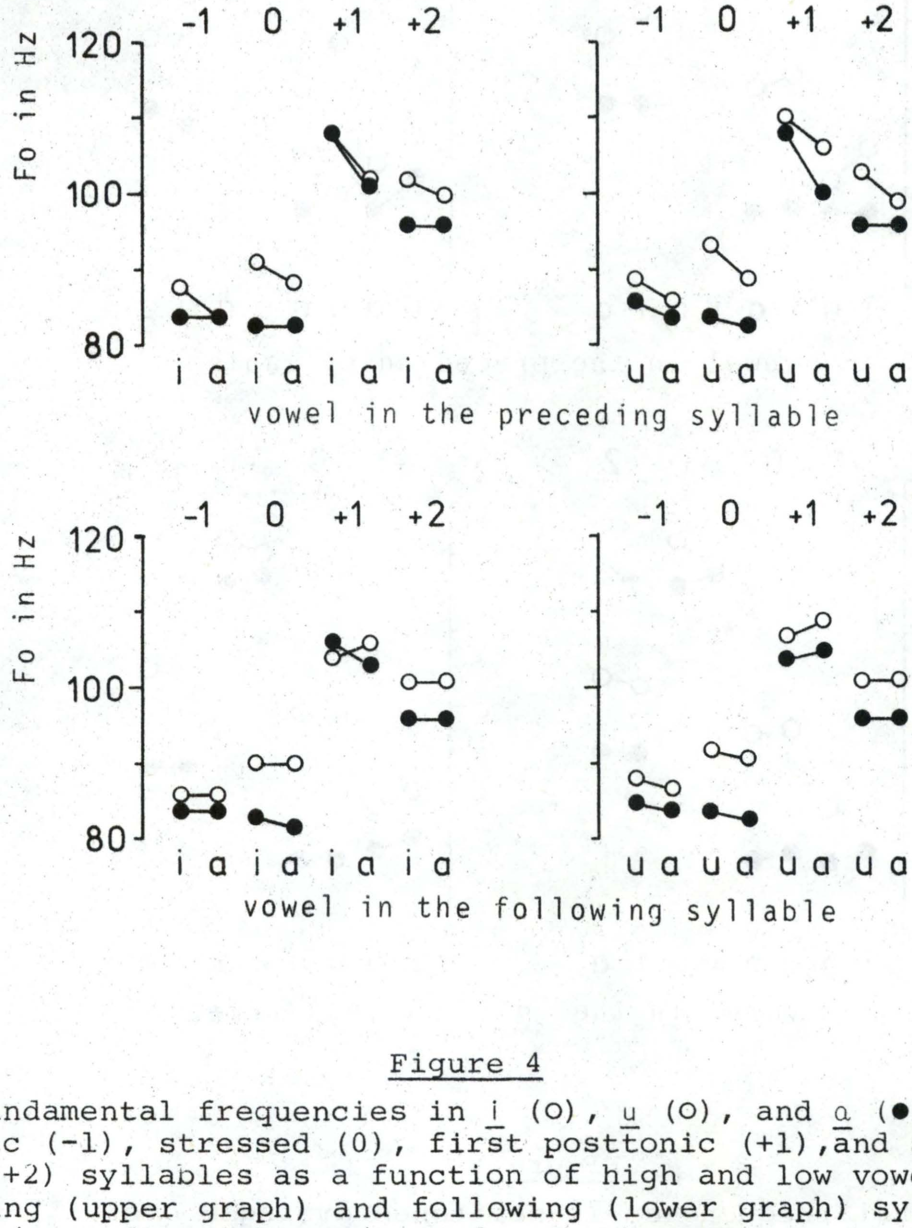

Figure 4

Mean fundamental frequencies in i (○), u (○), and a (●) in first pretonic (-1), stressed (0), first posttonic (+1), and second posttonic (+2) syllables as a function of high and low vowels in the preceding (upper graph) and following (lower graph) syllables. Left: i/a words; right: u/a words. Speaker NR.

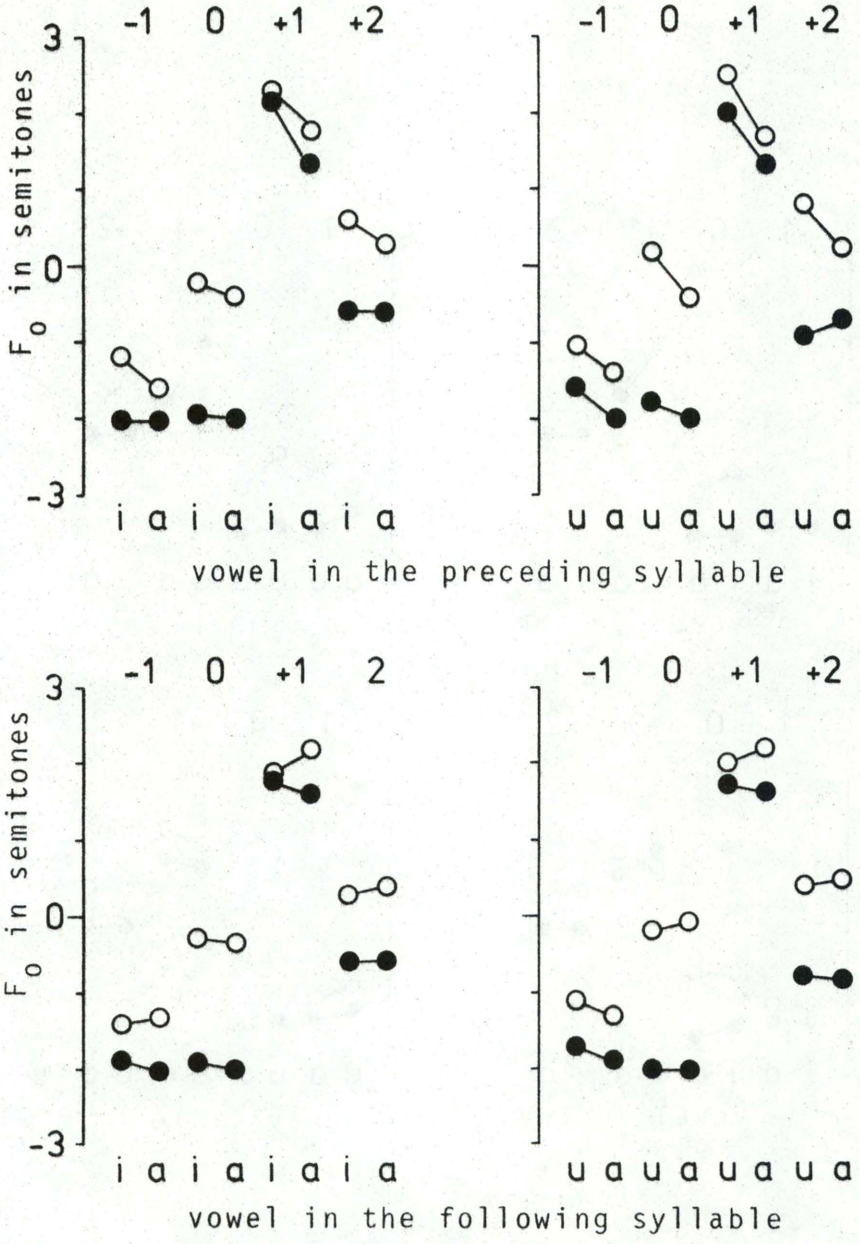

Figure 5

Mean fundamental frequencies in semitones averaged over all speakers in i (o), u (o), and a (●) in first pretonic (-1), stressed (0), first posttonic (+1), and second posttonic (+2) syllables as a function of high and low vowels in the preceding (upper graph) and following (lower graph) syllables. Left: i/a words; right: u/a words.

