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ANALYSIS OF THE SPECIFIC STRUCTURE OF THE FUNDAMENTAL COMPONENT OF VOCAL SOUNDS FROM THE POINT OF VIEW OF INTONATION EVALUATION

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Finding it necessary to develop the acoustic basis for the evaluation of the correctness of vocal sound intonation, with consideration given to the clarity of intonation, the correctness of pitch attack and pitch stabilization, investigations were performed on the formation in the process of intonation of an isolated sound, of parameters of the fundamental component which provide information about the deep structure of this sound. The method of intonographic plotting was used and statistical calculations performed. The following quantities were considered: the duration of an isolated sound over one breath (t), the formation time of the amplitude and frequency of the fundamental component of an isolated, freely intoned sound (τ_A, τ_F), the value and variation of the amplitude level (A and ΔA), the fidelity of standard frequency reproduction and frequency variation (σ, ν) within the limits of the quasi-steady state of sound. The investigations were performed on three groups of children and one of adolescents (20 voices in all).

The results obtained have led to the conclusion that there are distinct differences in the deep structure of the fundamental component of isolated sounds intoned by the different age groups. These differences can constitute a physical basis for evaluating the ability to intone vocal sounds.

1. Introduction

Vocal sounds are outstanding among music sounds, since they not only constitute the basic artistic material, but are also the most frequent standard. Knowledge of their specific structure is necessary for developing objective criteria which are equivalent to factors considered in subjective evaluation affecting the correctness of intonation, which continues to be the object of evaluation in the process of music education. Research on sound intonation problems has mainly been centred on the sounds of bow instruments [9], [12], Part of the problems considered in this research has also been concerned with vocal intonation. The so-called component tones of sound, included in the composition of the spectral structure of music sounds, are not homogeneous in terms of their characteristic parameters, both in reference to vocal and violin sounds. Over the range of individual sounds, both the frequency and amplitude vary continuously in time, forming a sort of complex substructure [7]. In order to distinguish it from the spectral structure, in the present paper it is called a "specific" or "deep" structure. The central problem in working towards objectivization of the process of evaluation of intonation correctness is selecting factors responsible for its quality — such factors which are perceptible by the ear and have their equivalents among the acoustic structural elements of sound. Wroński [17] took Garbuzov's theory [5] as the basis of theoretical evaluation of intonation. This theory can be the starting point in evaluating the agreement between the desired sound pitch and the pitch assumed as the standard, being closely related to the frequency. Correctness of intonation is determined not only by the fidelity of standard reproduction but also a number of other factors play their role. Lesman [8] drew attention to intonation certainty, which is related to variation in the pitch of a given sound as it lasts. Flesch [3] considered the problem of the possibility of correcting pitch over the time of sound formation, the so-called sound attack. Tjernlund [16], on the basis of the results of computer research and statistical calculations of sound parameters, drew attention to the intonation deviation of the fundamental frequency during playing. Björklund [1] already took into consideration variations of parameters which occur within individual sounds and studied the significance of vibrato in the process of intonation in untrained voices. Rags [13] and Rakowski [14] considered the effect of vibrato on the evluation of sound pitch. All the factors mentioned above are related to the formation of sound structure, spectral [15] or deep [4]. The problem of the correctness of the structure of vocal sounds intoned is particularly complex in the case of children's voices, in view of the differentiation of vocal activity among children of different age [10].

The purpose of the research described in this paper was to define the deep structure of the first component of sound which is equivalent to the theoretical fundamental tone (called the fundamental component below) of sounds intoned by children and adolescents. This problem was considered in terms of analysis of the possibility of assuming individual elements of the structure as the basis for evaluating intonation correctness.

2. Organization and technique of the investigations

The investigations were performed on voices from three age groups of children: 7-8 years, 9-11 years and 12-14 years and adolescent voices of one group of students (from the course of music education in Pedagogical University Zielona Góra), with five persons in each group, 20 persons in all.

The children were secondary school pupils, physically and mentally normal (doctor's and psychologist's data files having been consulted); they had good results in learning, in general and in music classes. Their music education was limited to a course in secondary school. All the children worked under supervision of a qualified teacher, an expert in music education.

The adolescent group was composed of average musically gifted persons, without professional vocal training.

All the groups underwent audiometric examination. No essential hearing loss, i.e. over 30 dB, was found.

The persons selected for the investigations underwent training consisting in a test session, combined with necessary instructions regarding the technique of recordings.

The recordings were made in a damped booth, under constant teacher supervision. The intoning persons sat in an armchair, which limited head movements. It was found at preliminary sessions, on the basis of sound intensity level measurements, that during intoning the children were very concentrated and almost still. Changes resulting from possible head displacements within one sound were below perception (less than 1 dB) and in the case of successive sounds they were smaller than those resulting from voice stabilization (not exceeding 2 dB). Chosen test music material, according to instructions given to all persons individually, was to be sung freely *"mf"*. Older children and students knew terms regarding dynamics; it was necessary to explain them to younger children in school language they understood. When it was noticed that a child was tense or his or her voice intensity was affected by the atmosphere in the damped booth, the teacher who knew the child's abilities in natural circumstances stopped the session and recording was repeated.

The sounds were recorded using an MCO 30 capacitance microphone, set in front of the singer, at a distance of 30 cm, and a MP 223 tape recorder. The source of standard sounds was a piano tuned before all sessions to an accuracy of 1 Hz. Frequency variations within one sound were in a 12-ct interval, i.e. within $+/-3$ Hz at a frequency of 440 Hz.

The range of test sound material was selected according to the abilities of the age groups, considering the scale range of individual children's voices and the programme recommendations for music classes in primary schools. For children's voices intoned sounds were from a (220 Hz) to e^2 (659.3 Hz); for adolescent voices, from c (130.8 Hz) to f^2 (698.5 Hz).

The number of sounds intoned by one voice was not the same, since the voices were untrained and, as it was already mentioned, could not always carry out the whole pitch scale.

Isolated sounds of the vowel *"a"* were intoned. All sounds were repeated five times.

