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VARIATIONS OF THE FUNDAMENTAL FREQUENCY IN POLISH VOICED CONSONANTS*

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The aim of work described in this paper was to verify and confirm the general thesis regarding the Polish language that the variations of the fundamental frequency in voiced consonants can sometimes agree with and sometimes differ from the global tone line plotted on a tonogram for the sequence of the vowels. The evolutions of this line are considered to be critical in the perception of the intonation contour. Qualitative and quantitative descriptions of the character of variations of the fundamental tone in the voiced consonants /b/, /d/, /g/, /ɟ/, /v/, /z/, /ʒ/, /γ/, /m/, /n/, /ŋ/, /r/, and /l/ are given.

The relation between these changes and the type of articulation of the consonant was investigated. The results of the investigations support the assumption that such a relationship exists. In many respects this fact is in agreement with the data given in the relevant literature, and its explanation can be sought in the articulatory and physiological properties of the individual consonants.

1. Introduction

It is known that certain features of speech, known as prosodic features, are related to variations of the fundamental frequency. These include various types of intonation, accent, the methods of indicating the completion of the sentence, etc. However, it is also known that the variations of the fundamental tone in segments that correspond to the individual speech sounds are important. The "microvariations" of F_0, analyzed in the voiced consonants, are brought about by many factors, both articulatory and physiological. One of the most important factors are the fluctuations in sub- and supraglottal pressure,

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related to the occurrence of the articulatory barrier in the upper part of the vocal tract and the variations of the frequency of the vocal chord vibration.

Although the significance of variations of the fundamental frequency in particular voiced consonants for the perception of the functional intonation units is problematic (various viewpoints on this problem are presented by JASSEM [7], WITTING [19], PIKE [17]), the results of a series of psychophysical experiments indicate that a listener can discern variations of the fundamental frequency over a comparatively short segment (HEINZ [6], LUBLINSKAIA [10]) and indeed uses them, in addition to other features, for distinguishing the phonemes (ČISTOVIČ [3], HAGGARD [5]).

Speech synthesis tests concerned with intonation contours (MATTINGLY [11], ÖHMAN, LINDQUIST [15], ÖHMAN [16], MEHNERT [13]) show the value of information about the "microvariation" of F_0 as regards the distinctness and natural sound of synthetic speech.

The papers by MOHR [14], MEHNERT [13], and STEFFEN-BATÓG [18] are concerned with a direct investigation of the variation of F_0 in consonants; the latter paper is the only, known to the authoress, investigation of the microvariation of the fundamental tone in Polish voiced consonants. The data concerning such microvariation in addition to their purely cognitive character may also be used in experiments concerning the synthesis, the automatic recognition and the automatic segmentation of the Polish language.

This paper is devoted to the qualitative and quantitative description of the variation of F_0 in some voiced consonants of the Polish language, with special attention being paid to the relation between these variations and the type of consonant articulation. A well-known thesis of the decrease of F_0 in voiced consonants or, in other words, of the decreasing effect of the voiced consonants on the F_0 contour has been verified on Polish sounds. A more complete description of the investigations carried out is published separately [12].

2. Material and methods of investigations

The analysis of F_0 variations was performed by using a tape recorder, oscillograph and "Tonograph"[1]). A newspaper text read four times by four people was used for this study giving a total of 48 sentences.

The segmentation of the oscillogram provided the basis for further investigations. The segmentation of the tonogram was performed in agreement

[1] The principles of operation of the device are described by KUBZDELA [8]. Fig. 1 shows by the way of an example one of the analyzed segments.

with this segmentation, with the delay of the tonometer indication by one period with respect to the oscillograph taken into account.

In some important but ambiguous cases the segmentation was checked with the aid of a spectrograph and an audio-monitoring device separator. F_0 contours were plotted on the tonograms and the values of F_0 were measured on them at the beginning, in the middle and at the end of each voiced consonant, by means of hyperbolic scales drawn separately for each voice.

