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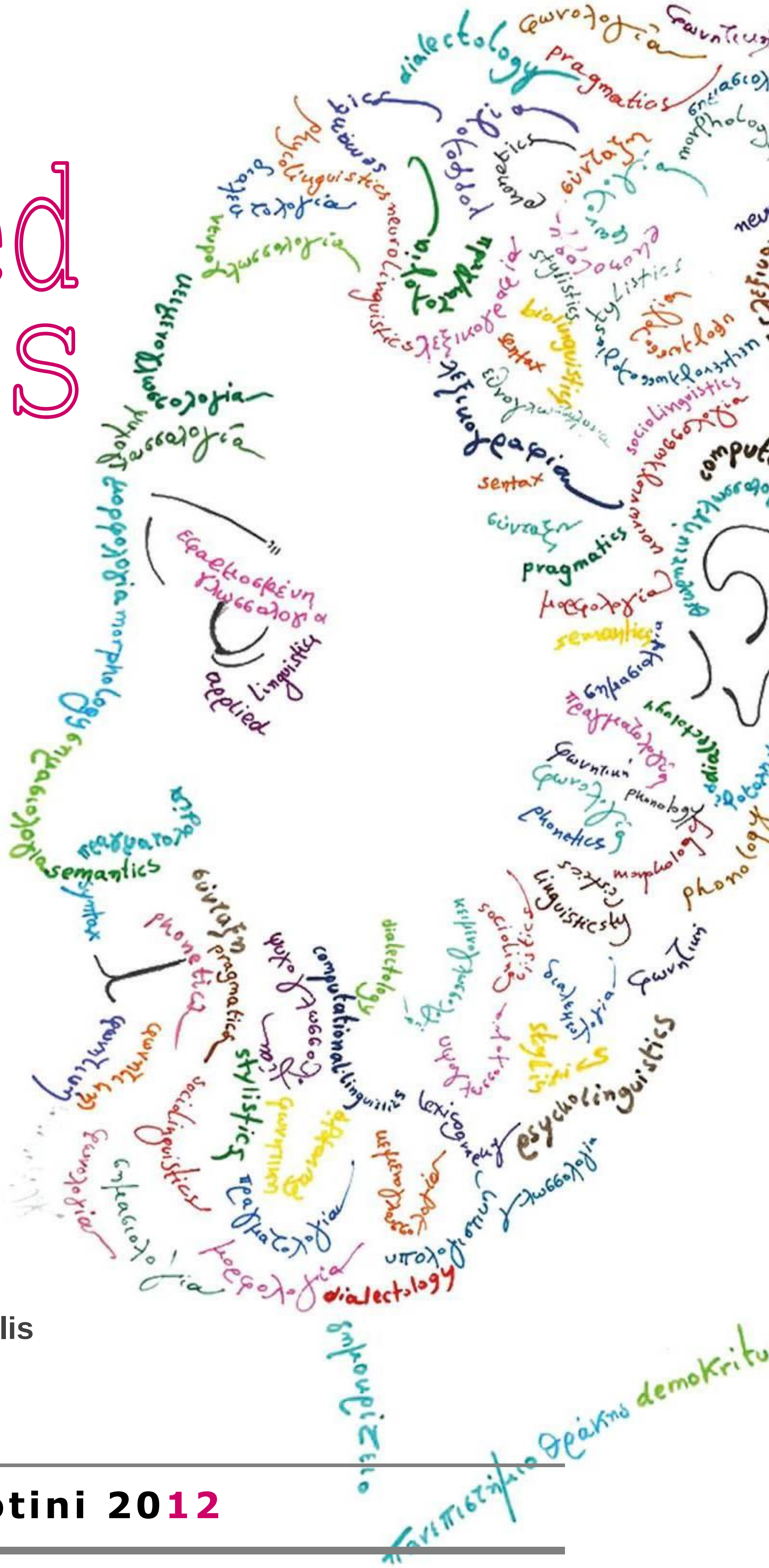


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Komotini 2012

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**ISBN** 978-960-99486-7-8

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Διεθνές Συνέδριο Ελληνικής Γλωσσολογίας
International Conference of Greek Linguistics
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# F1 COARTICULATION PHENOMENA IN THE PRODUCTIONS OF GREEK SPEAKERS WITH HEARING IMPAIRMENT

