Hrvatska revija za rehabilitacijska istraživanja 2010, Vol 46, br. 1, str. 41-56

VOICE QUALITY, ARTICULATION, NASALITY, PROSODY AND OVERALL INTELLIGIBILITY IN THE SPEECH OF SUBJECTS WITH HEARING IMPAIRMENT

MARTINA OZBIČ, DAMJANA KOGOVŠEK
Faculty of Education, University of Ljubljana

Primljeno: 28.05.2009.
Prihvaćeno: 31.03.2010.

Izvorni znanstveni rad
UDK: 376.1-056.264

Summary: *In early infancy, hearing loss significantly affects the development and intelligibility of speech in children with hearing impairment. Assuming that both speech and voice disorders occur in the speech of hearing-impaired speakers, the present study will 1) analyse the speech and overall intelligibility of 91 hearing-impaired speakers (from ages 5 to 23, M = 13 years, 56% males, 44% female) who exhibit an average hearing loss of air conductivity of 99 dB (SD = 19.48); 2) compare latent space in the hearing impaired (HI) subjects' speech and the International Classification of Functioning, Disability and Health (known as ICF) speech and voice functions to determine whether they overlap partially or totally; 3) investigate the presence of an autonomous factor of nasality and determine through analysis of the latent structure of speech whether nasality is a matter of articulation or phonation; and 4) investigate the correlations between derived factors and speech intelligibility of HI subjects from a closed list of words.*

Using principal component analysis, four relevant factors were determined that explained 65.650% of the total variance. The first prosodic factor, the fluency and rhythm of speech, explained 40.036% of the total variance, the second factor of quality of speech production (voice, articulation and resonance) explained 11.430%, the third factor of micro-chaining explained 7.970% and the fourth factor, nasality, explained 6.214%.

The ICF and speech factor distributions were similar but not identical. In this study, speech can be seen in terms of four dimension factors on the micro- and macro-segmental levels: prosodic factors, voice, resonance and articulation quality and nasality. The four factors, especially the second factor of voice, resonance and articulation quality, show statistically significant correlations with the intelligibility of speech in HI subjects (p < 0.01).

Key words: *Deafness, International Classification of Functioning, Disability and Health (ICF), speech production, intelligibility of speech, nasality, articulation, resonation, phonation.*

INTRODUCTION

Speech is a fluent flow of segmental and prosodic elements, including voice, resonance, prosody, articulation, and so forth, and dysfunction at any of these levels causes less intelligible speech. De Bodt et al. (2002) analysed speech samples of dysarthric patients through perceptual ratings covering the four main dimensions of speech production (voice quality, articulation, nasality and prosody as well as overall intelligibility). Their multiple regression model showed that intelligibility can be expressed as a linear combination of weighted perceptual dimensions. The authors claimed that the impact of articulation on intelligibility was dominant, but the inclusion of the dimensions "nasality", "voice" and "prosody" resulted in a more balanced estimation of intelligibility.

Some researchers have stressed the importance of prosody, especially in the motor planning of speech movement (Klopfenstein, 2009) in neurological disorders and the speech of deaf individuals. Children's appropriate use of intonation has been examined as a possible factor that aids intelligibility. Peppé (2009) noted that prosody can affect intelligibility, and Paterson (1986) discussed the role of prosody in spoken language comprehension, expression, and speech intelligibility in order to maximise the use of residual hearing in school-aged, hearing-impaired students. Other researches, including Le Dorze et al. (1998), claimed the opposite, arguing that the deficits in prosodic performance were not related to overall speech intelligibility.

Children with normal hearing learn their first language implicitly, but this is not the case in hearing-impaired children. Hearing loss in early infancy significantly affects the development of spoken language, and the normal development of speech is often disrupted, rendering speech less intelligible. Speech intelligibility is defined as the ability of listeners to understand the performance of speech accurately; it is a product of articulation, phonation, resonance and prosody. Speech intelligibility is highly important not only in individuals with hearing impairment (HI) but also in the hearing world. Articulation, resonance, phonation and prosodic disorders may affect the overall intelligibility of speech.

Deafness influences the entire spectrum of speech phenomena, including the generator, phonator, articulator, and resonator levels. Significant discrepancies in speech production occur between the speech of hearing-impaired subjects and that of hearing subjects. Several authors have studied the segmental and prosodic characteristics of speech, the latent space of speech and the correlation of these characteristics with speech intelligibility (Hudgins and Numbers, 1942; Angelocci et al. , 1964; John and Howarth, 1965; Markides, 1970; Monsen, 1976, 1978, 1983; Osberger and McGarr, 1982; McGarr, 1983; Markides, 1985; Metz et al., 1985; Abberton, 1990; Metz et al., 1990; Svirsky and Tobey, 1991; Bench, 1992; Svirsky et al., 1992; Ryalls et al., 1992; Fletcher, 1995; Tobey, 1995; McGarr et al., 1995; Metz and Schiavetti, 1995; Girgin, 2000; Van Lierde et al., 2005; Murphy and Dodds, 2007; Nicolaidis and Sfakiannaki, 2007).

According to current research, a person with hearing impairment is expected to exhibit non-standard speech/voice production in related functions, as outlined in the International Classification of Functioning, Disability and Health (ICF) categories b310, the voice functions of production (phonation and volume) and quality (pitch and resonance); b320, the articulation function; and b330, the function of rhythm and fluency (fluency, rhythm, speed, and speech melody).

According to Markides (1983), speech production by individuals with hearing impairment is commonly characterised by segmental errors, both vocalic and consonantal, and deviances in suprasegmental features, including problems in controlling phonation, fundamental frequency, and timing. Murphy and Dodds (2007) report that speech in those with severe and profound hearing loss is often characterised at the voice and suprasegmental levels by poor voice quality, slow rate of speech, poor breath control, poor rhythm, incorrect and/or unstable pitch, poor volume control and excessive laryngeal tension. On the segmental level, speech will suffer from lack of differentiation in the production of vowels; neutralisation; the substitution of diphthongs for vowels; incorrect pronunciation of true diphthongs; the insertion of extra breath before vowels; incorrect duration and nasalisation of vowels; and predictable and developmental consonant errors, such as assimilation, reduplication, cluster reduction, stopping, fronting, deaspiration, affrication, deaffrication, prevocalic voicing, postvocalic devoicing, initial /h/ deletion, weak syllable deletion, gliding of liquids, and vocalisation of liquids (Murphy & Dodds, 2007, 248-250). According to Girgin (2000), vowel errors, such as substitution, neutralisation and nasalisation, and consonant errors, such as initial consonant omission, devoicing of stops, final consonant omission, denasalisation and substitution occur in the speech of hearing-impaired speakers (Girgin 2000). The reasons for poor articulation in the speech of hearing-impaired children are slow articulatory movement and the slow articulation of syllables (Monsen 1978; Osberger & McGarr 1982).

