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ACOUSTIC-PHONETIC DESCRIPTION OF HEARING-IMPAIRED CHILDREN'S VOWELS IN POLISH*

The present paper is the first acoustic-phonetic analysis of Polish vowels producing by hearing-impaired students from the upper grades of elementary school. The group under examination was highly heterogeneous (aged 10…17). Nevertheless, many common features of vowel pronunciation among hearing-impaired speakers were found. The most significant phonetic processes are centralization (considerable reduction of articulatory movements of the tongue), nasalization in oral contexts and lack of voice pitch differentiation between girls and boys resulting from substantial vocal effort. The results were compared with data collected on the pronunciation of hearing adults and hearing nursery school students.

Preliminary assumptions

This article is one of a series of papers produced in the Department of Psycholinguistics, Adam Mickiewicz University, in recent years. Our goal is to provide an exact acoustic-phonetic description of the speech of school-age hearing-impaired children. The features of the speech should not be considered independently of all other means of communication available to the hearing-impaired. Those different means of communication include specific speech-processing mechanisms and possibilities of language production, either in the form of oral utterances or the use of so-called sign language. A separate problem is the development of phonological awareness during the process of reading and writing skill acquisition. It is common knowledge that, more and more frequently, hearing-impaired children begin to learn to read as early as the age of 2-3.

Despite the fact that speech is a difficult and not always effective means of communication for most hearing-impaired people and that substantial effort is required to master it, in most cases schools for hearing-impaired children in Poland offer the so-called 'oral method'. An alternative approach is 'cued speech' (Krakowiak, 1995;

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Leszka, 2000) which is far less popular. Strategies developed by speakers deprived of the important auditory feedback which reflect their efforts to use intelligible speech, differ significantly from the strategies developed by hearing children, especially as regards activating substitute procedures for receptive hearing functions. They are less effective at transmitting information to the central nervous system. Psychological factors should also be taken into consideration: some reluctance to communicate through speech is observed in hearing-impaired speakers as it poses a problem for them to control speech in the process of communication.

The fact that hearing-impaired speakers, who produce utterances in their native language, are judged bilingual by some researchers is particularly important from the viewpoint of our further considerations (Bryndal, 1998). Łobacz (2002) presented specific problems of bilingualism from three different research perspectives: language teaching, psycholinguistics and deaf speech therapy. She pointed out interactions between them. Most frequently, a deaf child learns to use speech as his/her second language. Although nowadays emphasis is laid on the fact that children start to learn to speak as early as possible, it is most often the case that it is at school where they first encounter the 'oral method'. Children's bilingualism is an important issue in the field of special pedagogy and rehabilitation of hearing-impaired children. Theoretical postulates suggested in numerous papers (e.g., Polish papers only: Perlin & Szczepankowski, 1991; Bryndal, 1998; Łobacz, 2002) depart significantly from reality due to the fact that sign language is mastered to differing extents by children in a given class, this being a consequence of a variety of social-educational factors. Fluency of speech is even more diversified as it is a product of a greater number of factors, such as the starting moment of learning to speak, the quality of speech therapy, the rehabilitation methods applied, motivation to use this means of communication, etc. (Cieszyńska, 2000). According to many experts, "Sign language is and will remain the basic means of communication of this group of handicapped (...). Thus, we can assume that this handicap determines hearing-impaired persons as a linguistic minority rather than a physically handicapped group of people. The hearing-impaired themselves do not want to be regarded as handicapped but as equal to hearing people, as a linguistic minority like the German or Ukrainian minorities..." (Szczepankowski, 1996, p. 83). It seems that recently the social sensitivity to the problems of minorities has been on the increase and that increasingly better methods of teaching speech are put into practice.

As to establishing a developmental norm for hearing-impaired children who use the vocal modality to communicate, it is important to consider the legitimacy of interpreting their speech development as 'delayed' speech development. In that case it would be necessary to study the analogies between speech development in hearing and hearing-impaired children. Nowadays, attempts are beeng made to find if there are any parallels between hearing and hearing-impaired children with regard to the stage of development of the phonological system in the course of ethnic language acquisition.

This paper presents an acoustic-phonetic report on vowel production by children with a profound hearing loss. A description from this perspective may be useful as a connection between audiological assessment and modern devices improving the teaching of speech to the hearing-impaired. From the point of view of the communicative function, in actual utterances it may appear not entirely correct to analyze vowels first. Consonants are used in ethnic languages to distinguish between meanings to a greater extent than vowels. Thus, most pronunciation mistakes result from incorrect consonant articulation. The choice of vowels for the present study was justified by the following circumstances:

1) earlier termination of the vowel acquisition process by children representing the so-called developmental norm,
2) simpler and more uniform research procedure, both as regards the choice of specific acoustic-phonetic parameters and ways of their interpretation,
3) preparation of the basis for the research on the prosodic structure of speech of the hearing-impaired which has been of interest for researchers in recent years because it is vowels that carry the phonetic features of stress, duration, and intonation.[1]

The acoustic analysis of speech of hearing-impaired children with a profound hearing loss presented in this study is confined to a description of Polish vowels. However, it offers an insight into neurophysiological strategies in the process of articulation and therefore enables a further description. A comparative analysis of the so-called standard pronunciation and the speech of hearing-impaired children may appear helpful in facilitating and improving speech development of this group of subjects. Among the aims of similar acoustic studies conducted over the world since the seventies or even earlier, is to help create an automatic feedback system which would facilitate practising speech by hearing-impaired people. The more we discover about the acoustic parameters of articulation of vowels, for example, about formant frequencies, formant bandwidths, formant amplitudes, and pitch, the easier it will be to create computer aids analyzing and at the same time improving the speech of hearing-impaired children. The four parameters mentioned above are rated among the most important features characterizing acoustic properties of vowels. Numeric values, especially the frequencies of the first two formants, constitute traditional vowel description in the form of the so-called acoustic vowel chart related to the articulatory vowel chart, i.e. the visualization of vowels on a plane which is used in phonetics to describe and classify vowels produced by any speaker when studying a person's idiolect, and to provide a description and classification of the vowel system of any language. The acoustic representation of the end product of articulation, i.e. the sound, allows us to complete the presentation and assessment of a person's verbal behavior. Objective physical sound parameters supplement the subjective perceptual representation. At the same time the analysis of distribution of particular vowels on the vowel chart provides a convenient instrument of comparison between the standard pronunciation and disordered speech. In this paper such a comparison is drawn between the results of acoustic analysis for hearing-impaired school-age children and hearing nursery school students.

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[1] A doctoral dissertation has only recently been done on the acoustic-phonetic analysis of selected consonant groups (fricatives, affricates and nasals) in the speech of profoundly hearing-impaired children (Kleśta, 2002). There is some Polish work concerning the melodic contours in the speech of deaf children (e.g., Sieńkowska, 1993; Karczewska et al., 2000; Sieńkowska et al., 2000).

Methodological issues

From a detailed analysis of methods applied in acoustic-phonetic studies describing speech of hearing-impaired people, a number of requirements can be postulated, viz. linguistic, formal, and technical ones that are necessary to ensure a correct interpretation of the results of the experiment. Methodologies applied in this field for other languages (e.g., Heidler, 1976; Monsen, 1976; Okalidou & Harris, 1999) also present some imperfections. However, on the basis of the suggestions made by researchers, an optimum research procedure can be established in terms of choice of speakers, test structure, and technical preparation of the material for analysis. The most important conditions are discussed below. Nevertheless, we must admit that it is difficult to meet all of them in a given experiment.

Selection of speakers

It is highly desirable that the group of people under examination should be homogeneous with respect to: age and (if need be) gender, the profundity of hearing loss, its duration, its etiology, the time of providing a subject with a hearing aid, the regularity of its usage, and finally, the period of rehabilitation and its intensity. It is assumed that the methods of working with each individual are to a large extent standardized. Moreover, it is important to establish the facts about possible speech disorders which appear irrespective of the hearing problems, and to collect essential information on past diseases, especially those which can have an effect on the future results of the test. Additionally, there is need to apply sufficiently uniform and clear-cut criteria concerning the overall cognitive development of each subject. This seems to be fulfilled by developmental research including IQ tests. It is also of concern to investigators to determine to what extent the subjects are bilingual (i.e. by assessing their fluency in sign language and establishing how often each language is used in everyday life) and which of the two languages is acquired, and which is learnt. Within the scope of social research, which is obviously crucial as well, comes information on: hearing/deaf parents (and siblings respectively), the quality of school-home co-operation, special educational needs, living in residential schools, etc.