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## ABSTRACT

*Τα φαινόμενα της συνάρθρωσης στην ομιλία των ατόμων με βαρηκοΐα/κώφωση παρουσιάζουν μεγάλο ενδιαφέρον. Ενώ το θέμα αυτό διερευνάται τα τελευταία χρόνια στην αγγλική γλώσσα, δεν υπάρχουν αντίστοιχες έρευνες στα ελληνικά. Η παρούσα εργασία εξετάζει τη θέση και τη διασπορά των τριών ακραίων φηνηέντων, καθώς και τη συναρθρωτική επιρροή από σύμφωνο σε φωνήεν και από φωνήεν σε φωνήεν, σε δισύλλαβες παραγωγές 14 Ελλήνων και Ελληνίδων, 9 με κώφωση (>91 dB HL), και 5 με φυσιολογική ακοή. Η συνάρθρωση μελετάται επί του πρώτου διαμορφωτή, ο οποίος έχει εξεταστεί πολύ λιγότερο από τον δεύτερο διαμορφωτή, παρ'ό,τι δίνει σημαντικές πληροφορίες για το ύψος της γλώσσας και τη θέση της κάτω γνάθου.*

**Λέξεις κλειδιά:** βαρηκοΐα/κώφωση, ελληνικά, συνάρθρωση, ακουστική ανάλυση, πρώτος διαμορφωτής

## 1. Introduction

Speakers with prelingual hearing impairment (HI) face serious perceptual constraints. They have acquired speech without the assistance of auditory feedback which has an essential role in the development and continual tuning of the speech production mechanism (Lane et al., 2007). As a consequence, they demonstrate a variety of deficits in their speech, including vocalic and consonantal errors as well as differential coarticulatory patterns and deviant temporal and prosodic characteristics. They tend to produce less differentiated vowels, restricted in formant range, resulting in a reduced vowel space and longer segmental durations (Monsen, 1976a; Whitehead & Jones, 1976; McGarr & Osberger, 1982; Rubin, 1985; Robb & Pang-Ching, 1992; Okalidou, 1996; Ryalls et al., 2003; Nicolaidis & Sfakianaki, 2007; Ozbič & Kogovšek, 2010). Concerning consonantal production, obstruents formed in the middle of the mouth have been found more problematic than more anterior or posterior segments (Nober, 1967; Smith, 1975; Gold, 1978; Barzaghi & Madureira, 2005). The sibilants are among the most problematic articulations for speakers with HI (Markides, 1970; McGarr et al., 2004). EPG patterns of the fricative [s] and the palatals [c] and [X] were found more deviant than that of other consonants produced by Greek speakers with HI (Nicolaidis, 2004).

Many models and theories have been developed to account for the phenomenon of coarticulation in normal hearing (NH) speech. Within the theoretical framework of coproduction, Recasens, Pallarès, & Fontdevila (1997) proposed the Degree of Articulatory Constraint (DAC) Model of Coarticulation. Drawing from the notion of coarticulatory resistance (Öhman, 1966; Bladon & Al-Bamerni, 1976), the DAC model assigns different DAC values to vowels and consonants depending on the articulatory demands for their production. The basic premise of the model concerns the tongue dorsum; the higher the involvement of the tongue dorsum in the constriction formation, the more constrained the phoneme (Recasens, 1985). Constrained phonemes display a high degree of coarticulatory resistance and aggression towards adjacent phonemes. Thus, a highly constrained consonant is expected to exhibit significant consonant-to-vowel (C-to-V) effects, while inhibiting vowel-to-consonant (V-to-C) and vowel-to-vowel (V-to-V) effects.

Regarding HI speech, smaller coarticulatory effects and less consistent coarticulatory patterns than normal have been reported by many researchers (Monsen, 1976b; Rothman, 1976; Baum & Waldstein, 1991; Waldstein & Baum, 1991; Ryalls et al., 1993; Barzaghi & Madureira, 2005). Smaller V-to-C effects compared with other consonants have been displayed for the Greek alveolars [t] and [s]; they

In Z. Gavriilidou, A. Efthymiou, E. Thomadaki & P. Kambakis-Vougiouklis (eds), 2012,
*Selected papers of the 10th ICGL*, pp. 520-527. Komotini/Greece: Democritus University of Thrace.

are realized with considerable contact at the palatal region, as shown in an EPG study of Greek HI speech (Nicolaidis, 2007). Reduced V-to-V coarticulation across the bilabial [b] and increased V-to-V coarticulation across the alveolar [d] has been located acoustically along the F2 dimension for American deaf speakers (Okalidou & Harris, 1999). Reduced V-to-C coarticulation for the bilabial [b] and increased coarticulation for the alveolar [d] and the palatal [|] has been observed in F2 locus equations of American HI speech, although patterns were variable among speakers (McCaffrey Morrison, 2008).

