Vowel production and intelligibility in hearing-impaired speech: Evidence from Greek

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ABSTRACT

Ομιλητές με προγλωσσική κώφωση (prelingual profound hearing impairment) κατακτούν το λόγο χωρίς επαρκή ακουστική ανατροφοδότηση. Κατά συνέπεια, πολλά χαρακτηριστικά της ομιλίας τους είτε αναπτύσσονται με καθυστέρηση, είτε εμφανίζουν διαταραχές που επηρεάζουν την καταληπτότητα του ομιλητή (speech intelligibility). Σκοπός του άρθρου είναι (1) να μετρήσει την καταληπτότητα της ομιλίας δέκα Ελλήνων ενηλίκων (πέντε ανδρών και πέντε γυναικών) με προγλωσσική κώφωση, που κάνουν χρήση κλασικών ακουστικών βαρηκοΐας και (2) να εξετάσει τη σχέση καταληπτότητας της ομιλίας και χαρακτηριστικών του φωνηεντικού συστήματος των ομιλητών (όπως διάρκεια, θέση στον ακουστικό χώρο και δειγματική μεταβλητότητα) σε σύγκριση με εκείνα μιας ομάδας ελέγχου πέντε Ελλήνων ομιλητών (δύο ανδρών και τριών γυναικών) με φυσιολογική ακοή. Τα αποτελέσματα της έρευνας έδειξαν ότι το επίπεδο καταληπτότητας των ομιλητών/τριών με κώφωση κυμαινόταν από μέτριο έως πολύ υψηλό με εξαίρεση μια ομιλήτρια, που εμφάνιζε ακατάληπτη ομιλία. Η ακουστική ανάλυση αποκάλυψε μειωμένη φωνηεντική αντίθεση, αυξημένη ακουστική μεταβλητότητα και μεγαλύτερη φωνηεντική διάρκεια στην ομιλία των συμμετεχόντων με κώφωση. Επίσης διαφάνηκε ότι η σχέση βαθμού καταληπτότητας και μεγέθους του ακουστικού χώρου τείνει να είναι αντιστρόφως ανάλογη στην ομιλία των συμμετεχόντων με κώφωση, κυρίως λόγω του φαινομένου εμπροσθοποίησης του /u/. Παράγοντες όπως ακουστική μεταβλητότητα και φωνηεντική διάρκεια δεν φάνηκε να παρουσιάζουν σαφώς αντίστροφη σχέση με τον βαθμό καταληπτότητας. Καθώς η καταληπτότητα της ομιλίας επηρεάζει άμεσα την ποιότητα της επικοινωνίας του ομιλητή, η μέτρηση και η συσχέτισή της με χαρακτηριστικά του παραγόμενου λόγου μπορούν να βοηθήσουν στο σχεδιασμό κατάλληλων μέσων λογοθεραπευτικής παρέμβασης με απώτερο σκοπό τη βελτίωση της επικοινωνίας.

ΛΕΞΕΙΣ-ΚΛΕΙΔΙΑ: acoustics; hearing impairment; speech intelligibility; vowel space

1. Introduction[*]

Intelligibility of hearing-impaired (HI) speech refers to how well an individual with hearing impairment can communicate the intended linguistic message carried though the acoustic signal to a listener (Boothroyd 1983). HI[1] speech presents various types of segmental and suprasegmental errors, which can compromise intelligibility. Since the fundamental purpose of speech is communication, being understood and hence being intelligible is of paramount importance. For this reason, longstanding research has focused on the assessment of intelligibility and its correlation with speech production and perception factors.

1.1. Factors affecting intelligibility assessment

The degree of hearing loss is among the determining factors of HI speech intelligibility (Elliot 1967, Boothroyd 1969, Markides 1970, Smith 1975, Levitt et al. 1976). Speakers with severe or mild HI have been documented to achieve higher intelligibility scores than speakers with profound HI (Markides 1970, Gold 1978). However, as stressed by many researchers, a pure-tone audiogram is only indicative of the deaf child's potential for auditory reception and speech production. An investigation of the correlation between acoustic dimensions and speech intelligibility with factor analytic procedures

[*] Many thanks are due to the participants of the study and the Association of Parents and Guardians of Deaf and Hard of Hearing Children of Central Macedonia. The authors would like to thank Dr. Laura Koenig (Haskins Laboratories) for her useful comments on the manuscript, as well as Dr. Giorgos Kafentzis and Dr. Maria Koutsogiannaki (Department of Computer Science, University of Crete) for their assistance in statistical processing.

[1] Here we follow a distinction between HI (hearing-impaired or hearing impairment) and NH (normally-hearing or normal hearing).

carried out by Metz et al. (1985) revealed that PTA had a relatively low association with a number of acoustic measures that account for 78% of intelligibility variance. Thus, it is not the degree of hearing loss per se, but the developmental and/or experiential aftermath of the hearing loss and the way residual hearing is utilized by the speaker with HI that affects intelligibility (Monsen 1978, Smith 1975, Osberger & McGarr 1982, Metz et al. 1985).

Large variability characterizes the average intelligibility scores of HI productions among different studies. This variability may be related to many factors such as the type of schooling and training of the speaker, the composition of the test material, the context of communication, the listener's experience or familiarity with the speaker. Regarding the type of education, an assessment of children with profound hearing loss attending a school for the deaf showed an average intelligibility level of 19% (Smith 1975), while children of the same hearing level in mainstream education, tested with the same material, were judged as 39% intelligible on average (Gold 1978). In their study of speech intelligibility of children with cochlear implants, tactile aids or hearing aids, Osberger et al. (1993) note a trend for high intelligibility among subjects who use oral communication regardless of implant type. Thus, educational setting and use of oral communication play an important role in speech intelligibility.

