An Acoustic Study of Coarticulation in the Speech of Greek Adults with Normal Hearing and Hearing Impairment

by

Anna Sfakianaki

A thesis submitted for the degree of
Doctor of Philosophy in Linguistics

at

ARISTOTLE UNIVERSITY OF THESSALONIKI
DEPARTMENT OF THEORETICAL AND APPLIED LINGUISTICS
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To my mother Anastasia
and
To my father Myron

Contents

Abstract

Research has shown that speech acquired in profound hearing loss presents differences on both the segmental and the suprasegmental levels compared with normal hearing speech. Recent studies focus on the dynamic aspects of hearing impaired speech, i.e., coarticulation as coproduction of gestures, but findings are variable. Although this issue has received a lot of attention in the English literature, phonetic research in Greek is still scant, this being the first study of coarticulation in Greek hearing impaired speech.

The main aim of the present thesis is the acoustic exploration of (a) vowel-to-vowel and consonant-to-vowel coarticulation in degree and/or temporal extent and (b) static characteristics such as vowel space, distribution and duration of the three point vowels, in the speech of Greek young adult male and female speakers with normal hearing (NH) and hearing impairment (HI). The aforementioned dynamic and static acoustic properties are investigated in relation to certain variables, i.e., vocalic and consonantal context, stress, syllable position, as well as speaker gender and intelligibility. The speech of nine subjects with profound HI, five male and four female, and five subjects with NH, two male and three female, was analyzed acoustically by measuring formant frequencies F1 and F2 at vowel onset, midpoint and offset of the Greek point vowels [i, a, u] in disyllables of the form [pV_1CV_2] with consonants [p, t, s] stressed on the first or the second vowel. An additional experiment was conducted in order to rate the intelligibility of the speakers with HI. Three groups, i.e., very high, high and medium intelligibility, were formed on the basis of judgements made by 60 naïve listeners with NH who rated 101 words and 25 short sentences produced by the speakers with HI.

The acoustic analysis showed some similarities in vowel characteristics and coarticulatory patterns between the two hearing groups, but also revealed significant differences. Differential relative coarticulatory resistance/aggression of the segments under study was observed in HI vs. NH speech. Most importantly, predominance of the anticipatory component in coarticulation was located in alveolar contexts in HI speech. Major findings regarding acoustic characteristics include [u]-fronting, reduced vocalic contrast, higher acoustic variability and longer durations for HI vowels. Moreover, differential effect of gender and stress on the acoustic characteristics of vowels and coarticulation was found in the two groups. Findings are discussed on the basis of possible articulatory strategies adopted by the two hearing groups and are considered in light of the coproduction framework and, in particular, the Degree of Articulatory Constraint (DAC) model.

Acknowledgements

This has been a long journey. Looking back, I have many people to thank for their valuable contribution to the completion of this research.

I would like to offer many thanks to all the participants of this study and especially to the speakers with hearing impairment. I am grateful to the Association of Parents & Guardians of Deaf & Hard of Hearing Children of Central Macedonia for helping me contact the participants and for providing access to their sound proof room for the recordings.

I am deeply grateful to my supervising committee, Dr. Katerina Nicolaidis, Dr. Areti Okalidou and Dr. Ioannis Papanastasiou, for their guidance over the years. I would like to offer special thanks to Dr. Areti Okalidou for her insightful comments and invaluable feedback. Thanks are also due to all members of staff in the Department of Theoretical and Applied Linguistics for their help, and especially Prof. Ianthi-Maria Tsimpli and Tasos Paschalis. I feel very grateful to many people who provided assistance and advice during the early years of my research, among them Prof. Marios Fourakis, Dr. Miltiadis Tsaligopoulos, Dr. Anestis Psifidis and Dr. Emmanuel Giahnakis. I also feel the need to acknowledge the important influence of three special people from my academic years at the University of Reading, Prof. Irene Philippaki-Warburton, Dr. Vassilios Spyropoulos and, last by not least, my master's thesis supervisor Prof. Peter Roach. I am greatly and eternally indebted to George Vlahavas for his prompt and invaluable help and support on countless occasions. I would like to express my appreciation to Dr. Kostastantinos Dimopoulos for his friendship and for the assistance he so readily provided over the years. I also wish to thank A.G. Leventis Foundation for providing financial support during the first year of my studies and the Ministry for National Education and Religious Affairs of Greece for granting a funded sabbatical for the completion of this research.