The whole test material recorded underwent subjective auditory evaluation, called auditory evaluation below, and intonographic analysis was performed on the deep structure of the fundamental component using instrumentation adapted for music purposes, consisting of an intonographic set [11] and a MERA 304 minicomputer (Fig. 1). Analog plotting (Fig. 2), being little accurate, was used only for evaluating the sound amplitude level and the signal to noise ratio. The error involved in frequency plotting depended on this ratio. Digital plotting was performed only for those sounds whose amplitude level exceeded 65 dB. A linear scale of the amplitude level (*AO*) was used with ac-

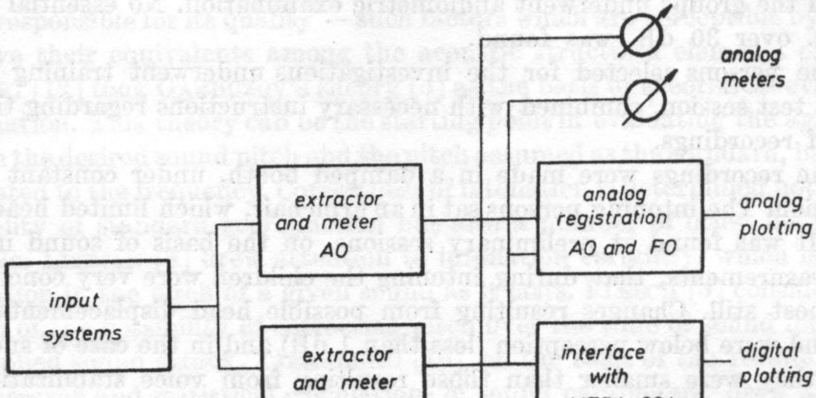

Fig. 1. A functional diagram of the intonograph [11]

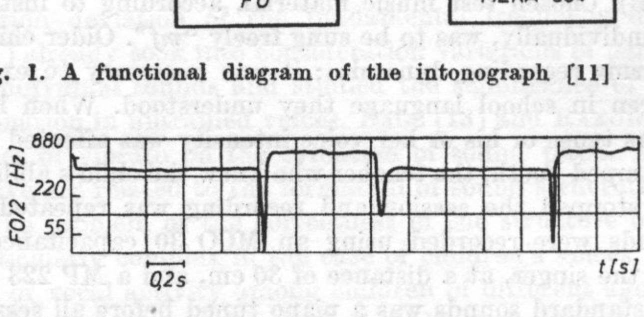

Fig. 2. An example of analog plotting (child 1/9, sound c^1)

curacy up to 1 dB over the range 50 dB to 90 dB and a logarithmic frequency scale (*FO*) from 85 Hz to 880 Hz. The frequency plotting density depended on the sampling frequency; the error in the plotting, on the signal to noise ratio. Intonographic plotting was made with constant time quantization at every 12.5 ms, providing the possibility of differentiating frequency in 12-ct zones for sounds of the little octave and half of the once-accented octave. Accomplishing such accuracy for higher sounds required their transposition by one octave lower. This made it possible to localize intonation deviations of frequency with respect to the frequency of the sounds on a 12-tone scale in a regularly tempered system, in intervals of 12, 25, 50 and 75 ct for most of the sounds investigated. In a few cases of the twice-accented octave, where two adjacent intonation zones merged in the same code gate, it was assumed that there was a greater deviation, i.e. one less convenient from the point of view of intonation correctness.

Intonograms underwent statistical elaboration by calculating the mean, median and modal values, the standard deviation and one normalized for all sounds intoned individually. The correctness of taking for further elaboration one of the first three indexes was discussed. The following scale was assumed in evaluating the intonation deviations from the standard frequency: up to 12 ct – intonation without error, the deviation being within the Garbuzov zone for the prime; 25 ct – intonation within norm, this being the optimum zone of interval perception by everage gifted child; 50 ct – uncertain intonation; 75 ct – erroneous intonation; above 75 ct – completely wrong, the sound entering the zone of the solfeggio error.

3. Auditory evaluation

In order to confirm to what extent the properties of intoned sounds as given in the literature can constitute distinct, specific objects of evaluation based on a subjective sensation of intonation correctness, auditory evaluation of the sounds recorded was carried out. Three properties were considered: intonation clearness (*I*), understood as the agreement between the pitch of the sound monitored and the pitch recommended for intoning, i.e. the pitch of a piano sound; certainty of sound attack (*At*) and pitch stabilization (*St*) within one single sound.

These properties were selected as a result of a discussion of the evaluating group during preliminary monitoring training sessions. This group consisted of five persons, representatives of such specializations as vocalism education, secondary school music education, ear training, education of teachers for initial teaching of music and acoustics. The whole group had participated in monitoring sessions related to research for five years. At the preliminary sessions, the evaluation scale was also established. A four-point scale was assumed (3 points – no error, 2 – almost good, 1 – erroneous, 0 – quite wrong, solfeggio error). Attempts to introduce a wider scale led to completely diverging results in the evaluating group. These differences distinctly decreased with the point system assumed. E.g. full agreement in the evaluation of intonation clearness of sounds intoned by female voices was achieved in 17 per cent, only in the case of correct productions (3 points). In turn, in evaluating the sound attack in girls' voices, full agreement was achieved in 18 per cent only for the lowest marks (0 points).

The agreement of evaluations for particular properties is shown in Fig. 3 and, divided into female and male voices, in Table 1. The evaluations were classified as follows: 4 – all the same, 3 – one different by 1 point, 2 – 2-3 grouping with 1 – point difference or 1+4 grouping with greater difference,

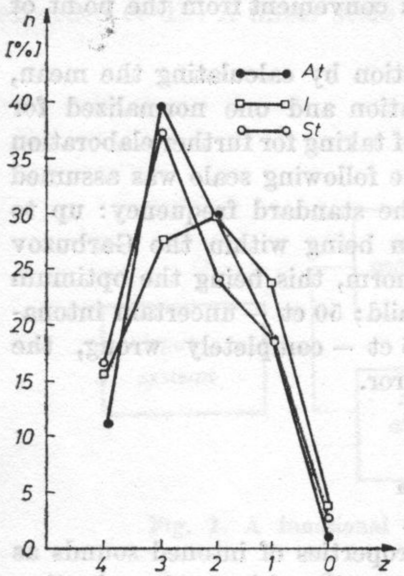

Fig. 3. The degree of agreement in auditory evaluation (*z*): correctness of pitch attack (*At*), intonation clearness (*I*) and pitch stabilization (*St*)

Table 1. The agreement in auditory evaluation

Voices	Total number of sounds evaluated	Agreement 4 full [%]	3 good	2 satisfactory	1 unsatis-factory	0 none
A. intonation clearness						
boys	98	19	19	24	32	6
girls	112	19	31	19	27	4
males	69	7	22	49	20	2
females	97	17	35	36	11	1
B. pitch attack						
boys	93	2	36	28	32	2
girls	112	18	36	27	18	1
males	65	11	48	23	18	0
females	82	11	45	35	9	0
C. pitch stabilization						
boys	91	14	36	21	28	1
girls	145	12	33	26	23	6
males	89	26	34	28	12	0
females	117	20	44	20	14	2

1 — evaluation differentiation by 2 points, 0 — evaluations from the highest (3) to the lowest (0) number of points. The greatest differences occurred in evaluating intonation clearness. A detailed analysis of this state of things is clearly beyond the scope of the present paper; it can only be mentioned that the results achieved previously [6] have been confirmed. This indicates the necessity of supporting auditory evaluation of intonation correctness with objectivizing methods, providing full control and also helpful in ear training.