Intelligibility scores can also significantly vary depending on the test material and its presentation to the listener, e.g. whether it consists of syllables, words or sentences, the phonetic composition and syntactic structure of the material, the number of repetitions, the recording quality, the visibility of the talker to the listener. As mentioned above, the average range of intelligibility scores of speakers with profound hearing loss were reported to be about 19-39% (Brannon 1964, Markides 1970, Smith 1975, Gold 1978). However, Monsen (1978) reports an intelligibility score of 76% for speakers with profound HI, an occurrence attributed to the use of phonemically and syntactically simpler and more familiar material. In his subsequent study, investigating the effect of various factors on the speech intelligibility of adolescents with severe and profound HI, Monsen (1983) notes that phonologic and syntactic complexity of the material significantly influences the scores of the least intelligible talkers when assessed by inexperienced listeners. In addition, polysyllabic words and consonant clusters, as well as sentences with complex syntactic structure are difficult to understand even for experienced listeners, while visibility of the talker's face boosts intelligibility by an average of 14% (cf. Mencke et al. 1983). Although to a speaker with HI, sentences may be more difficult to produce than words, as sentences may carry more phonemes and require the mastering of intonation patterns, McGarr (1981) found that intelligibility is greater when test words are embedded in sentences, because listeners make use of contextual information to understand HI speech.

The correlation between listener experience and intelligibility has been investigated by various researchers. "Intelligibility is rooted in characteristics of a speaker-listener dyad" (Kent et al. 1994: 81), therefore the listener's characteristics are bound to affect the intelligibility score (Boothroyd 1983, 1985, McGarr 1983, Monsen 1983). Higher mean intelligibility scores have been documented for experienced vs. inexperienced listeners (Mangan 1961, Thomas 1963, McGarr 1978). In addition, the recruitment of inexperienced listeners only has been deemed as a highly contributing factor to the low intelligibility levels reported in aforementioned studies (e.g. Markides 1970, Smith 1975), along with the use of more complex test materials, compared with other studies documenting higher intelligibility levels of speakers with HI (e.g. Monsen 1978). The superior performance of experienced listeners was initially attributed to better use of contextual information (Hudgins & Numbers 1942, Brannon 1964). In

opposition, McGarr (1981, 1983) found that better use of context does not account for experienced listeners' superiority in decoding deaf speech, as both experienced and inexperienced listeners demonstrate similar gain from context and suggests that their skills may relate to getting progressively accustomed to the perception task itself. Moreover, Monsen (1978) found a difference in performance between experienced and inexperienced listeners of just 9%. On the same trend, Mencke et al. (1983) observed a similar performance of experienced and inexperienced judges in auditory recognition of speech sounds in word contexts. In agreement with Thomas' observation (1963) that a significant increase of intelligibility occurs during the first year of a listener's contact with HI speech and decreases thereafter, Monsen (1983) claims that the existence of an advantage due to experience cannot be refuted but seems to be an advantage quickly and easily acquired.

1.2 Intelligibility and acoustic speech parameters

HI speech intelligibility has been examined in relation to various speech parameters, such as frequency of consonantal and vocalic errors, assessment of suprasegmental features, and temporal and spectral acoustic variables (Weismer & Martin 1992).

Variable results have been reported regarding the most frequent errors in vowels and consonants, depending on methods, materials and subject characteristics of the studies. Concerning consonantal errors, final consonant omission, voicing errors and cluster reduction have been generally documented as detrimental to speech intelligibility (Hudgins & Numbers 1942, Nober 1967, Markides 1970, Smith 1975, McGarr & Osberger 1978, Monsen 1978, Levitt & Stromberg 1983). Regarding vocalic errors, substitution, neutralization, diphthongization, nasalization, as well as diphthong splitting and/or simplification, have been documented (Hudgins & Numbers 1942, Markides 1970, Smith 1975, Osberger & McGarr 1982), although there is no consensus in the literature concerning their relative contribution to an overall intelligibility deficit in HI speech (Gold 1980).

In an attempt to evaluate the relationship between different acoustic characteristics of speech and intelligibility, Monsen (1978) found a 0.86 correlation of intelligibility with three acoustic variables, namely, the VOT difference between [t] and [d], the F2 difference between [i] and [ɔ] and a rating for the production of liquid and nasal formants. Further, in order to eliminate the intercorrelation among predictor variables, Metz et al. (1985) used 11 different acoustic measures in a stepwise regression analysis to account for intelligibility and found that a factor including these eleven acoustic measures (such as VOT distinctions, F1 difference between [a] and [i], F2 difference between [i] and [ɔ] and F2 change in the [a^{i}] diphthong) accounted for 78% of the variance in intelligibility. In an electropalatographic study of Greek HI speech (Nicolaidis 2004), increased number of consonantal articulation errors, high production variability and contrast neutralization have been reported as indicative of reduced intelligibility.

Longer segmental and utterance durations have been reported by a large number of studies on HI speech (Calvert 1961, Osberger & Levitt 1979, Okalidou 1996, Vandam et al. 2011 for English, Coimbra et al. 2011 for Portuguese, Nicolaidis & Sfakianaki 2007, 2016, Sfakianaki 2012 for Greek). Prolonged durations can cause inappropriate intonation and rhythm and have been reported to negatively affect intelligibility (Smith 1975, McGarr & Osberger 1978, Parkhurst & Levitt 1978). Nevertheless, the correction of timing errors via speech synthesis was found to bring about a nonsignificant average improvement of intelligibility (Osberger & Levitt 1979).

Additionally, as documented in an electropalatographic study of duration and variability in Greek consonant contact patterns (Nicolaidis 2007), speakers who produce prolonged consonants of similar duration can significantly differ in intelligibility level.

Intelligibility level is a useful indicator of oral communication abilities and its relation to speech production characteristics needs to be further explored, so as to design effective remediation for individuals with hearing loss. The purpose of the present study is to evaluate the relationship between intelligibility and acoustic characteristics of speech, providing data from Greek speakers with normal hearing (NH) and profound hearing impairment (HI). More specifically, we aim at:

a) assessing the intelligibility level of 10 Greek adults with profound HI using conventional hearing aids, and

b) investigating the relationship between intelligibility level and selected acoustic properties of the point vowels /i, a, u/, in terms of (i) position in the acoustic space, (ii) token-to-token variability and (iii) duration.