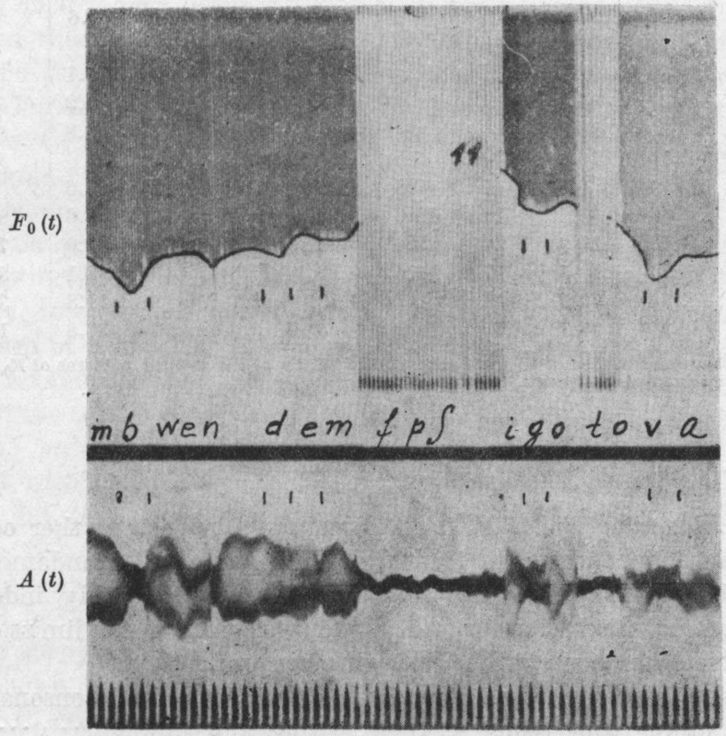

Fig. 1. Evolution of F_0 in the utterance: "błędem w przygotowaniach "(Female voice)

The method of plotting the contour on those segments of the tonogram that have irregularities in F_0 changes was chosen separately for each individual case, depending on the source of the irregularity.

The analyzed material contained different numbers (Table 1) of the following voiced consonants:

stop consonants	/b/, /d/, /ɟ/, /g/,
fricative consonants	/v/, /z/, /ʒ/, /γ/,
liquid consonants	/m/, /n/, /ŋ/, /r/, /l/.

Table 1. The frequency of the occurrence of typical patterns of variations of the fundamental frequency in voiced consonants. Male and female voices

Voiced consonant	Number of the cases considered	Pattern of variations of the fundamental frequency									
		... ∨ ...		... ∧ ...		.../...		...\\...		... — ...	
		Quantity	%	Quantity	%	Quantity	%	Quantity	%	Quantity	%
/b/	45	44	97.8					1	2.2		
/d/	161	152	94.4			8	5.0	1	0.6		
/ɟ/	13	13	100								
/g/	42	39	92.9					3	7.1		
/v/	260*	222	85.4			18	6.9	16	6.2	1	0.4
/z/	34	30	88.2			1	2.9	3	8.8		
/ʒ/	13	10	76.9			3	23.1				
/γ/	15	1	6.8	1	6.8			13	86.6		
/m/	87	4	4.6	11	12.6	12	13.8	51	58.6	9	10.3
/n/	106	12	11.3	24	22.6	29	27.4	34	32.0	7	6.6
/ŋ/	105	11	10.5	17	16.4	29	27.6	40	38.1	8	7.6
/r/	102	74	72.5			13	12.7	12	11.8	3	2.9
/l/	53	20	37.7	7	13.2	5	9.4	20	37.8	1	1.9

* 3 cases of the pronunciation of /v/ were not included in any of the typical patterns of $\overline{F}_0$, but lack of space prevents their detailed discussion in this paper.

3. Qualitative analysis of the typical microvariations of F_0

Types of microvariation of F_0. As a starting-point for further considerations the assumption was made that the evolution of the fundamental frequency can be described as the resultant of two relatively independent transients: a general pitch contour and smaller variations in the limits of voiced consonants which are superimposed on this contour.

Initially the following types of variation of F_0 in voiced consonants were distinguished: falling and rising ···∨···, rising and falling ···∧···, falling ···\\..., rising .../···, flat ...——.... Numerical data describing the frequency of occurrence of these patterns are given in Table 1.

Stop consonants /b,/, /d/, /ɟ/, /g/. It results from the data contained in Table 1 that for this group of consonants the variation of F_0 according to the pattern ∨ prevails. Also some utterances included in the pattern groups \\ and /(purely because the variations of F_0 are analyzed strictly between the consonants limits determined from the oscillograms) represent in fact versions of the pattern ∨. This occurs because the fall of F_0 in voiced consonants sometimes occupies the entire consonant segment, more rarely, only a part of this segment, but usually it extends into adjacent segments thus indicating that even in the case of the micro-variation of F_0 a kind of coarticulation occurs.