first posttonic vowels measured occurred earlier in time on the falling intonation contour of the sentence than did the stressed vowels measured, viz. in syllables number two and three, respectively, in the two types of test words.

The data were submitted to a series of two-way analyses of variance (preceding vowel x following vowel). Each of the 2 x 2 matrices of tables 1 to 4 was analyzed separately. The results of the analyses are summarized in table 5.

Table 5

Results of the two-way analyses of variance applied to the data presented in tables 1 to 4. ++ indicates $p < 0.01$, and + indicates $p < 0.05$. Parentheses denote that the effect is significant, but goes in the "wrong" direction, i.e. Fo is higher before or after low vowels than before or after high vowels.

		i/ɑ-words				u/ɑ-words			
		i		ɑ		u		ɑ	
		prec.	foll.	prec.	foll.	prec.	foll.	prec.	foll.
1st pretonic	KM	+				+			
	SI	+		+	+	++		++	++
	PA						+		+
	NR	++				++		+	
stressed	KM					++			
	SI					++			
	PA					+			
	NR	+				++			
1st posttonic	KM	++		++		++			
	SI			+		++			
	PA		(+)	+		+		+	
	NR	++		++	+			++	
2nd posttonic	KM	+				++		(++)	
	SI							+	
	PA					+			
	NR					+			

The data demonstrate clearly that the fundamental frequency of one vowel can be influenced by the quality of neighbouring vowels, but it is equally clear that it is the <u>preceding</u> vowel that exerts the greater and more consistent influence, Fo being in a vast majority of the cases higher after a high vowel than after a low vowel.

The effect of the following vowel is generally considerably smaller and much less consistent. It may be of interest to note that four out of the five cases, where the effect of the following vowel was statistically significant, occurred in the first pretonic syllable, i.e. before a stressed vowel, and across the stress group boundary.

The fundamental frequency of vowels in different positions in the stress group is not influenced to equal degrees by the quality of the preceding vowel. The strongest effect is found in the first posttonic syllable as a result of vowel height variation in the stressed syllable. It is seen from fig. 5 that the effect in the first posttonic approaches one semitone on the average. In the other unstressed syllables the influence is weaker and less consistent. The stressed syllable seems also to be the most resistent with respect to the influence on Fo of the tongue height of the preceding vowel. The vowel u, however, is an exception to this general tendency, Fo in stressed u being strongly affected by the preceding vowel. The behaviour of stressed u and the finding that first pretonic vowels can be influenced by following stressed vowels show that coarticulatory effects on Fo between syllables can occur across stress group boundaries, a fact which weakens the case for the stress group as an autonomous unit in the production of the fundamental frequency course. On the other hand, the effect of stressed vowel on the first pretonic was only statistically significant in four cases out of 16 (cf. table 5 upper row), and - as pointed out above - apart from u, Fo in stressed syllables are not affected by the quality of the preceding vowel; this, of course, can be due to the resistance of the stressed vowel itself, but it may just as well be due to a blocking effect of the preceding stress group boundary.

2.2.1 Fo rises from stressed to first posttonic syllables

In the results given above one point deserves special attention, namely the finding that the strongest effect on the fundamental frequency is that of the stressed vowel on the first posttonic. This is interesting because it might be taken to suggest that the Fo rise from the stressed to the first posttonic syllable, which seems to be an important characteristic of the Fo pattern in the stress group in ASC Danish, tends to remain constant irrespective of vowel heights (and hence Fo levels) in these syllables.

But the above data also suggest that the tendency towards constancy is not complete, in the sense that the inherent fundamental frequency level variation in the stressed syllables is not fully compensated for in the first posttonics. Now, the data presented above do not provide direct information about the Fo rises, since - as pointed out - the organization of the material does not permit intersyllabic comparisons between stressed and first posttonic syllables. Therefore, in order to obtain such information two additional sets of Fo measurements were made, viz. in stressed vowels in words with the stress on the first syllable and in first posttonic vowels in words with the stress on the third syllable. Thus, on the basis of these measurements and the measurements already made in first posttonic vowels and stressed vowels, respectively, two sets of Fo rises from stressed to first posttonic syllables could be derived, both sets containing all possible combinations of i and ɑ and u and ɑ in the two syllables. The rises were computed from raw (i.e. non-normalized) measurements.

The mean Fo rises and standard deviations are given in table 6, and figs. 6 to 7 show the mean Fo values in stressed and first posttonic syllables under the various tongue height conditions. It is seen that Fo rises starting from low stressed vowels are considerably greater than those starting from high stressed vowels, but also that some compensation occurs in the first posttonic vowels, the fundamental frequency in these vowels being higher after high than after low stressed vowels. This is in line with the tendency suggested by the data dealt with above. It also appears from figs. 6 and 7 that the height of the preceding vowel contributes more to the Fo level variation in first posttonic vowels than do the inherent Fo level differences in these vowels; on an average, the effect of high vs. low vowel in the preceding syllable amounts to 4 Hz for KM, 10 Hz for SI, 5 Hz for PA, and 6 Hz for NR, which can be compared to inherent Fo level differences of 4 Hz, 5 Hz, 4 Hz, and 2 Hz, respectively.

Table 7 gives the amount of compensation in pairs of stressed-first posttonic sequences having high vs. low vowels in the stressed syllable and identical vowels in the first posttonic (i.e. ˈi-i/ˈɑ-i, ˈi-ɑ/ˈɑ-ɑ, etc.). The compensation index was derived by dividing the effect on Fo in the first posttonic (i.e. the Fo after high minus Fo after low stressed vowel) by the high-low difference in the stressed vowels.