2. Materials and methods

Two experiments were carried out, the first one for rating the intelligibility level of the speech of 10 adults with profound HI and the second one for recording and analysing the speech of the 10 adults with profound HI and the speech of five adults with NH (control group). All participants agreed to participate in the study and signed an informed consent.[2] We recorded symmetrical disyllabic words, some real and some nonce, of the structure /pVpV/ for the acoustic experiment, and 101 real words and 25 sentences for the intelligibility experiment (see more information on materials in sections 2.1.2 and 2.2.2 below). The reason for selecting different sets of materials for the two experiments was that we wished to investigate vowel characteristics in a controlled context and especially a bilabial context that has a minimum influence on formant values, while at the same time we needed to capture intelligibility as a comprehensive measure stemming from spoken language in its natural form, hence the choice of real words and sentences. Thus we examined if and how low level parameters (i.e., F1, F2, vowel area, variability and duration) are related to high level parameters (i.e., word and sentence intelligibility), a methodology also adopted by other studies in speech disorders (e.g. Monsen 1983, Abel et al. 1990, Turner et al 1995, Bradlow et al. 1996).

2.1 The intelligibility experiment

2.1.1. Participants

The speakers taking part in the experiment were five men and five women, 20-35 years of age, with prelingual, bilateral, sensorineural hearing loss ranging from 91 to 105 dB HL (Pure Tone Average[3] at 500, 1000 and 2000 Hz). All speakers had had no other illnesses diagnosed, had been aided before the age of 4 with conventional hearing aids, had received no cochlear implants and spoke Standard Modern Greek. Except for one speaker (HI_04), who preferred using sign language and had attended the primary school for the deaf for five years, all other speakers used oral communication, had been mainstreamed during their school years and had been receiving speech therapy for many years.

[2] This study followed principles in the Declaration of Helsinki.

[3] Pure Tone Average is the average of hearing sensitivity in decibels at 500, 1000, and 2000 Hz. It is calculated by adding up the hearing threshold levels at the aforementioned frequencies and dividing by three. This calculation is routinely used by audiologists and occupational health specialists in order to assess an individual's degree of hearing loss.

The listeners were 60 Greek adults, undergraduate and postgraduate students of the School of English Language and Literature of the Aristotle University of Thessaloniki. They had never knowingly heard HI speech prior to the experiment (naïve listeners) and they all had no reported problems with speech and/or hearing.

Speakers with NH did not take part in this experiment. NH speech was considered to be 100% intelligible, as under the circumstances of the experiment (laboratory speech, quiet conditions, two repetitions of each item) speakers with no speech and hearing problems are expected to be fully understood by listeners with no hearing problems.

2.1.2. Speech material

The corpus recorded for the intelligibility experiment consisted of 101 words and 25 sentences. The words were adopted from the Phonetic and Phonological Development Test[4] developed by the Panhellenic Association of Logopedists and Speech & Language Therapists (Panhellenic Association of Logopedists 1995). A section with sentences was constructed for the experiment, as everyday speech is usually in context, hence this type of material is needed in order to obtain a more accurate and true depiction of the speakers' intelligibility level. The sentences were 8 to 14 syllables long and contained all Greek phonemes and frequently used clusters in word-initial position (see Appendix).

2.1.3. Experimental procedure

The experimental procedure comprised two stages. The first stage involved the recording of the corpus by the 10 speakers with HI. The recording took place in a sound proof room at the premises of the Association of Parents and Guardians of Hard of Hearing Children of Thessaloniki,[5] used regularly for audiological evaluations. All recordings were made using a YAMAHA external hard disk recording studio connected through a USB port to a laptop and a Shure microphone which was placed on a stand, approximately 15 cm from the subject's mouth and in parallel to the face so as to avoid overloading. Cool Edit 2000 software was used for checking the recording level and saving the files at a sampling frequency of 22050 Hz.

The second stage of the experiment took place at the Phonetics Laboratory of the School of English Language and Literature of the Aristotle University of Thessaloniki. The 60 listeners were divided into groups, so that the speech of each subject was evaluated by six listeners. Each listener only heard one speaker so as to eliminate any accumulating familiarity effects brought by repeated listener exposure to the same word and sentence material uttered by different speakers (Metz et al. 1985). The recorded material was randomized once for each speaker; first words and then sentences were played back for the listeners. After listening to each item twice, the listeners were instructed to write down the word or sentence they had heard. The two repetitions were played back 1 second apart from each other. When the second repetition was over the listeners immediately wrote down the item they had heard. The experimenter played back the next item as soon as all listeners had finished writing. After moving on to the next item, the listeners were not allowed to go back and change their response to previous items.

[4] The test was administered to 300 children aged 2;6 to 6;0 years from the County of Attica, Greece, during the years 1989-1992.

[5] This Association has been renamed Association of Parents & Guardians of Deaf & Hard of Hearing Children of Central Macedonia (http://www.varikoos.gr/75892D3E.el.aspx).

2.1.4. Scoring

The scoring system was based on systems devised for English intelligibility tests (Monsen 1978, 1983, Picheny et al. 1985, Osberger et al. 1993). Adjustments were made to accommodate our data due to the different morphology, grammar and syntax of Greek. A word would be scored as correct only if all its phonemes had been recognized. For example, ˈvimata (steps) instead of ˈcimata (waves) was allowed no points. However, words with incorrect tense/person of verb and number of noun were scored as half correct, in accordance with Monsen (1978, 1983) and Picheny et al. (1985). The following are examples of words that were scored as half correct:

- viˈvli**a** instead of viˈvli**o** ("books" instead of "book")
- ˈkan**un** instead of ˈkan**e** ("they do" instead of "you do"-imperative)
- ˈekan**a** instead of ˈekan**e** ("I did" instead of "he did")
- ˈleros**e** instead of ˈleros**es** ("he soiled" instead of "you soiled")