To the best of our knowledge, C-to-V and V-to-V coarticulation in HI speech has not been studied systematically along the F1 dimension. Emphasis has been rendered on the F2 axis which mirrors front-back tongue movement. However, F1 coarticulation data can also prove informative as it relates to the degree of tongue and jaw height variation. The vertical dimension has generally been found less problematic, as it is both visually and auditorily more accessible to speakers with HI (Monsen, 1976b). Hence, the main aim of the present study is to examine selected acoustic characteristics of the three point vowels in /pVpV/ disyllables and coarticulation effects along the F1 dimension in /p$V_1$C$V_2$/ disyllables with consonants [p, t, s] and vowels [i, a, u] produced by Greek speakers with HI as compared to speakers with NH. In particular we will look at the following characteristics in HI vs. NH speech:

- Position in the acoustic space of point vowels [i, a, u] uttered in bilabial context.
- Anticipatory and carryover C-to-V effects at the temporal midpoint of vowels [i, a, u] along the F1 axis induced by the alveolar stop [t] and the alveolar fricative [s].
- F1 V-to-V effects at $V_1$ offset (anticipatory) and $V_2$ onset (carryover) across consonants [p, t, s].

## 2. Method

Fourteen native speakers of Greek took part in the experiment. The control (NH) group was composed of 5 adults, 2 male and 3 female, without previously reported hearing problems. They were aged 18-21 and were undergraduate students at the Aristotle University of Thessaloniki. The experimental group consisted of 9 adults with HI, 5 male and 4 female, 20-35 years old. The speakers with HI were selected so as to form a group as homogeneous as possible. Their hearing loss was of prelinguistic onset, sensorineural, bilateral, stable and profound, ranging from 91 to 105 dB HL (at 500, 1000 and 2000 Hz). They had been fitted with hearing aid(s) before the age of 4 and made continuous use of them. Most participants had been in speech therapy since the age of 4-8 for 7-12 years at least twice a week. They primarily used oral communication and had a mainstream educational background. Most of them were university students. Their speech intelligibility level ranged from 73% to 98%, as judged by 54 naïve listeners.

The corpus comprised 54 disyllables of the type /p$V_1$C$V_2$/ with vowels [i, a, u] and consonants [p, t, s] embedded in the phrase "∪le∅e _____ ∪pali" (Say __again). Half the disyllables were stressed on the first and half on the second syllable, and each item was repeated 10 times. The 540 sentences were randomised and read from a list at a comfortable speaking rate. The speakers with HI were recorded in a soundproof room at the Association of Parents and Guardians of Deaf and Hard of Hearing Children of Central Macedonia, while the speakers with NH were recorded at the Phonetics Laboratory of the School of English, Aristotle University of Thessaloniki. A SHURE unidirectional dynamic microphone, Model BG3.1, attached to a YAMAHA external hard disk recording studio was used for the data acquisition. The data was sampled at 22,050 Hz.

The PRAAT program (Boersma & Weenink, 2011) was used for acoustic analysis. A script was written to provide automatic F1 and F2 frequency LPC measurements for each speaker, utilising a 15 ms Gaussian window at $V_1$ offset and $V_2$ onset for V-to-V effects, and a 25 ms Gaussian window at $V_1$ and $V_2$ temporal midpoint for vowel acoustic characteristics and C-to-V effects. The automatic measurements were also checked manually; errors were located and corrected. Formant measurements for the unstressed high back vowel [u] were in certain cases excluded due to low energy or extreme shortening/deletion of this vowel.

C-to-V coarticulatory effects were measured at the midpoint of $V_1$ (anticipatory) and $V_2$ (carryover) in the symmetrical disyllables /piCi/, /paCa/ and /puCu/. Consonantal effects induced by the two alveolars, [t] and [s], were analysed taking the bilabial context as a base for comparison, e.g., for /t/-to-/a/ anticipatory effects, the F1 of the first [a] in /papa/ and the F1 of the first [a] in /pata/ were compared. V-to-V coarticulatory effects were measured at $V_1$ offset (anticipatory) and $V_2$ onset (carryover) using a symmetrical disyllable as a base, e.g., for /i/-to-/a/ carryover effects over /t/, the F1 of the second [a] in disyllables /pata/-/pita/ is measured. The symmetrical disyllable defines the "fixed vowel" context, which, in this case is the "fixed [a]" context (Recasens & Pallarés, 2000). Univariate analyses of variance were run for variables F1 and F2 in SPSS (v. 17) and Tukey pairwise post-hoc tests were performed in Minitab (v. 15) so as to locate the contexts in which coarticulatory effects are statistically significant for each group.

# 3. Results

## 3.1 Vowel space

F1 and F2 formant frequency measurements at the temporal midpoint of the three point vowels [i, a, u] were made in symmetrical /pVpV/ disyllables. The interaction hearing*vowel was found statistically significant (F1: $F(2, 15036)=61.897$, $p<.0001$, F2: $F(2, 15045)=2650.994$, $p<.0001$). Post-hoc tests revealed that the F2 of [i] was significantly lower for the HI group and that of [u] was significantly higher compared with those of the corresponding NH high vowels. Thus, the high front vowel [i] seems to be more posteriorly articulated and the high back rounded vowel [u] significantly fronted in HI speech. In addition, the mean F1 value of the HI point vowels was overall relatively lower than that of the corresponding NH vowels, suggesting a somewhat less open vowel articulation by the speakers with HI. However, only HI [u] was found significantly higher than its NH counterpart (see Figure 1). These differences lead to a reduction of 36% on average in the vowel space as defined by HI point vowels compared with that of NH point vowels.