Another reason for the transformation of the pattern ⋁ into the pattern ⁄, ∖ or – is related to the phenomenon which is conventionally referred to as the "subordination" of the pattern of F_0 in one particular consonant to the general variation of F_0 in a larger fragment determined by all vowels. This is closely connected with the assumption of the resolvability of the F_0 variations into two independent elements. The phenomenon observed in this case can be described briefly as follows: the variation of F_0 in the consonant (e. g. a decrease in F_0) is subjected to a "deformation" due to the large rise or decrease of F_0 occurring in a longer fragment of the utterance.

When the variation of F_0 in the consonant itself is insignificant, the effect of the superposition of the patterns is even more evident. This is clearly shown in Fig. 2*a*, where the variation of F_0 in the consonant /*d*/ (which in other circumstances would mean a distinct decrease in F_0) is subordinated to the general large rise of F_0 from /*o*/ to /*e*/ in such a way that the beginning and the extremum are almost at the same level.

Fig. 2b presents an example in which the F_0 contour in the consonant /*g*/ is distinctly decreasing. This figure shows that as F_0 decreases from /*e*/ via /*g*/ towards the middle of /*z*/, one sees a microvariation in F_0 in /*g*/ in the form of a small bulge somewhat different from the generally decreasing contour. Examination of this point on the separator shows that this /*g*/, when cut out of the text, sounds like a liquid consonant, somewhat similar to /*ł*/. The consonant /*g*/, cut for a comparison out of the same segment of another recording (but with a marked ⋁ pattern), had the sound of a kind of voiced stop impulse and was quite different from the previous /*g*/.

Thus the evolution of F_0, presented in Fig. 2b, cannot be reduced to the same ⋁ pattern, presumably because of the specific combination of physiological and acoustical factors. It is not unlikely that the proximity of /*z*/ and the rapid decrease of the fundamental frequency had a decisive influence on the /*g*/ shown in Fig. 2b. It is possible that a combination of two successive drops in F_0 occurred with the "prevalence" of the drop in /*z*/. The difference in levels of the amplitude of /*z*/ in the above recording and in the same segment of another recording (in which the ⋁ pattern was observed for /*g*/), is also worth noting. It is not unlikely that the "local" increase of F_0 in /*g*/ was due to the increase in the intensity over a given segment (the occurrence of the pattern ∖ instead of the expected ⋁ pattern can be interpreted in this case as a "local" increase of the pitch).

Fricative consonants /*v*/, /*z*/, /*ʒ*/, /*j*/. According to the articulation of the fricative consonants, their pattern of F_0 should be similar to that in the stop consonants. The analysis has shown that this is the case only for /*v*/, /*z*/ and /*ʒ*/ for which, as for the stop consonants, the most typical variation in F_0 is the ⋁ pattern (Table 1).

In some of the pronunciations the phenomenon which has already been described for stop consonants was observed, namely the fall and subsequent

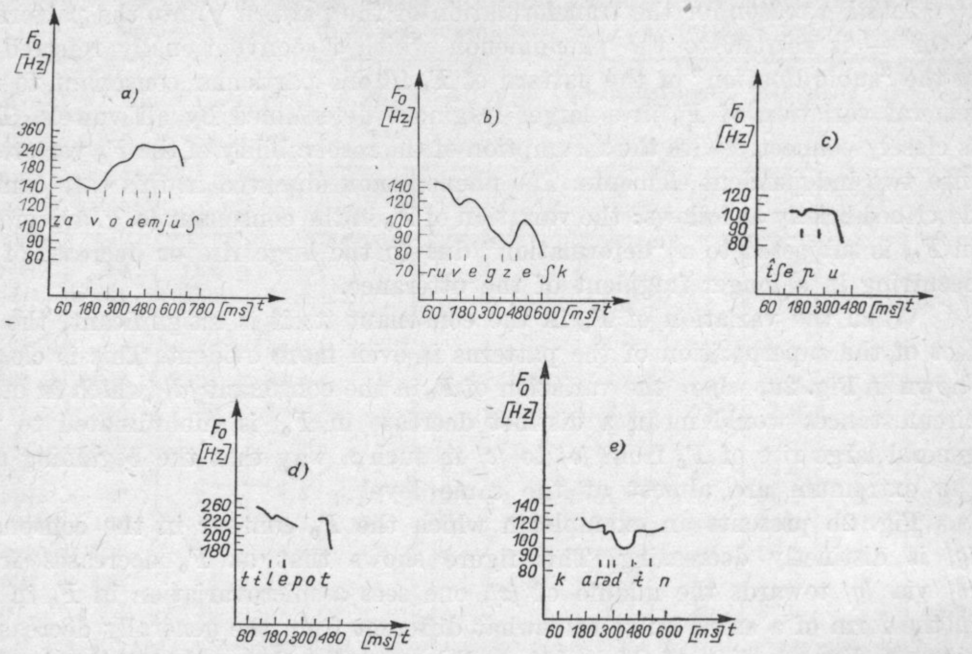

Fig. 2. Changes of F_0 in some utterances
a) "zawodem już" (male voice); b) "wędrówek do szkoły" (male voice); c) "po ukończeniu" (male voice); d) "tyle potem (female voice); e) "kardynalnym "(male voice)