In the speech of individuals with hearing impairment, there are prosodic errors, such as poor control of the fundamental frequency, which can result in a high average pitch level, insufficient intonation variability, or excessive intonation variability. Their speech may also exhibit abnormal voice characteristics, such as harshness, breathiness and nasality; abnormal uses of pauses, such as inappropriate placement and longer pause duration; poor respiratory control (Osberger & McGarr, 1982; Abberton, 1990, Girgin, 2000); omission or substitution of consonants; neutralisation of vowels; either monotonous or slower-than-normal speech; and the more frequent use of breaks in comparison with normal speakers (Girgin, 2000).

Typical errors in vowel production include substitution, neutralisation, prolongation, diphthongisation, nasalisation (Markides, 1983), less differentiation in vowels, more centralisation of vowel space, reduced ranges in F1 and F2 formant frequencies during the production of different vowel qualities, the possible extensive overlap of vowel areas, and a tendency toward the neutral schwa (Angelocci et al., 1964, Ryalls et al., 2003, Fletcher, 1995). Some aberrant features in vocal tract configuration, such as neutralisation of the tongue position, elevation of the hyoid, and a retraction of the tongue, were identified for vowels produced with excessive pharyngeal resonance. Retraction of the tongue is associated with a deflection of the epiglottis in the lower pharynx, consistent neutralisation of vowels, and the clustering of F2 values in the 1500–2100 Hz frequency range, which is attributed to the restricted horizontal movements of the tongue within the oral and pharyngeal cavities (Subtelny et al., 1992, 574-579). Such reduced differentiation of vowels has been attributed to limited auditory feedback and the relatively poor visibility of articulatory gestures required for vowel production (Monsen, 1976). More errors have been reported for high, middle and front vowels than low and back vowels (Nicolaidis & Sfakiannaki, 2007). If restrictions affect the production of all vowels, a lower F2 might be assumed for front vowels, which normally have a high F2; a higher F2 frequency would be anticipated for back vowels, which normally have a low F2 (Subtelny et al., 1992, 574-579).

All these characteristics lead to a decrease in intelligibility. The term “speech intelligibility” can be defined by the amount of speech understood by a listener. Speech intelligibility scores are affected by the speech material used as well as the characteristics of the listener and speaker (Girgin 2000). Listeners are affected by the speech quality of a hearing-impaired child, the visibility of the speaker, their experience of the child’s speech, and the repetition of utterances (Monsen 1983; Markides 1983; John et al. 1976; Hudgins & Numbers, 1942; Girgin, 2000). Nevertheless, important relationships between speech intelligibility and speech production skills in hearing-impaired children have been demonstrated. All of the segmental and prosodic speech characteristics cited above have an effect on speech intelligibility (John et al. 1965; McGarr 1983; Girgin 2000). However, profoundly hearing-impaired children show a wide range of spoken language abilities; some have highly intelligible speech while others have unintelligible speech (Abberton 1990; Monsen 1983). Segmental and prosodic errors also occur (Girgin 2000). Studies have found that two factors of segmental and prosodic production are strongly related to speech intelligibility and both. Hearing-impaired children with approximately the same number of segmental errors can exhibit wide ranges of speech intelligibility (Osberger, 1992). Most probably, these differences result from the influence of prosodic features of speech (Hudgins and Numbers, 1942; John and Howarth 1965). In any case, the direct relationship between intelligibility and prosodic features cannot be rejected (Girgin, 2000). In the research of Metz et al. (1985), regression analyses of the original 12 segmental, prosodic, and hearing ability parameters revealed that voice onset time differences in cognate pairs and mean sentence duration strongly predicted speech intelligibility, based both on readings of isolated words and contextual speech material. A principal components analysis derived four factors that accounted for the majority of the variance in the original 12 parameters. Subsequent regression analyses using the four derived factors as predictor variables revealed two factors with strong relationships to speech intelligibility measures: one factor primarily reflected segmental production processes related to the temporal and spatial differentiation of phonemes, whereas the other reflected prosodic features and production stability. Thus, intelligibility had high positive loadings on both factors, showing the differentiation of the temporal and spatial events underlying the production of distinct phonemes and the appearance of prolonged sentence duration, instability in the control of sentence duration, and instability in the production of cognate phoneme pairs (Metz et al., 1985). These results are consistent with prior research that suggests independent primary and secondary roles for segmental and prosodic speech characteristics, respectively, in determining intelligibility in speakers with severe to profound hearing impairment. This work confirmed the findings of previous studies by Monsen (1978) and others, most notably that speech intelligibility in severely and profoundly hearing-impaired speakers is determined independently by segmental features and prosodic characteristics (Bench 1992, 93 - 94).

In 1990, Metz et al. performed a regression analysis and a principal components analysis to examine the relationship between 28 segmental and suprasegmental acoustic parameters of speech production and measures of speech intelligibility in 40 persons with severe to profound hearing impairment. The principal components analysis derived six factors that accounted for 59% of the variance in the original 28 parameters. A subsequent regression analysis using these six factors as predictor variables revealed two factors with strong predictive relationships to speech intelligibility: one factor primarily reflected segmental production processes related to the temporal and spatial differentiation of phonemes, while the other primarily reflected suprasegmental production processes associated with contrastive stress (Metz et al., 1990). These results are consistent with the findings of Metz et al. (1985).

This duality between macro and micro spheres and between segmental and suprasegmental levels also appears in other studies. According to Tobey (1995, 458), studies that contrasted speech produced while an implant was turned on with speech produced while it was turned off suggest a dual role for auditory feedback (according to Svirsky & Tobey, 1991 and Svirsky et al., 1992). Auditory feedback appears to be used for long-term calibration of articulatory parameters, resulting both in relatively gross adjustments and in short-term adjustments for fine tuning.

In terms of nasality, movement of the velum is essential for distinguishing between oral and nasal sounds in speech. The velum and lateral pharyngeal walls control the degree of "coupling" between the nasal and oral cavities. The velum is capable of a range of motion and a rate of movement that meet the requirements of rapidly changing phonetic environments (Kent, 1997; Seikel et al., 2000; Fowler, 2004). Velopharyngeal activity may be placed in two categories: (a) elevation and lowering, which move the velum toward and away from the posterior pharyngeal wall respectively and (b) medial movements of the lateral pharyngeal walls (Kent, 1997; Moon and Kuehn, 1997; Zemlin, 1998; Fowler, 2004). The five muscles involved in velar closure are the *levator veli palatini, musculus uvulae, tensor veli palatini, palatoglossus* and *palatopharyngeus*. Elevation of the velum results primarily from the contraction of the *levator veli palatini* muscle (Kent, 1997; Netter, 2000; Seikel et al., 2000; Zemlin, 1998). The velum is moved superiorly and posteriorly toward the posterior pharyngeal wall during the production of oral speech sounds (Fowler, 2004, 5).