Finally, I wish to extend my deepest gratitude to my supervisor Dr. Katerina Nicolaidis. This thesis would undoubtedly not exist without her. Her guidance and her friendship have been of the utmost importance in my life, academic and personal.

Any expression of acknowledgement will fail to capture the essential role of my parents, Anastasia and Myron, in this endeavour. Their abundant love and endless support has helped me overcome all adversities. This thesis is dedicated to them.

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Chapter 1

Introduction

1.1. Identifying the Area of Research

Among the five basic human senses, it is hearing that is more closely linked to speech production. Loss of hearing affects the ability not only to perceive, but also produce speech. Extensive research on the English language documents significant effects on all aspects of speech production, both segmental and suprasegmental, on account of hearing loss. Early studies on English have looked primarily into static speech characteristics of individuals with hearing impairment; however, recent research focuses on the dynamic aspect of speech production and, more specifically, the issue of coarticulation.

Two basic lines of thought were developed to explain the phenomenon of coarticulation in normal hearing speech, that is, to account for the disparity between the invariant non-overlapping phonemes the listener perceives and the continuum of speech produced by the talker: the *translation theory* (Daniloff & Hammarberg, 1973) and the *action theory* or *theory of coproduction* (Fowler, 1980). The major difference between the two philosophies is that the former views the phoneme as an ideal unit modified by context, while the latter maintains that the phonemes are four-dimensional, inherently articulatory entities that overlap temporally. Thus, coarticulation is not viewed as a mere contextual influence of a sound on neighbouring sounds, but as the coproduction of sounds, i.e., their production with some degree of overlap. This theoretical standpoint gave rise to the development of the *gestural framework of speech production* (Browman & Goldstein, 1986) and, more recently, to the proposition of a model of coarticulation based on the *Degree of Articulatory Constraint* (DAC) (Recasens, Pallarès, & Fontdevila, 1997). As maintained by the DAC model, the degree of tongue dorsum activation during the production of a phoneme is correlated with its coarticulatory resistance and aggression. As a consequence, in vowel-consonant-vowel sequences, highly constrained segments in terms of tongue dorsum involvement induce large consonant-to-vowel coarticulatory effects and block vowel-to-consonant and vowel-to-vowel coarticulation.

Previous research on coarticulation in hearing impaired speech has yielded contradictory findings. Some researchers report reduced coarticulation compared to speakers with normal hearing (e.g., Baum & Waldstein, 1991; Waldstein & Baum, 1991), while others document greater or smaller degree of coarticulatory effects depending on context (e.g., Okalidou & Harris, 1999; McCaffrey Morrison, 2008). According to the latter, speakers with HI coarticulate less in bilabial but not in alveolar contexts. It has been hypothesized that certain coarticulatory patterns located in deaf speech resemble patterns of early developing speech, as, for different reasons in each case, gestural organization has not reached the high orchestration level characterizing mature speech.

To our knowledge, this is the first study of coarticulation in Greek hearing impaired speech. Its major contribution is to broaden our understanding of language-specific aspects of acoustic characteristics and coarticulatory patterns in speech acquired in profound hearing loss. Moreover, the literature on coarticulation in Greek normal hearing speech is fairly limited compared to that in English. Lingual coarticulation has been studied in Greek with the method of electropalatography (Nicolaidis, 1991, 1994, 1997, 1999, 2001, 2002, 2003), but acoustic studies are scarce (Okalidou & Koenig, 1999; Koenig & Okalidou, 2003; Asteriadou, 2008). Hence, among the major goals of the current thesis is to also extend current knowledge on coarticulation in Greek normal hearing speech by examining coarticulatory effects in several consonantal and vocalic contexts, in both F1 and F2 dimensions as well as in relation to factors such as stress, syllable position, and gender, the last constituting an original contribution.