rise of F_0 over a segment somewhat longer than the consonant itself, while the lengths of the part of the F_0 contour and the limits of the consonants are so related to one another that the pattern of F_0 within limits of the consonant may be increasing (if the fall has taken place before the consonantal limit) or decreasing (if the rise occurred only after the consonantal limit).

As in the case of the stop consonants, the examination of the fricative consonants reveals minor variations of the fundamental frequency which are "subordinated" to the pattern of F_0 over longer segments.

The sound /γ/ within the system of phonemes of the Polish language, is an allophone of the phoneme /x/ spoken in the position before a voiced consonant. Out of 15 utterances of /γ/ 13 featured a decreasing pattern of F_0, and this suggests that this consonant differs from the other fricative consonants as regards the variation of the fundamental frequency. In fact, the falls of F_0 which were noticed were mostly insignificant and did not deform the general contour of the melody. Such falls were not observed at all in some of the pronounciations.

A third group of utterances was identified in which fairly distinct or even considerable falls of F_0 displaced towards the left limit of /γ/ occur. (In Table 1 these utterances were included in the pattern groups ⟍, ⋁ or ⋀ of F_0 depending on the combination of the fall in F_0 with the general pattern of F_0.) Although the reason for this phenomenon is unknown, it can be said, ahead of next paragraphs that similar falls in F_0 in the proximity of the boundary of the consonantal segment were frequently observed in the liquid consonants, particularly the nasal ones.

Nasal consonants /m/, /n/, /ŋ/. The majority of utterances of these consonants are included in one of three patterns: increasing, decreasing, or flat F_0. The typical patterns actually coincide with the pattern of F_0 for a segment longer than the consonant itself. Nevertheless, in some of the utterances of the nasal consonants, larger or smaller deviations of the patterns from the F_0 contour in the longer segments can be observed. Among others there is a fall of F_0 on transitional segments from vowel to nasal consonant, or more rarely from nasal consonant to vowel (Fig. 2c).

In addition several utterances of the nasal consonants with a distinctly decreasing increasing pattern of F_0 were observed, but the magnitude of these changes is smaller than for the stop and fricative consonants.

The occurrence of $\wedge$ type patterns in the nasal consonants (Table 1) is not, as it appears in the case of the other consonants, a feature of the consonant itself. The occurrence of such a pattern is often associated with the consonant position being either in front of the pause in the phonation before which the fall of F_0 took place, or before a voiced fricative consonant in which an independent fall in F_0 occurs and this, for example in conjunction with a preceding rise of the fundamental frequency, led to the $\wedge$ pattern, or finally to a melodic breakdown.

Lateral consonant /l/. In many utterances of /l/ the tone fell. Close to this group are a number of utterances of /l/ with a pattern of F_0 of ⁄, ∖ or – which, as in the resonant consonants, can be considered as versions of the pattern *V*. There were also utterances of /l/ in which independent changes on F_0 could not be observed. A fall in F_0 over transient segments was also observed in some cases, as for instance in Fig. 2d where a drop at the boundary *v/l* in conjunction with the subsequent drop of the pitch before stopping results in the $\wedge$ pattern.

Vibrating consonant /r/. An analysis of the pattern of the fundamental frequency in this sound encountered difficulties related to the fact that /r/ is very short and the analysis could thus not comprise more than 2 to 4 periods. Out of 102 cases only 74 revealed any fall in F_0. An example of the pattern of F_0 for this consonant is presented in Fig. 2e.

Similar changes of F_0 were also observed in the majority of utterances which were originally assigned to the pattern groups ⁄, ∖ and –.

Since the variations were insignificant and occurred over a short segment, it was not possible within consonantal boundaries to read from the scale the magnitude of the fall or rise in F_0. The number of such cases totalled 18. In the other cases the pattern of F_0 appeared to coincide with the general pattern of the fundamental frequency.

4. Statistical analysis of the F_0 variations in voiced consonants

In addition to the qualitative analysis of the presented material quantative investigations were also carried out. For this purpose the differences in pitch between the initial point and the central peak were measured for all F_0 variations of the $\bigvee$ pattern. The difference was expressed as a percentage of the value of F_0 of the preceding vowel.

