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FORMANT FREQUENCIES OF POLISH VOWELS AS CUES TO ALLOPHONIC VARIATION

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1. INTRODUCTION

The main aim of the present work is the identification of phonetic contexts which cause strong and regular modifications of the acoustic features of Polish vowels. The research is fully based on the formant data contained in the phonetic-acoustic database of Polish vowels described in [1]. The analysis of the modifications concentrates on identifying consonantal contexts inducing significant shifts in the F1 and F2 values of a given vowel for all speakers. Taking into account the capacity limitations of the database as well as Dukiewicz's statement [2] that the most strongly modifying contexts in Polish are the palatal and the nasal ones, we decided to examine the effect of these two contexts on relative shifts in the first two formant frequencies of Polish vowels. According to Łobacz [3], the effect of the preceding consonant is stronger than that of the following one and Gonet [4] says that there is a considerable difference between the modifications induced by a unilateral and a bilateral context of a given type. For these reasons it was decided that left-hand, right-hand and bilateral contexts should be studied separately. It was also necessary to consider separately complex nasal-palatal contexts, which were included in the database. As vowels in the final position strongly coarticulate with *schwa* [ə] (cf. [2], [5]), vowels located at the end of a word were additionally investigated as being in a specific context.

2. GENERAL RESULTS

The vowel data contained in the acoustic-phonetic database were grouped, mathematically processed, and confronted with the results of other experiments presented in the literature. Table 1 includes the average values of the formants F1 - F5 for the individual Polish vowels, calculated on the basis of our database.

Table 1. Average formant values for Polish vowels realized in various consonantal contexts.

VOWEL	FEMALE FORMANT				
	F1	F2	F3	F4	F5
[i]	361	2752	3451	4504	5178
[ɨ]	484	2077	2930	4423	5136
[ɛ]	599	2140	2966	4349	5250
[a]	821	1627	2710	4232	5240
[ɔ]	619	1194	2738	4091	5165
[u]	418	963	2810	4278	5045
VOWEL	**MALE FORMANT**				
	F1	F2	F3	F4	F5
[i]	282	2096	2760	3338	3887
[ɨ]	388	1742	2388	3355	3889
[ɛ]	474	1750	2416	3357	3923
[a]	620	1315	2243	3379	3942
[ɔ]	491	1025	2288	3323	3812
[u]	354	918	2156	3216	3708

As can be seen, the largest variation related to the vowel quality concerns formants F1 and F2. F3 assumes similar values for all the vowels except [i], for which it is considerably increased (by 21,88% for women and by 20,09% for men in relation to the average F3 value for all the other vowels). Higher formants - F4 and F5 - display significant stability throughout all the vowels, which is especially distinct for male speakers. These results seem to confirm the earlier statements ([6], [7], [8], [9], [10]) to the effect that only the values of F1 and F2 are directly related to the phonetic quality of vowels and that the higher formants must be responsible for other vowel features (for example speaker-specific as suggested by Mokhtari et al [10]).

FORMANT FREQUENCIES OF POLISH VOWELS

As far as the variation range of individual formants is concerned, Fant [11] writes that the formant values of a given vowel realized in isolation by a group of speakers are characterized by the following standard deviation values (**SD**):

a) male: F1 – 35 Hz, F2 – 90 Hz, and F3 – 130 Hz.
b) female: F1 – 45 Hz, F2 – 130 Hz, and F3 – 240 Hz.

As can be concluded from the data contained in the base, the standard deviation is about twice as high when we consider vowels spoken in one- or two-syllable words with diversified phonetic contexts rather than in isolation. The average standard deviation values calculated on the basis of our database contents are as follows:

a) male: F1 – 71 Hz, F2 – 150 Hz, and F3 – 265 Hz.
b) female: F1 – 97 Hz, F2 – 182 Hz, and F3 – 236 Hz.

As for the standard deviation of F4 and F5, it is only slightly higher than the SD of F3 in spite of the fact that F4 and F5 assume values in a considerably higher frequency range than F3 (cf. table 1). The SD for F4 and F5 was as follows:

a) male: F4 – 257 Hz, F5 – 287 Hz.
b) female: F4 – 297 Hz, F5 – 333 Hz.