Thus, the main aim of this thesis is the acoustic investigation of coarticulatory patterns in Greek hearing impaired vs. normal hearing speech, and their interpretation within the framework of coproduction. For this purpose, three consonantal and three vocalic contexts with differing DAC values were selected. Disyllables of the form [pV_1CV_2], stressed either on V_1 or V_2, consisting of the bilabial consonant [p] or the alveolar consonants [t] and [s] and the point vowels [i, a, u], were uttered by 9 speakers with profound hearing loss (> 91 dB HL), five male and four female, and 5 speakers with normal hearing, two male and three female. Formant frequencies F1 and F2 were measured at the onset, midpoint and offset of V_1 and V_2 so as to examine the magnitude and temporal extent of V-to-V coarticulatory effects. In addition, C-to-V effects from the two alveolar consonants [t] and [s] were measured at the temporal midpoint of the vowels. Acoustic characteristics, such as mean F1 and F2 formant frequencies (vowel spaces), acoustic variability and vowel duration of the point vowels were also examined in bilabial symmetrical disyllables of the type [pVpV].

Therefore, patterns of C-to-V and V-to-V coarticulation as well as acoustic characteristics of vowel production are examined in the two groups, i.e., the normal hearing (NH) group and the hearing impaired (HI) group, in relation to the following factors: vocalic and consonantal context, stress, syllable position and gender. Moreover, it has been reported that the speech of individuals with similar degrees of hearing loss can have varying levels of intelligibility (Smith, 1975; Monsen, 1978; Osberger & McGarr, 1982; Metz et al., 1985). We do not know of any studies that have systematically looked into the correlation between coarticulation and speech intelligibility level; however, differences in speech intelligibility could potentially influence the coarticulation displayed in HI speech. Hence, an additional experiment with naïve listeners was conducted so as to rate the intelligibility of each individual's productions and examine the relationship of HI speech intelligibility with acoustic characteristics of vowel production and coarticulation.

On the basis of previous literature, it is hypothesized that speakers with HI will display some trends for normal-like patterns, although significant differences are expected in the acoustic characteristics of vowels and coarticulatory effects in terms of magnitude and directionality. Concerning vowel production, reduced distinctiveness, higher acoustic variability and prolonged durations have been reported by numerous researchers, while EPG studies on HI sibilants have shown heavy palatalization and articulatory instability (e.g., McGarr et al., 2004; Nicolaidis, 2004). Due to such production characteristics, differences in C-to-V and V-to-V coarticulatory patterns are expected to manifest in HI vs. NH speech. In addition to differences in context-induced effects, differential stress, syllable position and gender influence on the acoustic characteristics of vowels and coarticulation patterns is expected between the two hearing groups.

The analysis confirmed the above main hypothesis and revealed that the acoustic characteristics of vowels and coarticulatory patterns of the two hearing groups show similarities, but also present significant differences. Major research findings are summarized below.

- Regarding the acoustic characteristics of vowels:
    - Less contrast mainly due to increased [u]-anteriority, higher acoustic variability and longer durations were located for HI vowels.
    - The stress effect on vowel space was greater and more pronounced in the first syllable for the HI group as opposed to the NH group.
    - Higher acoustic variability and greater duration were located in female vs. male vowels in NH but not in HI speech.
    - Stress effects on vowel duration were reduced and differential patterns of the influence of consonantal and vocalic context on vowel duration were revealed in HI speech.
    - Intelligibility level (range: 73-98%) correlated with [u]-fronting but not with vowel duration.
- Regarding coarticulation:
    - Lower absolute magnitude of effects was located in both C-to-V and V-to-V F1 and F2 coarticulation in HI speech.
    - V-to-V coarticulation across the bilabial was reduced, while it was increased across the alveolars in HI speech especially in high vowel contexts.
    - Predominance of the anticipatory level was clearly observed in HI C-to-V and V-to-V coarticulation as opposed to prevalence of the carryover component in NH V-to-V coarticulation.
    - More coarticulatory aggression of [s] vs. [t] was found in HI speech, while the behaviour of the two alveolars was relatively similar in NH speech.

- Among the three point vowels, [i] showed more coarticulatory variability in the horizontal dimension and [a] in the vertical dimension in both NH and HI speech.
- No important differences were located in temporal extent, as most V-to-V effects did not reach the vowel midpoint in either NH or HI speech.
- C-to-V coarticulation was more pronounced on unstressed vowels, while the stress effect on V-to-V coarticulation was more variable in both NH and HI speech.
- V-to-V coarticulation was greater in female vs. male NH speech, while the opposite pattern emerged for HI speech.
- Intelligibility level did not correlate with V-to-V coarticulatory magnitude.