The data of the relative fall in tone were grouped into 2.5 % intervals. An example of the histogram of the percentage fall in tone for the stop consonants determined for all the voices is presented in Fig. 3, while the arithmetic averages and standard deviations of all the empirical distributions are given in Table 2.

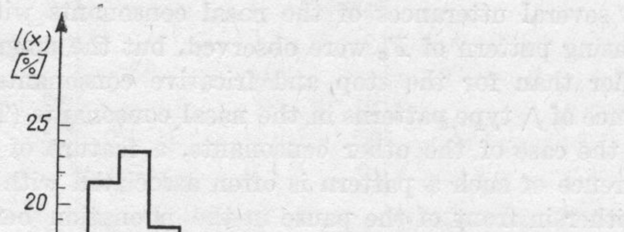

Fig. 3. Histogram of relative falls of F_0 in stop consonants. All voices included

From the data in Table 2 it can be seen that the mean relative fall of F_0 is the largest in stop consonants, smaller in fricative consonants and the smallest in nasal consonants. The lateral consonant /*l*/ and the vibrating consonant /*r*/ occupy an intermediate place between the stop and fricative consonants. In all likelihood the type of the articulation barrier plays the most important role for these cases.

In the group of stop and fricative consonants this regularity is confirmed in the data for the male and female voices considered separately. In both cases the mean relative fall in the stop consonants is higher than in the fricative ones. If the sounds /*d*/ and /*v*/ are to be considered as representatives for the stop and fricative groups (the numerical data were most numerous for these two consonants) one sees that for each individual voice the same sequence for the mean relative fall of F_0 is maintained.

Table 2. The parameters of empirical distributions of relative falls of F_0

Consonant or group of consonants	WJ		ZK		KD		MB		Male voices		Female voices		All voices together	
	$\bar{x}$	S	$\bar{x}$	S	$\bar{x}$	S	$\bar{x}$	S	$\bar{x}$	S	$\bar{x}$	S	$\bar{x}$	S
/*b*/									10.0	6.12	6.3	2.85	8.2	5.13
/*d*/	11.5	7.09	7.7	3.67	5.9	3.46	10.4	7.48	9.6	5.94	7.7	5.85	8.8	5.93
/*g*/													8.6	3.90
/*b, d, ɟ, g*/									9.3	5.46	7.2	5.15	8.5	5.40
/*v*/	8.5	5.05	5.6	4.63	4.3	2.73	5.7	4.07	7.2	5.07	5.1	3.52	6.2	4.51
/*z*/													9.6	6.65
/*v, z, ʒ, γ*/										5.06	5.5	3.94	6.4	4.58
/*m, n, ŋ*/													4.6	3.73
/*l*/													6.9	
/*r*/	8.4	7.20	5.8	3.19					7.0	5.56	6.2	3.49	6.7	4.97

In the series of histograms of the percentage fall of F_0, it can be clearly seen that all the empirical distributions have a marked asymmetry. The hypothesis is set forth, that the magnitude of the relative fall of F_0 in voiced consonants has a lognormal distribution. By treating the data obtained from the examined material as random samples from the population of all possible cases of a fall of pitch in voiced consonants, this hypothesis has been verified statistically.

For a preliminary verification of the validity of this hypothesis, and for the estimation of the parameters of theoretical distributions, the graphical method described, for example, in [1], § 4.5 was used. For this purpose the empirical distributions were marked on the lognormal paper. It was found that the distribution functions could be approximated by straight lines. This feature supported the hypothesis of a distribution for the fall in F_0 in voiced consonants. Fig. 4 shows the graphs plotted for the 3 fundamental groups of consonant and for /*r*/.

In addition to its simplicity and demonstrativeness the graphical method has another advantage since it enables to estimate directly the parameters of the theoretical distributions. Table 3 contains the estimates obtained for the parameters μ and δ, as well as for the expected values a, and standard deviations β of the theoretical distributions[2]).