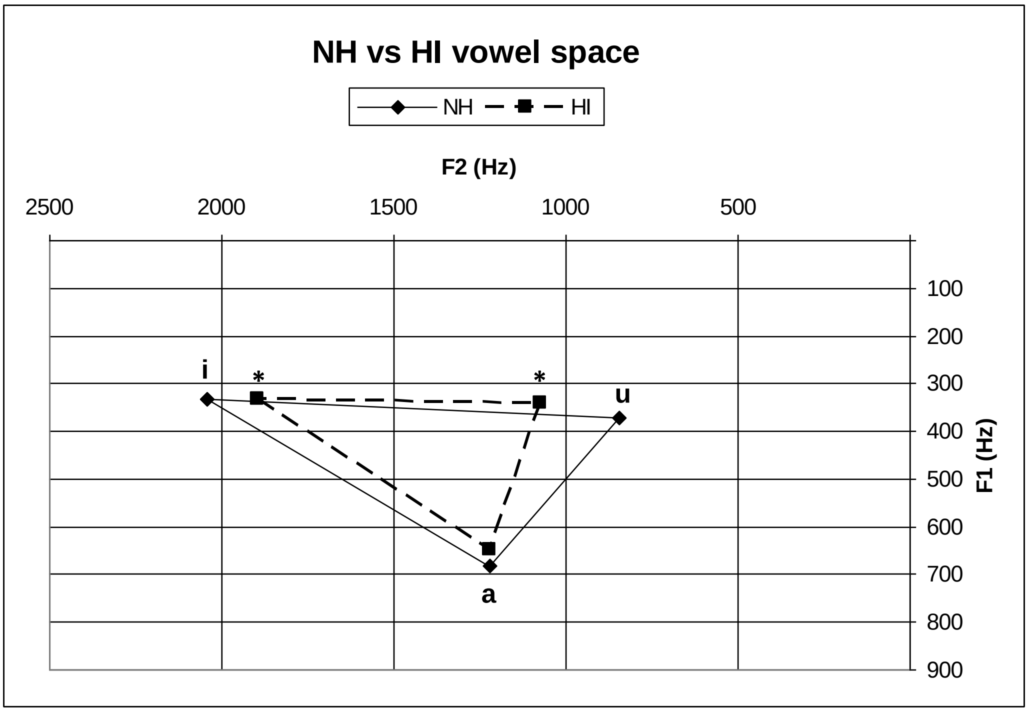



**Figure 1** NH (solid line) and HI (dashed line) vowel space. The symbol [*] denotes statistically significant difference ($p< .05$) between the NH and HI group in both F1 and F2 for [u] and in F2 for [i].

## 3.2 Consonant-to-Vowel Coarticulation

F1 formant frequency was measured at $V_1$ and $V_2$ midpoint in the consonantal context of [p, t, s] in /p$V_1$C$V_2$/ disyllables. The F1 difference between the bilabial and the alveolar contexts (ΔF1) for the NH and HI group is shown in Figure 2. The hearing, vowel and consonant factors were all found statistically significant as well as their interactions (hearing: $F(1, 15036)=463{,}755$, $p<.0001$, vowel: $F(2, 15036)=67791{,}626$, $p<.0001$, consonant: $F(2, 15036)=96{,}190$, $p<.0001$). Both groups present more coarticulation on the low vowel [a] than on the two high vowels [i] and [u], with effects reaching statistical significance only in HI /pasa/ vs. /papa/ disyllables in both directions. Hence F1 coarticulatory effects are overall more prominent for the HI group. It is therefore noteworthy that, in HI coarticulation, the fricative causes F1 lowering in all three vocalic contexts which is especially pronounced in the fixed [a] context (see bars with red stripes in Figure 2).