1.2. Thesis Outline

Chapter I presents the research area of the current thesis. The topic of the research and the methodology adopted are introduced. Major aims and elements of original contribution of the study are mentioned. Expectations on the basis of previous literature and current models of coarticulation are stated and major findings are summarized. The thesis outline concludes the chapter.

Chapter II comprises a review of the literature divided into four parts. The first part provides an overview of the phenomenon of coarticulation in speech production and perception theories. The second part contains a comprehensive outline of coarticulation studies in normal hearing (NH) speech focusing on the factors of variability investigated in the present study. The third part is devoted to studies on segmental and suprasegmental aspects of hearing impaired (HI) speech that are of relevance to the current investigation. The fourth part includes a description of Greek vowels and consonants with particular emphasis on the phonemes examined in this thesis. Finally, the main aims and specific research questions are stated, and hypotheses and expectations are formulated on the basis of the literature on HI and NH speech reviewed earlier in the chapter.

Chapter III begins with an outline of the experimental design. The research methodologies adopted for the acoustic and the intelligibility experiment are described. The results of the intelligibility experiment are reported here, as they were utilized in the subsequent analyses. In addition to the description of the methodology, an overview of the problem areas in the acoustic measurements of HI speech is included. Issues of homogeneity in the HI group of the study are discussed as well as ways in which we attempted to achieve it. A brief description of a pilot study and its effect on the final methodological design is also provided. The chapter concludes with a presentation of the statistical design of the thesis.

Chapter IV reports the results of the first part of the study: (a) the acoustic characteristics of the point vowels and (b) the consonant-to-vowel (C-to-V) effects located at vowel midpoint in HI and NH speech. Vowel spaces and distribution are presented in relation to gender and intelligibility level, while stress and syllable position effects on vowel space are also illustrated in the two hearing groups. In addition, the effect of context (consonantal and vocalic), stress, syllable position, gender and intelligibility on the vowel duration of the two groups is included. Finally, C-to-V effects of the alveolar consonants [t] and [s] are presented at the vowel midpoint for the two hearing groups in both F1 and F2 frequencies, and stress effects on C-to-V articulation are also reported.

Chapter V reports the results of the second part of the study which focuses on vowel-to-vowel (V-to-V) coarticulation in both F1 and F2 frequencies at the onset, midpoint and offset of V_1 and V_2 across the three consonantal contexts [p, t, s] in HI and NH speech. A concise presentation of the magnitude of F1 and F2 coarticulation for the V_1 offset and V_2 onset for the two groups ensues and the temporal extent of the effects is discussed. Next, the influence of stress, gender and intelligibility on F1 and F2 V-to-V effects is reported for the two groups.

Chapter VI discusses the results presented in Chapters IV and V in relation to reports of previous studies and discusses the findings of the current study with reference to the theory of articulatory phonology and the DAC model of coarticulation. A general discussion ensues that provides a synthesis of the major findings and their interpretation within the framework of coproduction. Implications of the findings for current theories and models as well as for clinical practice are discussed. Limitations of the study are mentioned and avenues for future research are finally proposed.

Chapter VII provides a brief, albeit comprehensive, review of all findings deriving from this research and the final conclusions drawn from the synthesis of the results.

Appendices regarding the methodology and the results of the statistical analyses are provided. Materials used for the acoustic and the intelligibility experiments are appended. Statistical analyses results regarding the main factors and coarticulation tables are also provided here. ANOVA tables and statistics plots with main factors and interactions results are available on CD ROM.

References are provided at the end of the thesis.

Chapter 2

Literature Review

2.1. The Issue of Coarticulation in Speech Production and Perception Theories

In this section we will touch upon the issue of coarticulation and see how past and present theories of speech production and speech perception account for its manifestation. Although reviewed independently here as well as in the literature, the functional intertwining of production and perception processes has been postulated since the early 1950s (Sperry, 1952), their direct matching gaining ground recently with the discovery of mirror neurons (Rizzolatti & Arbib, 1998).