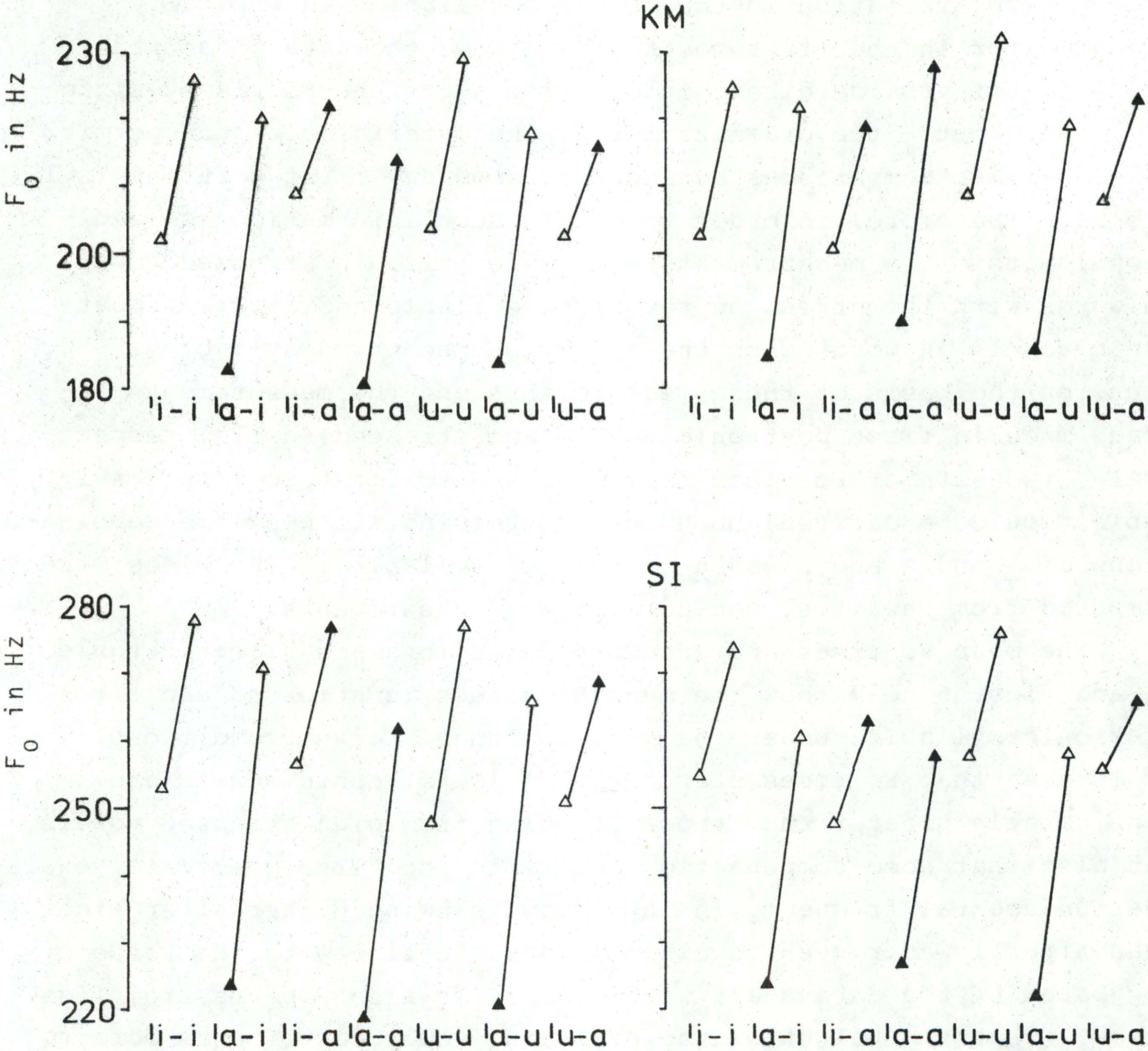

Figure 6

Mean fundamental frequencies in sequences of stressed-first post-tonic vowels (the data for each sequence are connected by lines). High and low vowels are indicated by open and filled triangles, respectively. The left and right columns depict data from words with the stress on the first syllable and from words with the stress on the third syllable, respectively. Speakers KM (upper graph) and SI (lower graph).