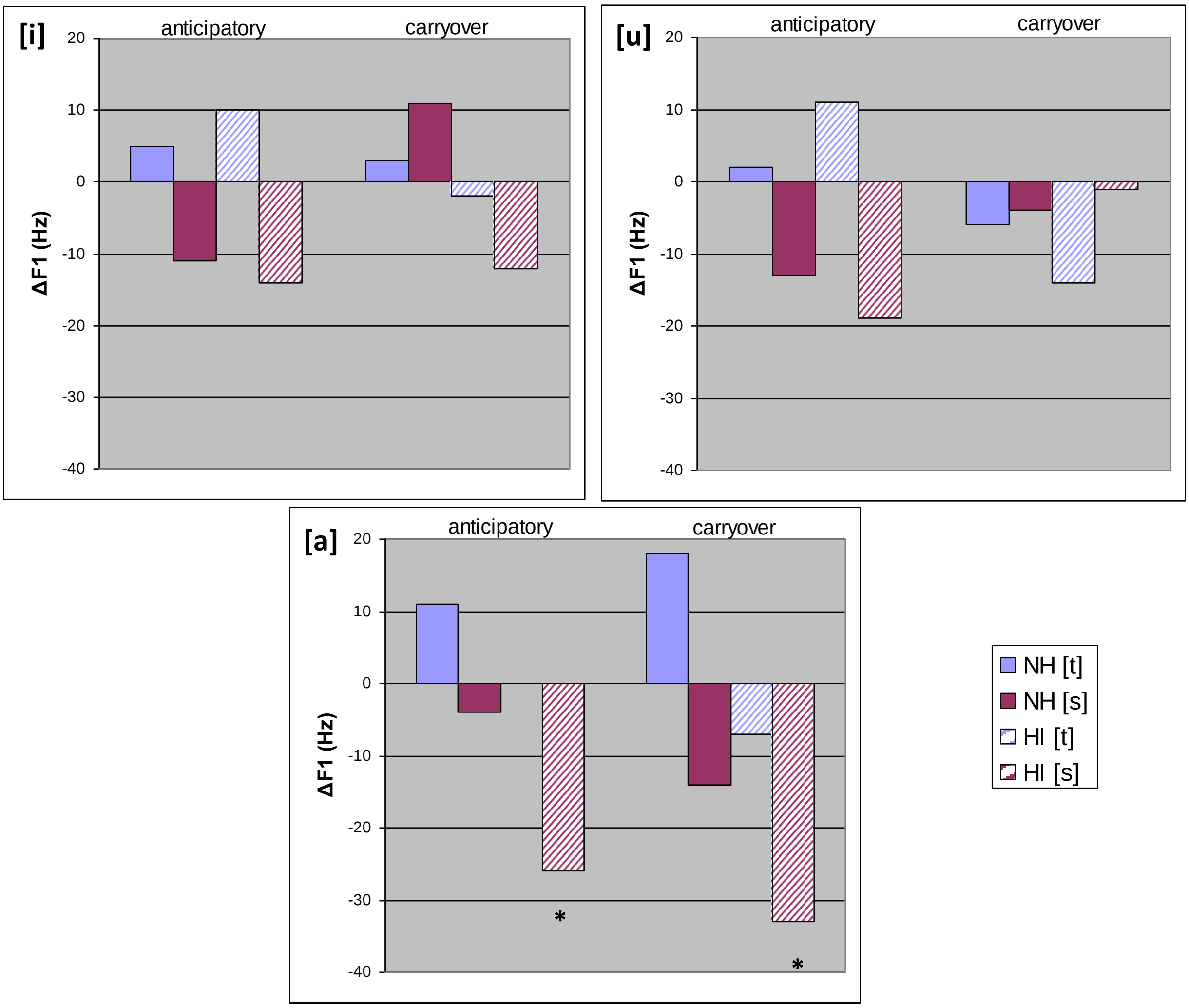
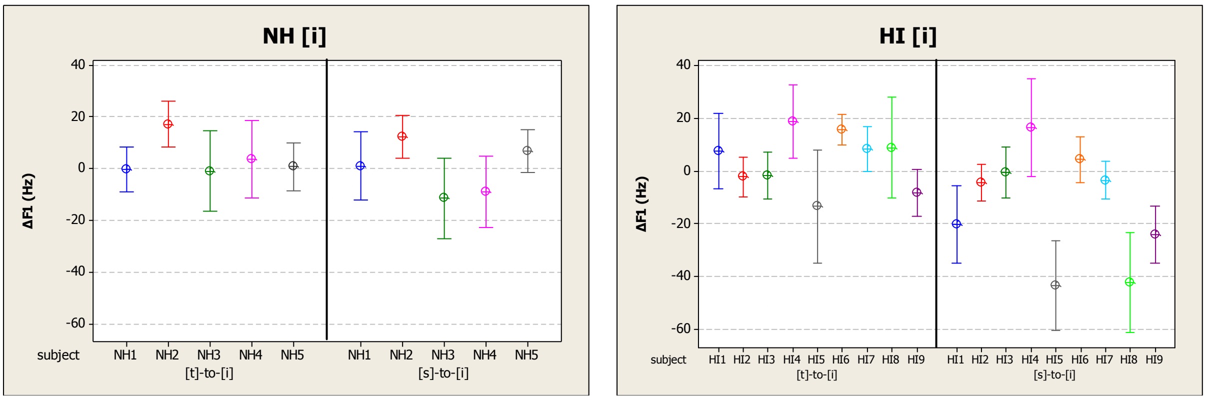