The structure of the test

The construction of linguistic tests has also been brought up in many discussions. To date standardized and normalized tests for a full phonetic evaluation of deaf people's articulation have not been worked out for the Polish language.

Older traditional tests applicable to audiology often made use of nonsense words that appeared on lists which were phonetically balanced with respect to their segmental and syllabic structure. This guaranteed that the so-called vowel distinctiveness would be precisely determined. Present-day audiometric testing makes use of word lists (e.g., Demenko et al., 1996, Demenko and Pruszewicz, 2000). The exact specification of vowel distinctiveness is not possible on the basis of such tests. Nevertheless, what gives them undeniable advantage over other tests is the intelligibility of language signs. Research on intelligibility has shown the need for language material to be worked out taking into consideration the scale of difficulty, the length of the list of presented units, etc. A common methodological procedure is to carry out a pre-test.

Many of these postulates are also important in the case of articulation tests. Requirements which such tests should meet are of three kinds: (1) formal – for example, the knowledge of words and legibility of their grammatical form, (2) developmental – taking into consideration articulatory abilities appropriate to the age of subjects, (3) phonetic – there should be equal numbers of representations of all the phonemes, their typical phonotactic combinations; a list should also contain the phonemes' occurrence in appropriate places of word structure: in the initial, medial or final position (Krajna, 1997). The present abandonment of syllabic tests in research on the speech of hearing-impaired people is motivated by the factors mentioned above. The syllable is a portion of the acoustic signal that is too small to draw conclusions about a dynamic phenomenon, such as intersegmental coordination (Rothman, 1976; Waldstein and Baum, 1991; Okalidou and Harris, 1999). The developmental factor is taken care of in such research in different ways. For example, in a study by Lee, Potamianos, and Narayanan (1999) the subjects aged 5 and 6 produced the target words (for vowels) in isolation, whereas 7- to 17-year-old children produced the target words in carrier sentences; although uniformity of the linguistic material for all participants ought to be a crucial criterion.

Technical precautions

The fulfilment of specific technical conditions, including in particular: high signal-to-noise ratio, type of frequency characteristic and appropriate digital processing techniques, ensures the authenticity of the recorded signal without artifacts. A separate issue that remains is the correct phonetic interpretation of the acoustic measurements. It is quite difficult to interpret the distortion products that appear in the signal in the case of disordered speech. Some predictable phenomena like excessive aspiration and nasalization, changes that are by-products of slower speaking rate, etc. can be rather accidental in complicated cases.

Measurement of formant frequencies

The most frequent techniques used to analyze vowels of hearing-impaired speakers in the frequency domain are as follows – (1) determining parameters directly on the wide-band spectrograms (Lieberman and Blumstein, 1988), (2) detection of frequencies from the spectra by Discrete Fourier Transform (DFT) (e.g., Chen, 1995; Lee at al., 1999), (3) cepstral analysis (Angelocci, Kopp, and Holbrook, 1964), (4) Linear Predictive Coding analysis (LPC, e.g., Huber et al., 1999) and (5) the "chirp *z*" transform (e.g., Levitt, 1972). The diversity of implemented methods is not significantly dependent on laboratory equipment. The authors utilized several different methods striving for some effective solutions that would accommodate the peculiarities of this type of speech. The most prevalent abnormalities in the speech of hearing-impaired speakers are: high fundamental frequency (often exceeding 300 Hz) characteristic for the child's voice, stronger nasalization which introduces additional nasal formants with an antiresonance, shouted articulation/voice, excessive aspiration and hoarseness.

Deaf speech in the light of earlier acoustic-phonetic analyses

In all studies attention is drawn to the following issues: (1) the correctness of utterances (substitutions and omissions, errors in nasality, chanting), (2) specific voice features – the value of fundamental frequency, disturbances of phonation, the presence of shouting or whispering, the realization of certain suprasegmental features, (3) the formant structure of vowels – formant frequencies as a function of age and gender, coarticulatory modifications and the phenomenon of articulatory centralization.

The general nature of substitutions and elisions in the speech of hearing-impaired children is presented in depth in a separate work (Łobacz, 2000). From the viewpoint of the present paper, special interest centres on vowel substitutions related to: (1) a tendency towards neutralization – the substitute has more neutral (centralized) articulation than the target vowel and it is often difficult to associate it either auditorily or by measurements with any standard target – any vocalic element of a given language (Smith, 1975), (2) different interpretation of accessible perceptual cues by hearing-impaired speakers. The linguistic opposition: tense versus lax is of greater significance in the speech of deaf subjects (Monsen, 1974). Kurkowski (1996) found that Polish six-year-old children produced the vowel [u] most correctly while productions of [a] and [o] had lower levels of accuracy. In the rare cases when [u] was distorted, it was replaced by [o] or strongly nasalized [o] and once by [ɨ]. The sound [a] was most frequently replaced by [o] and [e] or by something halfway between [a] and [o].

Perceptual studies show that the identification of nasalized sounds is a more difficult task than the identification of oral sounds. This could be a factor contributing to overall poorer intelligibility noted in deaf people’s speech. A stronger nasalization, often observed in utterances produced by deaf subjects, is a result of insufficient control of the velum (Hudgins, 1934; in Chen, 1995). Two articulatory processes should be distinguished in nasalization by deaf speakers. One is related to normal coarticulation as the effect of the phonetic environment concerning oral vowels in the neighborhood of nasal consonants. This kind of stronger or weaker vowel nasalization occurs in most languages. What is typical of deaf speakers is the much stronger nasalization than usual in such contexts. It is auditorily noticeable mostly for vowels that involve a substantial opening of the vocal tract, e.g. [a] and [e]. In our data presented below, it was concluded from auditory examination that a strongly nasalized [a] appeared in about 20% of all contexts which allowed such a phenomenon. Strongly nasalized [e] occurred in about 10% of possible contextual situations. The second process of nasalization concerns oral vowels in the neighborhood of oral consonants and is peculiar to hearing-impaired speakers. The authors of the present paper as well as their fellow researchers claim, on the basis of the auditory results, that vowels [a] and [e] undergo such nasalization changes most frequently. It is similar to the data obtained for the process mentioned earlier. Both types of nasalization can be explained by physiological factors. Vowels articulated with relatively low position of the tongue enable the velum to lower and hence, to entirely open the nasal cavity. Vowels demanding high position of the tongue (e.g., [i], [u]) make impossible such strong lowering of the soft palate (Lieberman & Blumstein, 1988). It is interesting to note that nasal [ĩ, ũ] are relatively rare even in languages which distinguish nasal vowels as distinct phonemes (e.g., Wright, 1975). The inappropriate nasalization contributes not only to reduced intelligibility of utterances but also causes additional difficulties in the interpretation of the spectrum of individual sounds. This is reflected in the formant structure as a replacement of the sharp spectral peak of the first formant by two peaks: a weakened first formant and an extra peak developing around 910 Hz. The first formant bandwidth is wider than normally (Chen, 1995).

The phenomenon of chanting can be described from two points of view: (1) ways of stressing and (2) characteristic pauses between consecutive syllables and words in a phrase. According to Mikiel et al. (1979), the departure from usual phrase production appears in the form of chanting all words. The authors indicated that the pauses between words in running speech were in the range of 200-500 ms.

One of the most frequently noted features in hearing-impaired speech is a tendency to raise the voice frequency. This has been well-documented by many studies and detailed analyses. Angelocci et al. (1964) reported that in their study, for all vowels the mean fundamental frequency (F_0) for deaf children was higher by about 1.7 tones than for a corresponding group of normal-hearing subjects. Additionally, the means for fundamental frequency and amplitude for individual speakers were much more scattered for the deaf. The authors attempted to establish the cause of this phenomenon. According to them, a deaf child tries to achieve vowel diversity by changing F_0 and amplitude of the voice more than the formant frequency and its amplitude. In other words, minimal articulatory variations are aided by additional and excessive variations in the pharyngeal resonator to achieve satisfactory vowel differentiation. Levitt (1972), describing an utterance produced by a deaf ten-year-old boy, also points at a minimal movement of articulators as well. However, the author suggests that modulating mainly F_0 and intensity of the voice is an attempt to create the effect of initial and final consonants. Furthermore, Levitt stresses that F_0 is a variable for which a deaf child has some kinaesthetic feedback. Results of the study by Jones and Munhall (2000) suggest that the fundamental frequency is controlled by means of auditory feedback and with reference to an internal pitch representation. A hypothesis is advanced that the ability of F_0 control is the result of the acquisition of proper articulatory positions for the vowels because the tongue and jaw positions affect the position of the larynx and the tension of the vocal folds, and consequently the F_0 values (Whalen and Levitt, 1995; in Lee at al., 1999). Hearing children as young as age 5 exhibit vowel-dependent F_0 patterns. In keeping with this account is the idea that higher and more variable fundamental frequencies in vowels of deaf speakers are not only an attempt to differentiate between vowel quality but also a side effect of limited and insufficient control of articulatory gestures.