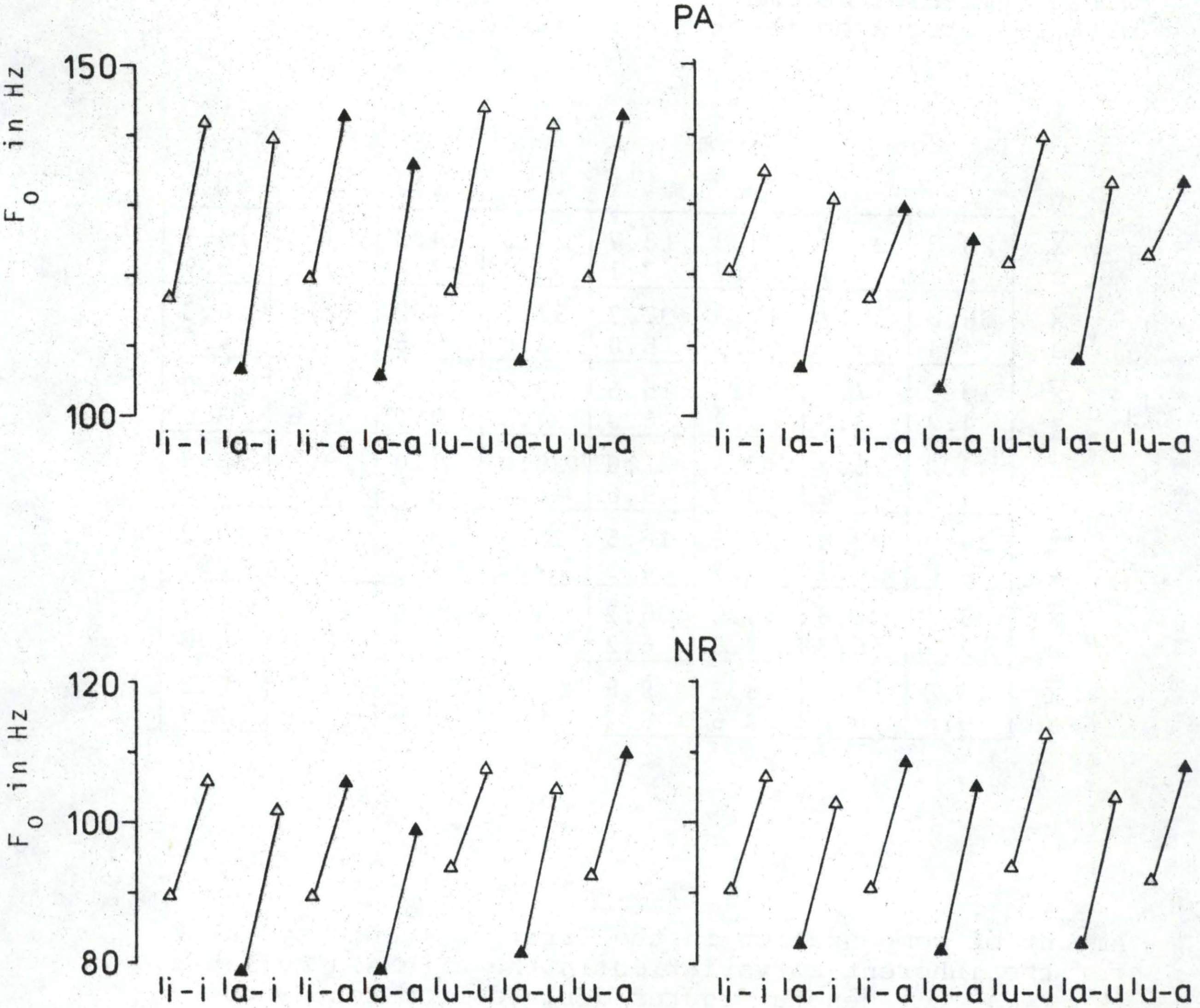

Figure 7

Mean fundamental frequencies in sequences of stressed-first post-tonic vowels (the data for each sequence are connected by lines). High and low vowels are indicated by open and filled triangles, respectively. The left and right columns depict data from words with the stress on the first syllable and from words with the stress on the third syllable, respectively. Speakers PA (upper graph) and NR (lower graph).

Table 6

Mean fundamental frequency rises (and standard deviations) from stressed to first posttonic vowels. Columns marked ˈooo list data from words with the stress on the first syllable, columns marked ooˈo list data from words with the stress on the third syllable.

		KM ˈooo	KM ooˈo	SI ˈooo	SI ooˈo	PA ˈooo	PA ooˈo	NR ˈooo	NR ooˈo
ˈi-i	$\bar{X}$	23.3	21.8	25.8	18.7	24.2	14.3	14.3	15.7
	s	3.0	5.6	4.2	7.1	3.4	7.3	2.7	3.9
ˈa-i	$\bar{X}$	36.8	36.7	47.0	37.7	32.7	24.2	22.5	20.3
	s	4.4	5.5	4.9	5.0	3.0	5.5	5.0	4.5
ˈi-a	$\bar{X}$	13.3	17.5	20.5	15.5	23.2	13.2	15.5	18.0
	s	4.2	3.6	6.4	6.3	4.5	2.6	2.6	3.6
ˈa-a	$\bar{X}$	33.3	38.0	43.5	31.0	30.0	21.0	19.2	23.3
	s	4.0	6.6	3.3	9.6	5.7	3.7	5.1	4.0
ˈu-u	$\bar{X}$	25.0	22.8	29.2	16.5	25.5	18.0	14.2	19.2
	s	4.0	6.7	5.3	4.3	2.2	6.1	3.0	2.1
ˈa-u	$\bar{X}$	33.7	32.8	45.0	36.2	34.0	25.0	22.3	21.2
	s	2.7	6.3	9.3	6.2	3.9	4.3	6.2	5.8
ˈu-a	$\bar{X}$	13.3	14.5	18.2	9.8	23.8	10.8	16.7	16.2
	s	5.0	10.0	2.6	9.2	5.9	2.9	1.5	3.7

Table 7

Amount of compensation in the first posttonic syllable for the inherent Fo variation in the stressed syllable. ˈooo and ooˈo denote figures derived from test words with the stress on the first and third syllable, respectively. Full compensation = 1.0.

		ˈi-i/ˈa-i	ˈi-a/ˈa-a	ˈu-u/ˈa-u	ˈu-a/ˈa-a
KM	ˈooo	0.32	0.29	0.55	0.09
	ooˈo	0.17	-0.82	0.57	-0.28
SI	ˈooo	0.24	0.39	0.41	0.22
	ooˈo	0.42	0.24	0.50	0.28
PA	ˈooo	0.20	0.50	0.20	0.50
	ooˈo	0.29	0.29	0.50	0.42
NR	ˈooo	0.36	0.70	0.25	0.85
	ooˈo	0.50	0.44	0.82	0.30

The degree of compensation varies a great deal, but no systematic trend in the variation can be seen; on the average the compensation amounts to 0.34, i.e. the inherent fundamental frequency variation due to vowel height in stressed syllables is compensated for by approximately one third of the amount in the first posttonics.

Although not entirely within the scope of the present paper, one point concerning the Fo rises should be mentioned, namely the tendency which appears in table 6 for the magnitude of the Fo rises beginning with high vowels to be nearly the same for all speakers, irrespective of their overall fundamental frequency level. This is more clearly illustrated in fig. 8, where the Fo rises from high and low stressed vowels are plotted as a function of the Fo level of the stressed vowels. It is seen that the regression line fitted to the 'i- and 'u-rises is almost constant, at a level of about 18 Hz (slope = 0.0137), throughout the fundamental frequency range covered by the four speakers. The magnitude of the Fo rises beginning with the vowel ɑ, on the other hand, show an increasing tendency through the Fo range (slope = 0.1234). The difference between the slopes is, of course, due to the fact that the inherent fundamental frequency differences increase with the general Fo level (as was also found by Reinholt Petersen, 1978), and that these differences are only partly compensated for in first posttonic vowels. The vertical dispersion of the data points within each category (rises from i and u and rises from ɑ) can - at least in part - be ascribed to inherent Fo differences between vowels in first posttonic syllables, rises to high vowels tending to be greater than rises to low vowels. The tendencies lined out here are interesting and deserve further experimentation, intended to see whether they hold in a larger sample of speakers, and to examine the mechanisms underlying them.

2.3 Discussion

In section 1 above it was suggested that the inherent Fo level differences between vowels could distort the intended Fo pattern of stress groups in such a manner that the stress distribution perceived by the listener would differ from that intended by the speaker. Two possibilities were hypothesized which might ensure the correct transmission of stress distributions from speaker to listener, namely (1) that the perceptual system compensates for