In speakers with hearing impairment, nasality often occurs (Nickerson, 1975; Fletcher, Daly, 1976); however, it does not occur in correlation with the degree of hearing loss (Tatchell et al., 1991; Fletcher et al. 1999). In 2006, Bonetti analysed nasal emission during speech in 12 children with hearing impairment. The results suggested that the ability of the children to control velo-pharyngeal activity was limited and did not depend on the level of phonation control or the control of speech rate but on individual factors.

The aim of this study was to analyse the speech and overall intelligibility (including voice characteristics, articulation, and the prosodic elements of fluency and rhythm of speech) of hearing-impaired speakers according to the functions listed in the ICF. In addition, we planned to compare the latent space of the HI subjects' speech with the classification of ICF speech and voice functions in order to determine whether they overlapped partially or totally and to investigate the presence of an autonomous factor of nasality. We also aimed to investigate, using a closed list of words, the effect of certain speech characteristics on speech intelligibility in HI subjects.

Our hypotheses were as follows:

H1: In accordance with the ICF, the factor analysis will derive three factors of fluency and rhythm, *articulation, and voice quality, and the latent structure will be match the classes of ICF speech and voice functions, including nasality.*

H2: All of the factors will exhibit statistically significant correlation with speech intelligibility, with the highest correlation reflecting prosodic functions.

Methods

The research sample included 91 Slovenian pre-lingual deaf subjects of both sexes with ages varying from 5 to 23 years old who did not show any additional disorders. The research was carried out in compliance with the code of the association of special rehabilitation teachers of Slovenia as well as the Helsinki and Tokyo Declarations. The observed group (ages 5 to 23, M = 13 years, 56% males, 44% female) exhibited an average hearing loss of air conductivity of 99.06 dB in the right ear (SD = 19.18) and 98.18 dB in the left ear (SD = 19.78); the majority of subjects had an average hearing loss above 100 dB, which represents a major obstacle for speech learning.

Their hearing impairments were detected and diagnosed during neonatology screening tests in early childhood or up to 3 years of age. All of the children were fitted with analogue, behind-the-ear hearing aids. All of the speakers used their hearing aids continuously (often or always during the day). None used cochlear implants. Three had deaf parents. All of the study participants were enrolled in non-inclusive kindergartens and schools for the deaf and hard of hearing in the three centres for speech and language impairments in Slovenia. The dominant educational methods were oral or bilingual (oral and signed) with emphasis on speech and language. Thus, they were sign language users in the deaf community and were orally trained for communication with those who do not use sign language.

The variables, assessed according to the ICF, referred to audiological status (from 125 to 8000 Hz of air conduction in both the right and left ears) and to speech, voice, and articulation production (subjective evaluation and scoring):

b310 - voice functions: b3101 - quality of voice (voice, resonance and timbre variables):

I. control of voice: quality of voice: *breathy speech/hoarse voice* was evaluated as absent (0) or present (1); any degree of breathiness was rated as 1.
II. quality of timbre or oral / pharyngeal resonance:
   - *sonorousness*, observed by auditory evaluation and evaluated on a five-point scale; extremely unsonorous voicing was rated as very poor (1); very unsonorous voicing as poor (1.5); quite unsonorous voicing as moderately poor (2); little unsonorous voicing as slightly poor (2.5); sonorous voicing was rated as normal (3).
   - *formant spectrum clarity*, observed by visual evaluation of sonograms and evaluated on a five-point scale; very clear, visible, defined and loud formants were rated as normal (3); less clear, still visible, still defined and less loud formants as slightly poor (2.5); unclear, still visible, less defined formants as poor (2); unclear, undefined, but still visible formants as moderately poor (1.5); undefined, unclear and soft formants with clouds of resonances were rated as very poor (1).
   - *cul-de-sac resonance*, observed by auditory evaluation and evaluated as absent (0) or present (1); damp voicing was rated as 1, normal voicing was rated as 0.
   - *nasal resonance*, observed by auditory evaluation: degree of nasality evaluated as absent (0) or present (1); very nasalised voicing was rated as 1, normal nasalisation was rated as 0.

b320 - variables concerning articulation functions at the segmental level: the quality of articulation of phonemes in words, i.e., the *sum total of mistakes*; the raters transcribed the speech and compared the uttered words and their phonemes with standard speech production of Slovenian standard language in normal-hearing speakers without speech disorders. Distortions, substitutions, metatheses, insertions of sounds/phonemes were labelled as articulation errors.

b330 - fluency and rhythm of speech, or speech variables concerning speech flow:

b3300 - fluency of speech:

- *fluency of speech*, evaluated on five-point scale: a high but normal uninterrupted flow of speech was rated as normal (5); a normal uninterrupted flow of speech was rated as slightly poor (4); slightly hesitated speech was rated as moderately poor (3); interrupted speech with some pauses was rated as poor (2), and very interrupted speech with hesitations, many pauses, and segmentations was rated as very poor (1).
- *syllabic fragmentation*, or irregular breaks in speech I, evaluated as absent (0) or present (1); occurrence of the pauses between syllables was rated as 1.
- *phoneme fragmentation*, or irregular breaks in speech II, evaluated as absent (0) or present (1); the occurrence of pauses between phonemes merited a rating of 1.
- *interposition of sounds/phonemes between phonemes*, evaluated as absent (0) or present (1); the occurrence of sounds/phonemes between phonemes merited a rating of 1.
- *interposition of sounds/phonemes between syllables*, evaluated as absent (0) or present (1); the occurrence of sounds/phonemes between syllables merited a rating of 1.
- *finger spelling,* evaluated as absent (0) or present (1); if the speakers helped him/herself during reading with finger spelling, the rater assigned a value of 1

b3301 - rhythm of speech:

- *lengthening of syllables*, evaluated as absent (0) or present (1); every abnormal lengthening of syllables, in most cases realised with vowel lengthening or lengthening of some phonemes, like nasals and fricatives, was rated as 1.
- *contrast reduction*, evaluated as absent (0) or present (1); if the speaker uttered the syllables without any stress, the rater assigned a value of 1.
- *scanned speech*, evaluated as absent (0) or present (1); if the speaker uttered all syllables with effort and stress, the rater assigned a value of 1.

b3302 - *speed of speech*, evaluated on five-point scale; high but normal speed was rated as 5; slightly slower and still normal speed as 4; moderately slow speech as 3; slow speech as 2; very slow speech was rated as 1.

b3303 - melody of speech:

- *inappropriate prosody* or *intonation variability*, evaluated as monotonous (1), normal (0) or too variable (2); the use of normal prosody according to the rules of the Slovenian language was rated as 0; monotonous speech was rated as 1; highly variable speech with unusual pitch contour was rated as 2.