2.1.1. Speech Production Theories

Although almost 80 years have gone by since the introduction of the term *coarticulation* by Menzerath and de Lacerda[1] in 1933, the study of phenomena related to this concept remains in the limelight of scientific research. Speech production theories have been attempting for decades to adequately model the presumed transformation of separate and serially ordered invariant linguistic units (input) into the variable and continuous speech at the acoustic and articulatory level (output). The question has been approached by two different standpoints; the mentalist, originating from Chomskian theory[2] and leading to the development of *translation* or *extrinsic-timing* theories, and the physicalist or empiricist, relating models of motor behaviour

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[1] The term 'coarticulation' appeared in their work as 'Koartikulation' or 'Synkinese' referring to the preparation of the articulators for a sound during the production of a preceding segment (Kühnert & Nolan, 1999:11).

[2] However, Fowler (1983:306) argues that "phonemes" and "allophones", terms used by proponents of the mentalist approach, had been rejected by Chomsky (1964) and Halle (1959) as components of linguistic competence.

to the control of speech articulators and providing the basis for *action*, *intrinsic-timing* or *coproduction* theories. The two opposing frameworks provide different definitions and models of coarticulation.

Translation theories consider the segment “internally generated, the creature of some kind of perceptual-cognitive process” (Hammarberg, 1976:355). In the human mind segments exist in a canonical form, that is, they are “invariant, ideal, unarticulated target forms” (Daniloff & Hammarberg, 1973:240). In the continuum of speech a *feature spreading* mechanism promotes the interaction of these canonical entities, the *phonemes*, turning them into coarticulated, variable *allophones*. Hence, coarticulation is viewed as a process whereby the inherent properties of segments are altered by those of neighbouring segments so as to achieve a smooth and easy flow of articulation movements. Coarticulation can be anticipatory (right-to-left) or carryover (left-to-right); the former is assumed to be the product of motor preplanning that orders specific adjustments for upcoming segments and the latter has been attributed to the sluggish mechanical response of the articulators that results in a delay of the execution of new commands and the persistence of the motion or position ordered by the old commands even after their cessation. Studies of lip protrusion in French (Benguerel & Cowan, 1974) and velar lowering in English (Moll & Daniloff, 1971) provided evidence that anticipatory coarticulation can extend up to six segments in advance and over a word boundary, respectively. Such long range anticipatory effects had to be a deliberate spread of features facilitated by a look-ahead scanning device (Henke, 1966) that would scan for future units and allow the anticipation of their features when not conflicting with those of currently articulated segments. Thus, in Henke’s articulatory model, spread of features is blocked only by a specified feature.

For instance, a nasal consonant will be anticipated by all preceding phonemes unspecified for nasality.

Within a related framework, Kozhevnikov and Chistovich (1965) also attempt to explain anticipatory coarticulation, suggesting that commands for a vowel start as soon as the first consonant in the syllable, on the condition that their features are not contradictory (Daniloff & Hammarberg, 1973). Although their goal-oriented model accounts for coarticulation within the syllable, it fails to predict effects crossing syllable boundaries as those described by Moll and Daniloff (1971). Along similar lines, MacNeilage (1970) proposes the *target-based* model which translates phonemes into articulatory targets and transmits movement command patterns to the muscles. Although the issue of motor equivalence in speech, i.e., the "…achievement of relatively invariant motor goals from varying origins…" (MacNeilage, 1970:182), is taken under consideration, many questions involving the degree and nature of target specifications and the range of coarticulatory effects remain unanswered.

Another feature-based model is that proposed by Wickelgren (1969), according to which the context-sensitive allophone, rather than the "context-free" phoneme, is the basic unit of articulation. Based on an investigation of errors in short-term recall of six English vowels, Wickelgren (1965) maintains that a vowel phoneme is coded in the short-term memory, not as an atomic unit, but as a set of distinctive features. Within this framework, an allophone is "a phoneme in a particular context of phonemes on either side" or "a class of similar speech sounds or gestures occurring in a specified environment" (p. 6). For example, the word *struck* would be composed of the following string of allophones: /${}_{\#}s_{t}$, ${}_{s}t_{r}$, ${}_{t}r_{u}$, ${}_{r}u_{k}$, ${}_{u}k_{\#}$/. Wickelgren (1969:11) argues that by adopting the context-sensitive allophone as the basic unit of articulation, coarticulation effects become a fundamental feature of the speech code at all levels, including the motor neuron level. Although he claims that the number of neurons in the human nervous system is sufficient to code speech allophonically, other researchers maintain that the existence of an exhaustive allophonic list stored in the speaker's mind would create a great burden on the central nervous system since no neuromotor strategy is suggested in Wickelgren's model (Kent & Minifie, 1977). Despite this criticism, the two distinctive features, i.e., place of articulation and openness of vocal tract, used by Wickelgren (1965) to explain the coding of vowels in short-term memory, are the basic two parameters needed to describe the tongue shapes of vowels of the languages of the world, as asserted by Ladefoged (1980). Tatham and Morton (2005) comment that, although Wickelgren's theory of motor control of speech is not preferred by contemporary phoneticians, his model is precisely the one used by speech synthesis systems which are based on the selection of units from a large database in order to capture the required variability within the stored database.