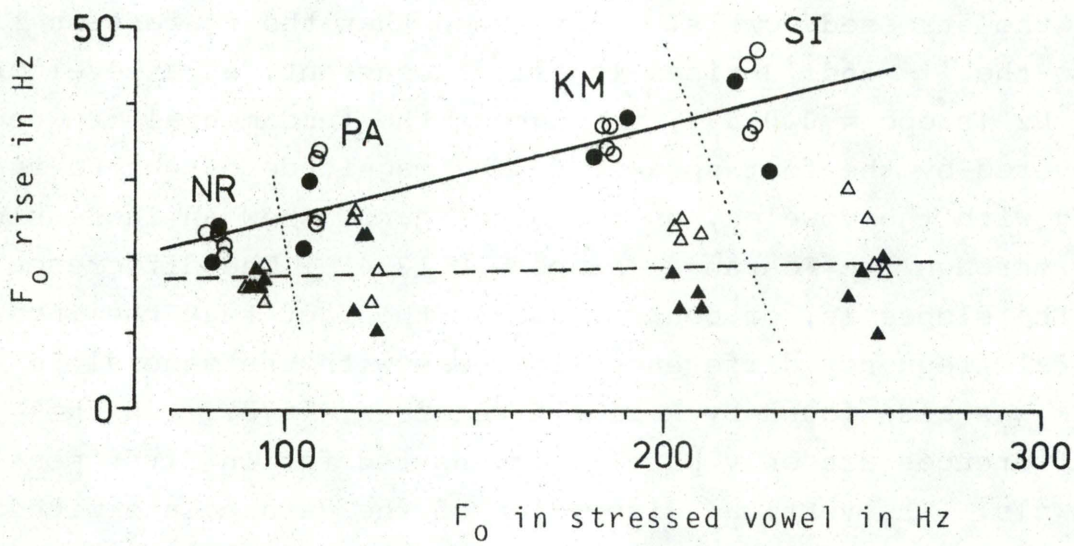

Figure 8

Mean F_0 rises from stressed to first posttonic vowels plotted as a function of F_0 in the stressed syllables. ˈi-i and ˈu-u rises are indicated by △, ˈi-ɑ and ˈu-ɑ rises by ▲, ˈɑ-i and ˈɑ-u rises by ○, and ˈɑ-ɑ rises by ●. The full and broken lines are regression lines fitted to the data points representing rises starting with low stressed and with high stressed vowels, respectively. The dotted lines separate the data for NR and PA and the data for KM and SI.

the inherent Fo variation and thus restores the intended Fo course, or (2) that the compensation takes place in the speech production system in the shape of coarticulation of inherent Fo level across syllable boundaries so that the linguistically irrelevant Fo variation is smoothed out and the intended Fo pattern preserved.

The above experiment has shown that the inherent Fo level differences are to some degree smoothed out as a result of carry-over coarticulation of Fo from one syllable to the next. This is particularly true of the effect of stressed vowels on Fo in first posttonic vowels. On the other hand, in the majority of cases in the present material the Fo rises from stressed to first posttonic syllables seem to be sufficiently great in comparison with the inherent Fo level differences between high and low vowels for them to be preserved even if no coarticulatory compensation for the inherent differences had occurred. But there are a few cases of stressed i or u followed by first posttonic ɑ, where the compensation effect is almost entirely responsible for the rise (see e.g. KM's ˈi-ɑ vs. ˈɑ-ɑ (left column of fig. 6), SI's ˈu-ɑ vs. ˈɑ-ɑ (right column of fig. 6), and PA's ˈu-ɑ vs. ˈɑ-ɑ (right column of fig. 7)). Even in such cases, however, it is a question whether the observed effect can be assumed to be a necessary prerequisite for - or to facilitate - the perception of stress. A further discussion of this matter will, however, be postponed till section 4 below, where the results of Experiment II will also be taken into consideration. The present discussion will focus upon the mechanisms responsible for the coarticulation of inherent Fo levels across syllable boundaries. More specifically the question will be considered whether it is tongue height that is coarticulated or it is Fo (or rather the laryngeal conditions which produce the inherent Fo level differences between vowels).

Before proceeding any further, it may be appropriate to review briefly the current hypotheses advanced to explain the inherent Fo level differences.[1] One hypothesis rests on the assumption that the acoustic impedance in the glottis is sufficiently low, relative

1) The following review is neither exhaustive nor does it attempt to evaluate the hypotheses sketched. Critical and more detailed reviews are given in e.g. Ewan (1979), Ohala (1973), and Reinholt Petersen (1978).

to the comparatively high input impedance to the vocal tract at low first formant frequencies, for some coupling to occur between the vocal tract and the glottis (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 lower the first formant, i.e. the closer the first resonance is to the Fo range, vowels with low first formants (e.g. i and u) will have higher fundamental frequency than vowels with high first formants (e.g. ɑ).

Another hypothesis suggests 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 then thought to be translated into an increased longitudinal tension of the vocal cords, which in turn leads to a higher fundamental frequency.

A third hypothesis, advanced by Ohala (1973) and elaborated upon by Ewan (1975, 1979), is also based on the pull of the tongue on the laryngeal structures. But according to this hypothesis the increased tongue pull in high vowels gives rise to an increased vertical tension in the vocal cords, which is established through the mucous membrane and other soft tissues without involving the hyoid bone and the hard tissues of the larynx. Ewan (1975, 1979) has proposed a modification of the hypothesis, emphasizing not so much the pull as the retraction of the tongue and the constriction of the pharynx in low vowels, which increase the vibrating mass and decrease the vertical tension of the vocal cords, with a lower Fo as the result.

Now, in the present material the Fo variation in first posttonic syllables attributable to the variation in tongue height of the preceding (stressed) vowel approaches one semitone. If an effect of that magnitude were to be explained by coarticulatory assimilation of tongue height, a radical quality shift should be expected in first posttonic vowels. This applies no matter whether the inherent Fo level differences between vowels are to be accounted for by the acoustic source/tract coupling hypothesis or by the physiologically based tongue pull hypothesis. Listening to the recorded material did not, however, reveal any such changes of vowel quality. In order to obtain quantitative data to illuminate this point, the frequencies of the first and second formants in <u>a</u> in first posttonic syllables were measured in the recordings of the two male speakers PA and NR. The mean formant frequencies are plotted in fig. 9 as a function of the vowels in the preceding and following syllables, respectively. The formant data were submitted to a series of two-way analyses of variance (preceding vowel x following vowel), the results of which are summarized in table 8.

<u>Table 8</u>

Results of the two-way analyses of variance applied to the formant data for the vowel <u>a</u> depicted in fig. 9. ++ indicates $p < 0.01$, and + indicates $p < 0.05$.

	first formant				second formant			
	i/a-words		u/a-words		i/a-words		u/a-words	
	prec. vowel	foll. vowel	prec. vowel	foll. vowel	prec. vowel	foll. vowel	prec. vowel	foll. vowel
PA			+		++	++	++	
NR		+			++	+	++	++

It is seen (as could be expected on the basis of the auditory evaluation) that the formant frequencies of first posttonic syllables are only moderately influenced by the adjacent vowels; and the very small - and in most cases non-significant - effect observed in the first formant precludes the possibility of the influence on Fo from the preceding vowel to be accounted for by acoustic coupling between the vocal tract and the glottis. Furthermore, to the extent that the formant frequencies are influenced by the vowels in adjacent syllables (this applies to the second formant in particular), they are influenced by <u>both</u> preceding <u>and</u> following vowels, whereas Fo is influenced mainly by preceding vowels.