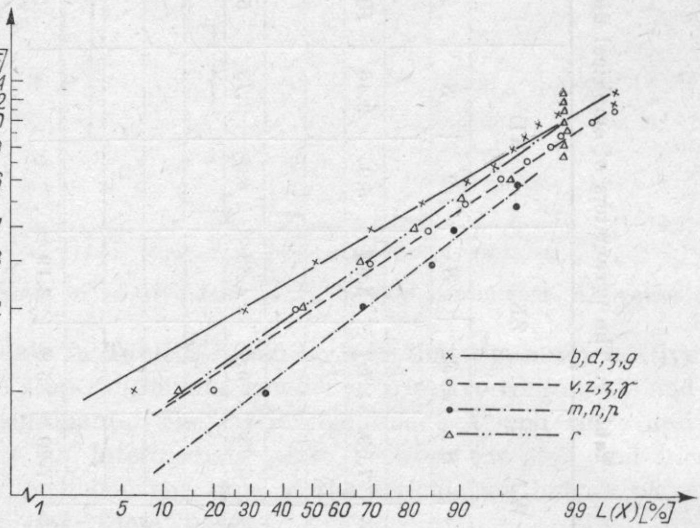

Fig. 4. Values of the relative falls of F_0 in voiced consonants on a lin-log scale

[2] It is known that the probability density function of a random variable with a lognormal distribution $\Lambda(\mu, \sigma^2)$ is described by the formula

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2\sigma^2}(\ln x - \mu)^2\right].$$

The expected value of the random variable $a = \exp(\mu + \frac{1}{2}\sigma^2)$, while the variance $\beta^2 = \exp(2\mu + \sigma^2)(\exp\sigma^2 - 1)$.

Table 3. Estimations of the parameters of the theoretical distributions of relative falls of F^0

Voices	Consonant or group of consonants	μ	σ	α	β
all	/b/	1.99	0.501	8.33	4.42
all	/d/	1.94	0.572	8.17	5.14
all	/g/	1.99	0.447	8.09	3.81
male	/b, d, g, ɟ/	2.04	0.503	8.76	4.65
female	/b, d, g, ɟ/	1.80	0.636	7.39	5.18
all	/b, d, g, ɟ/	1.96	0.523	8.17	4.53
all	/v/	1.61	0.650	6.17	4.46
all	/z/	1.93	0.588	8.17	5.32
male	/v, z, ʒ/	1.76	0.649	7.17	5.19
female	/v, z, ʒ, γ/	1.44	0.685	5.31	4.14
all	/v, z, ʒ, γ,/	1.59	0.665	6.11	4.55
all	/m, n, ŋ/	1.25	0.775	4.71	4.28
all	/r/	1.66	0.737	6.89	5.84

It is worth noting that the estimated theoretical parameters of the distributions of the relative fall of F_0 in voiced consonants exhibit the same regularity as regards the mean magnitude of the fall for the groups of homogenous consonants as it was mentioned above., i. e., the expected value of the distribution is highest for the stop consonants (8.17 %), smaller for the fricative consonants (6.11 %) and smallest for the nasal consonants (4.71 %). From these estimates it can also be seen that the distributions of the relative

Table 4. Values of the Kolmogorov test statistics for verification of the hypothesis of the lognormal distribution of the relative falls of F_0

Voices	Test	Sample size	Empirical value of the test statistics	Critical value of Kolmogorov test statistics *
all	/b/	44	$D_{44} = 0.0835$	$D_{44}(0.05) = 0.2006$
all	/d/	152	$\lambda = 0.986$	$\lambda_{0,05} = 1.358$
all	/g/	39	$D_{39} = 0.0997$	$D_{30}(0.05) = 0.2127$
male	/b, d, g, ɟ/	149	$\lambda = 0.7483$	$\lambda_{0.05} = 1.358$
female	/b, d, g, ɟ/	99	$D_{99} = 0.376$	$D_{99}(0.05) = 0.1347$
all	/b, d, g, ɟ/	248	$\lambda = 0.6913$	$\lambda_{0.05} = 1.358$
all	/v/	222	$\lambda = 1.229$	$\lambda_{0.05} = 1.358$
all	/z/	30	$D_{30} = 0.0515$	$D_{30}(0.05) = 0.2417$
male	/v, z, ʒ/	146	$\lambda = 0.611$	$\lambda_{0.05} = 1.358$
female	/v, z, ʒ, γ/	117	$\lambda = 0.784$	$\lambda_{0.05} = 1.358$
all	/v, z, ʒ, γ/	263	$\lambda = 1.0801$	$\lambda_{0.05} = 1.358$
all	/m, n, ŋ/	27	$D_{27} = 0.0219$	$D_{27}(0.05) = 0.2544$
all	/r/	74	$D_{74} = 0.0387$	$D_{27}(0.05) = 0.1554$

* From [20] (Tables 47 and 48)

fall of the pitch in stop and fricative consonants differ considerably in terms of this parameter for male and for female voices (in stop consonants the respective values of a are 8.76 % and 7.39 % while in fricative consonants 7.17 % and 5.13 %, respectively).