Intelligibility of speech using a closed set of words, evaluated on five-point scale where each grade indicates that 20% of the words were pronounced intelligibly. According to some studies, the degree of oral speech communication skills of hearing-impaired children can be tested by means of speech intelligibility (Metz, 1985). The intelligibility of the speech of hearing-impaired speakers can also be measured through item identification-- the percentage of words correctly understood-- as scaled on a six- or five-point scale (Girgin, 2000).

We recorded the subjects' speech with a Sony (DAT) digital recording device (model number TCD-D8), a Sony microphone (model number ECM-719), and digital tapes. We placed the microphone at a distance of 30 cm in front of the subject's mouth. The sound samples consisted of 5-10 minutes of reading/denominating from a closed set of words/pictures from the Slovenian three-position test for evaluating articulation of first-grade students (Globačnik, 1999). An additional list of seven words was used. The words from the test were frequent, concrete and simple words with few or no dialectal variations. The test battery of articulation, used by all speech and language therapists in Slovenia, is a set of well-known, frequent words with simple and complex phoneme structures. The words were as follows: *Klop, kapa, pipa, boben, riba, balon, krof, telefon, fižol, veverica, krava, vetrnica, pas, pismo, sova, koš, hruška, škarje, zvezde, vaza, zibelka, polž, roža, žaba, lonec, vilice, copate, luč, očala, čevelj, metulj, kolo, ladja, sir, ura, roka, zmaj, jajce, jabolko, kruh, kuhar, hiša, lok, kača, gugalnica, noga, gumbi, list, avto, trobenta, duda, medved, drevo, dim, omara, metla, slon, banana, nogavica, jadrnica, lopar, zajec, zavesa, mačice, sneženi mož,*

Table 1. *Descriptive Statistics (mean, standard deviation, median, mode, minimum and maximum) of the variables related to speech properties of 91 Slovenian pre-lingual deaf subjects (ages from 5 to 23, M = 13 years, 56% males, 44% female): quality of voice (b310), articulation (b320), fluency and rhythm of speech (b330) and intelligibility of speech*

	Mean	Std. Deviation	Median	Mode	Minimum	Maximum
b310						
b3101						
Breathy speech/hoarse voice	.38	.49	0	0	0	1
Sonorousness (auditory observation)	2.13	.67	2	2	1.0	3.0
formant spectrum clarity (visual evaluation)	1.99	.70	2	2	1.0	3.0
Cul de sac resonance	.54	.50	1	1	0	1
nasal resonance	.38	.49	0	0	0	1
b320						
Articulation mistakes, total number	22.02	23.38	16	0	.00	95.00
b330						
b3300						
Fluency of speech	3.24	1.32	4	4	1	5
syllabic fragmentation	.30	.46	0	0	0	1
phoneme fragmentation	.10	.30	0	0	0	1
interposition of sounds / phonemes between phonemes	.20	.40	0	0	0	1
interposition of sounds / phonemes between syllables	.21	.41	0	0	0	1
Finger spelling	.05	.23	0	0	0	1
b3301						
lengthening of the syllables	.36	.48	0	0	0	1
contrast reduction	.38	.49	0	0	0	1
Scanned speech	.46	.50	0	0	0	1
b3302						
speed of speech	3.51	1.00	4	3	1	5
b3303						
Prosody	.45	.65	0	0	0	2
Overall evaluation						
Intelligibility	3.41	1.37	4	5	1	5

sonce, strašilo, šilček, klešče, sveča, žoga, cesta, oči, uho, jezik, miza, voda[1]. In this set of elicited words, the most frequent stressed syllables were the initial syllables. The most frequent stressed syllable structure was CV.

To edit and evaluate the data, the CoolEdit96/ CoolEdit2000 program was used to prepare the recorded material, and Praat and Speech Analyser programs were used for analysing the resulting sound files. For data processing, we used Excel for Windows XP and the SPSS 13.0 statistical package for Windows. The data were evaluated twice, using the test-retest method (concordance values were 87%) and re-evaluation. The data were normalised.

Results

In Table 1, we show descriptive statistics for each variable, including the mean and SD values,

1 Bench, cap, pipe, drum, fish , balloon, doughnut, telephone, bean, squirrel, cow, weathervane, belt, letter, owl, basket, pear, scissors, stars, vase, cradle, snail, flower, frog, pot, fork, slipperslight, glasses, shoe, butterfly, bicycle, ship, cheese, watch, hand, dragon, egg, apple, bread, cook, house, bow, letters, snake, swing, leg, buttons, leaf, car, trumpet, pacifier, bear, tree, smoke, wardrobe, broom, elephant, banana, sock, sailing boat, racket, mole, rabbit, curtain, kittens, snowman, sun , scarecrow, pencil sharpener , pliers, candle, ball, road, eyes, ear, dog, garden,tongue, table, water.

minimum and maximum, median and mode. In Tables 2, 3, 4 and 5 we present percentages, listed according to the ICF codes b310, b320, and b330, as well as percentages for overall speech intelligibility. Tables 2 and 4 show that, in the speech of hearing-impaired speakers, we mainly observed problems with resonance and fluency/rhythm of speech: a 53.8% occurrence of cul-de-sac resonance; a 46.2% occurrence of scanned speech; a 38.5% occurrence of contrast reduction, hoarse voice and nasality; a 36.3% occurrence of lengthening of syllables and a 29.7% occurrence of syllabic fragmentation. The most severe speech difficulties occurred on the fluency level, followed by resonance problems.

Furthermore, as indicated in Tables 2, 3 and 5, speech fluency was normal in only 12.1% and not normal in 87.9%, the formants spectrum clarity was not normal in 78.0% of subjects, the sonorousness of speech was not normal (from very poor to slightly poor) in 72.5% of cases; and finally the speed of speech was very slow to moderately slow in 49.5% and normal to high in 50.6%. These speech characteristic had repercussions on speech intelligibility; the intelligibility of speech (table 5) was profoundly to slightly impaired in 71.4% and normal in 28.6%.