Thus, the formant data reveal a discrepancy between the effect of neighbouring vowels on the fundamental frequency and the effect of neighbouring vowels on the position of the tongue body, both as regards the magnitude and the direction of the effects. This interpretation of the formant data presupposes, of course, that the formant frequency changes observed in the present material can be ascribed to tongue body position changes. This can be assumed to be the case with reasonable certainty in the <u>i/a</u> words, but not,

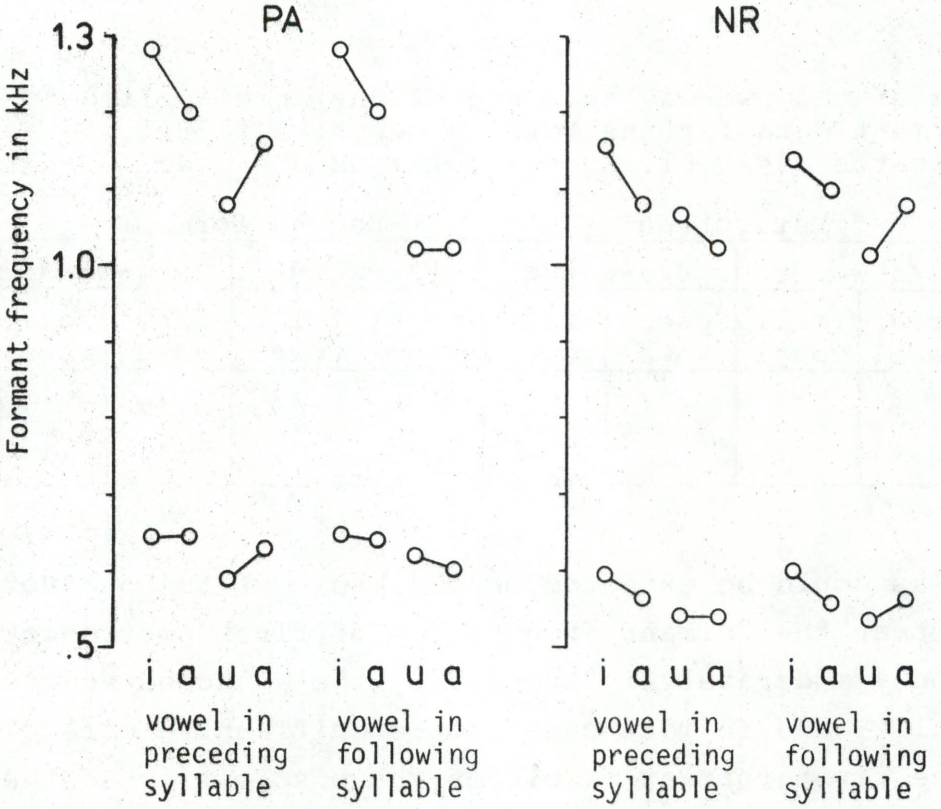

Figure 9

Mean frequencies of formant 1 and formant 2 in first posttonic a as a function of preceding and following high and low vowels. Speakers PA (left) and NR (right).

perhaps, in the u/ɑ words, where lip rounding is also involved.

The discrepancy can be explained under the tongue pull hypothesis - but not under the source/tract coupling hypothesis - if the relation between tongue height and the laryngeal conditions responsible for inherent Fo level differences between vowels can be described in terms of a damped spring-mass system, where the driving force is the tongue body, the spring represents the connection between the tongue body and the laryngeal structures, and the mass represents the tension and/or mass of the vocal cords. If this description is tenable, changes of the laryngeal conditions, and hence of the fundamental frequency, will occur with a delay relative to the changes in tongue height which produce them.

3. Experiment II

Experiment II was primarily intended to examine, as a supplement to Experiment I, whether the effect of a high vs. a low vowel in one syllable on the fundamental frequency in the following one would also show up if the consonant between the two syllables was voiceless instead of voiced as in Experiment I, but since it would imply only a limited extension of the material it was decided also to consider the question whether a segmentally determined Fo level variation in one syllable conditioned not by vowel height but by the initial consonant could produce an effect on Fo in the following syllable similar to that produced by a high vs. a low vowel.

3.1 Method

3.1.1 Material

Since the results of Experiment I indicated that Fo in one syllable is influenced almost exclusively by tongue height differences in the preceding syllable, and since the effect turned out most markedly in the first posttonic, it was thought appropriate to make up the test material so as to focus on the influence on Fo in the first posttonic from the segmental variation in the stressed syllable. The present material was limited to include only the vowels i and ɑ, and the consonants chosen were the labials m and f.

The test material consisted of all possible 'CVCV combinations of the two consonants and the two vowels. The test words were embedded in carrier sentences similar to those of Experiment I.

3.1.2 Recordings and speakers

The sixteen test sentences and eight distractor sentences were arranged in six different random orders in a reading list, i.e. six repetitions of each word were obtained. The recordings were made under the same conditions as in Experiment I, and with the same subjects (see section 2.1.2 above). Since the list was comparatively easy to read all six randomizations were recorded in one session.

3.1.3 Registrations and measurements

The following acoustic curves were made: duplex oscillogram, two intensity curves (HiFi linear and HP-filtered at 500 Hz, logarithmic, integration time 2.5 ms for both), and a fundamental frequency curve. The fundamental frequency of the stressed and first posttonic vowels were measured at a point in time two thirds from vowel onset.

3.2 Results

Since all six randomizations of the test words were read in one session it was not considered necessary to carry out a normalization of the measurements as was done in Experiment I, and inspection of the variability of the present data did not reveal any systematic deviation from the variability of the normalized data of Experiment I.

3.2.1 Effect of initial f vs. m on Fo in the vowel

A prerequisite for considering at all whether f vs. m and i vs. ɑ in the stressed syllable have similar effects on the fundamental frequency in the first posttonic syllable was that the intrinsic Fo differences produced in the stressed syllable by the two different types of segmental variation (f vs. m and i vs. ɑ) were of the same order of magnitude. In order to see whether this was the case, means and standard deviations for Fo in the vowels of all mi, fi, ma, and fa syllables in stressed position were computed, and a series of t-tests were applied to test the statistical significance of the differences between means in the vowels following f and m. Table 9 gives the means, standard deviations, differences between means, and levels of significance achieved. The means are displayed graphically in fig. 10 in Hz for the individual subjects and in semitones averaged over the subjects.

It is seen that there is a clear tendency for Fo to be higher after f than after m, and the effect was significant at a very high level in all cases. Furthermore, the effects of initial consonant and of vowel height seem to be of comparable magnitudes, although the former effect is slightly smaller than the latter. On the average the Fo difference between i and a amounts to 1.3 semitones compared to a difference of 0.9 semitones between vowels following f and m. The initial consonant also influences Fo in first posttonic vowels, but to a lesser degree than in stressed syllables. The difference in the posttonic vowels after m vs. f were 0.6 semitones on the average. The Fo intrinsic level difference between i and a in first posttonic vowels was 0.5 semitones on the average.