After graphical estimation of the parameters of the individual distributions the hypothesis that the observed values of the fall of F_0 originate from the lognormal populations with the same parameters, was verified by means of the Kolmogorov test.

The verification was performed at the significance level $p = 0.05$. The results of the verification procedure are presented in Table 4. In all cases the empirical values of the proper statistics (Dn for small n and λ for $n > 100$) are smaller than the critical value, and thus the Kolmogorov test provides no basis for rejecting the assumed hypothesis in all cases under investigation, at 5 %-significance level.

5. Conclusions

Stop and fricative voiced consonants in the majority of cases exhibit local falls of the fundamental frequency. The patterns of F_0 in the other utterances (that is those which are not of the V pattern) can be frequently regarded as variants of this pattern, resulting from the influence of many factors. The analysis has shown (although it did not raise any doubts previously) that the form and magnitude of the fall of pitch in a consonant are affected by such factors as the accent on the syllable with a given consonant, the accent of the neighbouring syllables, the character of the melody over segments longer than a syllable (e. g. in a word). Another important factor influencing the pattern of the pitch in a consonant is the phonetic environment of a consonant (in the form of the neighbouring sounds and pauses in the phonation).

In the investigated material one can find examples of the effects of all the above factors. Amongst others it would be of interest to investigate the consonantal combinations for which, according to our observations, a cumulation of the falls of F_0 is possible, as this would result in a single joint fall forming a considerable deviation from the level of F_0 determined by the vowels. It would be also worth -while to investigate the relation between the nature of the variations of F_0 in consonants and the accent. It appears that an accent on the preceding vowel favours an increase of F_0 in the following consonant (it might well be the result of the remanent tension of the vocal cords on the accented syllable).

Generally one can talk of suprasegmental factors (accent, general melody contour) and segmental factors (phonetic environment of a consonant) influencing the character of the pitch variations in individual consonants. In the case of the latter factors a co-articulation in the field of the fundamental frequency can be observed, and this is evidenced by the fact that the fall of F_0 related to the presence of a consonant frequently starts on a tonogram before the moment at which the initial boundary of a consonant can be determined from the oscilloscope trace. The subsequent rise of the pitch often extends through the boundary between the consonant and the next vowel.

The mean fall of F_0 for stop consonants calculated from the data contained in this paper is 8.5 % of the fundamental frequency of the preceding vowel. For fricative consonants /*v*/, /*z*/, /*ʒ*/, /*γ*/, the corresponding value is 6.4 %. This does not agree with the data contained in previous papers, [18] and [9], p. 176, according to which the fall of F_0 for fricative consonants is higher than the fall of F_0 for stop consonants.

It seems reasonable to suggest that the difference of the mean values of the fall in stop and fricative consonants is related to the character of the articulatory barrier – a complete occlusion in the first group of consonants, and a gap through which air coming out of the lungs is partly exhaled in the second group.

From the viewpoint of the variation of F_0 occurring in the voiced consonant /*γ*/ the latter occupies an intermediate position between the fricative and nasal consonants, since in the majority of utterances, the pattern of the pitch changes in the consonant /*γ*/ coincided with the general contour of F_0.

A fall of F_0 occurs in the vast majority of utterances of the vibratory consonant /*r*/ (with a mean value of 6.7 %), and places this consonant, in terms of the nature of the variations, in one group with stop and fricative consonants. Local falls of the fundamental frequency in the lateral consonant /*l*/ also occurred frequently, the mean fall in the investigated sample being 6.96 %. Sometimes the frequency pattern of the pitch in the two last sounds agrees (more frequently for /*l*/ than for /*r*/) with the general contour of F_0.

For the nasal consonants /*m, n, ŋ*/ the pattern of F_0 in the consonants themselves is most typically superposed on the pattern of the tone over longer segments, in agreement with other reports on this subject. However, a fall of F_0 also occurs, the relative mean value of the fall being 4.65 % for the investigated material. A number of utterances of the nasal consonants include an insignificant boundary fall of F_0 (on the vowel/consonant and, more rarely, consonant/vowel boundaries).

Without additional investigation it is difficult to formulate a hypothesis about the origin of these boundary falls of F_0. They may, for example, be related to the articulation of the nasal consonants or to the nasalization of particular segments[3]. However, it is known that in the perception of synthetic sounds the boundaries between vowels and liquid consonants are the worst to be recognized [2], thus it may well be the case that the falls of F_0 observed

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[3] S. Smith in his list of the distinctive features of "opened nasality" points to the absence of essential variations of fundamental frequency ([4], p. 146).

at boundaries of the nasal consonants, even though insignificant, are essential for perception.