**Figure 2** Anticipatory and carryover C-to-V effects from [t] and [s] on the F1 of vowels [i, a, u] produced by the NH and the HI group. The asterisk [*] indicates statistically significant difference from the bilabial context (p<.05)

Variation in F1 C-to-V coarticulation for each speaker based on standard deviation values is illustrated in Figure 3 below. Speakers with HI seem to be more variable overall than speakers with NH. Among speakers with HI, subjects HI1, 4, 5 and 8 display the highest value dispersion.



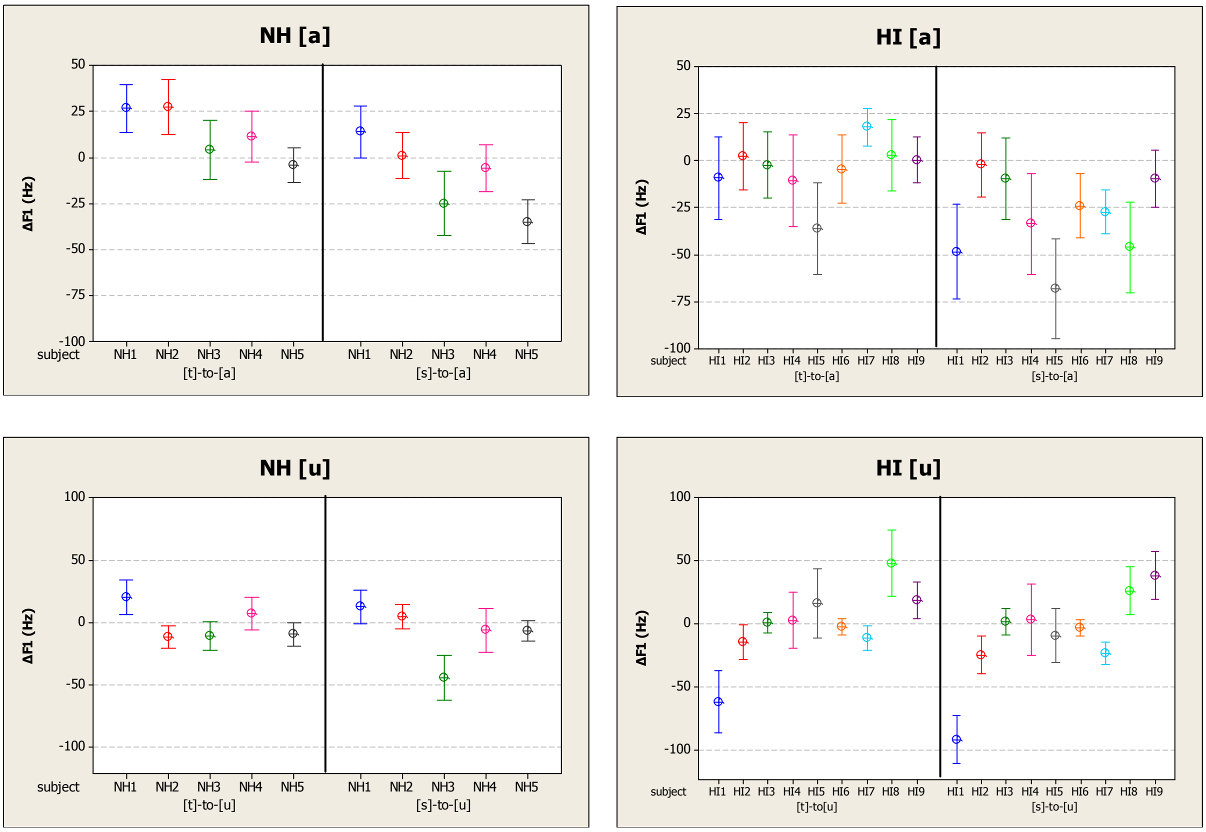



**Figure 3** Individual variation of C-to-V coarticulation along the F1 axis displayed by the five speakers with NH (left panels) and the nine speakers with HI (right panels)