For the scoring of the words in the sentences, two different methods were tested with part of the data (Monsen 1978, 1983, Osberger et al. 1993).[6] Since no significant differences were located, the method adopted by Osberger et al. (1993) was preferred due to its simplicity. In line with this method, no weighting was applied to words according to their semantic contribution to the sentence, hence all words were assigned the same value. For example, the sentence *Ζητούσε να τον δει ένας φίλος του* (/ziˈtuse na ton ði ˈenas ˈfilos tu/ "A friend of his came looking for him") is assigned 7 points because it contains 7 words. If a listener writes down *Ζήτησε να δει ένα φίλο του* (/ˈzitise na ði ˈena ˈfilo tu/ "He asked to see a friend of his"), 3 words are correct (/na/, /ði/, /tu/), 3 words half correct (/ˈzitise/, /ˈena/, /ˈfilo/) and 1 word is missing (/ton/), so the sentence receives (3 + 1,5 + 0 =) 4,5 points. If a listener writes down *Ζήσε με το φίλο του* (/ˈzise me to ˈfilo tu/ "Live with a friend of his"), 1 word is correct (/tu/), 1 word is half correct (/ˈfilo/) and the rest are incorrect, hence the sentence receives (1 + 0,5 =) 1,5 points.

Reliability among listeners' answers was examined with Cronbach's Alpha statistic. Its value in the great majority of cases was between 0.7 and 0.9 indicating good internal consistency (see Table 1).

[6] According to Monsen's scoring system, all sentences are equal in value regardless of length or difficulty. Hence, each sentence is assigned a value of 100%, out of which 70% is accorded to content words, as they contribute more heavily toward the total message of the sentence, and 30% to function words of the sentence. Furthermore, depending on their semantic contribution and their frequency of occurrence in the language, each content and function word of the sentence is assigned a slightly different value (Monsen 1983: 290). According to the Osberger et al. (1993) system, judges' responses are scored in terms of percentage of words correctly understood, but all words have the same value, hence scoring is unweighted, as their pilot data suggested that it had no difference in the result.

Table 1. Cronbach's alpha values for internal consistency among the six listeners' judgments of each speaker

Speakers	Words	Sentences
HI_01	0.703	0.622
HI_02	0.722	0.866
HI_03	0.889	0.845
HI_04	0.768	0.760
HI_05	0.845	0.853
HI_06	0.886	0.754
HI_07	0.745	0.567
HI_08	0.844	0.654
HI_09	0.838	0.896
HI_10	0.910	0.816

2.2 The acoustic experiment

2.2.1 Participants

Two groups took part in the acoustic experiment, the HI group and the control group. The HI group consisted of the 10 adults with HI (see section 2.1.1. above). The control group comprised five adults, two men and three women, with no history of hearing or speech problems. They were 18 to 21-year-old undergraduate university students and spoke Standard Modern Greek. No participant reported any speech or hearing problems.

2.2.2. Speech material

The material included symmetrical disyllabic words, some meaningful and some nonsense, of the structure /pVpV/ with the point vowels /i, a, u/. Half the words were stressed on the first syllable and half on the second syllable i.e., /ˈpipi/, /piˈpi/, /ˈpapa/, /paˈpa/, /ˈpupu/, /puˈpu/. The words were embedded in the carrier phrase /ˈleje _____ ˈpali/ ("Say _____ again."). Each phrase was repeated 10 times providing a list of 60 randomized phrases in total per speaker.

2.2.3. Experimental procedure and data analysis

The speech material and the material for the intelligibility experiment (see section 2.1.3. above for procedure) were recorded in the same session with a short break between them. The recording by the speakers with NH took place at the Phonetics Laboratory of the School of English Language and Literature of the Aristotle University of Thessaloniki with the equipment described above. The editing and analysis of the data was carried out with the Praat software program (Boersma & Weenink 2013). The sample analysed was 1800 vowels (15 speakers x 60 phrases x 2 vowels per phrase). Formants F1 and F2 were automatically measured by the system at the vowel midpoint using LPC and a Gaussian analysis window of 25 ms. Number of formants was set at five, as recommended by the system, and the maximum formant value was set at 5000 for male and 5500 for female speakers. Next, the measurements were manually checked. Vowel duration in both syllable positions was also measured. To facilitate duration measurement boundaries were placed at the beginning and end of the vowel. The start point boundary was manually set at the start of the first cycle, which coincided with the onset of the formant structure on the spectrogram (F1, F2), and the end point boundary was manually set again at end of the last cycle where the clear formant structure ended. The F1 and F2 formant values were subsequently normalised using the modified Watt & Fabricius (2002) method *(*ModWF or mW&F*),* available via the online normalisation tool NORM (Thomas & Tyler 2007). This method expresses

formant values relative to the centroid of a speaker's vowel space (Watt & Fabricius 2002) and is suitable for direct visual and statistical comparison of vowel triangles for multiple speakers of different sexes. In a recent study that compared twenty different vowel formant normalisation methods, among them Bark-diff, Nordström, LCE, Gerstman, Lobanov, mW&F, Nearey, etc., the mW&F method was ranked among the top ones (Flynn & Foulkes 2011). Regarding statistical treatment, univariate analyses of variance were run for variables F1, F2 (normalised values) and duration vs. factors intelligibility level (see next section for subjects' grouping) and vowel in SPSS (v. 19) and Tukey pairwise post-hoc tests were performed in Minitab (v. 15) so as to locate statistically significant differences between groups. An additional ANOVA was conducted in order to examine if intelligibility level had an effect on the vowel space area. The vowel space area for each group was calculated using the formula abs((xB*yA-xA*yB) + (xC*yB-xB*yC) + (xA*yC-xC*yA))/2, where x = F2/S(F2), y = F1/S(F1) (normalised formant values), A = /i/, B = /a/ and C = /u/. Pairwise post-hoc comparisons were run between groups.

3. Results

3.1. Speech intelligibility

Table 2 shows the results of the intelligibility experiment (in %) for words and sentences as well as the total score for each speaker with HI. We note that:

1. Nine out of the 10 speakers were above 73% intelligible, while speaker HI_04 was far less intelligible with a mean score of 15%.