Some of the criticism regarding feature-spreading models stems from their treatment of the coarticulatory process as an absolute phenomenon. Data has shown that coarticulatory effects do occur despite feature contradiction between segments or are not evident to the expected degree regardless of an unspecified segment's neutrality (Farnetani & Recasens, 1999). Bladon and Al-Bamerni's *coarticulation resistance* model (1976) and Keating's *window* model (1988), as well as other hierarchical models, such as Liberman's (1970) or Tatham's (1970), endeavour to take into account the graded nature of coarticulation. The *coarticulation resistance* or *CR* model, in an attempt to describe the variation of /l/ in English, moves past the binary feature analysis and proposes the assignment of a coarticulatory resistance coefficient to allophones and boundary conditions which can also be language-specific. Regardless of its advantages when compared with feature-based models, the *CR* model does not go beyond restating the presence of coarticulatory effects without providing principles that would allow their prediction or explain their pattern (Kent & Minifie, 1977).

The aforementioned notion of *coarticulation resistance* also exists in Keating's model (1988) in the form of a *window* which represents the range of values associated with a certain feature. For example, a segment unspecified for a certain feature is allowed considerable variability, thus its window is wide. However, width is also language-specific because languages may differ in the way they interpret unspecified features. A study of vowel nasalization comparing nasal flow contour in vowels of different languages demonstrated that, in French and Sundanese, nasalization is phonological, whereas in English it rises from phonetic interpolation rules (Cohn, 1993). The window model explains cross-language differences in coarticulation also on the basis of grammatical rules. Variability in production represented by window width reflects "default rules and phonetic detail rules of a language" (Keating, 1988:24). Manuel and Krakow (1984), however, postulate a different account for interlanguage differences in V-to-V coarticulation. Their comparative analysis of V-to-V coarticulation in Swahili, Shona and English showed that coarticulation is related to the number and distribution of contrastive vowels in a language so as to preserve perceptual contrast. Their *output constraint hypothesis* can make predictions about coarticulatory degree across languages without the need for language specific rules. Overall, Keating's window model can handle articulatory variability more satisfactorily than feature-spreading models, and also account for V-to-V coarticulation, but the phonological and the phonetic level are still kept separate and effects of speech style or rate on window size and thus on the degree of coarticulation are overlooked (Farnetani & Recasens, 1999).

The aforementioned critique relating to the lack of correspondence between the phonological and the physical component as a major characteristic of translation theories was put forth by advocates of *action* or *intrinsic timing* or *coproduction* theories (Fowler, 1980; Bell-Berti 1981). In contrast to Hammarberg's view (1982) that segments are mental or psychological, Fowler (1983:307) maintains that they are also "inherently articulatory" and that their properties are given in acoustic speech signals. The *segment* yields its role to the *phonetic gesture* which, linguistically, constitutes the basic unit of a language-user's phonological system and, physically, generates "coordinated movements of the vocal tract in order to achieve a phonetically significant goal" (Fowler & Saltzman, 1993:172). Within this framework, coarticulation is viewed as "the overlapping production of successive, continuous, four dimensional segments" or the *coproduction of gestures* (Fowler, 1980:119). What makes coproduction mechanically feasible is that vowels and consonants are two separate classes of articulatory gestures, an idea originally proposed by Öhman (1966) in an acoustic study of VCV utterances. He notes that VCV utterances involve a V-to-V diphthongal gesture on which the consonantal gesture is superimposed. In his numerical model of coarticulation, Öhman (1967) argues that the tongue is a system of three independent articulators, the apical and dorsal articulator for consonants and the tongue body articulator for vowels. Vocalic and consonantal gestures are allowed to blend as the articulators are independently controlled and able to execute simultaneous neural instructions. Furthermore, Perkell (1969:61) observes that "the general differences in velocity, complexity, precision of movement, and in anatomy suggest that different types of muscles are generally responsible for consonant and vowel production". Hence, consonants and vowels are products of different coordinative neuromuscular systems and can be coproduced.