4. Measured and calculated results

a. Duration and formation of the fundamental component

The duration of the fundamental component depends on the ability of sustaining a sound effortlessly in one breath. It was calculated from digital plotting of the amplitude level, considering the whole behaviour of the fundamental component from its initial excitation to the decay of the amplitude level to the noise level. The results were given in the form of histograms, with data grouped with an accuracy of 0.5 s. With children's voices this duration acheived its maximum value (and only in few cases) of about 1.5 s (Fig. 4). Sounds

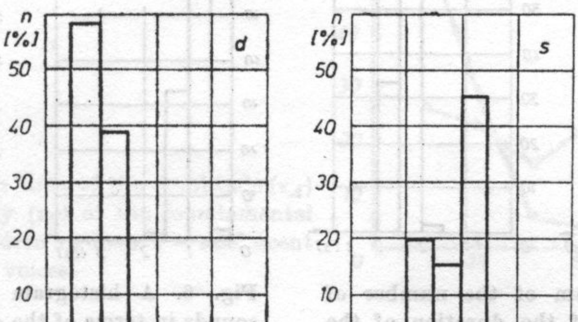

Fig. 4. A histogram of the number of sounds in terms of the duration of the fundamental component in the groups of children's (*d*) and adolescent (*s*) voices

n — the percentage of the sounds investigated

were most frequently kept in one breath for 0.5 to 1.0 s. This is an order of magnitude corresponding to the psychological present. According to BIELAWSKI [2], the centre of the psychological present corresponds to 659 ms. The doubt arises as to whether over such a short time as the duration of the stabilized state of a sound intoned by a child, the listener can carry out an immediate analysis of pitch changes within the sound, resulting from frequency variation, and necessary in evaluating the stabilization. In teaching, this evaluation is most frequently performed by a person without acoustically trained analytic abilities.

Adult persons, without professional vocal training, tend to keep a sound in one breath for 2.0 to 2.5 s. With female voices the duration of the fundamental component is longer than with male ones (Fig. 5). It is therefore possible to assume an attitude towards the stabilization state of a sound while listening

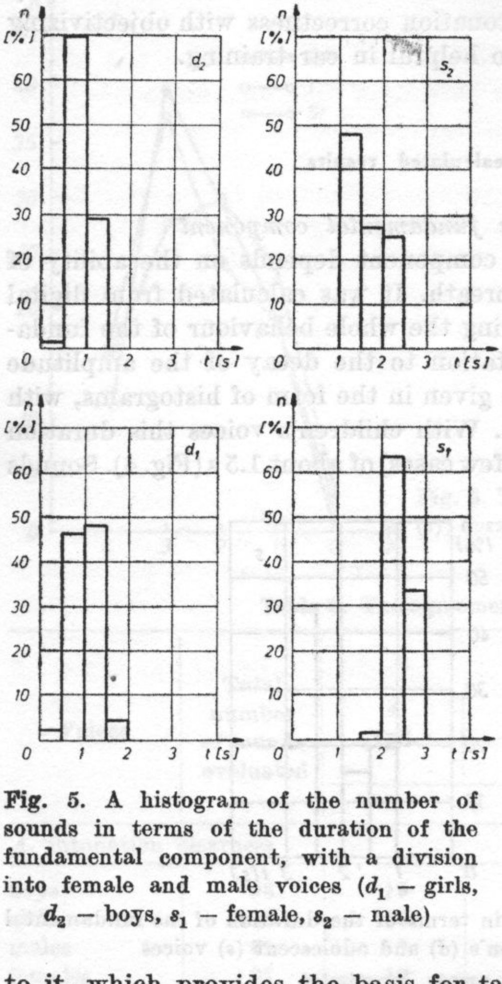

Fig. 5. A histogram of the number of sounds in terms of the duration of the fundamental component, with a division into female and male voices (d_1 – girls, d_2 – boys, s_1 – female, s_2 – male)

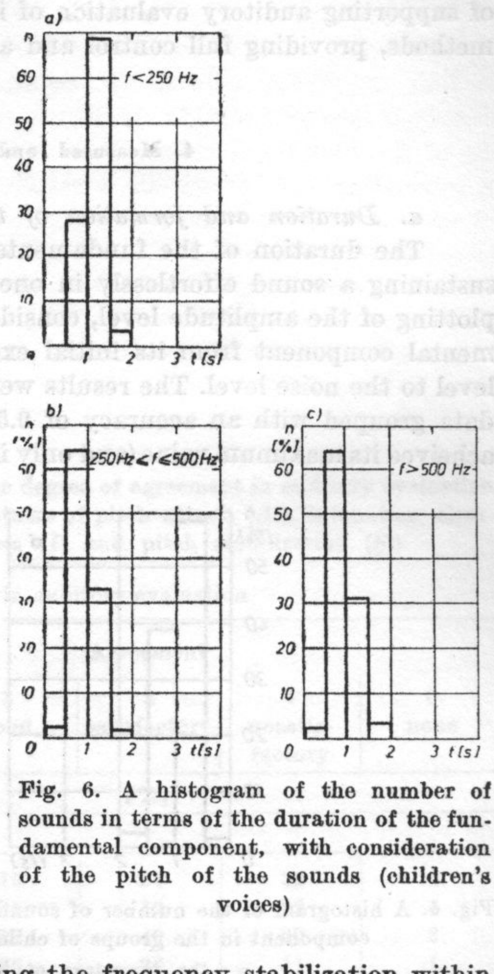

Fig. 6. A histogram of the number of sounds in terms of the duration of the fundamental component, with consideration of the pitch of the sounds (children's voices)

to it, which provides the basis for taking the frequency stabilization within a sound as one of criteria of evaluation of intonation correctness.

Adolescent voices were found to have greater ability to sustain in one breath higher sounds rather than lower ones. Children's voices did not show any distinct dependence of the duration of the fundamental component on the pitch of intoned sounds (Fig. 6).

Children attack sounds with great determination. The time necessary for the fundamental component frequency to stabilize is very short. In most cases the time does not exceed 37.5 ms, with the majority of results coinciding with 25.0 ms (Fig. 7). Over the sound attack interval in the behaviour of the amplitude and frequency there sometimes occur variations which make it difficult to distinguish the moment when the stabilized state begins. Such "uncertain" intervals were included in the attack time. The formation times of both the frequency and the amplitude level above 50 ms are more often characteristic of adult (*s*) than children's (*d*) voices.