The factor analysis of speech and voice variables identified areas within the latent space of

Table 2. *Percents of occurrences of speech properties – voice functions - of 91 Slovenian pre-lingual deaf subjects (ages from 5 to 23, M = 13 years, 56% males, 44% female) defined by the variables ICF: b310: b3101 nasality, cul-de-sac resonance, breathy speech, sonorousness, formant spectrum clarity*

ICF: b310: b3101	0 (absent)		1(present)		
Nasality	61.5%		38.5%		
Cul-de-sac resonance	46.2%		53.8%		
Breathy speech / hoarse voice	61.5%		38.5%		
	1.0 (very poor)	1.5 (poor)	2.0 (moderately poor)	2.5 (slightly poor)	3.0 (normal)
sonorousness	12.1%	16.5%	33.0%	11.0%	27.5%
formants spectrum clarity	19.8%	16.5%	31.9%	9.9%	22.0%

Table 3. *Percents of occurrences of speech properties – fluency of speech - of 91 Slovenian pre-lingual deaf subjects (ages from 5 to 23, M = 13 years, 56% males, 44% female) defined by the variables of ICF: b330: b3300 syllabic fragmentation, interposition of sounds / phonemes between syllables, phoneme fragmentation, interposition of sounds / phonemes between phonemes, finger spelling, fluency of speech*

ICF: b330: b3300	0 (absent)		1 (present)		
syllabic fragmentation	70.3%		29.7%		
interposition of sounds / phonemes between syllables	79.1%		20.9%		
Phoneme fragmentation	90.1%		9.9%		
interposition of sounds / phonemes between phonemes	80.2%		19.8%		
Finger spelling	94.5%		5.5%		
	1 (very poor)	2 (poor)	3 (moderately poor)	4 (slightly poor)	5 (normal)
Fluency of speech	17.6%	12.1%	11.0%	47.3%	12.1%

Table 4. *Percents of occurrences of speech properties – rhythm of speech - of 91 Slovenian pre-lingual deaf subjects (ages from 5 to 23, M = 13 years, 56% males, 44% female) defined by the variables of code ICF: b330: b3301 scanned speech, contrast reduction, lengthening of the syllables.*

ICF: b330: b3301	0 (absent)	1 (present)
Scanned speech %	53.8%	46.2%
contrast reduction %	61.5%	38.5%
lengthening of the syllables	63.7%	36.3%

speech. Factor analysis followed the KMO criteria (0.849 > 0.5) and Bartlett's test (approx. Chi square = 797.097, df = 136, sig. 0.000 < 0.05). Extraction was performed according to the method of principal components, resulting in four factors with an eigenvalue > 1. Table 6 displays communalities from highest (variable contrast reduction: 0.818) to lowest (variable formant spectrum clarity: 0.483).

Table 5. *Percents of occurrences of speech properties – speed of speech and melody of speech - of 91 Slovenian pre-lingual deaf subjects (ages from 5 to 23, M = 13 years, 56% males, 44% female) defined by the variables of ICF: b330: b3302 speed of speech, b3302 prosody, and speech intelligibility.*

Speed of speech (ICF: b330: b3302)	**%**
1 (very slow)	2.2
2 (moderately slow)	13.2
3 (Slow)	34.1
4 (Normal)	33.0
5 (High)	17.6
prosody (ICF: b330: b3303)	
0 (normal)	63.7
1 (monotonous)	27.5
2 (great variations)	8.8
Speech intelligibility (overall evaluation)	
1 (profoundly impaired)	9.9
2 (severely impaired)	22.0
3 (moderately impaired)	14.3
4 (slightly impaired)	25.3
5 (normal)	28.6

Table 6. *Communalities after extraction in the factor analysis, arranged by descending value, of the variables concerning speech properties in 91 Slovenian pre-lingual deaf subjects (aged from 5 to 23, M = 13 years, 56% males, 44% female): nasality, cul-de-sac resonance, breathy speech, sonorousness, formant spectrum clarity, fluency of speech, syllabic fragmentation, interposition of sounds / phonemes between syllables, lengthening of the syllables, phoneme fragmentation, interposition of sounds / phonemes between phonemes, finger spelling, speech intelligibility, speed of speech, contrast reduction, scanned speech, prosody*

Variables	**initial**	**extraction**
Contrast reduction	1.000	.818
Interposition of phonemes/sounds between phonemes	1.000	.763
Nasality	1.000	.746
Sum of articulation mistakes	1.000	.742
Syllabic fragmentation	1.000	.737
Lengthening of the syllables	1.000	.726
Sonorousness	1.000	.716
Cul de sac resonance	1.000	.696
Fluency of speech	1.000	.650
Hoarse voice	1.000	.613
Scanned speech	1.000	.607
Interposition of phonemes/sounds between syllables	1.000	.585
Speed of speech	1.000	.575
Phonemic fragmentation	1.000	.571
Finger spelling	1.000	.566
Prosody – intonation variability	1.000	.565
Formant spectrum clarity	1.000	.483

Seventeen factors were derived using principal component analysis; four of them had an eigenvalue > 1 (see Table 7). These explained 65.650% or about two-thirds of the total variance. Since the structure was not sufficiently clear, rotation of the matrix was performed using the Varimax rotation method, which did not provide sufficiently transparent factors. Thus, rotation with the Oblimin method with Kaiser normalisation was performed, leading to the clearest structure. The first factor explained 40.036% of total variance, the second 11.430%, the third 7.970% and the fourth 6.214%.

The first factor explained 40.036% of the total variance and included those variables in category b330 and its subclasses of fluency and rhythm of speech: contrast reduction, syllabic fragmentation, syllabic lengthening, fluency of speech, scanned speech, prosody and speed of speech. The first factor was projected on variables of segments larger

Table 7. *Eigenvalues and total variance explained by the set of variables concerning speech properties of 91 Slovenian pre-lingual deaf speakers (ages from 5 to 23, M = 13 years, 56% males, 44% female) in the factor analysis*

Component	Initial Eigenvalues			Rotation Sums of Squared Loadings
	Total	% of Variance	Cum.%	Total
1	6.806	40.036	40.036	5.598
2	1.943	11.430	51.466	3.732
3	1.355	7.970	59.436	3.875
4	1.056	6.214	65.650	1.910
5 - 17	omitted			

Table 8. *Pattern coefficients of rotated factors (Oblimin rotation) of the set of variables concerning speech properties of 91 Slovenian pre-lingual deaf speakers (ages from 5 to 23, M = 13 years, 56% males, 44% female): nasality, cul-de-sac resonance, breathy speech, sonorousness, formant spectrum clarity, fluency of speech, syllabic fragmentation, interposition of sounds / phonemes between syllables, lengthening of the syllables, phoneme fragmentation, interposition of sounds / phonemes between phonemes, finger spelling, speech intelligibility, speed of speech, contrast reduction, scanned speech, prosody*