Many hearing-impaired subjects speak with maximum vocal effort and this means that F_0 is additionally raised. As a general rule, the high F_0 and the large concentration of energy in its range leads to the deformation of vowel-formant structure. The harmonics are widely spaced. The first formant generally becomes less prominent. Hence, even at the appropriate prediction order, the linear prediction analysis quite often does not yield an accurate estimation of the F1 value. The same difficulty sometimes appears also in case of normal-hearing speech. F_0 may be an obstacle to estimating F1 in vowels produced by children (Łobacz, 1996). The interference of F_0 is prominent in shouted utterances (Rostolland, 1982; Traunmüller, 1988; Traunmüller and Eriksson, 2000).

In the case of Polish speakers, there were a few studies that determined the average voice frequency of hearing-impaired children. According to Mikiel et al. (1979), the average fundamental frequency of the voices of ten 7- to 8-year-old children was 320 Hz. The participants (mostly boys) read simple sentences from a reading primer. The analogous value calculated for normally-hearing children, aged 3 to 7, was 273 Hz (Łobacz, 1996). This comparison confirms the conclusions drawn from other studies that deaf individuals tend to have higher pitch. A similar comparison was made for children aged 3 to 12. Over twenty parameters that characterize the larynx at work during the speech of deaf subjects and of normally-hearing controls were determined (Szkiełkowska et al., 2000). For two groups of children: (1) subjects with a minor hearing loss who used hearing aids and vocal communication every day and (2) profoundly deaf who did not wear hearing aids every day and mostly used signed modality, the respective average fundamental frequencies were 261 Hz and 265 while the average value of the fundamental frequency for the control group was 215 Hz which was significantly lower.

One of the more significant problems in an account of the mechanisms involved in vowel articulation by deaf subjects is centralization. It was mentioned above that a particularly strong centralization leads to substitutions. The weaker one leads to distorted articulation. In general, it is an articulatory phenomenon that consists in a tendency to maintain a mid position for opening and advancement in the supraglottal vocal tract. This means that high vowels are lowered, low vowels are raised, front vowels are retracted and back ones are advanced. This change of place of articulation entails a change of the sound's acoustic characteristics – viz. change of the first two formants. These frequencies are of the greatest importance for the vowel quality. On the whole, the value of the first formant is connected with the opposition open – close and the value of the second formant corresponds to the front – back distinction. As mentioned in §1, a graphic representation of the relationship between the first two formants is, using the appropriate scale, the traditional articulatory vowel chart in the form of a stylized quadrilateral. In the case of strongly centralized vowels in a given language, this figure is smaller. This means that vowels that are close to each other on the vocal chart are much less distinct auditorily.

The differences between the frequencies of the first two vowel formants in the speech of hearing and hearing-impaired children have been studied since the sixties of the last century (e.g. Angelocci et al., 1964). It was observed that English vowel areas overlapped to a much greater extent in the speech of hearing-impaired than of hearing children despite the fact that the average values of the first two formants were parallel for both groups of speakers. The most substantial deviations were noted for [æ] (also in: Holbrook & Fairbanks, 1962). According to Smith (1975) hearing-impaired children produce low central vowels most correctly (92% of correct productions of [ʌ]), and that there is a general tendency to articulate all vowels as more neutral. Heidler (1976) drew similar conclusions. For each German vowel the average deviation from 500 Hz and 1500 Hz was calculated (500 Hz and 1500 Hz are the values of the first and second formant respectively for the most central sound [ə]). For hearing subjects, the range of deviation was between 0 and 1450 Hz, while for the hearing-impaired the range narrowed to 0-650 Hz. The minimal values of the ranges (0 Hz and 50 Hz) are similar for both groups of speakers, which means that both hearing and hearing-impaired subjects produce strongly centralized vowels. However, the maximum deviation for the hearing-impaired (only 800 Hz) indicated a much smaller degree of decentralization. One of the most important discrepancies was observed for [i]. Butcher (1999) attributes the smaller diversification of vowel quality in disordered speech to a switch in vowel articulation in a direction other than towards the centre of the articulatory tract (it is most often the case that the articulation is raised, i.e. vowels are produced as less open).

Until now, few studies have focused on the coarticulation mechanisms in the speech of hearing-impaired speakers. Researchers analyzed mainly the modifications taking place in an isolated consonant-vowel syllable. The interaction of neighboring segments in the process of speaking is a very dynamic process, hence the analysis of simple, isolated syllables is not sufficient, especially as regards establishing the basic rules for normative speech synthesis. The effect of coarticulation on the acoustic properties of a vowel is related to changes of formant frequencies in time. It was observed that for undisordered speech the second formant is the most susceptible to contextual modifications in time. The tendency is much less obvious for hearing-impaired speakers. Unsteady states of this formant i.e., changes of frequency in time are more flattened for hearing-impaired subjects and the changes in frequency are smaller than for hearing people (Monsen, 1976; Rothman, 1976; Heidler, 1976). This, according to the researchers, proves weaker coarticulation in the speech of people with a substantial hearing loss. Nittrouer et al. (1989) presented an opposite interpretation of this phenomenon: "(...) deaf speakers coarticulate more than hearing, because flat, and sometimes shorter, formant transitions in CV sequences can also occur when most of the anticipatory lingual movement of the vowel gesture takes place during the consonant closure preceding the vowel" (1989, p. 120-132).

Okalidou and Harris (1999) studied the frequencies of the second formant in disyllables (ə # CVC) minimally contrasting in vocalic ([i], [u], [ɑ]) and consonant ([b], [d]) context and observed that in hearing-impaired speakers consonants had a smaller effect on the target of the stressed vowel. The effects of the consonantal context were weaker and less consistent even when the rate of speech was accelerated. According to the authors, the reduced consonant - vowel coarticulation in the speech of hearing-impaired subjects is a result of a smaller differentiation of articulatory movements. Tongue movements are less precise, slower, flatter, and severely reduced for the whole consonant - vowel sequence. It appears difficult for the hearing-impaired to control the movements of the independent articulators (mouth and tongue), and their components such as the tip of the tongue, mediodorsum, postdorsum. The decreased precision of consonant production is compensated by increased precision of vowel production.

On the other hand, it is worth emphasizing that Okalidou and Harris (1999) modified the controversial thesis about the consistently reduced coarticulation shown by deaf speakers. In their study, the stressed vowel influenced a preceding [ə] in alveolar context more strongly in the speech of deaf speakers.

Gender	Age groups							
	10	11	12	13	14	15	16	17
Male	2	2	3	7	1	4	1	1
Female	2	1	4	4	2	3	-	-
Total	4	3	7	11	3	7	1	1

Table 1. Distribution of speakers by age (in years) and gender

It follows from the short review of literature presented here that some issues deserve special consideration when studying the vowel-articulation features that are characteristic of the hearing-impaired. These are: the vowel-formant structure being a reflection of vowel quality, the correct production of voicing and the effect of consonant neighborhood (coarticulation).

The experiment

The previous chapter presented some methodological difficulties and a number of requirements to fulfil during the acoustic-phonetic study on the speech of hearing-impaired people. The methodology of the present study departs from the model one in many respects, especially regarding the selection of speakers and linguistic material.

Subjects

37 children from six different forms (from the 3rd to the 8th form) of the same Polish school for hearing-impaired children participated as speakers in the study. There were 21 boys and 16 girls in the age range of 10 to 17 years (see Table 1). The children were selected by the headmistress to meet our expectations concerning their reading skills and their abilities to do the test. Children of different ages were taught together in each class. However, there were divisions in the forms 4 and 5 in order to teach separately pupils of very different levels of skills and achievements in speech therapy. All children presented profound hearing loss/deafness. For the substantial majority of subjects the degree of hearing loss did not change from the beginning of educational training; it deteriorated for 4 children and slightly improved for 2.

The group of children under examination is also heterogeneous as regards the etiology of hearing loss. Furthermore, the school did not always have complete documentation in this respect. It was hereditary deafness in five cases, the result of maternal rubella in 3 cases. It was impossible to trace the cause for 5 students, and for 6 it was diagnosed that the impairment was acquired as a result of: drugs, meningitis, premature delivery and hydrocephalus. It was impossible to unambiguously establish the cause of hearing loss for roughly half the students. Even greater difficulties emerged determining the onset of deafness (at least for part of the subjects). Hearing loss from birth was diagnozed for 22 children. It was discovered for 8 children in the first month of life, for 6 others over a period of the first twelve months, and only for one subject aged three.