The frequency of the occurrence of local falls of F_0 in the analyzed consonants and the relative magnitudes of these falls, decrease in the order in which particular groups of consonants have been mentioned here, namely: stop — fricative — nasal. It would appear that the conclusion may be drawn that the smaller the constriction (the degree of occlusion) of a consonant, the smaller is the mean value of the fall of F_0 in the consonant. The conclusions drawn for /r/ and /l/ need further confirmation because of the small statistics of the results.

It seems that the use of information on the behaviour of F_0 at the transitions between particular sounds would have a beneficial effect on the quality of synthetic speech.

The statistically verified hypothesis of a lognormal distribution for the magnitude of the relative fall in F_0 for consonants, throws some light on the mechanism of these falls, since it may give evidence of the function of the vocal chords being subject to a law of proportionality in the cases under discussion. It would appear that use can be made of the estimated parameters of the theoretical distributions in speech synthesis when one is anxious to obtain speech with a highly natural sound. In this case one should define the fall of F_0 at the end of a consonant by means of a random numbers generator, modulating the lognormal distribution with parameters that correspond to a particular group of consonants (stop, fricative or liquid).

References

[1] J. Aitchinson, J. A. C. Brown, *The Lognormal Distribution*, 4.5 Cambridge 1957.

[2] W. M. Belawski, L. W. Jeżowa, *Spektralno-vremennyje priznaki dla segmentacii reči na zvuki*, ARSO, 8, 2, 36 (1974).

[3] L. A. Čistovič, *Metod issledovanija rešajuščich pravil, primenjajemych pri vosprijatii reči.* Proceedings of the Sixth International Congress of Phonetic Sciences (Prague, 7-13 Sept. 1967), Academy of Sciences, Prague 1970, p. 23-34.

[4] G. Fant, *Acoustic Theory of Speech Production*, S'Gravenhage, 1960.

[5] M. Haggard, St. Ambler, McCallow, *Pitch as a voicing cue*, JASA, 47, 2, 613-617 (1970).

[6] J. M. Heinz, B. E. F. Lindblom, I. Ch. Lindqvist, *Patterns of Residual Masking for Sounds with Speech—Like Characteristics*, In: Conference on Speech Communication and Processing, Boston 1967, p. 246-251.

[7] W. Jassem, *Fundamentals of acoustic phonetics* (*in Polish*) Warszawa, 1973.

[8] H. Kubzdela, *Automatic extraction of the fundamental frequency and of the first three formants of a speech signal*, (in Polish) IPPT Reports, n° 51 (1973).

[9] R. P. Léon, Ph. Martin, *Prolégomènes à l'Etudes des Structures Intonatives*, Studia Phonetica, II-Ottava 1970.

[10] W. W. Lublinskaja, *Vosproizvedenije prostych konturov izmenenija častoty osnovnogo tona zvukov*, In: Problemy fiziologičeskoj akustiki, 7, Analiz rečevych signalow čelovekom, Leningrad 1971, s. 66-74.

[11] I. G. MATTINGLY, *Synthesis by Rule of Prosodic Features*. Language and Speech, **9**, 1, 1-13 (1966).
[12] O. MATUSZKINA, *Effect of consonantal articulation on the pattern of the fundamental frequency in the Polish language* IPPT Reports n° 37 (1976).
[13] D. MEHNERT, *Untersuchungen zur Feinstruktur der Grundfrequenz bei der stimmhaften Anregungsfunktion*, In: 14, akusticka konferencia "Akustika reči a vnimanie zwuku", Bratislava 1976, p. 114-118.
[14] B. MOHR, *Intrinsic Variations in the Speech Signal, Phonetica*, **23**, 65-93 (1971).
[15] S. ÖHMAN, J. LINDQVIST, *Analysis-by-synthesis of prosodic pitch contours*, STL QPRS, 4, 1-6 (1965).
[16] S. ÖHMAN, *Word and sentence intonation: a quantitative model*, STL QPRS, 2-3, 20--54 (1967).
[17] K. L. PIKE, *The Intonation of American English*, Ann Arbor (1945).
[18] M. STEFFEN–BATÓG, *The effect of consonants articulation and intonation on fundamental frequency*, In: Speech Analysis and Synthesis, 3, Warszawa 1973, p. 121-134.
[19] C. WITTING, *A method of evaluating listeners transcription of intonation on the basis of instrumental data*, Language and Speech, **5**, 3, 138-150 (1962).
[20] R. ZIELIŃSKI, *Statistical tables* (in Polish), Warszawa 1972.

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