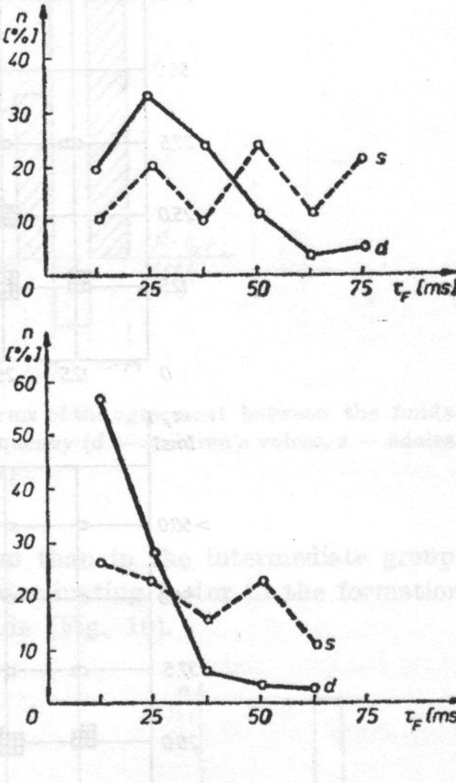

Fig. 7. The formation time of the amplitude (τ_A) and of the frequency (τ_F) of the foundamental component (*d* – children's voices, *s* – adolescent voices)

It is only in few sounds that the formation times of the frequency (τ_F) and of the amplitude level increase (τ_A) are equal (Fig. 8).

b. Fundamental component frequency vs nominal standard frequency

In order to determine the agreement between the fundamental component frequency and the nominal standard frequency of intoned sounds, the mean, median and modal values were calculated. These indexes were determined with reference to a section of the fundamental component indicating the properties of pitch stabilization or stabilization of pitch variation form, not shorter than 0.5 s. In about 90 per cent of analysed sounds these three indexes fell within the same interval of intonation accuracy. With large frequency scatter the modal value was not very distinct. In further calculations its mean value ($\bar{F}$) was taken as the frequency index.

The difference between the mean frequency ($\bar{F}$) and the nominal standard frequency (F_M) was assumed to be the measure of intonation deviation.

The fundamental component frequency was found to decrease only in 1 per cent of sound in the group of adolescent voices and in 16 per cent in the

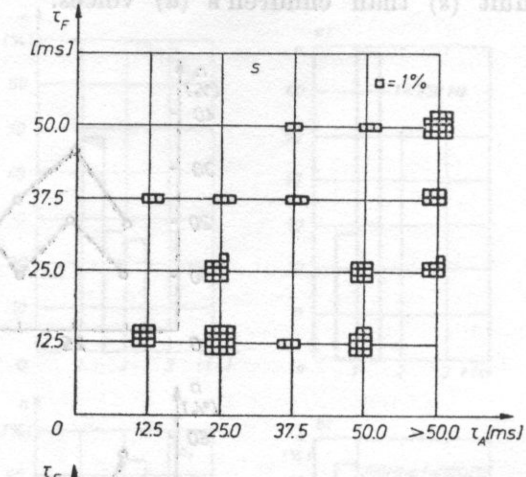

Fig. 8. The mutual relation between the formation time of the amplitude (τ_A) and that of the frequency (τ_F) of the fundamental component (*d* – children's voices, *s* – adolescent voices)

group of children's voices. In the other voices there was a distinct tendency towards an increase in the fundamental component frequency (Fig. 9).

Subjective evaluations of the intonation clearness appeared to be very lenient compared to the measurement results. Of 376 sounds evaluated, 226 were evaluated at 2 and 3 points. As it was already mentioned, there was, however, no full agreement in the evaluating group. It can be expected that apart from subjective pitch sensation, complex factors played their role in this.

As the age of children's groups tested increases, the distribution of intonation deviation changes. Large deviations are more frequently found in the

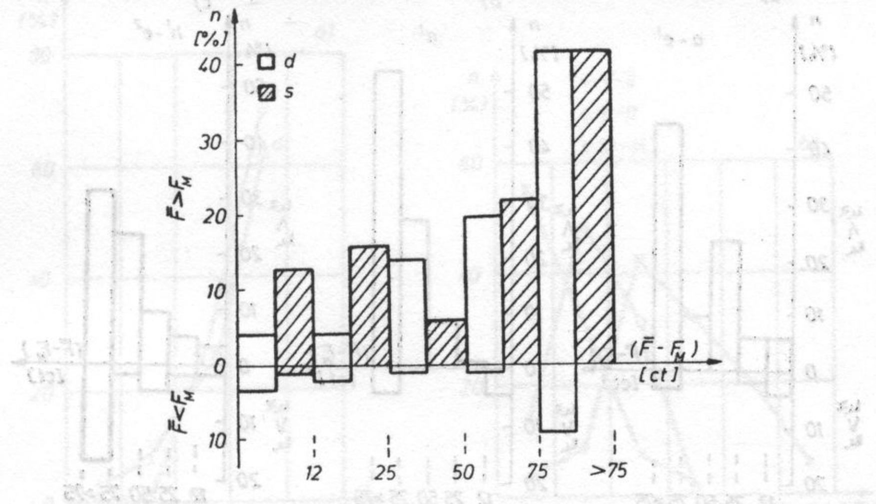

Fig. 9. A histogram of the number of sounds in terms of the agreement between the fundamental component frequency and the standard frequency (*d* — children's voices, *s* — adolescent voices)

groups of the youngest and eldest children than in the intermediate group, indicating that music training is not the dominating factor in the formation of the deep frequency structure of sounds (Fig. 10).

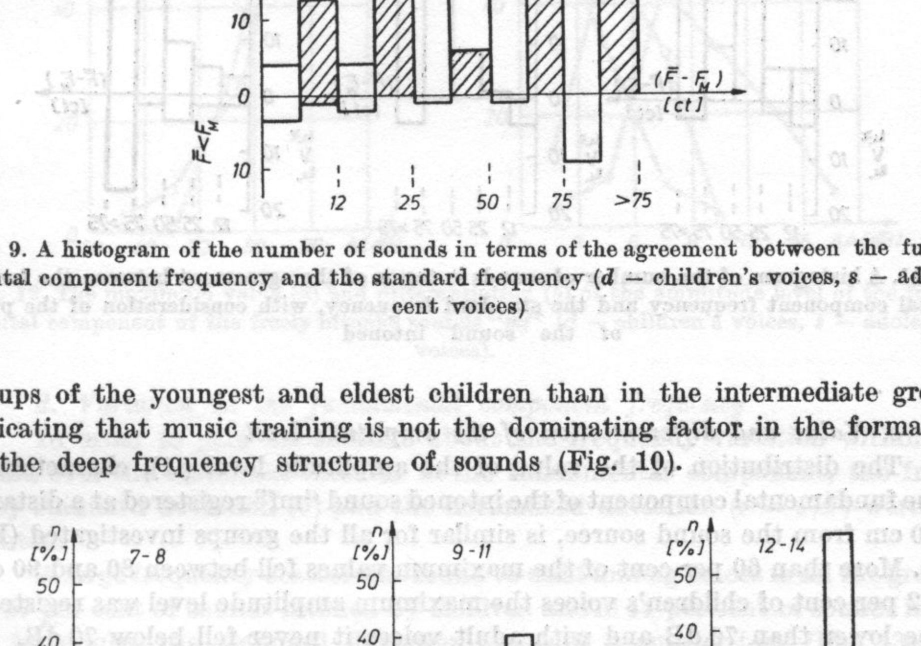

Fig. 10. A histogram of the number of sounds in terms of the agreement between the fundamental component frequency and the standard frequency, with consideration of the division of the intoning children into age groups

The intonation deviations were not found to depen don the pitch of intoned sounds (Fig. 11).