			Component			
factor	**ICF code**	**Variable**	**1**	**2**	**3**	**4**
1	**b3300**	**syllabic fragmentation**	.885			
	b3301	**lengthening of the syllables**	.769			
	b3302	**speed of speech**	-.346			
	b3300	**fluency of speech**	-.760			
	b3301	**Contrast reduction**	.895			
	b3301	**Scanned speech**	.736			
	b3303	**Prosody**	.667			
2	**b3101**	**Breathy speech / hoarse voice**		-.792		
	b3101	**Cul de sac resonance**		-.787		
	b3101	**sonorousness**		.745		
	b3101	**Formant spectrum clarity**		.608		
	b320	**sum of articulation mistakes**		-.517	.324	.353
3	**b3300**	**Interposition of phonemes between phonemes**			.783	
	b3300	**Finger - spelling**			.781	
	b3300	**Interposition of phonemes between syllables**			.657	
	b3300	**phoneme fragmentation**	.377		.539	
4	**b3101**	**Nasality**				.843

than the phoneme: the syllable, word, and sentence. Thus, we witnessed a general fluency factor of macro-chaining at the general macro-rhythmical/temporal level. This was an overall dynamic factor of chaining and, more specifically, a prosodic factor.

The second factor was more static and explained 11.430% of total variance. This factor included voice and resonance variables from categories b3101 and b320 (hoarse voice, cul-de-sac resonance, sonorousness, formant spectrum clarity) as well as articulation (total number of articulation mistakes). This factor determines overall quality of speech production (good phonation – F0, articulation and resonance, or formants). It also involves sound production within the larynx, the pharynx and other speech organs and refers to sonorants, obstruents, and their spectra (generator, phonator, resonator, and articulator). The variable of the sum of articulation mistakes was also projected on the third and fourth factors, indicating that nasality and a degree of poor micro-chaining can affect articulation.

The third factor explained 7.970% of total variance and was projected on the variables reflecting insertion of pauses and phonemes or sounds between the borders of segments, such as interpositions of phonemes between phonemes and syllables, finger spelling where interposition of the schwa occurs, and phoneme fragmentation (b3300). This factor reflects phoneme fluency on the micro-temporal/rhythmical and segmental phonemic/phoneme levels. It was a dynamic factor of micro-chaining. The variables of phoneme fragmentation and interposition of pauses between phonemes also has projections on the first factor (due to the characteristic of fragmentation).

The fourth factor explained 6.214% of total variance and reflected accompanying nasal sounds or nasality (b3101). It reflects velo-pharyngeal inadequacy and indicates the quality of resonance (a static characteristic) during speech production.

Table 9 indicates that the components are in statistically significant correlation (0.40 and lower) from -0.313 to -0.101 and from 0.141 to 0.272 at sig. 0.005. Speech production is intercorrelated.

Regarding speech intelligibility, Table 10 that the four factors are in statistically significant cor-

Table 9. *Component correlation matrix between the four factors derived from the set of variables concerning speech properties of 91 Slovenian pre-lingual deaf speakers (ages from 5 to 23, M = 13 years, 56% males, 44% female): nasality, cul-de-sac resonance, breathy speech, sonorousness, formant spectrum clarity, fluency of speech, syllabic fragmentation, interposition of sounds / phonemes between syllables, lengthening of the syllables, phoneme fragmentation, interposition of sounds / phonemes between phonemes, finger spelling, speech intelligibility, speed of speech, contrast reduction, scanned speech, prosody in the factor analysis after Oblimin rotation*

Component	1 Prosodic, macrochaining	2 Voice Timbre articulation	3 microchaining
1 Prosodic, macrochaining			
2 voice/timbre/articulation	-.313		
3 microchaining	.401	-.279	
4 nasality	.272	-.101	.141

Table 10. *Correlations between speech intelligibility of 91 Slovenian pre-lingual deaf speakers (aged from 5 to 23, M = 13 years, 56% males, 44% female)and the derived factors from the set of variables concerning speech properties: nasality, cul-de-sac resonance, breathy speech, sonorousness, formant spectrum clarity, fluency of speech, syllabic fragmentation, interposition of sounds / phonemes between syllables, lengthening of the syllables, phoneme fragmentation, interposition of sounds / phonemes between phonemes, finger spelling, speech intelligibility, speed of speech, contrast reduction, scanned speech, prosody in the factor analysis after Oblimin rotation*

	factor score 1	factor score 2	factor score 3	factor score 4
Intelligibility of speech	Prosodic, macrochaining	Voice timbre articulation	microchaining	nasality
Spearman's rho	-.587(**)	.698(**)	-.380(**)	-.401(**)
Sig. (2-tailed)	.000	.000	.000	.000
N	91	91	91	91

relation with the intelligibility of speech in HI subjects (sig. = 0.000). The correlation coefficients show a negative correlation, from -0.587 to -0.401, with the first, third and fourth factors and a positive correlation (0.698) with the second. The highest correlations appear in the second and first factor, indicating that voice characteristics, resonance, good articulation and fluent prosodic chaining lead to intelligible speech.

Discussion and conclusions

The principal component analysis derived 4 factors with an eigenvalue > 1; these factors explain 65.650% or approximately two-thirds of the total variance, which is higher than in the studies cited above (Metz et al. 1990). The scope of the four factors exhaustively covers the phenomenon of speech production and reflects all of the components of speech production. The criteria of the factor conceptualisation are A. dynamic versus static, B. micro versus macro, and C. oral versus nasal.

A. There are two factors reflecting the dynamic aspects of speech: the prosodic factor of macro-speech fluency and that of micro-speech fluency. In other words, the first factor operates at the prosodic and syllabic macro-level and the third at the phonemic level. There are two static factors: a voice-articulation-resonance oral factor (the second factor) and a nasal resonance factor (the fourth). The spectra are connected with the static dimension of speech and consequently with resonance, sonority, and formants. This axis shows the duality of speech production: the quality of speech units and how they are chained. The second and the fourth factors are factors of basic speech units; the first and third show how they are implemented. The first and third factors are dynamic and reflect the chaining of units, whereas the second and fourth factors are static, reflecting the quality of units themselves (quality of articulation and spectra).

B. The third factor and, to a degree, the second are factors in the production of units of speech (phonemes and chaining of phonemes). The first, second (partially), and fourth factors relate to the production of units larger than phonemes and thus reflect the prosodic elements of speech.

C. Factor analysis provides three oral factors: two factors of speech chaining (the first and third) and one (the second) that reflects quality of voice, resonance and articulation. In addition, there is a nasal factor (the fourth). The nasal factor is independent.