The group was also heterogeneous as regards the time of providing the child with hearing aids. It was only possible to ascertain that no child had a hearing aid in the first year of life, 3 children used it from the second year, 8 children started to use it during the third year, 8 in the fourth, 8 in the fifth year, 19 as 6-year-olds, and one older than 7 years. If the so-called zero age is assumed to be (among other things) the beginning of fairly regular wearing of hearing aids, then it will be significantly lower than the biological age. It will drop from the range of 10 to 17 years to the range of 3 to 11 years (this is the age when children attend nursery and primary school, Kurkowski, 1996; Łobacz, 2002).

A rehabilitation program was realized variously for the individual subjects. Three attended a playgroup for the hearing-impaired for at least one year, eight children were in constant phoniatric care that lasted 1-3 years and 12 children attended speech therapy fairly regularly.

The children differed in the time spent in the present school for the hearing-impaired. This had an effect not only on their diversity as regards general cognitive development but also on the fluency of their first language – sign language for most of them (Polish Sign Language). In the teachers' opinion, somewhat less than half of the group under examination reached intermediate level of sign language, a dozen or so children were still learning sign language, including 9 pupils who knew it at elementary level, and 3 children did not use this language at all.

The group appeared to be less diversified as regards the family background factor. Only 5 children had deaf parents. Children who had hearing siblings were in the majority – 28 subjects, 7 children had hearing-impaired siblings, 4 speakers had hearing siblings as well as deaf ones and 3 were only children.

It is shown above that the group in our study was heterogeneous in many respects. This was reflected in the general assessment of their speech intelligibility. Kleśta (2002) found that the average speech intelligibility of all the children, established on the basis of a word test, varied from 5 to 55% with an average of 21%. A word test, which is described in detail below, is (from the speech intelligibility point of view) a more strict criterion than a sentence test or than auditory evaluation of spontaneous speech samples. Nevertheless, the result should be regarded as rather low. The present analysis is cross-sectional and the choice of speakers reflects authentic school reality – substantial diversity among children with respect to speaking abilities occurring in the same class.

The selection of linguistic material and recordings

Selection of material was made according to the suggestions of the educators at a school for hearing-impaired children. After consultations, a 40-word test by Golanowska was selected. The test was originally designed to study the pronunciation of 2-3 year-old children[2] An articulatory test as a naming test assumes a certain active vocabulary and adequate general knowledge. For the purpose of the present examination of hearing-impaired children, the test was specially normalized. The manner of asking questions was revised to suit the children's age, the school reality, etc. All words occurring in the test (excluding two onomatopoeias: [hawhaw] and [mjawmjaw]) belong to the active vocabulary of nursery school students which was established on the basis of

[2] Golanowska's word test has not yet been published.

VOWEL	PRECEDING CONTEXT	FOLLOWING CONTEXT
[i]	**m**, g, z	ɕ, t, **c**
[ɨ]	**m**, r, ʧ	j, b, t
[e]	s, l, ɕ	r, f, **ʥ**
[a]	t, ʒ, ʃ	t, b, f
[o]	v, f, k	d, t, t
[u]	**z**, ts, w	p, **c**, ʃ

Table 2. Consonantal contexts of the analyzed vowels. The contexts strongly modifying the first and the second vowel formant in Polish are printed in bold

the frequency lists by Zgółkowa and Bułczyńska (1987). The word list used in the test was as follows: *nie* [ɲe], *mama, tata, dom, woda, biały* [bjawɨ], *siedzi* [ɕed͡ʑi], *misie* [miɕe], *pociągi* [pot͡ɕoŋɟi], *pies* [pjes], *cukierki* [t͡sucerci], *czyta* [t͡ʃɨta], *łóżko* [wuʃko], *zielony* [ʑelonɨ], *ryba, lew* [lef], *czapka* [t͡ʃapka], *ziemia* [ʑemja], *myje się* [mɨjeɕe], *kot, buzia* [buʑa], *zupa, jedzenie* [jed͡zeɲe], *dziura* [d͡ʑura], *nos, oczy* [ot͡ʃɨ], *szafa* [ʃafa], *żaba* [ʒaba], *guziki* [guʑici], *hauhau* [xawxaw], *język* [jẽzɨk], *wąsy* [võsɨ], *fotel, dzwonek* [d͡zvonek], *ciasto* [t͡ɕasto], *ser, fartuszek* [fartuʃek], *kieszeń* [ceʃeɲ], *gitara* [ɟitara], *miaumiau* [mjawmjaw]. The test was a picture-naming one. The picture form secures higher degree of naturalness of the answer but carries the risk of no reaction. Apart from the naming test, all the hearing-impaired children were asked to read the words relating to the pictures. In the course of the construction of the articulatory test much more attention was paid to the selection of consonants than to the contextual balancing of vowels which was in keeping with its purpose to examine the speech of 2 to 3-year-old children.

The recordings were made in a school speech therapy office. The children attended the sessions separately, always in the presence of two experimenters. One person showed the test to a child (the successive pictures or the word list), the other person was responsible for the technical quality of the recording. The experiment procedure (i.e. the order of the test, the word order on the list and the order of the pictures, the set of questions and explanations) was uniform (the test was standardized). The experimenters used only speech – the children read from their lips. It occurred occasionally that the children used sign language, but only in cases when they did not know the answer in spoken language. The recordings were carried out during one meeting for each speaker. Additional meetings were not held despite the fact that children failed to produce some words. High quality of the recordings was achieved by using a SHURE SM 48 microphone and a Panasonic DAT. The recorded data were transferred to a computer with a sampling frequency of 20 kHz.

In the present experiment, the method of ‘voluntary extracting’ was used to elicit spontaneous one-word utterances. Occasionally, the imitation method was applied (a hearing-impaired child read from lips). As regards the naming test (guessing the objects or situations represented in pictures), no child managed to give all the answers. Knowledge of particular words varied for the hearing-impaired children examined. For some of them, the words that were subject of exercise in the earlier grades at school (e.g. *guziki* 'buttons') were missing from the so-called active vocabulary or the children failed to recall the appropriate name at the moment of the test.

18 words were selected out of 40 words recorded by all children, such that each of the 6 Polish oral vowels ([i, ɨ, e, a, o, u]) occurred in three different consonantal contexts. The choice of words for further analysis was based on four further postulates:

1) the target vowel should occur in stressed syllables – mostly word initial,
2) in view of the location of stress in Polish, the words must be at least two syllables long to avoid stressed word final position,
3) the consonantal context should not significantly affect the vowel quality (it is advisable to avoid palatal and nasal contexts),
4) the words for which the smallest number of missing items occurred should be analyzed first.

Finally, the following words were selected for further analysis: *tata, misie, cukierki, ser, zupa, woda, kot, lew, żaba, ryba, szafa, łóżko, fotel, myje się, guziki, gitara, siedzi,* and *czyta* (*'daddy, teddy-bears, candies, cheese, soup, water, cat, lion, frog, fish, wardrobe, bed, armchair, he is having a wash, buttons, guitar, he is sitting'*, and *'he is reading').* Table 2 shows the preceding and following contexts of the target vowels.

In the reading test all target vowel productions were elicited, whereas in the naming test the largest number of missing items concerned the vowel [i]. The original test did not include many words containing this vowel. Moreover, [i] occurred in words which were not familiar to the children, like for example *gitara* (the instrument was physically accessible to the children in their school dormitory but it did not appear in textbooks for hearing-impaired children). All in all, 28 items were found missing for this word in the recorded data. For the word *guziki* (see above) 26 items were missed. The verb *czyta* also appeared difficult for the hearing-impaired children (verbs generally pose more problems than nouns in naming tests).

Results

Estimating acoustic-phonetic parameters

Vowel formant frequencies were estimated using the Computerized Speech Lab (CSL50) of Kay Elemetrics. There were 1998 measurements in all for the reading test (37 speakers x 18 words x 3 measurements)[3] and 1707 measurements for the naming test. In the case of the naming test, the smaller data size was due to the fact that talkers failed to produce some words. In order to yield reliable results, the following procedure was used:

(1) a dynamic spectrogram of each utterance, aided by listening to the recorded signal, was analyzed to choose relatively steady state fragments of each phone; then, a 16^{th}-order linear-prediction analysis was carried out at three points at 15-ms intervals to obtain the first four formant frequencies and the appropriate bandwidths,

[3] Three observations should be subtracted from the total because of elision of a vowel in one word.