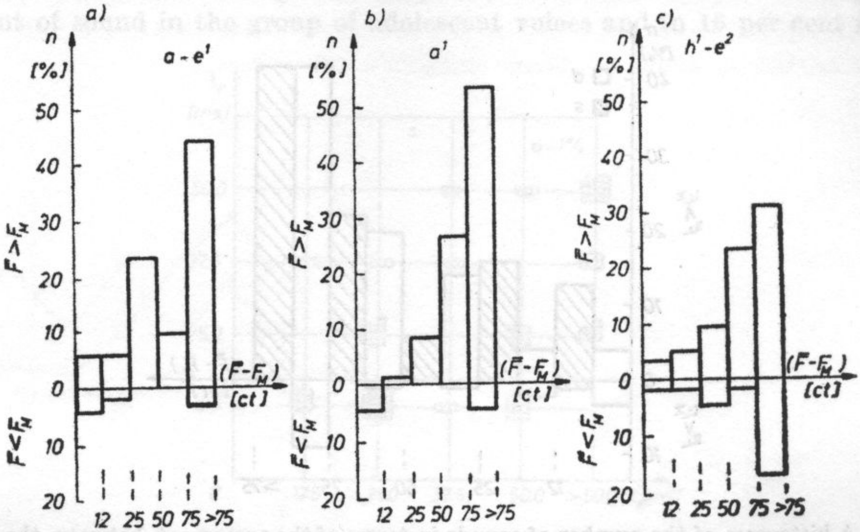

Fig. 11. A histogram of the number of sounds in terms of the agreement between the fundamental component frequency and the standard frequency, with consideration of the pitch of the sound intoned

c. Value and differentiation of the amplitude level

The distribution of the value of the amplitude level (A), characteristic of the fundamental component of the intoned sound "mf" registered at a distance of 30 cm from the sound source, is similar for all the groups investigated (Fig. 12a). More than 60 per cent of the maximum values fell between 80 and 90 dB. In 12 per cent of children's voices the maximum amplitude level was registered to be lower than 70 dB and with adult voices it never fell below 70 dB.

In their free intonation of "*mf*" children reach over the interval of the stabilized state of the fundamental component an intensity level between 55 and 90 dB. There is a distinct dependence on the age of the group. In the youngest group more than 86 per cent of sounds were intoned above 80 dB. This intensity level was acheived by the intermediate group for 64 per cent sounds and only 32 per cent in the eldest one. In the latter group, in 57 per cent the amplitude level of the fundamental component over the stabilized state interval varied about 75-80 dB.

The differentiation in the amplitude level variation over the stabilized state interval of the fundamental component of individual sounds (ΔA) decreases as the group age increases, with a maximum moving from 6-9 dB for the youngest group to 0-3 dB for the eldest (Fig. 12b).

In the voices of the adult group the amplitude level of individual sounds also varied. This variation over the stabilized interval of the fundamental component is mostly 3-4 dB for female voices and 6 dB for male ones.

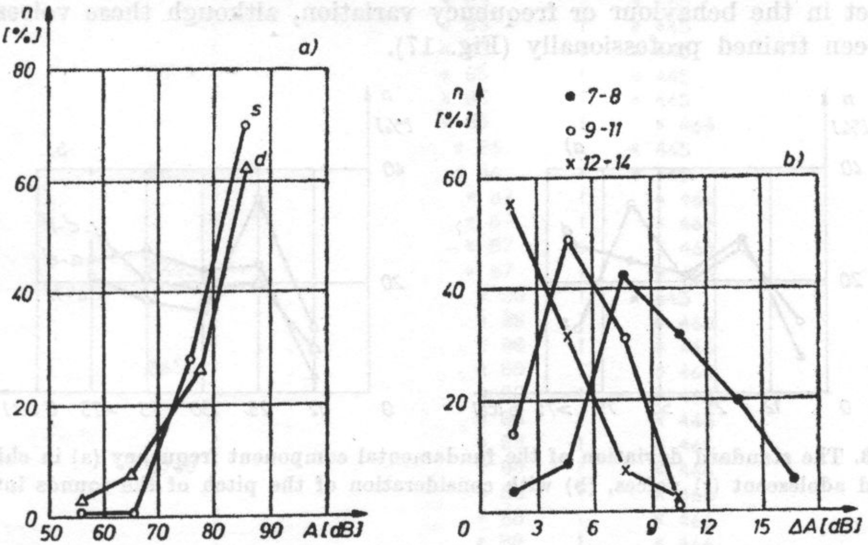

Fig. 12. The maximum value (*a*) and differentiation (*b*) of the amplitude level of the fundamental component of the freely intoned sounds "*mf*" (*d* — children's voices, *s* — adolescent voices).

d. Variation in the fundamental component frequency

In order to gain information about the frequency variation within one sound over the stabilized interval of the fundamental component, the frequency standard deviation (σ) and the normalized deviation ($\nu = \sigma/\bar{F}$) were calculated.

A large frequency scatter was found to exist among voices in all the groups. In 47 per cent of sounds intoned by children and in 44 per cent of sounds intoned by adults, the standard deviation exceeded a quarter-tone (Fig. 13a). In the children's groups there was the least variation in the fundamental component frequency of sounds with the mean pitch, close to the 440 Hz standard most often used in school education (Fig. 13b). Male voices were characterized by smaller standard deviation in frequency than that of female voices (Fig. 14).

Apart from the standard deviation, the characteristics of frequency variation should also account for the behaviour of this variation. This behaviour differs and is characteristic of different age groups. In the youngest age group the frequency is the most stabilized (unlike the amplitude level), and when changes occur, they are irregular (Fig. 15). In the intermediate age group changes of vibrato nature occur. This vibrato is spontaneous and not controlled by the intoning person [17]; it has no artistic significance. With the usual relatively short time over which a child keeps a sound in one breath, he or she is unable to form a stabilized vibrated interval. With the eldest children, in all the sounds there occurs vibration of the fundamental component frequency (Fig. 16). In adult voices, particularly female ones, the vibrato form is quite distinct in the behaviour or frequency variation, although these voices have not been trained professionally (Fig. 17).