The relatively slight variation of these formant values throughout the speakers may mean that energy concentrations above the frequency of the third formant are not only independent of the vowel phonetic quality but also of the speaker-specific features. It might suggest that the energy concentrations in the frequency ranges of F4 and F5 are not connected with the production of a vowel of a given timbre or with the construction of a given articulatory apparatus but are generally characteristic of the vowel-type phonetic segment production. This hypothesis, however, would require a wide multi-language research, which goes far beyond the scope of the present work.

Fant [12] claims that the differences between the values of the first three formants for men and women average 17%. On further research [11] he states that the differences are actually slightly larger and they range from 18% to 20%. On the basis of the material investigated in this paper it has been found that they can be even larger and on an average they amount to 26% for F1, 20% for F2, and 24% for F3. The differences for F4 and F5 averaged respectively 30% and 34%. It is especially remarkable, however, that the comparison of the second formant values of the vowel [u] for male and female voices yields entirely different results. F3 in vowels produced by women is only 5% higher than in male articulations. This irregularity has been reported in the literature and its explanation is still being worked on [13].

Table 2 presents average values of the formants F1-F4 for Polish vowels spoken in isolation. The results contained in the table have been calculated from the raw data published in [14].

Table 2. Average formant values for Polish vowels realized in isolation.

FEMALE				
VOWEL	FORMANTS			
	F1	F2	F3	F4
[i]	247	2775	3510	4155
[ɨ]	329	2335	3041	4214
[e]	625	2210	2979	3964
[a]	999	1545	2756	3951
[o]	641	1080	2793	3885
[u]	324	731	3140	4001
MALE				
VOWEL	FORMANTS			
	F1	F2	F3	F4
[i]	213	2316	2971	3542
[ɨ]	323	1996	2821	3422
[e]	553	1794	2561	3408
[a]	753	1261	2513	3422
[o]	538	883	2571	3326
[u]	280	652	2459	3232

According to Lobacz [3], "...the values of F1 and F2 are much more strongly affected by context than by variations in speech rate." and further "When isolated vowels are compared with vowels in phrases, the greatest differences are observed in the F2 values of the most retracted vowels, which have low F2. In consonantal context F2 of those vowels is, on an average, about 400 Hz higher than in isolation." It follows from the calculations performed for the present study that these differences are smaller when we consider vowels in single words instead of vowels in phrases. The relevant differences averaged 128 Hz for [o] and 249 Hz for [u]. This doesn't alter the fact, however, that the realization of *any* vowels in context is connected with their centralization in relation to their realization in isolation, which is most clearly depicted by the articulation polygons in figures 1 and 2. This phenomenon was also partially confirmed in identification tests [15], where the presentation of any vowel without the context it had been realized in resulted in a shift in its identification towards schwa [ə] i.e. the so-called neutral (central) vowel.