Our factor analysis mirrors speech production. It covers the macro-temporal level (the chaining of syllables as well as the overall sequencing and chaining of words) and the micro-temporal level, in which phoneme fluency affects the chaining of sounds. It also reflects voice and articulation characteristics and the role of velo-pharyngeal control or nasality.

Interestingly enough, nasality, which is the primary factor in the (in)appropriate functioning of resonators, velopharyngeal occlusion and other functions not directly related to the voice organ, forms an additional dimension as a separate factor. It stands in opposition to the other oral factors. The ICF proposes a three-dimensional model of speech (b310, b320 and b330). The first and the third factor correspond to the b330 class (the fluency and rhythm of speech functions, including b3300 fluency of speech, b3301 rhythm of speech, b3302 speed of speech and b3303 melody of speech), while the second and fourth match the b310 category of voice functions (b3101 quality of voice) and the b320 classes (articulation). The fourth factor is hidden in b3101.

Thus, our first hypothesis regarding the distribution of fluency and rhythm, articulation, and voice quality as well as the equality of ICF classes and derived factors can be partially refuted. Nevertheless, we can accept the similarity between our categorisations and those of the ICF. In our research, there are four dimensions of speech, whereas there are three in the ICF. In our findings, there is a distinction between macro- and micro-chaining, between dynamic and static characteristics of speech, and between oral and nasal dimensions. The distinction between dynamic and static characteristics of speech corresponds to the studies cited above (Metz et al. 1985, 1990; Tobey, 1995) as well as theories of neurolinguistics in which the left hemisphere monitors the dynamic parts of speech (temporal information) and the right hemisphere monitors the static parts (spectral information) (Gandour, 1998, 213, Hellige 1998, 407).

Hypothesis 2 then can be partially accepted. In our research, the correlation coefficients between intelligibility and the four factors are statistically significant. The highest correlation with intelligibility of speech is that of the second factor (0.698), followed by the first (- 0.587), the fourth (0.401) and finally the third (-0.380). Although the nasal factor plays no small role, voice quality and articulation are the most important factors, followed by the prosodic factor. According to the correlation between the four factors, we can state that speech is in fact "a product of a series of interactive processes such as articulation, phonation, resonance and prosody" (De Bodt et al. 2002).

These results could be useful in speech therapy not only for hearing-impaired speakers but for the hearing as well. Training in one of several elements of speech can improve overall speech production. In speech therapy, articulation is not the only goal. Correct breathing, good phonation, good overall chaining of segments, velopharyngeal function and good control of the larynx can all lead to intelligible speech. Knowledge of the latent space of verbal production represents a suitable starting point for rehabilitation at the vocal, speech segmental and suprasegmental levels. Nasality is not simply a matter of voice production or articulation but an autonomous domain of velopharyngeal functionality. By developing and improving all elements of speech production, the goal of sufficiently intelligible speech in deaf or hard-of-hearing subjects can be achieved. Speech does not simply mean good articulation but rather a coordinated pneumo-phono-articulation-hearing system.

REFERENCES

Abberton, E., Hazan, V., Fourcin, A. (1990): The development of contrastiveness in profoundly deaf children's speech. *Clinical Linguistic and Phonetics*, 4 (3), 209-220.

Angelocci, A.A., Kopp, G.A., Holbrook, A. (1964): The Vowel Formants of Deaf and Normal - Hearing Eleven - to Fourteen-Year-Old Boys. *Journal of Speech and Hearing Disorders, 29 (*2), 156 - 170.

Bench, J.R. (1992): *Communication skills in hearing - impaired children. Studies in disorders of communication.* London: Whurr Publishers.

De Bodt, M., Hernandez-Diaz, H., Van De Heyning, P. (2002): Intelligibility as a linear combination of dimensions in dysarthric speech. *Journal of Communication Disorders, 35*, 283-292.

Bonetti, L. (2006): Kvantitativna procjena nazalnosti u govoru djece s oštećenjem sluha i čujuće djece. *Hrvatska revija za rehabilitacijska istraživanja*. 2006, 42 (2), 3-18.

Le Dorze, G., Ryalls, J., Brassard, C., Boulanger, N., Ratté, D. (1998): A Comparison of the Prosodic Characteristics of the Speech of People with Parkinson's Disease and Friedreich's Ataxia with Neurologically Normal Speakers. *Folia Phoniatrica et Logopaedica,* 1998, 50, 1-9.

Fletcher S.G., Mahfuzh, F., Hendarmin, H. (1999): Nasalance in the Speech of Children with Normal Hearing and Children with Hearing Loss. *Journal of Speech-Language Pathology,* 8, 241-248.

Fletcher, S.G. (1995): Visual articulatory modeling and shaping: a new approach to developing speech of the deaf. *Proceedings of the 18th International Congress on Education of the Deaf.* Volume II, 757-758.

Fletcher, S. G., Daly D. A. (1976): Nasalance in utterances of hearing-impaired speakers. *Journal of Communication Disorders,* 9 (1), 63-73.

Fourakis, M., Botinis, A., Katsaiti, M. (1999): Acoustic characteristics of Greek vowels. *Phonetica, 56*, 28-43.

Fowler, L.P. (2004): Comparison of nasalance between trained singers and non-singers. The Florida State University, College of Communication. Department of Communication Disorders.

Gandour, T.J. (2008): Phonetics and phonology. In B. Stemmer and H. Whitaker (eds), *Handbook of Neurolinguistics* (pp. 208 – 218). San Diego: Academic Press.

Girgin, C. (2000): Speech Intelligibility of Turkish Hearing-Impaired Children. *ISEC: Including the excluded, International Special Education Congress.* University of Manchester.

Hellige, J.B. (2007): Unity of language and communication. In B. Stemmer and H. Whitaker (eds), *Handbook of Neurolinguistics* (pp. 405 – 414). San Diego: Academic Press.

Hudgins, C.V. and Numbers F.C. (1942): An investigation of the intelligibility of the speech of the deaf. *Genetic Psychology Monographs, 25*, 286-392.

ICF, retrieved 24 March 2009 from www.who.int/classifications/icf/site/onlinebrowser/

John, J.E.J. Howarth, J.N. (1965): The effect of time distortion on the intelligibility of deaf children's speech. *Language and Speech, 8*, 127-134.

John, J.E.J., Gemmill, N., Kitzenger, M., Sykes, N. (1976): Some Factors Affecting the Intelligibility of Deaf Children's Speech," In S., D., G.Stephens (Eds), *Disorders of Auditory Function.* London: Academic Press.

Kent, R.D. (1997): *The Speech Sciences.* San Diego, London: Singular Publishing.

Klopfenstein, M. (2009). Interaction between prosody and intelligibility. *International Journal of Speech-Language Pathology*, 11 (4), 326 – 331.