## 3.3 Vowel-to-Vowel Coarticulation

As described in section 2 (Method), V-to-V effects were measured at $V_1$ offset (anticipatory) and $V_2$ onset (carryover). The mean F1 difference (ΔF1) in Hz resulting from the subtraction between F1 of the vowel in the symmetrical syllable and F1 of the corresponding vowel in the asymmetrical disyllable is provided separately for the NH and HI group in Table 1. Overall, we note that absolute ΔF1 magnitude is larger for the NH group, especially in high fixed vowel contexts. In the fixed low vowel [a] context, both groups show substantial V-to-V influence over all three consonants, with the HI group surpassing the NH group in absolute influence magnitude in certain cases (i.e., /papa/-/papi/, /pata/-/pati/, /papa/-/papu/, /pata/-/patu/). In the two fixed high vowel contexts, effects are overall minimal for both groups, except for the NH group across the bilabial consonant. Coarticulatory variability for the two high vowels seems to be comparable between the two groups, whereas V-to-V effects on the low vowel [a] were found somewhat more variable for the HI group.

| direction | fixed [i] | ΔF1 (StDev) | | fixed [a] | ΔF1 (StDev) | | fixed [u] | ΔF1 (StDev) | |
|---|---|---|---|---|---|---|---|---|---|
| | | NH | HI | | NH | HI | | NH | HI |
| | [a] on fixed [i] | | | [i] on fixed [a] | | | [a] on fixed [u] | | |
| anticipatory | pipa-pipi | 13 (41) | 10 (51) | papa-papi | 4 (58) | 16 (85) | pupa-pupu | *60 (88) | 21 (56) |
| | pita-piti | 17 (48) | -5 (49) | pata-pati | 34 (58) | *46 (80) | puta-putu | 0 (60) | 6 (60) |
| | pisa-pisi | -3 (37) | -1 (38) | pasa-pasi | 42 (117) | 23 (83) | pusa-pusu | 9 (50) | 1 (44) |
| carryover | papi-pipi | *56 (43) | 7 (50) | papa-pipa | *52 (57) | *33 (66) | papu-pupu | *65 (71) | 22 (64) |
| | pati-piti | 25 (43) | 6 (48) | pata-pita | *48 (55) | 22 (60) | patu-putu | 33 (50) | -1 (41) |
| | pasi-pisi | 36 (94) | 8 (39) | pasa-pisa | *50 (64) | *39 (69) | pasu-pusu | 19 (49) | 7 (43) |
| | [u] on fixed [i] | | | [u] on fixed [a] | | | [i] on fixed [u] | | |
| anticipatory | pipu-pipi | 8 (40) | 3 (48) | papa-papu | 49 (73) | *55 (92) | pupi-pupu | *73 (98) | 8 (54) |
| | pitu-piti | 5 (44) | -6 (45) | pata-patu | *54 (64) | *71 (93) | puti-putu | -13 (48) | -3 (62) |
| | pisu-pisi | -3 (45) | -7 (41) | pasa-pasu | *78 (113) | *18 (168) | pusi-pusu | -10 (46) | -3 (41) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| carryover | pupi-pipi | 25 (35) | 6 (41) | papa-pupa | *92 (61) | *49 (72) | pipu-pupu | *50 (65) | 14 (58) |
| | puti-piti | 0 (42) | 3 (42) | pata-puta | *62 (58) | *32 (59) | pitu-putu | -2 (51) | -12 (39) |
| | pusi-pisi | -5 (36) | 0 (37) | pasa-pusa | *70 (69) | *53 (68) | pisu-pusu | -3 (49) | -4 (41) |

**Table 1** V-to-V anticipatory and carryover influence over consonants [p, t, s] on the first formant F1 of the fixed vowels [i, a, u] produced by the NH and the HI group expressed in Hz (mean and StDev values). The asterisk [*] denotes within-group statistical significance (p <.05)

## 4. Discussion

The present study examined selected acoustic characteristics and coarticulation phenomena along the F1 axis in disyllables produced by Greek speakers with hearing impairment (HI) and normal hearing (NH). Regarding the position of the three point vowels [i, a, u] in the acoustic space, HI high vowels [i] and [u] were found to deviate more than the low vowel [a] from normal, as [i] was realized more posteriorly and [u] was fronted and raised in HI speech. Although variable findings concerning vowel errors are reported in the literature, our results agree with studies documenting [u]-fronting (McGarr & Gelfer, 1983) and relatively better low vs. high vowel production in HI speech (Smith, 1975; Geffner, 1975, Gold, 1980). A 36% vowel space reduction was noted mostly due to an F2 range restriction in agreement with previous research (on English: Monsen, 1976b; Rothman, 1976; McCaffrey & Sussman, 1994; on Greek: Nicolaidis & Sfakianaki, 2007).