Besides bridging the disparity between the mental and the physical, the coproduction theory also manages to provide a relatively *open-loop* model of speech reducing the requirement of auditory or visual feedback. Many studies of speech production which examine the unexpected perturbation of an articulator, e.g., the successful production of vowels with a bite-block between the teeth (Lindblom, Lubker & Gay, 1979; Fowler & Turvey, 1980) and the movement of the upper and lower lip to compensate for impedance of the jaw during a bilabial closure (Kelso, Tuller, Vatikiotis-Bateson & Fowler, 1984; Shaiman, 1989), show that compensations occur at very short latencies, indicating that they are the consequence of articulatory coupling; hence acoustic feedback or cognitive replanning are not necessary to account for them. In addition, evidence that cannot be explained along the lines of a feature spreading account are predicted and accounted for within the coproduction framework. Such examples are (a) V-to-V coarticulation (Öhman, 1966; Carney & Moll, 1971; Butcher & Weiher, 1976; Fowler, 1980, 1981; Magen, 1989; Recasens, 1984b, 1987, 1989, 2002a, 2002b, 2009; Farnetani, 1990, 1992), (b) effects which do not begin neatly at onset and offset of segments (Benguerel & Cowan, 1974), and (c) *troughs* (Gay, 1978a; Boyce, 1990), i.e., reduction of lip rounding during the production of a consonant string between two rounded vowels.

A key element in the theory of coproduction is the concept of *coordinative structure*, i.e., a group of muscles that are functionally interlinked. Thus a set of articulators acts in coordination so as to achieve a gestural goal. For example, in order to form a bilabial closure, the jaw, the lower lip and the upper lip are constrained by a coordinative structure. Coordination among articulators accounts for motor equivalence in speech; an increased contribution from one articulator of the structure will lead to the decreased contribution of another so that the gestural goal is always accomplished (Fowler, 1977; Saltzman & Munhall, 1989). Coordinative structures are hereby deemed the units of speech and “these units are not timeless, but rather incorporate time in an intrinsic manner” (Kelso, Satzman & Tuller, 1986:31). As mentioned above, in extrinsic timing theories, segments are considered canonical entities with discrete boundaries perpendicular to the time axis which are serially ordered in utterances. In coproduction theories, on the other hand, gestures (instead of segments), albeit distinct events, are coordinated temporally in the form of an activation wave, so that each increases and decreases smoothly in time, taking its turn of predominance on the vocal tract (Fowler & Saltzman, 1993).

Articulatory phonology (Browman & Goldstein, 1993) and the *task dynamic model* (Saltzman & Kelso, 1987; Saltzman & Munhall, 1989; Turvey, 1990; Fowler & Saltzman, 1993) were developed within the intrinsic timing framework. The task dynamic model treats speech gestures as mass-spring systems with point attractor dynamics and provides equations to describe the change of the systems’ state according to time (Fowler, 2007). The formation and release of constrictions in different regions of the vocal tract are defined by *tract variables*, that is, values for the dynamic parameters of stiffness, equilibrium position (position and degree of constriction) and damping ratio (Browman & Goldstein, 1993). The system includes two levels, the intergestural level that deals with patterns of relative timing and cohesion among activation intervals for the gestures participating in a given utterance, and the interarticulator level responsible for coordination among articulators (Fowler & Saltzman, 1993). In an older version of the theory (Browman & Goldstein, 1986), utterances are ascribed *gestural scores* by calculating the values for the parameters of the gestures they are composed of and defining their time span. In a later version, Saltzman, Löfqvist and Mitra (2000) replace gestural scores with a *central clock* that regulates time in gestural patterning and describes how peripheral events, such as speaking rate, influence the temporal structure of language. An increase in spatial and temporal overlap of gestures as in fast speech will result in a decrease of segmental duration and increase in coarticulation (Saltzman & Munhall, 1989). The computational implementation of the latest version of the model is named TADA (TAsk Dynamics Application; Nam, Goldstein, Browman, Rubin, Proctor & Saltzman, 2007) and can be used to model phonological planning and gestural coordination (Terband, 2011).