2. Nine out of the 10 speakers got a higher score in sentences than in words, with the exception of speaker HI_04.

3. Some speakers with a higher degree of hearing loss were more intelligible than speakers with a lower degree of hearing loss (e.g. speaker HI_01 vs. speaker HI_09).

Table 2. Mean intelligibility score and standard deviation for words and sentences as well as the total for each speaker with HI. Information about the speakers' gender and PTA (Pure Tone Average at 500, 1000 and 2000 Hz) is also provided

Speaker	Gender	PTA (dB)	Intelligibility Score (%)				
			Words		Sentences		Total
			Mean	SD	Mean	SD	Mean
HI_01	F	101.7	94.55	1.29	95.27	1.47	94.91
HI_02	F	101.6	96.12	1.97	99.12	0.31	97.62
HI_03	M	103.3	67.90	3.53	81.00	5.89	74.45
HI_04	F	105.0	15.84	3.91	11.74	3.76	13.79
HI_05	M	101.0	62.05	6.65	83.78	3.52	72.92
HI_06	F	103.3	88.53	2.20	89.96	3.62	89.25
HI_07	M	98.3	86.63	2.26	96.46	2.92	91.55
HI_08	M	99.0	82.76	3.14	95.33	2.34	89.05
HI_09	F	91.7	83.17	3.22	89.52	4.13	86.35
HI_10	M	98.3	89.19	4.29	97.35	0.63	93.27

According to their intelligibility score, the 10 speakers with HI were divided into four groups as illustrated in Table 3. Speakers in Group 1 were very highly intelligible (>95%, two female), speakers in Group 2 were highly intelligible (86-93%, two female and three male), while speakers in Group 3 were moderately intelligible (73-75%, two male). Group 4 consisted only of one female speaker (HI_04) who achieved a very low intelligibility level (14%).

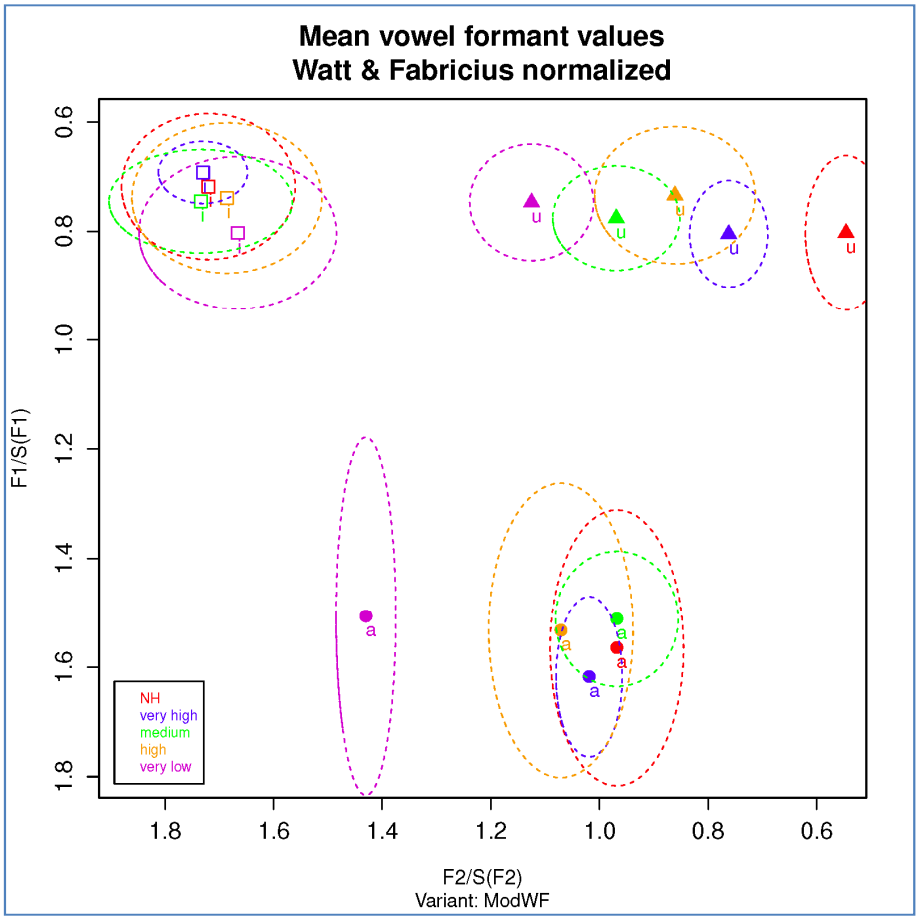
Table 3. Speakers with HI grouped according to their intelligibility level

Group	Speakers	Intelligibility Level
1	HI_01, 02	very high
2	HI_06, 07, 08, 09, 10	high
3	HI_03, 05	medium
4	HI_04	very low