Table 9

Mean fundamental frequencies and standard deviations in the stressed vowels i and a and differences between means after initial f and m. The levels of significance of the differences between f and m are indicated by +++ for $p < 0.001$ and ++ for $p < 0.01$.

			f-	m-	f-m
KM	-i	$\bar{X}$	194.5	186.7	7.8+++
		s	5.595	5.247	
	-a	$\bar{X}$	184.2	175.6	8.6+++
		s	3.978	3.717	
SI	-i	$\bar{X}$	229.8	218.0	11.8+++
		s	5.838	3.989	
	-a	$\bar{X}$	210.5	203.0	7.5+++
		s	6.454	5.668	
PA	-i	$\bar{X}$	111.3	106.2	5.1++
		s	7.910	3.293	
	-a	$\bar{X}$	105.0	100.4	4.6+++
		s	3.257	2.618	
NR	-i	$\bar{X}$	102.0	95.5	6.5+++
		s	2.136	1.351	
	-a	$\bar{X}$	92.4	88.0	4.4+++
		s	1.974	2.828	

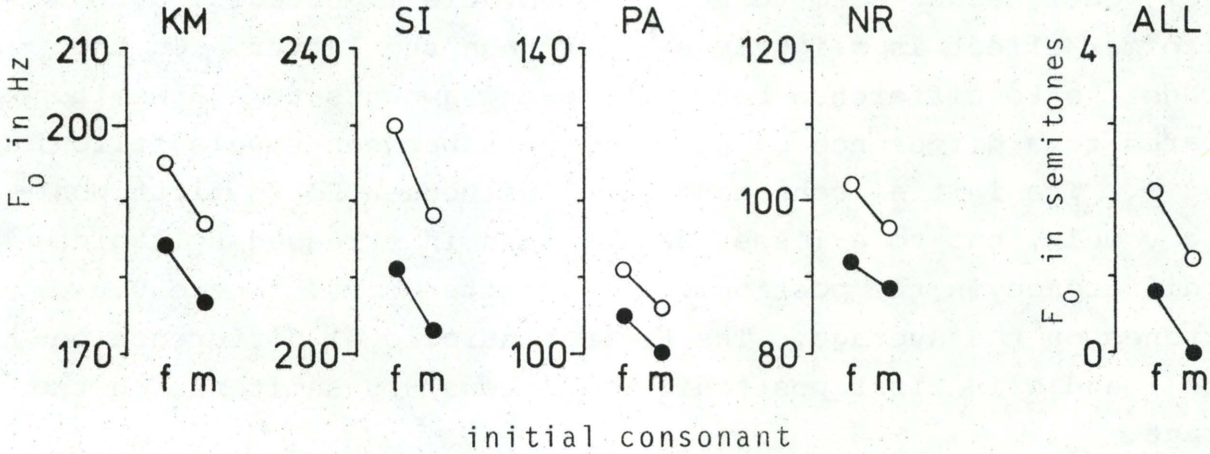

Figure 10

Mean fundamental frequencies in stressed i (o) and ɑ (•) as a function of initial f and m for the four subjects individually and averaged over all subjects (in semitones).

3.2.2 The effects of i vs. ɑ and f vs. m initially in the stressed syllable on Fo in the first posttonic

Table 10 presents the means and standard deviations of the Fo measurements in first posttonic fi, fɑ, mi, and mɑ syllables after i vs. ɑ and initial f vs. m in the preceding, stressed syllable. The means are displayed graphically in fig. 11 for the subjects individually in Hz, and averaged over the subjects in semitones. The data were submitted to a series of two-way analyses of variance (tongue height x consonant type in the stressed syllable). Each of the 2x2 matrices in table 10 were analysed separately. The results of the analyses of variance are given in table 11.

Before further considering the results, it should be noted that the data for one of the subjects, PA, seem to show a rather atypical pattern. From fig. 11 it is seen that in 3 out of the 4 posttonic syllables examined, PA has a higher Fo after ɑ than after i in the preceding syllable. This is in disagreement with what is found for the other subjects in the present experiment and also with PA's results in Experiment I (see fig. 3 above). In view of this, the evaluation of the data will be based mainly on subjects KM, SI, and NR.

The data show - like those of Experiment I - that the tongue height of the vowel in the stressed syllable influences the fundamental frequency of the first posttonic vowel. Furthermore, it is evident that this effect exists irrespective of whether the intervening consonant is voiced or voiceless.

In contradistinction to the effect of tongue height, Fo variation due to the initial consonant in the stressed syllable has no effect on the fundamental frequency of the first posttonic vowel. There is a slight, but not consistent, tendency for Fo in that vowel to be higher after an f than after an m initially in the stressed syllable, but the effect could be proved statistically significant only in one case (se table 11) out of 12 (leaving PA out), which can be compared to 9 out of 12 cases of significant tongue height effects.

Table 10

Mean fundamental frequencies (in Hz) and standard deviations in first posttonic -fi, -fa, -mi, and -ma syllables after i vs. a and f vs. m in the preceding (stressed) syllables.

	prec. vowel	-fi: initial cons. in prec. syl. f	m	$\overline{X}_{r.}$	-fa: initial cons. in prec. syl. f	m	$\overline{X}_{r.}$	-mi: initial cons. in prec. syl. f	m	$\overline{X}_{r.}$	-ma: initial cons. in prec. syl. f	m	$\overline{X}_{r.}$
KM	i	202 6.2	203 2.0	203	201 6.0	198 4.7	200	205 3.5	200 4.3	203	199 3.1	199 2.3	199
	a	203 3.6	203 1.9	203	196 4.9	198 3.4	197	198 5.2	199 5.4	199	197 3.0	193 3.6	195
	$\overline{X}_{c.}$	203	203		199	198		202	200		198	196	
SI	i	243 3.8	239 5.2	241	239 4.8	231 5.3	235	234 4.8	234 7.5	234	230 5.2	230 4.3	230
	a	238 2.5	237 2.3	238	226 5.1	230 4.8	228	229 3.8	229 5.8	229	224 2.2	223 2.2	224
	$\overline{X}_{c.}$	241	238		233	231		232	231		227	227	
PA	i	133 5.9	125 3.3	129	129 15.3	123 3.4	126	123 6.9	124 4.3	124	117 6.0	124 7.9	121
	a	128 7.1	131 5.1	130	121 4.1	123 4.8	122	126 8.2	124 5.3	125	125 5.6	118 5.7	122
	$\overline{X}_{c.}$	131	128		125	123		125	124		121	121	
NR	i	111 2.2	114 2.4	113	112 2.3	111 2.2	112	106 2.5	106 2.5	106	104 3.4	104 2.8	104
	a	111 2.3	109 0.8	110	106 3.4	108 2.6	107	102 4.7	101 3.4	102	100 3.4	99 3.5	100
	$\overline{X}_{c.}$	111	112		109	110		104	104		102	102	