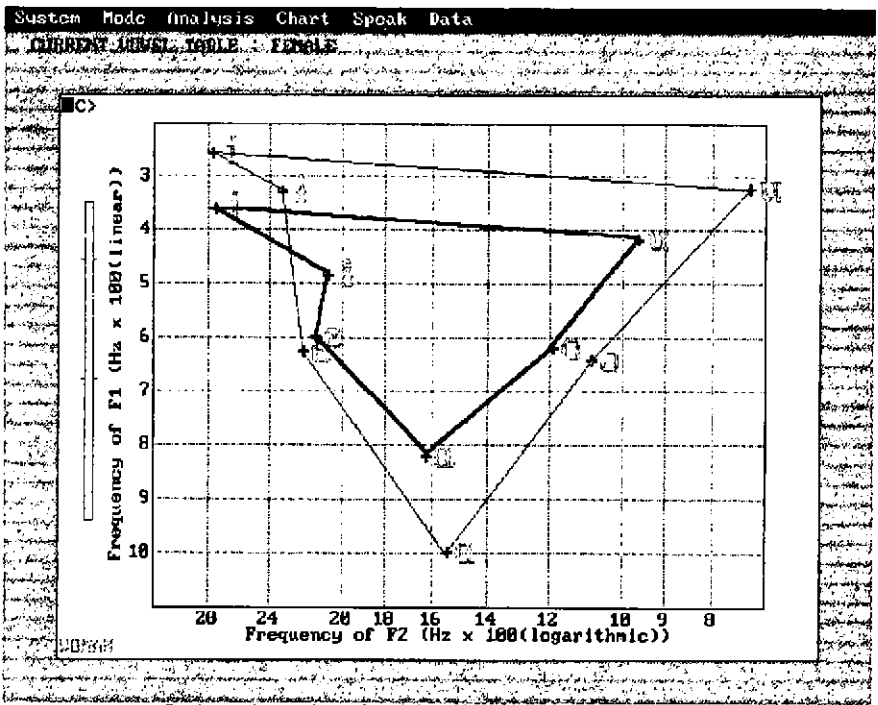

Fig. 1. Articulation polygons for Polish vowels spoken by women (average values). Bold line - vowels in context, thin line - vowels in isolation (based on tables 1 and 2).

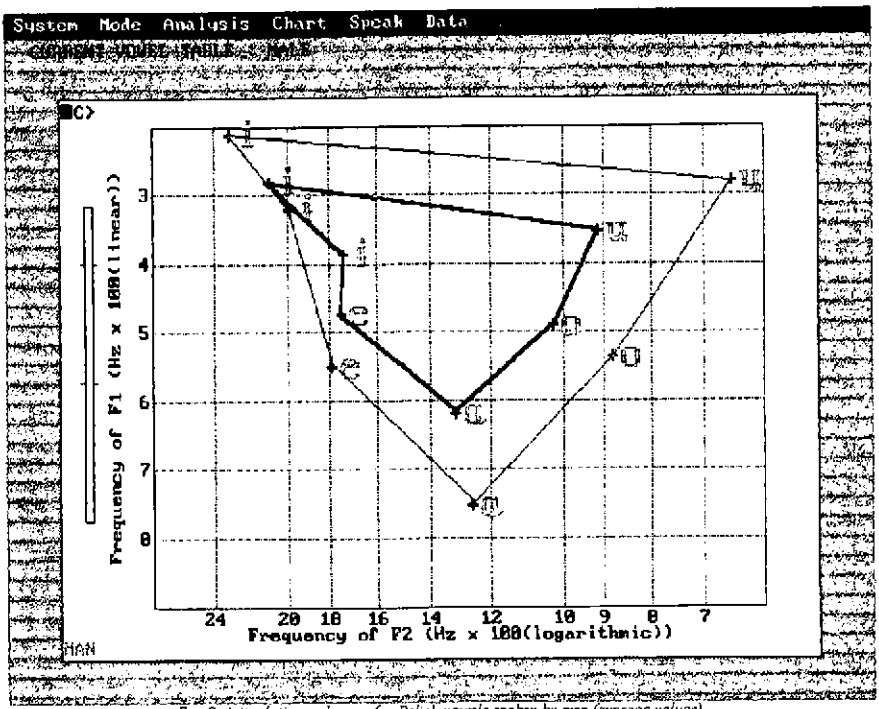

Fig. 2. Articulation polygons for Polish vowels spoken by man (average values). Bold line - vowels in context, thin line - vowels in isolation (based on tables 1 and 2).

This centralization, which is different for different vowels, resulted, in the present study, in a similar range of F2 values for the pairs of vowels [i] / [ɛ] and [ɔ] / [u] (see figures 1 and 2). The centralization was also a factor that contributed partially to the overlapping of F2 variation ranges for the vowels [i], [ɨ], and [ɛ], which was observed in the case of some speakers. The main source of this frequency range overlap was, however, the allophonic variation of formant values related to the appearance of vowels in different contexts, which will be the topic of the next sections.

3. REGULAR CONTEXTUAL FORMANT VALUE MODIFICATIONS.

As the aim of the research was to identify regular relative shifts in formant values, it was necessary to determine, for each vowel and each speaker, the so-called neutral values of formants, related to the appearance of vowels in neutral contexts, which would be the reference values for any shift calculations. It turned out that the determination of such reference values was not a simple task. One of the possibilities was to assume as the contextually non-modified values (i.e. neutral values) formant frequencies from sustained vowels. However, vowels articulated in this way, which have been used in numerous experiments ([11], [14], [16]), are characterized by very long duration (2,5 - 5 sec.) and they do not have much to do with the vowels from natural rate speech. As Fant [11] says, vowels realized like that have much more to do with singing than with natural human speech. For this reason, as Lobacz [3] claims, typical F1 and F2 ranges for isolated vowels cannot be used in research on continuous speech.