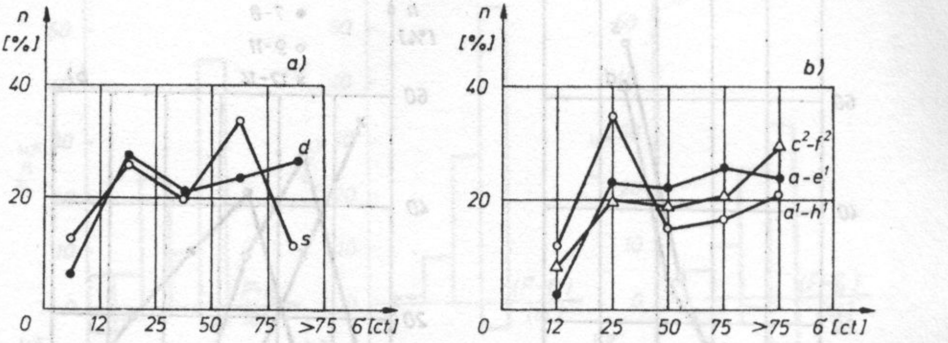

Fig. 13. The standard deviation of the fundamental component frequency (a) in children's (*d*) and adolescent (*s*) voices, (b) with consideration of the pitch of the sounds intoned

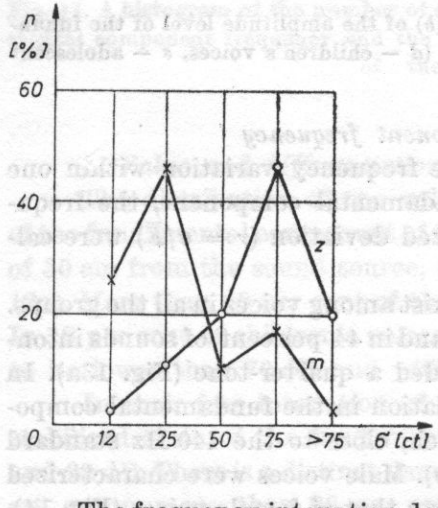

Fig. 14. The standard deviation of the fundamental component frequency in male (*m*) and female (*z*) adolescent voices

The frequency intonation deviation, measured by the normalised deviation (ν), usually takes values from 2 to 8 per cent (Fig. 18a).

The least regular distribution is characteristic of the lowest sounds (Fig. 18b). Low sounds are often difficult for the youngest children to intone. The distribution of the normalised deviation in children's voices is similar to those of the youngest and eldest groups of children (Fig. 19a), but its causes are different for the two groups. In the group of children 7-8 years old the great frequency variation within the stabilized state of the first fundamental component of a sound results from their inability to intone, i.e. from the uncertainty of