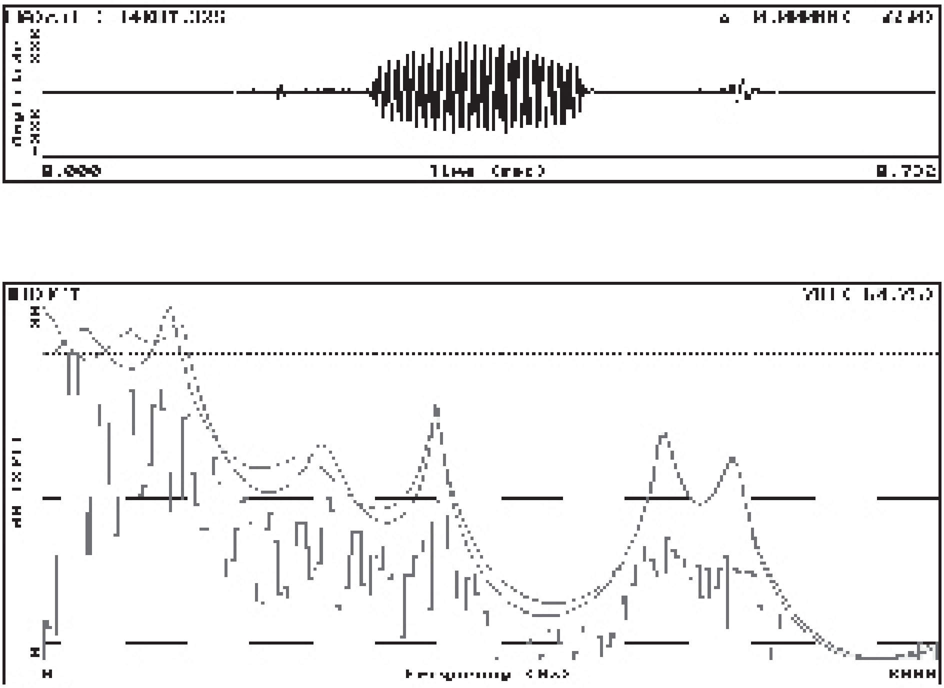

Figure 1. 16th-order LPC, 20th-order, and FFT for vowel [o] in the word *kot* (‘cat’)

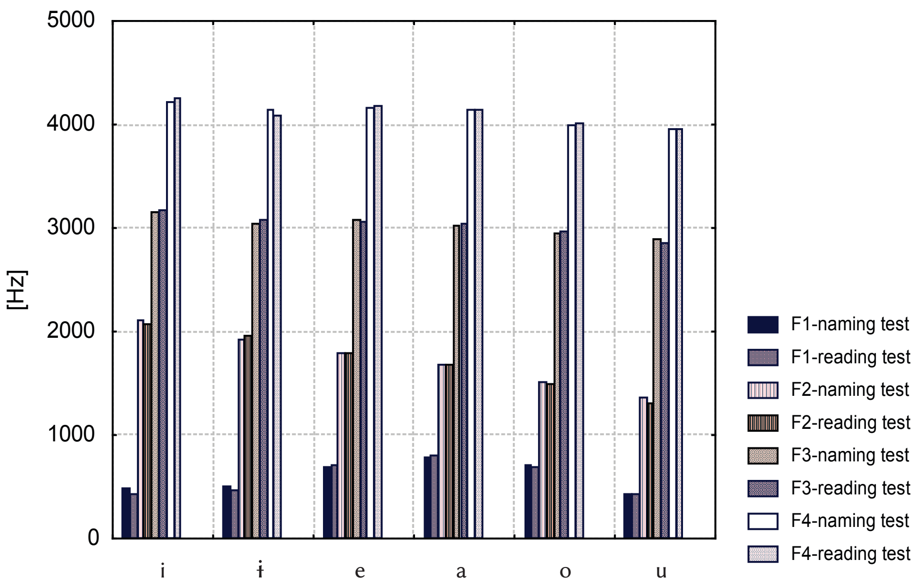

Figure 2. The mean values of F1, F2, F3 and F4 (for all 37 speakers) – the reading test compared to the naming test

MAIN EFFECTS	F	LEVEL OF SIGNIFICANCE
1	55.8	0.001
2	5.9	0.001
1 × 2	1.2	n.s.

Table 3. Analysis of variance 1 – vowel, 2 – age (by year), 1×2 – interaction of both factors for F1 values of Polish vowels produced by hearing-impaired children

MAIN EFFECTS	F	LEVEL OF SIGNIFICANCE
1	57.5	0.001
2	5.4	0.001
1 × 2	2.7	0.001

Table 4. Analysis of variance (1 – vowel, 2 – age (by year), 1×2 – interaction of both factors) for F2 values of Polish vowels produced by hearing-impaired children

(2) numerical data (obtained automatically) were evaluated by comparing the 3 measurements for a given vowel in order to estimate the correlation between formant frequencies and their bandwidths because the wider the formant bandwidth the lower the formant energy and the probability of a characteristic peak appearing for a given vowel is reduced,

(3) in doubtful cases an LPC analysis of higher order (coefficient 20) was performed together with fast Fourier transform (FFT) analysis.

Figure 1 shows the waveform of the word *kot* (*cat*) spoken by a girl from the 6th form and, below, three methods of the frequency domain analysis of the vowel [o] (at the point marked by a cursor on the top image). The "smoother" line was derived by the 16th-order LPC, the more "wriggled" line was derived by the 20th-order LPC. The line beneath it is fast Fourier transform. This example illustrates how an actual location of F1 peak in the [o] is estimated on the frequency scale. Vowel nasalization not always motivated by the context, was considered as a serious obstacle in evaluations because of frequent additional energy reinforcements (spectral peaks) that merged with the regular formants reflecting the quality of the vowels. In such cases, several measurement techniques were also applied and only consistent results were taken into further consideration.

Statistical analysis

The statistical analysis, using the CSS: Statistica software package, was carried out for the following factors: age (both biological and linguistic), gender, and for factors resulting from the structure of linguistic material such as the type of the test (reading or naming) and the effect of consonant context. All results presented below in the tables and in the figures are given for the first four (or the first two) mean vowel formant frequencies.

MAIN EFFECTS	F	LEVEL OF SIGNIFICANCE
1	55.1	0.001
2	7.8	0.001
1 × 2	0.8	n.s.

Table 5. Analysis of variance (1 – vowel, 2 – linguistic age, 1×2 – interaction of both factors) for F1 values of Polish vowels produced by hearing-impaired children

MAIN EFFECTS	F	LEVEL OF SIGNIFICANCE
1	56.1	0.001
2	2.6	0.001
1 × 2	1.9	0.001

Table 6. Analysis of variance (1 – vowel, 2 – linguistic age, 1×2 – interaction of both factors) for F2 values of Polish vowels produced by hearing-impaired children

FORMANT [Hz]	children	[i]	[ɨ]	[e]	[a]	[o]	[u]
F1	younger	418	467	719	845	684	417
	older	461	465	692	737	682	438
F2	younger	2122	1981	1803	1660	1460	1263
	older	1987	1941	1738	1701	1550	1428
F3	younger	3215	3154	3117	3121	3008	2898
	older	3090	2902	2946	2864	2882	2780
F4	younger	4304	4154	4195	4163	4023	3975
	older	4144	3965	4157	4078	3989	3926

Table 7. Mean F1, F2, F3, and F4 values for the vowels in the speech of hearing-impaired children for two age groups – the reading test

FORMANT [Hz]	children	[i]	[ɨ]	[e]	[a]	[o]	[u]
F1	younger	489	504	697	800	637	441
	older	485	519	680	760	718	412
F2	younger	2146	1950	1814	1676	1498	1322
	older	2044	1911	1751	1680	1544	1406
F3	younger	3193	3111	3147	3045	2963	2941
	older	3037	2934	2929	2985	2912	2804
F4	younger	4223	4172	4165	4120	3977	3968
	older	4140	4066	4154	4173	4000	3929

Table 8. Mean F1, F2, F3, and F4 values for the vowels in the speech of hearing-impaired children for two age groups – the naming test

Type of test

As mentioned above the group of school children under examination in this study was heterogeneous in many respects, also as regards their reading abilities. Hearing-impaired children who were well rehabilitated started learning to read much earlier than normally-hearing children. At school all the children read a lot. They used their textbooks while doing their homework. Moreover, there were many captions in classrooms prompting the children while they were speaking. On the other hand, the children preferred signing to speaking during the breaks and out of school (e.g., in the residences). It was therefore assumed that all these factors may result in differences between the quality of read and spoken utterances in favour of spoken productions and this may refer to the vowel articulation. The mean formant frequencies of individual vowels for the whole subject group with respect to the type of test are shown in Fig. 2. It can be concluded that differences between the values of the factors under comparison were slight. The greatest differences were noted for F1 of the two highest vowels: [i] and [ɨ]. However, they are not significant because they come to about 10% of the average formant frequencies for these vowels. That means that the subjects' greater skill at reading than at spontaneous speaking (manifesting itself even in lexical difficulties) did not have any significant effect on the phonetic shape of their utterances. Since, as shown above, the differences between the types of test were not significant, we shall more often be referring to the reading test as it included all compared data. Nevertheless, for some factors (e.g. age), the naming test will be also taken into consideration.