Lock, R.B., Seaver III, E. J. (1984): Nasality and velopharyngeal function in five hearing impaired adults. *Journal of Communication Disorders*, *17* (1), 47-64.

Markides, A. (1970): The speech of deaf and partially-hearing children with special reference to factors affecting intelligibility. *British Journal of Disorders of Communication, 5* (2), 126-40.

Markides, A. (1983): *The Speech of Hearing Impaired Children.* Manchester: Manchester University Press.

McGarr, N.S. (1983): The intelligibility of deaf speech to experienced and inexperienced listeners. *Journal of Speech and Hearing Research, 26*, 451-458.

McGarr, N.S., Mcnutt Campbell, M. (1995): Ephphatha: Opening Inroads to Understanding Articulatory Organization in Persons with Hearing Impairment. In F. Bell - Berti, L.J. Raphael (eds), *Producing speech: contemporary issues (*pp. 433 – 454). New York: AIP Press. American Institute for Physics.

Metz, D.E., Samar V.J., Schiavetti, N., Sitler R.W., Whitehead R.L. (1985): Acoustic Dimensions of Hearing-Impaired Speakers' Intelligibility. *Journal of Speech and Hearing Research, 28,* 345-355.

Metz, D.E., Samar, V.J., Schiavetti, N., Sitler R.W. (1990): Acoustic Dimensions of Hearing-Impaired Speakers' Intelligibility Segmental and Suprasegmental Characteristics. *Journal of Speech and Hearing Research, 33,* 476-487.

Metz, D.E., Schiavetti, N. (1995): Speech Breathing Processes of Deaf and Hearing – Impaired Persons. In F. Bell - Berti, L.J. Raphael (eds), *Producing speech: contemporary issues* (pp. 187 – 198). New York: AIP Press. American Institute for Physics.

Monsen, R.B. (1976): Normal and reduced phonological space: the production of English vowels by deaf adolescents. *Journal of Phonetics, 4*, 189-198.

Monsen, R.B. (1978): Toward measuring how well hearing impaired children speak. *Journal of Speech and Hearing Research, 21*, 197-219.

Monsen, R.B. (1983): The oral speech intelligibility of hearing-impaired talkers. *Journal of Speech and Hearing Disorders, 48,* 286-296.

Moon, J.B., & Kuehn, D.P. (1997): Anatomy and physiology of normal and disordered velopharyngeal function for speech. In K. Bzoch (Ed.), *Communicative disorders related to cleft lip and palate* (4th ed.), (pp. 45-67). Austin, Texas: Pro-Ed.

Murphy, E., Dodds, B. (2007): Hearing impairment. In B., Dodds (eds), *Differential diagnosis and treatment of childen with speech disorder* (pp. 244 – 257). London and Philadelphia: Whurr publishers.

Netter, F.H. (2000): *Atlas of human anatomy.* East Hanover, New Jersey: Hoechstetter Printing Company.

Nickerson, R.S. (1975): Characteristics of the Speech of Deaf Persons. The Volta Review, 77, 6, 342-363.

Nicolaidis, K., Sfakiannaki, A. (2007): An acoustic analysis of vowels produced by Greek speakers with hearing impairment. *ICPhS*, Saarbrücken.

Osberger, M.J. (1992): Speech intelligibility in the hearing impaired: Research and clinical implications. In Kent, R.D. (eds), *Intelligibility in Speech Disorders.* John Benjamins Pub. Co.

Osberger, M.J., Mcgarr N.S, (1982): Speech production characteristics of the hearing impaired. In N.J. Lass (Eds), *Speech and Language: Advances in Basic Research and Practice:* Vol. 8 (221-283). Washington, D.C.: Academies Press, Inc,

Paterson, M. (1986): Maximizing the Use of Residual Hearing with School-Aged Hearing-Impaired Students - A Perspective. *Volta Review*, *88*, 5, 93-106.

Peppé, S.J.E. (2009): Aspects of identifying prosodic impairment. *International Journal of Speech-Language Pathology, 11* (4), 332-338.

Ryalls, J., Larouche A., Giroux, F. (2003): Acoustic comparison of CV syllables in French–speaking children with normal hearing, moderate-to-severe and profound hearing impairment. *Journal of Multilingual Communication Disorders*, *1*, 99-114.

Seikel, J.A., King, D.W., & Drumright, D.G. (2000). *Anatomy and physiology for speech, language and hearing* (2nd ed.). San Diego: Singular Publishing Group, Inc.

Subtelny, J.D., Whitehead, R.L., Samar, V.J. (1992): Spectral Study of Deviant Resonance in the Speech of Women Who Are Deaf. *Journal of Speech and Hearing Research, 35,* 574-579.

Svirsky, M., Lane, H., Perkell, J., Webster, J. (1992): Speech of cochlear implant patients: Results of a short-term auditory deprivation study. *J. Acoust. Soc. Am. 92,* 1284-1300.

Svirsky, M.A., Tobey, E.A. (1991): Effect of different types of auditory stimulation on vowel formant frequencies in multichannel cochlear implant users. *J. Acoust. Soc. Am*. *89*, 2895–2904.

Tatchell, J.A., Stewart, M., Lapine, P.R. (1991): Nasalance measurements in hearing-impaired children. *Journal of Communication Disorders, 24* (4), 275-285.

Tobey, E.A. (1995): Auditory Feedback Delivered by Electrical Stimulation from a Cochlear Implant and Speech Production. In F. Bell - Berti, L.J. Raphael (eds), *Producing speech: contemporary issues* (pp. 455 – 465). New York: AIP Press. American Institute for Physics.

Tüfekçioglu, U. (1996): Comparative Results of the Spoken Language Analyses of Hearing Impaired Children Attending Two Different Programs in Turkey. In K. Verch, (eds). *Hard of Hearing, Deafened, Born Deaf*. Germany: International Organization of the Rehabilitation Institutions for Hearing Impaired Persons, reg. (IOR).

Tye-Murray N., Spencer L., Gilbert Bedia E., Woodworth G. (1996): Differences in Children's Sound Production When Speaking With a Cochlear Implant Turned On and Turned Off. *Journal of Speech and Hearing Research, 39,* 604-610.

Van Lierde, K., Vinck, B.M., Baudonck, N., De Vel, E., Dhooge I. (2005): Comparison of the overall intelligibility, articulation, resonance, and voice characteristics between children using cochlear implants and those using bilateral hearing aids: A pilot study. *International Journal Of Audiology, 44*, 452-465.

Zemlin, W.R. (1998): *Speech and hearing science; Anatomy and physiology* (4th ed). Boston: Allyn and Bacon.