Another alternative was to use vowels of natural duration, spoken in isolation. One has to remember, however, that this kind of vowel realization in Polish is always connected with the articulation of a glottal stop [ʔ] preceding the vowel. So it would be very risky to assume that a single phonetic segment being an element of consonantal systems in other languages (in some forms of standard English the glottal stop [ʔ] is an allophone of the phoneme [t], realized in words like *certain* or *button*, cf. [17]) is the only determinant of the neutral vowel context in Polish.

An additional disadvantage of the above two solutions would be the necessity to refer in our calculations to figures not included in the database of Polish vowels as the base only contains formant values of vowels produced in various consonantal contexts. Thus, it was necessary to search for the neutral formant values within our database. If the base contained a sufficient number of data including all the existing contexts of Polish vowels, it would be possible to assume that the best representations of the neutral formant values are their averages, calculated on the basis of the F1 and F2 values characterizing vowels appearing in all the potential consonantal contexts. It transpired, however, that the base is not only limited in size but also has highly non-uniform distribution of particular phonetic contexts. It was especially conspicuous that as many as fifteen contexts of the vowel [e], out of twenty contained in the base (i.e. 75%), were palatal. Moreover, six of them (40%) were bilaterally palatal contexts. Similarly, twelve out of eighteen [o] contexts included in the base (67%) were nasal. This non-uniform representation of particular contexts made it impossible to determine any average formant values which might be used as reference values in further calculations. At the same time, it is highly interesting that the representation of the palatal contexts of [e] and the nasal contexts of [o] is so high in a database which was based in its construction on the word frequency rates. While the high proportion of nasal contexts for the vowel [o] may be partially due to the assumption of phonemic status for the phones [j̃] and [w̃] in the present work, it might also suggest that these two contexts are the most frequent ones for the above two Polish vowels. However, the confirmation of this hypothesis would require wide distribution research in the domain of phonetic contexts.

For all the above reasons it was finally decided that the reference formant values in the present study would be the average values of vowel formant frequencies in contexts which are known not to be strongly-modifying according to the results of articulatory phonetics research. In other words, we decided to use formant values characterizing vowels realized in contexts which are neither palatal, nor nasal or word-final and these contexts will be called 'neutral' henceforth.

Afterwards, a tentative analysis of contextual formant value variation was carried out. The average F1 and F2 values of a given vowel in a given context were compared with the average F1 and F2 values of this vowel in the neutral context for each speaker separately. The aim of the analysis was to identify contexts which induce regular formant shifts in a given vowel for at least 90% of speakers (i.e. contexts which cause an increase or a decrease of F1 or F2 in a given vowel for at least 9 out of 10 speakers whose data are contained in the base).

4. ANALYSIS RESULTS AND STATISTICAL VERIFICATION

As a result of the analysis described above, we singled out (for six vowels altogether) a group of 17 contexts involving regular modifications of vowel formants for all the ten speakers and a group of 14 contexts which caused regular vowel formant modifications for 9 speakers (i.e. 90% of the subjects).

Table 3. Contexts connected with regular formant value modifications for all the ten subjects.

VOWEL	CONTEXT	FORMANT	MODIFICATION
[i]	BILATERAL PALATAL	F2	INCREASE
[i]	LEFT NASAL	F2	INCREASE
[i]	LEFT NASAL / PALATAL + RIGHT PALATAL	F2	INCREASE
[i]	LEFT NASAL / PALATAL	F2	INCREASE
[i]	RIGHT PALATAL	F1	DECREASE
[i]	RIGHT PALATAL	F2	INCREASE
[i]	LEFT NASAL + RIGHT PALATAL	F2	INCREASE
[e]	LEFT PALATAL + RIGHT NASAL	F2	INCREASE
[e]	LEFT PALATAL + THE VOCOID [i̯]	F2	INCREASE
[e]	LEFT PALATAL + RIGHT NASAL / PALATAL	F2	INCREASE
[e]	RIGHT NASAL / PALATAL	F2	INCREASE
[e]	LEFT NASAL / PALATAL	F1	DECREASE
[e]	LEFT NASAL / PALATAL	F2	INCREASE
[a]	LEFT PALATAL	F2	INCREASE
[a]	BILATERAL PALATAL	F1	DECREASE
[a]	BILATERAL PALATAL	F2	INCREASE
[a]	WORD-FINAL	F1	DECREASE

Table 4. Contexts connected with regular formant value modifications for 90 % of the subjects.