Age

As mentioned earlier, the biological age of the subjects was in the range of 10-17 years and the individual age groups were not of equal size (see Table 1). A two-way analysis of variance (ANOVA) was carried out to find whether the age of children (divided into year groups) had a significant effect on formant frequencies (F1 and F2). The results are shown in Tables 3 and 4.

The ANOVA made for the main vowel – age effects for successive age groups showed statistical significance of the age factor at a probability level of 0,1%. In the case of F1, the interaction between age and vowel was not significant.

An analysis of variance was also carried out for the effects (1) vowel, (2) linguistic age (after the so-called 'zero age' correction for individual speakers). The values of F and the level of significance are included in Tables 5. and 6. The effect of age on both F1 and F2 was significant. For F2, the interaction between the two factors was also significant. These results are similar to those for the age effect in groups divided into years. However, the F ratio is higher for the linguistic age for F1 and is lower for F2 (in the latter, the level of significance is higher for the effect of linguistic age) and for the interaction between the factors for F2.

The subject group was divided into two sub-groups: younger subjects in the range of 10 to 13 years (67% of speakers) and older 14 to 17-year-old subjects (33% of speakers), so as to increase the clarity of the results. This division was motivated mainly by developmental but also by practical factors. Most of the children were 13 years old. They were rated among younger children in order to have children show-

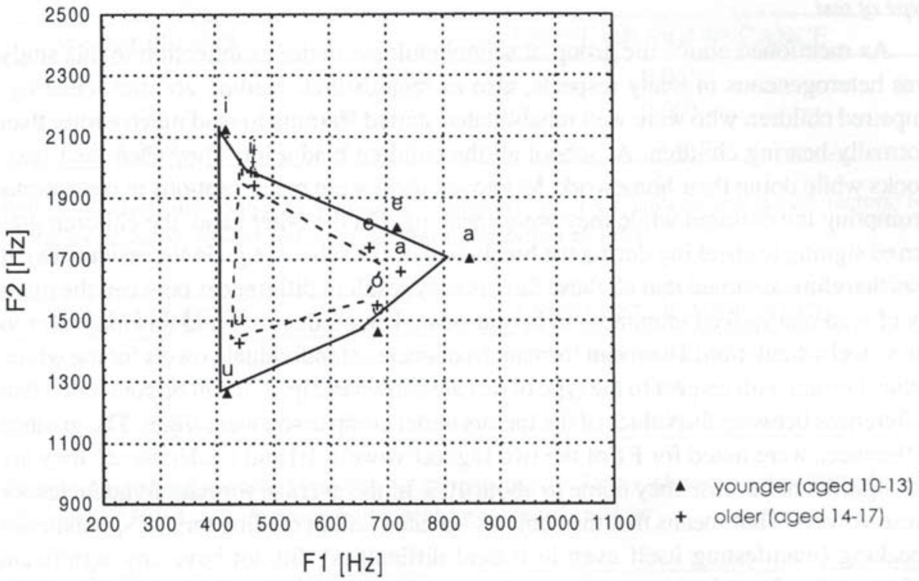

Figure 3. The vowels in the F1×F2 plane for two age groups of hearing-impaired children – the reading test

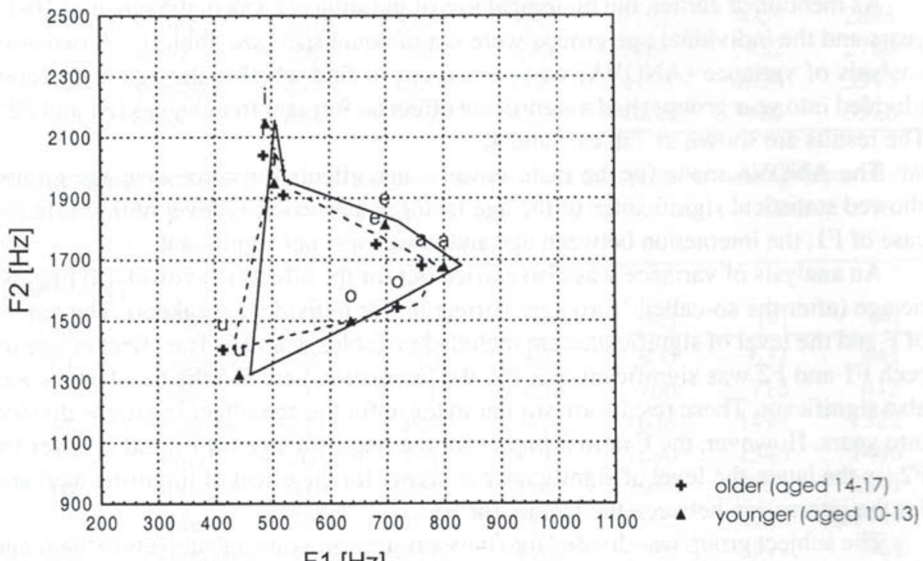

Figure 4. The vowels in the F1×F2 plane for two age groups of hearing-impaired children – the naming test

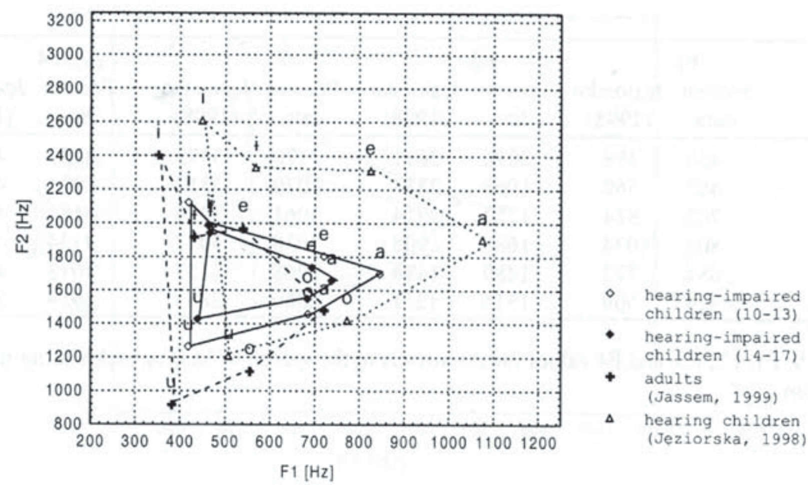

Figure 5. The vowels in the F1×F2 plane for hearing-impaired children, hearing children (Jęziorska, 1998), and hearing adults (Jassem, 1999)

ing a vocal tract comparable with mature speakers and boys at least at the stage when voice break usually starts in the older group.

Tables 7 and 8 show the mean values of vowel formants for the reading test and the naming test respectively. In the reading test (see Table 7) the means for F1 for the younger children are slightly higher than those for the older children in vowels [ɨ], [e], [a], [o], and lower in [i], [u], but the differences are not significant (40 Hz at most).

Mean F2 values are lower for the older children than for the younger in the vowels [i], [ɨ], [e] (by about 100 Hz), and higher in the low vowels [a], [o], [u] (40–160 Hz). These differences in F2 are the reason why the vowel chart for the 14 to 17-year-old hearing-impaired children is more compact, and it is inside the analogous figure for the children aged 10-13 (which is presented in Fig. 2). As to F3 and F4 values, they are lower for all vowels in the utterances produced by the older children by 200 Hz on average (in the reading test).

In the naming test (Table 8) the mean F1 values are higher for the younger children in vowels: [i], [e], [a], [u] by 40 Hz at most, and lower than for the older children in [ɨ] and [u] by 15 Hz and 80 Hz respectively. As in the reading test, these differences are not significant. Mean F2 values in this test are higher by 40-100 Hz for the younger speakers than for the older in vowels [i], [ɨ], [e]. They are lower for the younger age group in vowels [a], [o], [u] by about 85 Hz at most, which was also observed in the reading test. Although the differences in F2 between the two age groups are less significant here, the vowel plane for the older children (Figure 4) is still inside the plane for the younger speakers (apart from [u], which has a lower F1 value).