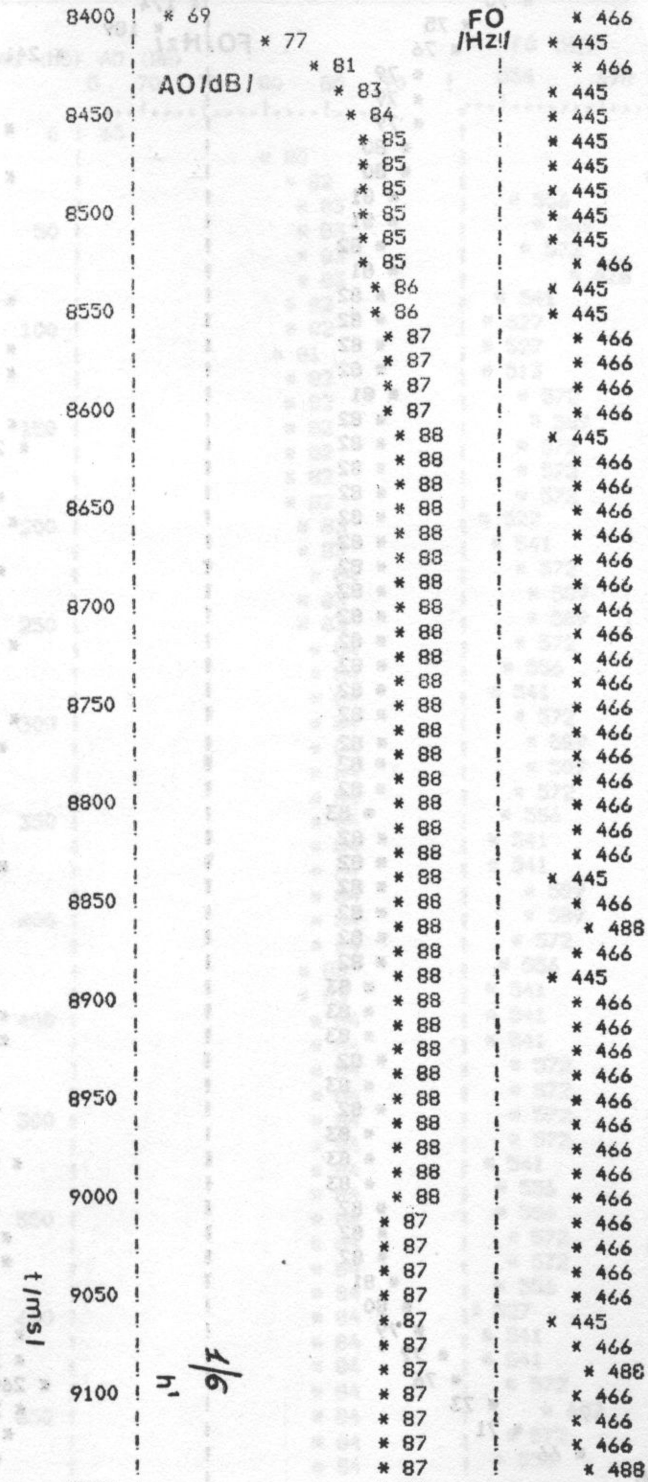

Fig. 15. The intonogram of the sound h^1 intoned by an 8-year-old child

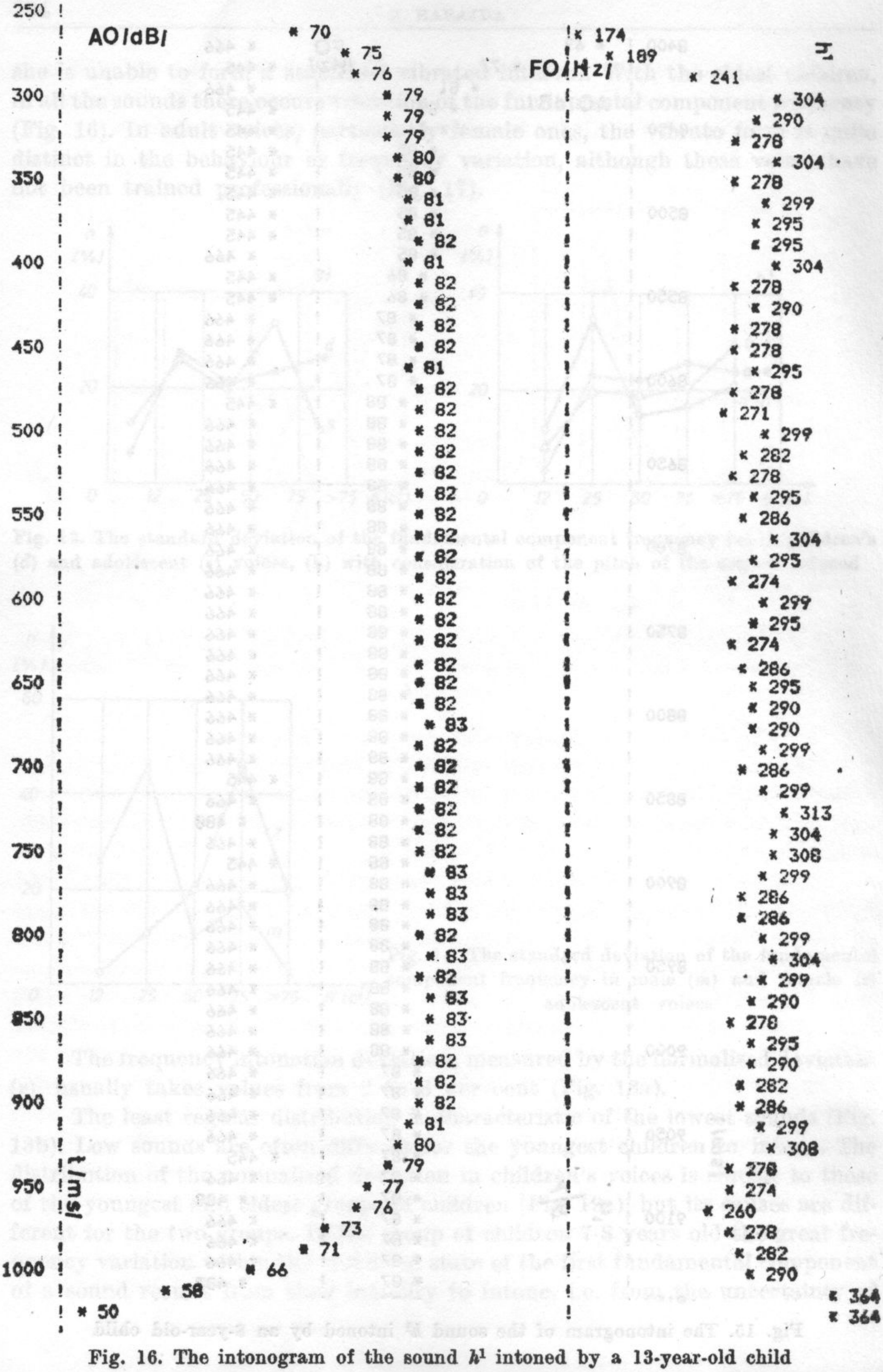

Fig. 16. The intonogram of the sound h^1 intoned by a 13-year-old child

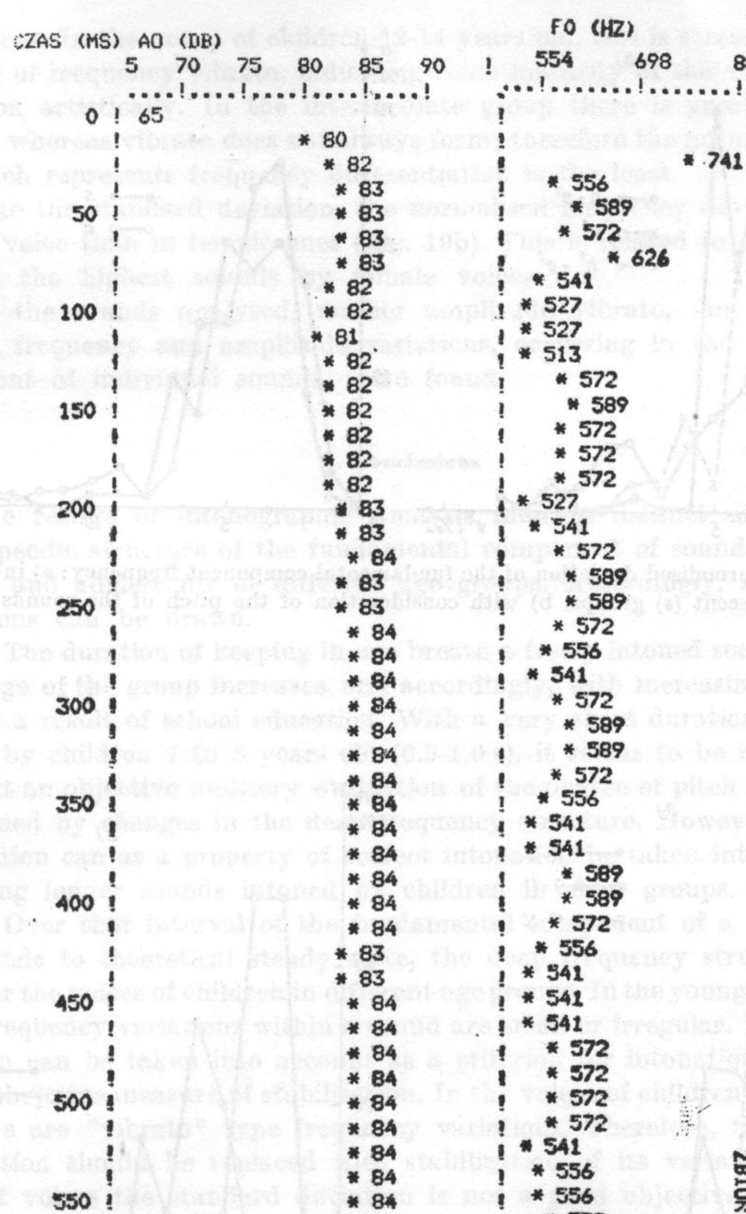

Fig. 17. The intonogram of the sound c^2 intoned by an adult (female adolescent voice)