3.2. Acoustic characteristics

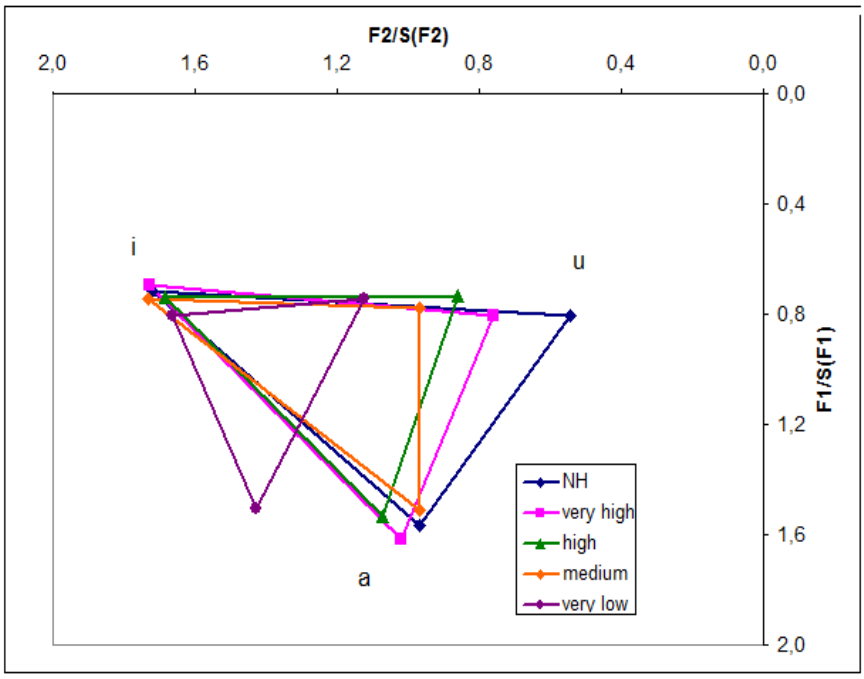
The ANOVA main effect of intelligibility level was significant for all variables (F1: $F(4, 1799) = 3.630$, $p < 0.01$, F2: $F(4, 1799) = 177.463$, $p < 0.001$, duration: $F(4, 1796) = 314.124$, $p < 0.001$. Figure 1 demonstrates the normalised mean vowel formant values (see section 2.2.3. above for normalisation method) of the four intelligibility groups (very high, high, medium and very low), as well as the NH group. We can observe that the lower the intelligibility level the more anteriorly HI /u/ was realized and the longer its distance from NH /u/. The mean value and standard deviation of the high front vowel /i/ was found to be similar for all groups, while the low open vowel /a/, which in Standard Greek is realized more centrally as [ɐ] (Nicolaidis 1991), was significantly fronter than normal for the very low intelligibility group. Token-to-token variability did not seem to associate with intelligibility level, as the high intelligibility group showed more /u/ and /a/ variability than other groups.

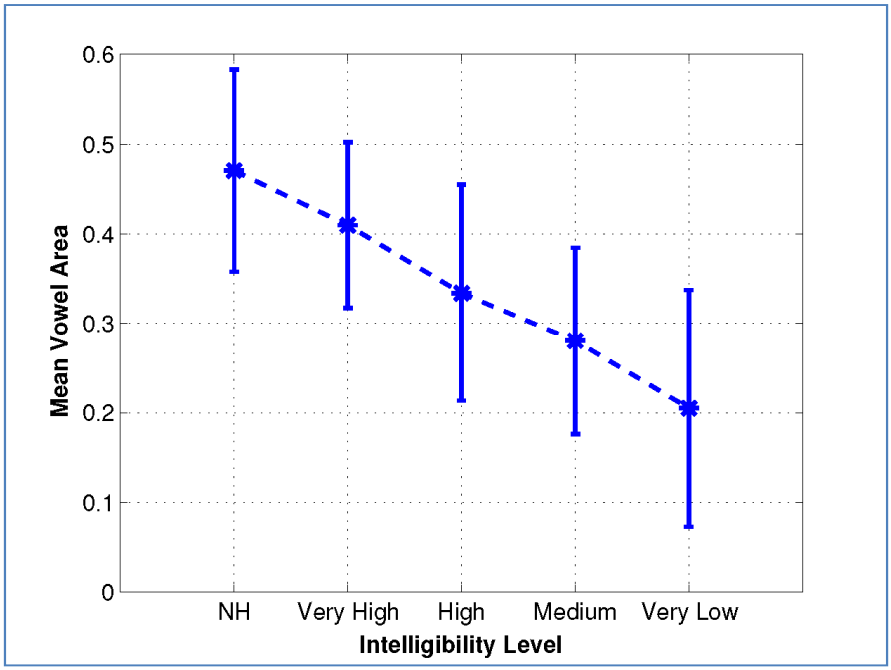
Figure 1. Normalised mean formant values of vowels /i, a, u/ with ellipses drawn with radii of two standard deviations of the four intelligibility groups and the NH group



The vowel space area for each group is shown in figure 2a. We note that the vowel space of the NH group covered the largest area and that as intelligibility level fell the area decreased. Figure 2b demonstrates the mean vowel space area and standard deviation for each group. The main effect of intelligibility level was found significant F1: $F(4, 590) = 79.34$, $p < 0.001$. All pairwise comparisons among the five groups were also found statistically significant.

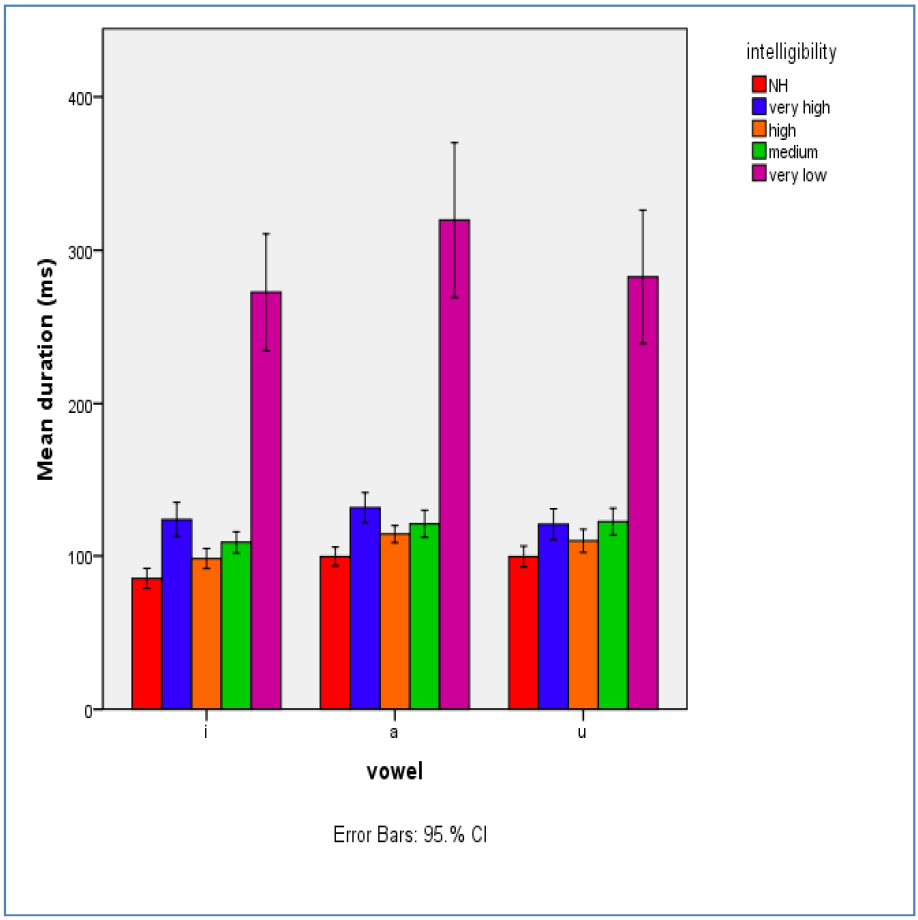
Figure 2a (top) Normalised vowel spaces, and **2b (bottom)** vowel space area values (means and standard deviations) of the four intelligibility groups and the NH group