Figures 3 and 4 show that the location of points in the vowel charts in the F1×F2 plane for the naming test and the reading test differ mainly with respect to F1 values. In the naming test F1 [i] for the younger children (Fig. 4) is by 70 Hz higher, which brings it close to F1 for the older children for both types of test. In the same graph F1

	F1		F2		F3		F4	
	Present data	Jęziorska (1998)	Present data	Jęziorska (1998)	Present data	Jęziorska (1998)	Present data	Jęziorska (1998)
[i]	430	498	2078	2611	3176	3373	4251	4214
[ɨ]	467	569	1968	2333	3070	3312	4093	4211
[e]	702	824	1782	2314	3061	3259	4183	4124
[a]	804	1074	1688	1905	3038	3057	4134	4015
[o]	684	772	1489	1424	2968	3157	4013	4089
[u]	424	509	1315	1211	2860	2884	3959	3977

Table 9. F1, F2, F3, and F4 values for the vowels in the speech of hearing and hearing-impaired children

Formant	Gender	[i]	[ɨ]	[e]	[a]	[o]	[u]
F1	F	433	462	713	848	694	439
	M	430	470	692	769	675	412
F2	F	2119	2070	1831	1716	1462	1329
	M	2048	1889	1743	1666	1509	1304
F3	F	3174	3142	3118	3114	2993	2861
	M	3176	3014	3018	2978	2948	2859
F4	F	4218	4093	4234	4179	4054	3965
	M	4275	4093	4143	4101	3979	3954

Table 10. Mean Polish vowel F1, F2, F3, and F4 frequencies split for gender (F – girls, M – boys) in the hearing-impaired children's speech – the reading test

MAIN EFFECTS	F	LEVEL OF SIGNIFICANCE
1	1.68	n.s.
2	87.58	0.001
1 × 2	0.61	n.s.

Table 11. Analysis of variance (1 – gender, 2 – vowel, 1×2 – interaction) for F1 values of Polish vowels in the hearing impaired speech

MAIN EFFECTS	F	LEVEL OF SIGNIFICANCE
1	6.08	n.s.
2	96.91	0.001
1 × 2	1.64	n.s.

Table 12. Analysis of variance (1 – gender, 2 – vowel, 1×2 – interaction) for F2 values of Polish vowels in the hearing impaired speech

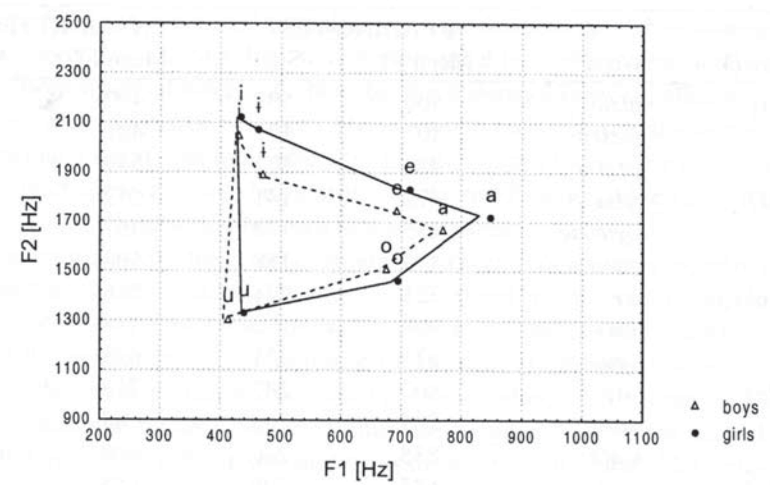

Figure 6. Average F1/F2 values separately for each gender – the reading test

[a] for the younger speakers is lower by 45 Hz and for the older it is a little higher, which also brings closer the points representing the two age groups. Two important factors affecting the location of points on the graphs under discussion should be emphasized: (a) the numbers of speakers in the two age groups were not equal and (b) there were less data in the naming test.

Figure 5 shows mean F1 and F2 values for Polish vowels in the speech of hearing-impaired children (present data), hearing children (Jęziorska, 1998), and in the speech of adult speakers (Jassem, 1999). The deviations from the adult norm concerns raising the frequency of the first two formants for all the six Polish vowels, though in different degrees for each of them. This tendency is related to higher voice frequency typical of children. The greatest deviation from the adult norm occurs for [a]. F1 is higher by about 370 Hz (51%) for nursery school pupils, and F2 is raised by 481 Hz (32%). On average, formants in the speech of small children are higher by 20%-30% than in the speech of adult male and female speakers (Peterson and Barney, 1952; Huber et. al., 1999). The most significant increase was noted for the most open and neutral articulation. Lieberman (1980) reported similar observations for 3-year-old American children. In the case of the remaining vowels the raising of the first two formants did not exceed 26% on average, and slightly exceeded the established norm. The 6% difference may be due to the fact that the methods of analysis applied in both of the studies were quite different (the two papers were published 50 years apart).

The data for the graph for the hearing-impaired children (Fig.5) comes from the reading test. Taking into consideration the information mentioned above, the experimenters anticipated vowel centralization which is reflected in the restricted size of the plane of the F1×F2 graph approximating the mean values. It was assumed that extreme articulation (high front and high back) presents much more difficulty in the case of deaf speakers. This hypothesis was only partially confirmed. The subjects' age in this experiment was quite high, thus the pitch of their voices was lower (especially in the

		READING TEST		NAMING TEST	
Vowel	Word	Mean F1	S.D.	Mean F2	S.D.
[i]	*misie*	460	192	490	218
	guziki	407	127	401	97
	gitara	425	121	549	281
[ɨ]	*ryba*	472	141	552	169
	myje się	455	172	457	100
	czyta	473	158	508	140
[e]	*ser*	721	221	736	198
	lew	738	172	718	224
	siedzi	671	221	613	199
[a]	*tata*	802	247	776	268
	żaba	786	250	788	254
	szafa	838	246	800	218
[o]	*wodą*	685	206	655	186
	kot	704	198	751	179
	fotel	660	194	715	192
[u]	*cukierki*	405	98	419	103
	zupa	435	114	444	106
	łóżko	431	145	426	99

Table 13. Mean F1 and F2 values and standard deviations for Polish vowels in the speech of hearing-impaired children as affected by neighboring consonants

older age group). That is why, despite the assumed centralization, individual formant frequency values were expected to be similar to those for adult speakers (Huber et. al., 1999). This was confirmed only with reference to the normatively centralized front vowel [ɨ]. As to the rest of the vowels, the following relationships were observed: F1 [i] was compatible with the norm for children. F2 (reflecting tongue advancement) shows centralization. The articulation of [e] by younger hearing-impaired children was centralized. A disproportionately larger raising of F1 frequency appeared to be a characteristic feature of this vowel in the pronunciation of the older children. A similar phenomenon was noted for the articulation of [a] by the same age group. The vowels [o, u] are consistent with the developmental norm for nursery school children.

Gender

The subject group was not evenly balanced as regards to gender. Boys made up 57% of the test group and girls 43%. This fact complicates the assessment of gender significance for vowel frequency values.

Almost all mean F1, F2, F3 and F4 frequencies for individual vowels (except for F1 [ɨ], F2 [o], F3 [i], F4 [i]) were slightly lower for the boys than for the girls. The greatest difference of 80 Hz in F1 average values was noted for vowel [a]. F2 was on average 100 Hz lower for the boys (except vowels [o] – F2 higher and [u] – F2 equal, see Fig. 6). In the F1/F2 plane, a vowel pentagon for the boys is included in a pentagon for the girls (with the exception of [u]) and it is shifted towards lower values on both axes when compared to the other. However, F3 and F4 values were almost equal for both genders in all vowels or slightly lower (by about 100 Hz) for boys but this difference is not significant.

A two-way analysis of variance (ANOVA) with vowel and gender as main effects indicates that a significant main effect for gender was not found for F1 (see Table 11). Gender effect appeared not to be significant also for F2 value (Table 12) as well as the vowel-by-gender interaction for both vowel formants.

In the present study, the effect of gender on vowel frequencies is found not significant even though the mean frequencies of all measured vowel formants appeared to be slightly higher for the girls than for the boys in most cases. A small statistical significance of the gender factor is confirmed by Łobacz' (1996) and Jęziorska's (1998) results but they were established for much younger children. Differences in F1, F2, F3 between males and females become significant at age of 14-15 years (e.g., Huber et al., 1999; Lee et al., 1988). In our study, it is the age typical of the older group, which was less numerous than the group of younger children. Most children were 12-13 years old, that is, before the period of clear differentiation of voice pitch depending on gender and concurrent lowering of vowel formants by 15-20% in boys.