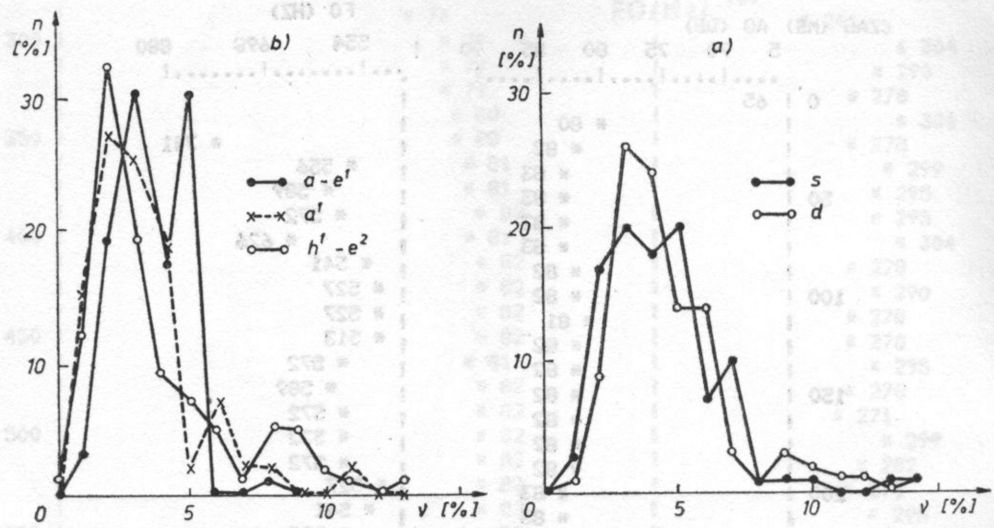

Fig. 18. The normalised deviation of the fundamental component frequency: a) in children's (*d*) and adolescent (*s*) groups, b) with consideration of the pitch of the sounds intoned

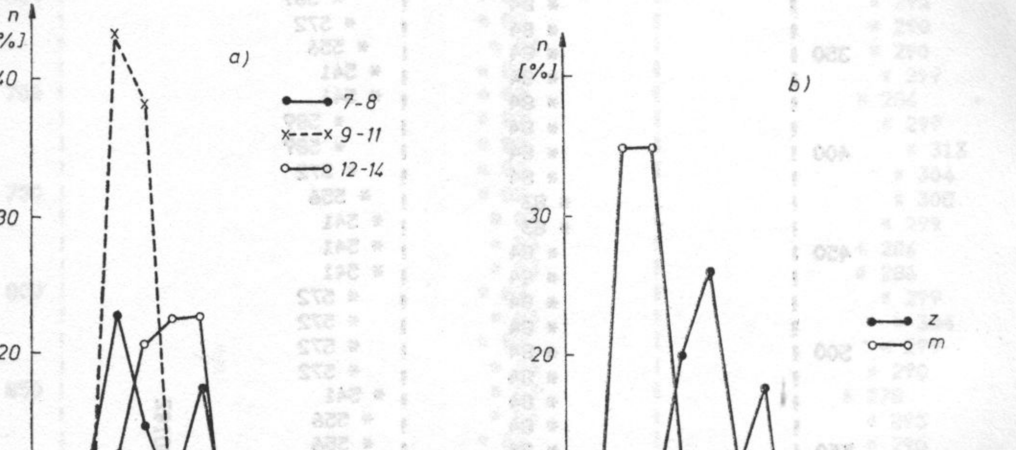

Fig. 19. The normalised deviation of the fundamental component frequency: a) with consideration of the age groups of the children, b) in male (*m*) and female (*z*) adolescent voices

their voices. In the group of children 12-14 years old, this is a result of the occurrence of frequency vibrato, indicating some maturity of the voice to shape intonation artistically. In the intermediate group there is greater certainty of voice, whereas vibrato does not always form; therefore the normalised deviation which represents frequency differentiation is the least.

Like the standard deviation, the normalised frequency deviation is less in male voice than in female ones (Fig. 19b). This is related to difficulties in intoning the highest sounds by female voices.

In the sounds analysed, neither amplitude vibrato, nor coincidences between frequency and amplitude variations, occurring in the fundamental component of individual sounds, were found.

5. Conclusions

The results of intonographic analysis indicate distinct differentiation in the specific structure of the fundamental component of sounds intoned by children and adolescents of different age groups. Accordingly, a number of conclusions can be drawn.

1. The duration of keeping in one breath a freely intoned sound increases as the age of the group increases, and accordingly, with increasing music abilities, as a result of school education. With a very short duration of a sound intoned by children 7 to 8 years old (0.5-1.0 s), it seems to be impossible to carry out an objective auditory evaluation of the degree of pitch stabilization, conditioned by changes in the deep frequency structure. However, the pitch stabilization can as a property of correct intonation be taken into account in evaluating longer sounds intoned by children in elder groups.

2. Over that interval of the fundamental component of a sound which corresponds to theoretical steady state, the deep frequency structure is different for the voices of children in different age groups. In the youngest children's voices frequency variations within a sound are small or irregular. The standard deviation can be taken into account as a criterion for intonation correctness and an obejctive measure of stabilization. In the voices of children 9 to 11 years old there are "vibrato" type frequency variations. Therefore, the frequency stabilization should be replaced with stabilization of its variation. For this group of voices the standard deviation is not a good objective criterion for pitch stabilization. In the voices of the eldest children and in adolescent voices changes in the fundamental component frequency show a distinct "vibrato" character. The problem of achieving a good objective criterion for the evaluation of the stabilization of such changes is related to the problem of evaluating the correctness of vibrato. As a criterion for the evaluation of the behaviour of frequency variations, the standard deviation is degraded to the role of one of a group of criteria for the evaluation of the stabilization degree of frequency behaviour.

3. In the voices investigated no "vibrato" type changes were found in the behaviour of the amplitude level, nor, as BJÖRKLUND [1] suggests, any changes in the regularity of the variation of its level.

4. The desired fundamental component frequency of a sound and its highest amplitude level are not achieved in the same time. The time of the frequency attack is usually shorter than the time of amplitude level stabilization. In children's voices, irrespective of a child's age, it is very short. In adolescent voices the time of the frequency attack is longer than in children's voices, but not so long as to permit the listener to grasp with his ear differences over that interval and to be assumed as the criterion for intonation correctness. Therefore, the conception mentioned by LESMAN [8], regarding bow instruments, that intonation should be corrected over the interval of the sound attack, does not seem to be useful in evaluating the correctness of attacking the pitch of vocal sounds.

However, the stabilization time of the amplitude level of the fundamental component, which is longer than the pitch attack time, justifies the taking into account of this parameter as one of criteria potentially useful in evaluating intonation correctness.

5. Calculations of the intonation deviation from the differences between the mean fundamental component frequency and the nominal standard frequency have shown that the frequency tends to increase in all the groups investigated, except the youngest. In 60 per cent of subjective auditory evaluations sounds of increased fundamental component frequency were estimated as completely or almost correct in terms of intonation clearness.

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