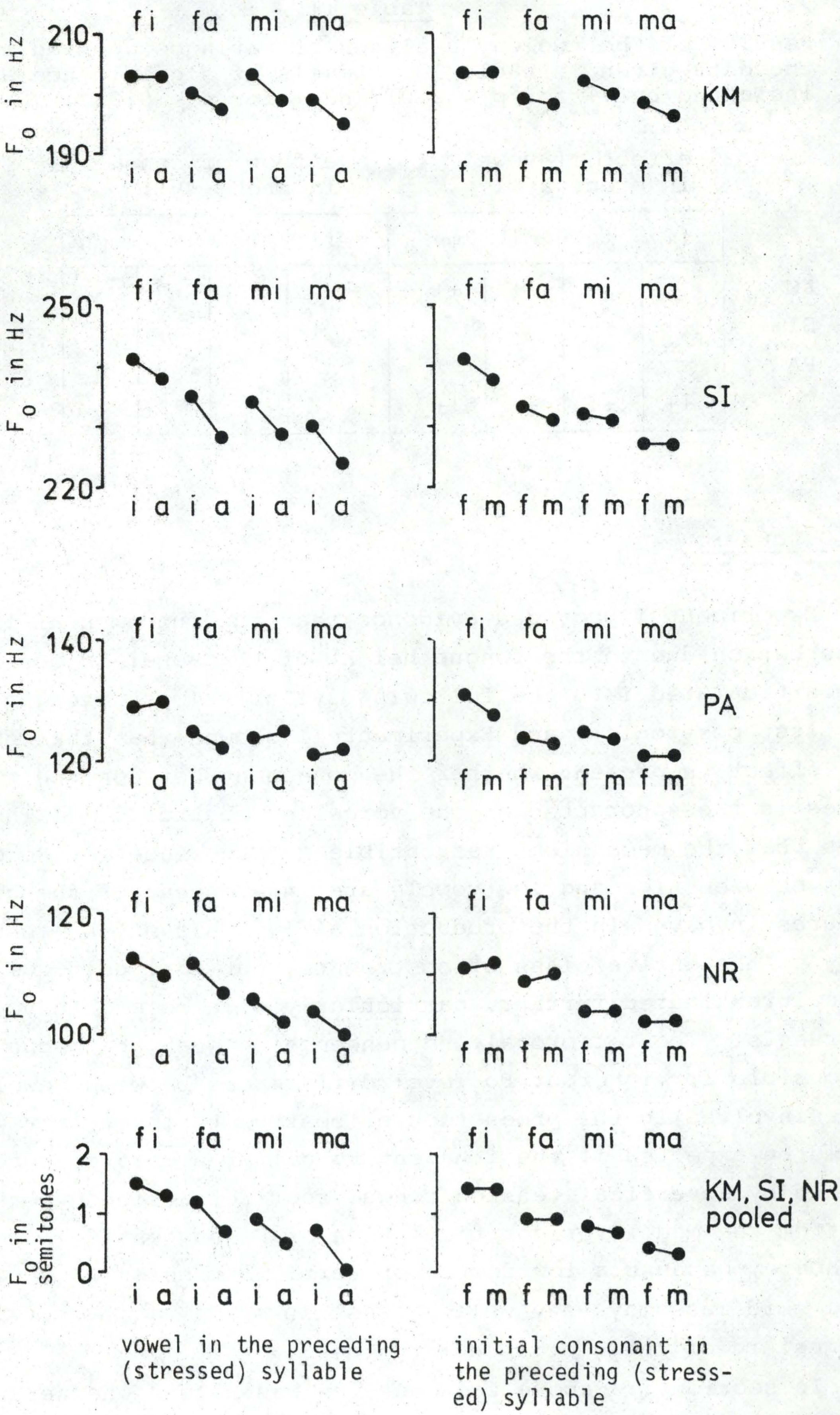

Figure 11

Mean fundamental frequencies in the vowels in first posttonic -fi, -fa, -mi, and -ma syllables as a function of i and a in the preceding syllable (left column) and initial f and m in the preceding syllable (right coulumn), for the speakers individually and averaged over the subjects KM, SI, and NR (in semitones).

Table 11

Results of the two-way analyses of variance applied to the data given in table 10. Levels of significance are indicated by ++ for $p < 0.01$ and + for $p < 0.05$.

	effect of vowel in prec. syll.				effect of cons. in prec. syll.			
	fi	fa	mi	ma	fi	fa	mi	ma
KM			+	++				
SI	+	++		++	+			
PA								
NR	++	++	++	++				

4. Discussion

Experiment I provided evidence that the fundamental frequency perturbation due to the tongue height of the vowel in one syllable is coarticulated into the following syllable (most clearly so in the first posttonic), and Experiment II showed that this carry-over effect is present whether the consonant between the two syllables is the sonorant *m* or the voiceless obstruent *f*. Thus, it seems that the mechanisms responsible for the inherent Fo differences between high and low vowels are independent of the glottal gestures involved in the production of *f*. This may be assumed to apply to the entire class of obstruents, but that point will have to be investigated further, particularly with regard to voiced obstruents. The reciprocal independence between the mechanisms responsible for inherent Fo level differences between vowels and those involved in the production of obstruents is in fact what should be expected if the inherent Fo differences are to be explained by a vertical tension/tongue root retraction hypothesis and from the model for coarticulation of Fo suggested in section 2.3 above, because a low degree of vertical tension or an increased vocal cord mass may very well persist in spite of the opening-closing gesture of the glottis during the *f*.

In section 2.3 above the question was raised whether the coarticulation of inherent Fo levels between syllables is a necessary prerequisite for the correct perception of stress patterns. The results of the experiments reported in the present paper can hardly be assumed to give an affirmative answer to that question. First, the compensation in one syllable for the Fo variation ascribable to tongue height found in Experiment I is only partial (even in first posttonic syllables, where it is greatest), and secondly - and more important, perhaps - the effect on Fo of the initial consonant in the stressed syllable is not (although of a magnitude comparable to the effect of tongue height in that syllable) carried over to the first posttonic. Thus, the perceptual system seems to be able to do without the smoothing out of (i.e. to compensate for) the segmentally determined fundamental frequency variation. This view is corroborated by the finding in Experiment II of cases in words of the type 'fima, where the rise from the stressed to the first posttonic vowel is extremely small or even negative. (The rises range from -2 to 8 Hz for KM, from -1 to 8 Hz for SI, from 4 to 16 Hz for PA, and from -3 to 4 Hz for NR in such words.) Furthermore, Thorsen (1980b) reports that in stress groups with only one unstressed syllable there may be (but is not always) no or a reduced Fo rise from the stressed to the unstressed syllable.

But, of course, this reasoning will have to be supplemented by perceptual experimentation before the question can be answered with reasonable certainty. In particular, experiments are called for which take into consideration the role of segment duration - and its interaction with the fundamental frequency - in the perception of stress patterns.

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