Consonantal context

The results of previous studies suggest the formant course in the speech of the hearing-impaired is quasi-stationary, i.e. formant transitions are frequently missing or are replaced by simple raising or falling of the formant (Heidler, 1976). This means that utterances produced by deaf speakers are characterized by poorer differentiation of articulatory movements, which is also connected with lesser coarticulation (mutual effects of neighboring phones, Rothman, 1976). In the present study the effect of consonantal context on the formant frequencies was analyzed at the steady-state part of the formant.

Table 13 shows mean F1 and F2 values of the analyzed vowels produced in different contexts, in 18 words separately for the reading and the naming test. Table 13 also contains the values of standard deviation.

As stated earlier, the analyzed vowels occurred either in the neighborhood of palatal or nasal consonants, which strongly modify the articulation of vowels, or in a relatively neutral context. We shall therefore focus on these two contexts in the following comparison. It was observed that shifts in the values of the first two formants occur depending on these contexts:

1. Vowel [i] is produced with the highest tongue position (the highest F2 frequency) in the nasal-palatal context (*misie* – [miçe]). This tendency is consistent with the so-called adult norm (Kleśta, 1998). The high standard deviation values indicate large inter-speaker differences. The vowel [i] was frequently produced as a lowered and centralized sound, which was shown by a substantial increase in F1 frequency in relation to standard pronunciation.

2. The preceding nasal context caused lowering of F1 and raising of F2 in the vowel (in *myje się*).

3. The preceding palatal context only partly raised the articulation of the vowel [e] because F2 values in the words *siedzi* and *lew* were similar, while according to

normative expectations F2 [e] in the word *siedzi* should be raised by about 200 Hz (Gonet, 1993; Kleśta, 1998). However, lowering of F1 was observed for this vowel in the bilateral palatal context, which was consistent with the norm.

4. Lowering of mean F1 value was noted for [u] in the succeeding palatal context (e.g. in the word *cukierki*). Kleśta (1998) reports that the succeeding palatal context lowers F1 [u] for 90% of adult hearing speakers.

A relatively large dispersion of the results in the measurement of formant frequencies for all vowels is a reflection of low stability of articulatory targets in hearing-impaired children. The above-mentioned modifications of F1 and F2 of vowels caused by their phonetic neighborhood are merely preliminary observations as they are pooled over all subjects. Similar interspeaker differences were not investigated at this stage.

Final remarks

The present study constitutes the first attempt to provide an acoustic-phonetic description of vowels in speech of the hearing-impaired Polish speakers. That is why our intention was to describe primarily the features common to all subjects with a profound hearing loss who have not finished primary school. Although in the current paper the inter-speaker differences are not investigated in detail, some tendencies have been noted.[4] They are as follows:

1. There is a concentration of all vowels in a small area in the F1×F2 plane which indicates considerable similarity in their quality.
2. No proper differentiation between F1 values indicates that the contrast low versus high vowel is reduced (e.g., [a]-[i]), while the front-back distinction is preserved.
3. There are non-significant differences in F2 values – a tendency opposite to that mentioned in 2 – because vowels are central from the point of view of the front-back position of the tongue; however, their low or high position in the vocal track remains unchanged.
4. All vowels have high F2 values which indicates that they are produced as front vowels.

Although some individual differences occur between speakers, one important feature of vowel articulation was observed for all subjects i.e., a decrease in the number of articulatory dimensions differentiating vowels. This results in a specific centralization: a substantial reduction on the vowel area in the F1×F2 plane in comparison with the analogous area for hearing speakers. The specificity of the centralization consists in the fact that it is speaker-dependent. However, the differences between vowels are most often neutralized in the direction of the frequency of the central vowel [ə] (e.g., Heidler, 1976). For the whole group of subjects a general centralization tendency is observed. This phenomenon is characteristic for other languages as well (e.g., Shukla, in Farmer, 1997). The next, more general tendency in vowel articulation in hearing-

[4] A separate study, using classifications carried out by a neural network, will deal with a detailed analysis of the pronunciation of individual speakers in this group of subjects.

impaired speakers reduced the differentiation between the two front and high vowels: [i – ɨ]. Their phonological distinctiveness was not sufficiently clear for these speakers. A similar phenomenon was reported for English with reference to the vowels: [i, ɪ] (e.g., Angelocci et al., 1964).

Stronger vowel neutralization in the speech of the hearing-impaired shows that they miss correct articulatory intentions or they are not able to realize the targets. There are various hypotheses (e.g., Monsen, 1974) concerning the deaf phonological system and the phenomenon of speech production under the condition of permanently limited auditory 'input' and feedback.

Angelocci et al. (1964) advanced the hypothesis that the observed tendency towards centralization results from difficulties in the production of articulatory targets by hearing-impaired children. Similarly, Butcher (1999) claims that this is brought about by the insufficient control of vocal tract muscles and the resultant poor accuracy in configuring the articulators. Heidler (1976) explains a tendency for deaf speakers to produce front and back close vowels as more neutral ones by poor adherence in the region of the tongue and lips. Excessive jaw movements that could not be balanced by articulatory compensation would cause this. Nevertheless, the author stipulates that (taking into consideration, among other things, the small sample of speakers) there is a risk of interpreting individual speakers' features as typical of the hearing-impaired as a group. Next, Smith (1975) brings up for discussion the issue that hearing-impaired children who have poor awareness of the quality of most vowels may never try to produce these vowel targets and they realize a more or less neutral vowel instead (regardless of consonant context). Monsen (1974) favours the thesis that in characterizing deaf speech we talk about such large numbers of errors in vowel pronunciation because we compare two different linguistic systems. The system of hearing people is regarded as a standard here. The role of auditory feedback in creating an abstract phonological system and in the control of one's own articulatory movements is maximally reduced in hearing-impaired children.

Obrębowski et al. (1993) found on the basis of the ultrasonographic images of peripheral speech organ activity that in the case of 6-14 year old profoundly hearing-impaired children, the greatest departure from the norm occurs in the articulation of [a, o, ɨ]. Two of these vowels are neither quite front nor quite back and one is back in normative pronunciation. These preliminary results could mean that even in the most central articulatory space, the tongue surface is often deformed.

Dikkenberg-Pot et al. (1998), comparing the phonological development of hearing and deaf children in the age range of 2.5-18.0 months, tried to explain how the auditory perception influences sound production. They found that the differences between these two groups start to be significant at about 8.5-10.5 months of age. Hearing children begin, in this period, to produce varying articulations. In contrast, deaf children start replacing articulatory differences by varying phonation or for quite short periods, produce utterances with one articulation without phonation. Simultaneous modelling of articulation and phonation is too difficult for them. The lack of auditory feedback can be compensated only to some degree by the usage of other cues and mechanisms of articulatory control. At the speaker's disposal are also: visual, vibrotactile (Monsen, 1974), kinaesthetic (Levitt, 1972) and proprioceptive cues as well as their internal neural representations. "Recently, there has been considerable interest in the role of feedback and internal models in motor control in general. Internal models are hypothesized neural representations of the spatial (kinematic), force (dynamic), and/or proprioceptive characteristics of movements that could be used by the nervous system to predict movement outcome. These predictive movements could provide internal feedback to planning and control systems without the delays associated with natural proprioceptive feedback" (Jones & Munhall, 2000, pp. 1246-1251).

The subjects with profound loss had the least trouble with correct production of the vowel [u]. The values of standard deviation for this vowel were the smallest and it was noticed that the mean values of formants F1 and F2 do not depart from those calculated for hearing children by Łobacz (1996). This result is consistent with Szczepankowski's thesis (1985) about the best visual distinctiveness of the oral vowel [u] as compared with other vowels because of clear lip rounding and protrusion that makes easier its acquisition by the hearing-impaired. In Kurkowski's study (1996), the vowel [u] also turned out to be the most rarely distorted vowel (about 85% of correct realizations). It is worth emphasizing that the studies for English on perceptual identification of vowels in the deaf speech lead to similar conclusions. In the experiment by Angelocci et al. (1964), hearing students correctly identified vowels uttered by deaf speakers between 49% for the best identified [u] and just 21% for central vowel [ɜ].

The fact that the present results are consistent with those established for other languages leads us to create a general description of hearing-impaired speech. It enables better explanation of the articulatory mechanisms specific to the hearing-impaired and provides more effective ways of teaching pronunciation. Consequently, it will lead to better intelligibility of speakers with profound hearing loss.

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