Regarding vowel durations, as illustrated in Figure 3, all HI intelligibility groups produced significantly longer vowels than normal. Pairwise comparisons between the NH and the intelligibility groups were statistically significant. However, all groups followed the NH vowel duration pattern /a/ > /u/ > /i/. The very low intelligibility speaker prolonged her vowels far more than the other three intelligibility groups. Among the rest of the groups, however, the very high intelligibility group showed the highest duration values, while the high intelligibility group had the lowest values among the intelligibility groups, coming closer to the NH group in terms of vowel duration. Tukey pairwise comparisons between the NH and the intelligibility groups were statistically significant.

Figure 3. Duration (mean values in ms and standard deviations) of vowels /i, a, u/ of the four intelligibility groups and the NH group



4. Discussion

The results of the intelligibility experiment carried out to assess the speech of 10 Greek young adults with prelingual profound HI, ranging from 91 to 105 dB, demonstrated that nine out of the 10 speakers were moderately to very highly intelligible (73% to 98%). This outcome is quite encouraging, as it shows that under certain circumstances individuals with prelingual, profound hearing loss are able to develop speech that can be understood by naïve listeners. According to our intelligible speakers' profiles, these circumstances seem to involve an early and consistent use of hearing aids, almost exclusive use of oral communication, attendance of mainstream classroom and substantive speech training for many years. In general, the degree of hearing loss was not found to associate with the intelligibility level, as some speakers with a higher

degree of hearing loss were found to be more intelligible than others with a lower degree of hearing loss. This is in line with previous findings that report no direct relationship between hearing level and intelligibility especially for speakers with profound hearing loss (Smith 1975, Monsen 1978, Osberger & McGarr 1982, Metz et al. 1985, Öster 2002).

However, the speaker with the lowest intelligibility level (14%) also had the highest degree of hearing loss (105 dB mean PTA with no response at 2000 Hz). In addition, her preferred way of communication was sign language and she did not feel comfortable using oral communication, as opposed to the rest of the speakers with HI. Her schooling background was also different; she had attended the School for the Deaf for almost all her primary school years. Therefore, besides the degree of hearing loss, communication method and type of schooling could also have played a role in her not having developed intelligible speech. In accordance with previous literature, high intelligibility ratings have been documented for children who use oral communication (e.g. Osberger et al. 1993, Tobey et al. 2003, Girgin & Özsoy 2008). However, reported intelligibility scores differ across studies, as speaker profiles and materials used in experiments have been variable. For the present study, both words and sentences were used to evaluate intelligibility level. Our results are in accordance with literature on English documenting higher intelligibility scores when words are placed in meaningful sentences than in word lists (McGarr 1981). Nevertheless, our results showed that context did not seem to assist the listeners evaluating the low intelligibility speaker; hence when speech is not intelligible, context may not play a significant role in facilitating understanding.

An interesting finding is that /u/-fronting varied significantly among different intelligibility groups. The back vowel /u/ was realised more anteriorly for the groups with lower intelligibility levels, with the most fronted production for the group with the lowest intelligibility. Thus, the distance from the NH /u/ was the largest for the group with the lowest intelligibility level. A more anterior /u/ production certainly decreases the contrast with the high front vowel /i/ and may impoverish vowel identification, hence speech intelligibility. Similar results regarding intelligibility deterioration due to decreased vowel contrast in HI speech have been reported for English. McGarr & Gelfer (1983) observed significant fronting of /u/ tokens leading to overlap with /i/ tokens and resulting in an 88.5% misidentification of the back high English vowel by experienced and inexperienced listeners. Additionally, a significant correlation between speech intelligibility and F2 difference between [i] and [ɔ] in English has been reported by Monsen (1978) and Metz et al. (1985). A high correlation between vowel space and speech intelligibility has also been found for individuals with amyotropic lateral sclerosis (Turner et al. 1995). According to the study, the vowel space area composed by American vowels [i], [æ], [ɑ] and [u] accounted for 45% of the variance in speech intelligibility. Significant fronting of /a/ by the very low intelligibility speaker was also observed in our data. In general, vowel fronting has been documented in English HI speech as well (Hudgins & Numbers 1942, Stein 1980, McGarr & Gelfer 1983, Rubin 1984). A strong relationship between vowel working space area and intelligibility was also documented in a study on Mandarin dysarthric speech (Liu et al. 2005).

Concerning vowel variability and intelligibility level, we did not observe an inverse relationship as with /u/-fronting and vowel space shrinkage. The high intelligibility group demonstrated the highest variance for /u/, the very low intelligibility group showed the highest variability for /i/ and /a/, while the very high intelligibility group displayed the lowest vowel variability –lower even than normal. However, differences in the composition of the groups e.g. in subject number and gender (see

Tables 1 and 2 in section 3.1.) may have interfered with the result even after normalisation, thus the issue should be further investigated with more balanced groups.