VOWEL	CONTEXT	FORMANT	MODIFICATION
[i]	LEFT NASAL / PALATAL	F1	INCREASE
[i]	RIGHT NASAL	F1	INCREASE
[i]	LEFT PALATAL	F2	INCREASE
[e]	LEFT PALATAL	F1	DECREASE
[e]	LEFT PALATAL	F2	INCREASE
[e]	BILATERAL PALATAL	F1	DECREASE
[e]	BILATERAL PALATAL	F2	INCREASE
[e]	WITH THE VOCOID [i̯]	F2	INCREASE
[e]	LEFT PALATAL + RIGHT NASAL / PALATAL	F1	DECREASE
[a]	LEFT NASAL	F2	INCREASE
[a]	RIGHT NASAL / PALATAL	F2	INCREASE
[o]	BILATERAL NASAL	F2	DECREASE
[u]	LEFT PALATAL	F2	INCREASE
[u]	RIGHT PALATAL	F1	DECREASE

As the modification regularities determined above were based exclusively on the comparison of average formant values, it was necessary to carry out an analysis testing the existence of statistically valid differences between F1 and F2 frequencies in the neutral context and their values in particular modificational contexts.

The aim of the analysis was to accept the alternative hypothesis H_1, stating that formant values in the neutral context and their values in a given modificational context are data samples belonging to two different statistical populations (which is tantamount to establishing the existence of statistically valid differences between them). Therefore, it was necessary to reject, in the course of the statistical analysis, the H_0 hypothesis stating that both samples belong to the same data population.

The statistical analysis was performed with the aid of the Wilcoxon rank test. The test critical values $w_{n,m}(\alpha)$ and $w'_{n,m}(\alpha)$ were calculated for each phonetic context considered in the analysis and the **W** statistic was calculated for each speaker and each context. The **W** statistic value was an expression of similarity between a given speaker's formant values in the neutral context and his formant values in the modificational context. If the **W** statistic value for a given speaker and a given context exceeded the $(w_{n,m}(\alpha); w'_{n,m}(\alpha))$ range, it was possible to reject the H_0 hypothesis and to accept the alternative hypothesis H_1 stating the existence of statistically valid differences between formant values in the neutral context and their values in a given modificational context (for a given speaker and vowel). Otherwise (when $w_{n,m}(\alpha) < W < w'_{n,m}(\alpha)$), the rejection of the H_0 hypothesis was impossible and it was necessary to assume that the differences between the values from the above mentioned two samples weren't statistically valid. The analysis was performed with the standard confidence level $1 - \alpha = 95\%$.

Table 6 contains the critical values of the Wilcoxon test for all the contexts considered as well as W statistic values related to these contexts for all the ten speakers. The last column of the table includes the number of subjects for whom the differences under investigation proved to be statistically valid.

Table 6. The critical points of the Wilcoxon test for particular contexts and the W statistic values for individual speakers. Contexts connected with regular modifications for 100 % of the subjects are placed in the upper part of the table, those being regular for 90 % of the subjects - in its lower part.