As far as C-to-V coarticulation is concerned, effects were of small magnitude in NH speech. Similarly, consonantal context does not cause significant variation in the height of NH vowels according to physiological studies on Italian (Farnetani & Faber, 1992) and on English and Swedish (Keating et al., 1994). As expected, the low vowel [a] seems to receive more consonantal influence than the two high vowels, in line with Recasens et al. (1997), since the articulatory distance between the low [a] and the alveolar consonants is greater. This is observed for both the NH and the HI group, although the latter seems to show more pronounced vocalic raising than normal in the environment of the fricative [s]. As mentioned in section 1 (Introduction), more tongue dorsum involvement and palatal contact have been observed via EPG during the production of this consonant by Greek speakers with HI (Nicolaidis, 2004). Consequently, the more sizeable influence observed in our F1 data in the [s] context may reflect a higher jaw or tongue position than normal during HI /pVsV/ sequences. Regarding individual variation, in most cases HI coarticulation displayed higher variability than normal, in agreement with Okalidou (2002) who also found reduced coarticulatory stability than normal for American speakers with HI. Since speakers with HI had been selected carefully so as to have similar clinical profiles, individual differences in coarticulatory magnitude cannot be easily attributed to specific audiological or educational characteristics. We note, however, that the four speakers with HI, displaying the higher coarticulatory variability, also show the most vocalic raising effects. Hence assuming a higher tongue/jaw position than normal during /VtV/ or /VsV/ production could often concur with increased coarticulatory instability.

Regarding V-to-V coarticulation, effects in the fixed high vowel contexts are minimal for the HI group suggesting a more constrained production of [i] and [u] than normal. Effects on the NH high vowels are larger in comparison but reach substantial magnitude only across the bilabial. This outcome is in line with the DAC model (Recasens et al., 1997) which predicts more V-to-V coarticulatory influence across unconstrained consonants, such as [p]. Additionally, for both groups, the low vowel [a] exhibits less coarticulatory resistance compared with the high vowels, in agreement with the DAC model that claims more coarticulatory sensitivity for vowels that involve less tongue dorsum raising (Recasens et al., 1997). More coarticulatory variability in height for the Greek [a] vs. [i] in NH speech has also been documented with EPG (Nicolaidis, 1997), while similar findings have been reported on other languages as well (e.g., Gay, 1974; Keating et al., 1994; Mok, 2011). It is noteworthy that substantial effects on fixed [a] seem to span the two alveolars and especially the fricative, contrary to the predictions of the DAC model, but in line with previous EPG findings on Greek NH speech (Nicolaidis, 1997). A possible explanation is that [s] displays increased variability in Greek NH speech due to the absence of contrastive fricatives in the alveolar region, thus allowing for more coarticulatory effects. V-to-V effects spanning the fricative are not as prominent in HI speech especially anticipatorily, consistent with the hypothesis that the HI fricative has a more constrained production than normal. However, anticipatory V-to-V effects seem to be relatively favoured across the alveolar stop [t] for the HI group which could denote a lower jaw/tongue position during its production compared with that of the fricative, as also supported by our C-to-V coarticulation results.

As regards coarticulatory directionality, the carryover component is relatively more prominent in NH coarticulation. The prominence of carryover vocalic effects across bilabials in NH speech has also been noted by research on other languages and is associated with the slow articulation of the massive jaw (Sussman et al., 1973; Magen, 1997; Recasens & Pallarès, 2000). HI effects follow a more variable directionality pattern depending on consonantal context. Concentrating on V-to-V coarticulation on [a], since effects on the high vowels are minimal, we note that the fricative appears to favour the carryover component, while the alveolar stop displays a slightly stronger preference towards the anticipatory direction. Less consistent prominence of the carryover level in vocalic effects may suggest differential coarticulatory patterning in HI coarticulation. Further statistical treatment of the data may reveal significant differences between NH and HI coarticulation.

## 5. Conclusions

According to the results of the current study, HI point vowels, and especially the high vowels [i] and [u], display a more restricted F2 and, secondarily, F1 range in comparison with NH vowels. Looking into coarticulatory effects, the fricative [s] was found to induce more vocalic raising than normal probably due to its more constrained manner of production in HI speech. Moreover, the examination of V-to-V effects along the F1 dimension showed that HI high vowels are more constrained in height than normal. Effects on the low vowel [a] are substantial for both hearing groups, although HI effects do not show consistent preference towards the carryover component as occurring in NH coarticulation.

Although the F1 frequency has been regarded as less problematic than the F2 frequency due to its visual and auditory accessibility to speakers with HI, the present data suggest that F1 coarticulation in Greek HI speech shows certain differences from that observed in NH speech. Further analysis of the current data and parallel investigation of coarticulatory effects in the F2 axis may shed more light on the differences between NH and HI coarticulatory patterns, broadening our knowledge on tongue-jaw coordination and interarticulatory organization of speakers with profound hearing loss with data from the Greek language.

### Acknowledgements

This study reports preliminary results from a part of the author’s doctoral thesis supported by the Greek Ministry of Education, Lifelong Learning and Religious Affairs. I gratefully acknowledge the help of my supervisor Dr Katerina Nicolaidis and co-supervisor Dr Areti Okalidou. 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.

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