Concerning vowel duration, the NH durational pattern /a/ > /u/ > /i/ was observed by the speakers with HI regardless of intelligibility level. This pattern follows the universal trend for intrinsic vowel duration, i.e. low vowels are longer than high vowels (House 1961, Lehiste 1970, Maddieson 1997) and has been reported for Greek vowels in numerous previous studies (e.g. Dauer 1980, Fourakis et al. 1999, Arvaniti 2000). However, in accordance with the literature (see 1.2.), HI vowels were consistently longer than NH vowels. Although the very low intelligibility speaker produced the longest vowels, vowel duration did not seem to associate with intelligibility level for the rest of the groups, as the very high intelligibility group of our study displayed longer vowel durations than the three remaining groups. These results suggest that the relationship between speech intelligibility and segmental duration may not necessarily be a linear one. This is also supported by evidence on the duration of HI consonants; Greek speakers with HI differing significantly in intelligibility level have been found to produce similarly prolonged consonants (Nicolaidis 2007). As mentioned in the literature, it is not the slowness of speech due to prolonged absolute segmental durations that impairs HI speech intelligibility, but rather relative timing characteristics and various interarticulatory timing abnormalities in speech production (e.g. McGarr & Osberger 1978, McGarr & Löfqvist 1982, McGarr & Campbell 1995, Okalidou 2002).

5. Conclusions

The intelligibility level of the Greek speakers with HI examined here ranged from 65% to 97%, with the exception of one almost totally unintelligible speaker. This result may be to some extent associated with the less consistent use of the hearing aid, as well as with the less oral-based educational background of this speaker compared with that of the rest of the speakers. Context was found to facilitate intelligibility, especially for moderately intelligible talkers, but its role became less significant when intelligibility reached very high or very low levels. An important finding of the present study is that /u/-fronting and vowel space shrinkage leading to vocalic contrast reduction was found to increase as intelligibility level decreased. Such a straightforward relationship was not revealed for token-to-token variability or vowel duration, i.e., intelligibility level did not necessarily drop as acoustic variability and point vowel duration increased. Relative timing rather than segmental duration could be of more consequence to intelligibility. However, further research with larger groups balanced for number of subjects and gender is necessary in order to reach firmer conclusions.

The present study constitutes a first attempt to assess intelligibility and investigate its relationship with selected acoustic characteristics in Greek HI speech. Intelligibility level is a useful indicator of oral communication abilities, and its relation to speech production characteristics needs to be explored, so as to design effective remediation for individuals with hearing loss.

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APPENDIX

The following 25 sentences were part of the intelligibility experiment:

1) to aˈɣori ðjaˈvazi viˈvlia sto sxoˈlio
Το αγόρι διαβάζει βιβλία στο σχολείο/The boy reads books in school.
2) ˈʝemisa to buˈkali me neˈro
Γέμισα το μπουκάλι με νερό/I filled the bottle with water.
3) afˈti i ˈɣata ɲauˈrizi ðinaˈta
Αυτή η γάτα νιαουρίζει δυνατά/This cat meows loudly.
4) to moˈro ˈklei ˈmesa stin ˈkuɲa
Το μωρό κλαίει μέσα στην κούνια/The baby is crying in the cradle.
5) to ˈpsari zi ˈmesa sti ˈθalasa
Το ψάρι ζει μέσα στη θάλασσα/The fish lives in the sea.
6) ˈçonize ˈolo to proˈi
Χιόνιζε όλο το πρωί/It snowed all morning.
7) ˈesfikse ta ˈʝemja tu aˈloɣu
Έσφιξε τα γκέμια του αλόγου/He tightened the horse's reins.
8) i fotˈça sto ˈdzaki ˈiçe ˈzvisi
Η φωτιά στο τζάκι είχε σβήσει/The fire at the fireplace had gone out.
9) to ʎoˈndari ˈksaplose sta ˈxorta
Το λιοντάρι ξάπλωσε στα χόρτα/The lion lay on the grass.
10) ˈleroses to ˈkitrino ˈforema
Λέρωσες το κίτρινο φόρεμα/You stained the yellow dress.
11) ˈrotisa ti miˈtera mu to ˈvraði
Ρώτησα τη μητέρα μου το βράδυ/I asked my mother in the evening.
12) o uraˈnos ˈʝemise aˈsterja
Ο ουρανός γέμισε αστέρια/The sky filled with stars.
13) ˈekane mja meˈɣali ˈgafa sti ðuˈʎa
Έκανε μια μεγάλη γκάφα στη δουλειά/He made a blunder at work.
14) min ˈanʝiksis to tiˈɣani ʝaˈti ˈcei
Μην αγγίξεις το τηγάνι γιατί καίει/Don't touch the frying pan because it's hot.
15) θiˈmame to paraˈmiθi me to ˈkastro
Θυμάμαι το παραμύθι με το κάστρο/I remember the castle fairy tale.
16) ˈotan ˈʎoni to ˈçoni ˈʝinete neˈro
Όταν λιώνει το χιόνι γίνεται νερό/When ice melts it turns into water.
17) ˈkane mja ˈtumba sto ˈpatoma
Κάνε μια τούμπα στο πάτωμα/Do a turnover on the floor.
18) ˈexase ʝaˈti ˈiçe ˈʝiɲa
Έχασε γιατί είχε γκίνια/He lost because of bad luck.
19) to aeroˈplano ˈmbice sta ˈsinefa
Το αεροπλάνο μπήκε στα σύννεφα/The aeroplane entered the clouds.
20) ˈndiθice vjastiˈka ce ˈefiʝe ˈɣriɣora
Ντύθηκε βιαστικά και έφυγε γρήγορα/He/she dressed hastily and left quickly.
21) me to ˈuzo meˈθas ˈefkola
Με το ούζο μεθάς εύκολα/You get drunk easily on uzo.
22) ziˈtuse na ton ði ˈenas ˈfilos tu
Ζητούσε να τον δει ένας φίλος του/A friend of his came looking for him.
23) to roˈloi ˈxtipise meˈsanixta
Το ρολόι χτύπησε μεσάνυχτα/The clock struck midnight.

24) ˈekana poˈla ˈlaθi sta ˈɲata mu
Έκανα πολλά λάθη στα νιάτα μου/I made many mistakes when I was young.
25) greˈmizun to paˈʎo mu ˈspiti
Γκρεμίζουν το παλιό μου σπίτι/My old house is being torn down.