THE ANALYZED CONTEXT			CRITICAL VALUES		SPEAKERS										ST. VAL.
VOWEL	CONTEXT	FORMANT	$W_{n,m}$ (α)	$W'_{n,m}$ (α)	J.I.	J.K.	P.W.	T.Z.	W.J.	A.D.	A.J.	A.L.	K.K.	L.R.	
[i]	BILATERAL PALATAL	F2	13	44	42	51	51	51	51	33	41	45	51	33	6
[i]	LEFT NASAL	F2	13	44	42	51	43	32.5	33	51	49	39	28	41	3
[i]	LEFT NAS/PAL + RIGHT PAL.	F2	13	44	42	51	51	51	50	51	51	48	51	50	9
[i]	LEFT NAS. / PAL.	F2	13	44	48	51	51	39	51	51	44	51	47.5	33.5	8
[i]	RIGHT PALATAL	F1	19	65	29	30	6	6	13	6	18.5	18	7. 5	20	7
[i]	RIGHT PALATAL	F2	19	65	44.5	78	78	78	70	78	78	78	69	64	8
[i]	LEFT NASAL + RIGHT PAL.	F2	19	65	78	75	75	60	78	78	78	78	69	66	9
[e]	LEFT PAL. + RIGHT NASAL	F2	28	50	21	21	21	21	21	21	21	21	21	21	10
[e]	LEFT PAL+[j̃]	F2	28	50	28	21	21	21	21	21	21	21	21	21	10
[e]	LEFT PAL. + RIGHT NA./PA.	F2	33	63	21	21	21	21	21	21	21	21	21	21	10
[e]	RIGHT NASAL / PAL.	F2	8	22	24	23	24	24	24	18	24	24	24	24	9
[e]	LEFT NASAL / PAL.	F1	8	22	6	6	6	7	6	6	6	7	15	6	9
[e]	LEFT NASAL / PAL.	F2	8	22	24	24	24	24	24	24	17	24	24	24	9
[a]	LEFT PALATAL	F2	133	203	222	236	198	209	251	196	182	226	244	221	7
[a]	BILATERAL PALATAL	F1	13	44	17	6	13	6	6	6	8	6	7	14	8
[a]	BILATERAL PALATAL	F2	13	44	51	51	51	51	51	37	51	51	51	51	9
[a]	WORD-FINAL	F1	84	141	55	63.5	65	51.5	106	45	47	45	87.5	73	8
[i]	LEFT NASAL / PAL.	F1	13	44	15	41	51	45	42	42	51	44	51	51	6
[i]	RIGHT NASAL	F1	13	44	14.5	51	51	32	51	42	32	42	51	43	4
[i]	LEFT PALATAL	F2	192	273	216	257	238	226	276	266	256	287	276	248	3
[e]	LEFT PALATAL	F1	33	63	75	65.5	51.5	51	60	69	65	75	52.5	75	6
[e]	LEFT PALATAL	F2	33	63	43	26	31	24	39	33	49	21	21	49	6
[e]	BILATERAL PALATAL	F1	8	22	6	6	6	15	6	6	6	6	6	6	9
[e]	BILATERAL PALATAL	F2	8	22	24	24	24	24	24	24	24	24	24	12	9
[e]	WITH [j̃]	F2	28	50	27	21	21	21	21	57	30	21	21	21	8
[e]	LEFT PALAT.+ RIGHT NA./PA.	F1	33	63	75	59	75	75	75	62	44	75	61	75	6
[a]	LEFT NASAL	F2	13	44	34.5	51	51	51	45.5	38.5	30	21	51	51	6
[a]	RIGHT NASAL / PAL.	F2	13	44	51	50	51	42	51	27	24	45	50	51	7
[o]	BILATERAL NASAL	F2	11	37	20.5	6	24	12	6	6	6	6.5	6	24	6
[u]	LEFT PALATAL	F2	76	164	191	136	172	211	124	110	168	167	102	107	5
[u]	RIGHT PALATAL	F1	138	249	136	226	71.5	114	181	66	115	274	72	161	6

As a result of the statistical analysis, it was ascertained that there are three phonetic contexts connected with regular and statistically valid modifications of formant values for all the subjects. Additionally, it was determined that there are 8 contexts involving this kind of modifications for 9 out of ten subjects i.e. for 90% of the speakers. The relevant contexts are presented in table 7.

Table 7. Contexts in which vowel formant values are different from their values in the neutral context with statistical validity.

FOR ALL THE SPEAKERS			
VOWEL	CONTEXT	FORMANT	MODIFICATION
[e]	LEFT PALATAL + RIGHT NASAL	F2	INCREASE
[e]	LEFT PALATAL + THE VOCOID [j]	F2	INCREASE
[e]	LEFT PALATAL + RIGHT NASAL / PALATAL	F2	INCREASE
FOR 90% OF THE SPEAKERS			
VOWEL	CONTEXT	FORMANT	MODIFICATION
[e]	BILATERAL PALATAL	F1	DECREASE
[e]	BILATERAL PALATAL	F2	INCREASE
[e]	RIGHT NASAL / PALATAL	F2	INCREASE
[e]	LEFT NASAL / PALATAL	F1	DECREASE
[e]	LEFT NASAL / PALATAL	F2	INCREASE
[i]	LEFT NASAL + RIGHT PALATAL	F2	INCREASE
[i]	LEFT NASAL + RIGHT PALATAL	F2	INCREASE
[o]	BILATERAL PALATAL	F2	INCREASE

As for the bilateral palatal context of the vowel [e], the tenth speaker was characterized by a slight formant value modification in the opposite direction to what was the case with the other speakers (both for F1 and F2). Therefore, we decided to uphold the claim that at the confidence level $\mathbf{1 - \alpha = 95\%}$ this context involves statistically valid modifications of formant values for 90% of speakers. In the case of the other contexts we decided to calculate the confidence level α at which the modifications of the given formant values are statistically valid for all the ten speakers. The t-Student statistical test was used for this purpose. The maximum confidence levels $\mathbf{1 - \alpha}$ at which the differences between the compared samples are still statistically valid were calculated for particular contexts and speakers. The minimum value for a given context (included in the column $\mathbf{1 - \alpha}$ of table 8) was, at the same time, the maximum confidence level at which the differences between formant values in the neutral context and in a given modificational context were statistically valid for all the ten speakers. As can be seen in table 8, in some cases the maximum $\mathbf{1 - \alpha}$ level ranged from 80% to 90%, in other cases, however, it was much lower and it reached only about 50%.

Table 8. The minimum α at which the differences are statistically valid for the individual speakers, and the maximum $1 - \alpha$ at which the differences are statistically valid for all the 10 speakers.

CONTEXT			SPEAKER										α_{min}	$1-\alpha_{max}$
Vow.	Context	For.	J.L.	J.K.	P.W.	T.Z.	W.J.	A.D.	A.L.	A.L.	K.K.	L.R.		
[e]	RIGHT NAS. / PAL.	F2	.0002	.0146	0	.0546	.0001	.5633	0	0	.0620	.0003	.5633	43,67 %
[e]	LEFT NAS. / PAL.	F1	.0018	.0080	.0001	.0162	.0043	0	.0113	.0044	.5111	.0012	.5111	48,89 %
[e]	LEFT NAS. / PAL.	F2	.0005	.0005	0	.0104	0	0	.2894	0	0	0	.2894	71,06 %
[i]	LEFT NASAL + RIGHT PAL.	F2	.0963	0	.0001	.0074	.0032	0	.0096	.0083	.0029	.0523	.0963	90,37 %
[i]	LEFT NASAL + RIGHT PAL.	F2	0	.0017	.0031	.1621	.0002	.0034	0	.0022	.0501	.0295	.1621	83,79 %
[o]	BILATERAL PALATAL	F2	0	.0002	0	0	0	.2991	.0015	0	.0002	.0001	.2991	70,09 %

5. FINAL CONCLUSIONS

In the course of the investigation we have identified three contexts of the vowel [e] which always involve a statistically valid increase of the second formant of this vowel:

- left palatal context + right nasal context
- left palatal context + the vocoid [j]
- left palatal context + right nasal-palatal context

It is remarkable that none of the three contexts was a simple unilateral nasal or palatal context. On the contrary, all of them were complex bilateral contexts involving nasalization and palatalization at the same time.

With an acceptable confidence level (70% - 90%) we can also consider as general and statistically valid an increase of F2 of the vowel in the following four contexts:

- the left nasal-palatal context of the vowel [e]
- the left nasal + the right palatal context of the vowel [i]
- the left nasal + the right palatal context of the vowel [i]
- the bilateral palatal context of the vowel [o]

Another strong contextual formant modification that, however, doesn't apply to all the speakers is a decrease of F1 with a simultaneous increase of F2 of the vowel [e] in the bilateral palatal context, which is in accordance with Gonet's results [4].

The fact that all the above formant value modifications display statistical validity and that they are typical of all the subjects whose data were analyzed in the research gives foundation for distinguishing nasal-palatal allophones of the relevant vowel phonemes. However, a precise description of those allophones in acoustic terms is still very difficult as the extent of modifications wasn't identical for all the speakers. Usually, the relative formant shifts in relation to their values in the neutral context averaged 20% but in the case of some speakers they ranged from 15% to nearly 40%. Furthermore, we have to remember that our data corpus included articulations of ten speakers only and any generalization of the obtained results requires further research on a larger scale. Nonetheless, the results of the present work should be taken into consideration in the design of automatic speech recognition systems as well as in the realization of speech synthesis by rule.

6. REFERENCES

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