The aforementioned interarticulatory coordination is closely associated with the notion of *coarticulation resistance* first introduced by Bladon and Al-Bamerni (1976) (see above). According to coproduction, overlapping gestures share articulators to a smaller or larger degree. If two adjacent segments involve different prime articulators, e.g., in a /VpV/ utterance, where the tongue body and the lips are engaged independently by the vowel and the consonant respectively, then there is no conflict between the gestures. If, on the other hand, sequential gestures involve the same articulators, e.g., in a /VsV/ utterance where the tongue is shared by both the vowel and the consonant, there is incompatibility and the gestures will need to compete and blend their influence on the common articulator (Fowler & Saltzman, 1993). The outcome of this competition will depend on the extent to which a vowel or a consonant resists coarticulatory overlap. Stevens and House (1963) were among the first to categorize vowels and consonants according to *contrasting degrees of stability* which relate to the extent they allow context-dependent effects to occur.

A model developed by Bell-Berti and Harris (1979, 1981, 1982) along the lines of coproduction is the *frame* or *time-locked* model. In contrast to the feature-based theories and the look-ahead model mentioned above which advocate extensive anticipatory influence on preceding unspecified segments, this model proposes that anticipatory coarticulation begins at a fixed time before the acoustic onset of a segment. Their conclusions, based on experimental data on lip rounding and velar lowering, are nonetheless contradicted by other experiments which demonstrate more extensive anticipatory effects in agreement with the look-ahead model (e.g., Daniloff & Moll, 1968; Sussman & Westbury, 1981) as well as spatial and temporal differences in anticipatory labial coarticulation in English and Swedish (Lubker & Gay, 1982) attributed to language specific differences regarding the perceptual significance of lip protrusion. Lubker and Gay's (1982) experiment on anticipatory lip rounding was recently partially replicated by Gabrielsson, Kirchner, Nilsson, Norberg and Widlund (2011) with the aim to compare results based on EMG measurements and magnetometry with results obtained from The Wave Speech Research system (NDI) that utilizes an electromagnetic field to register small movements. They demonstrated that more dimensions than the traditional one associated with lip protrusion can signal onset of lip rounding, e.g., jaw opening and torsion of the lower lip, which had not been taken into account in older experiments using less modern techniques. The results showed that lip rounding in Swedish was not temporally locked for the three of the five speakers but was influenced by the length of the consonantal string, lending some support to the look-ahead model. Data from more experiments (Al-Bamerni & Bladon, 1982; Perkell & Chiang, 1986; Perkell, 1990) point to the co-existence of both the time-locked and the look-ahead strategy which ultimately led researchers to the compromising solution of a *hybrid* model.

However, other studies (Gelfer, Bell-Berti & Harris, 1989; Boyce, 1990; Bell-Berti & Krakow, 1991; Perkell & Matthies, 1992) have shown that consonants previously thought as unrelated to rounding, such as /s/ and /t/, are nevertheless associated with lip-rounding, while vowels in an oral context are associated with velum lowering. As a consequence, coarticulation data of earlier studies would have to be re-evaluated, taking into account these newly found inherent segment characteristics. Instead of a hybrid strategy the patterns observed might be related to two independent gestures overlapping. Fowler and Saltzman (1993) are also in support of the time-locked model and state that the onset of anticipation is essentially fixed and occurs at about 200-250 ms before the target phoneme regardless of context (also Fowler & Brancazio, 2000). The foregoing evidence points to a less extensive field of anticipatory influence than previously suggested but does not render full support to a purely time-locked strategy as different trends can prevail across languages, speakers or even within-subject repetitions (Farnetani & Recasens, 1999). Overall, coarticulation phenomena seem to depend largely on competing kinematic and acoustic constraints, language inventory size and phoneme distribution (see below) (Clumeck, 1976; Manuel & Krakow, 1984; Manuel, 1990, but see Fowler & Brancazio, 2000), prosodic organization (Diakoumakou, 2005, for nasal coarticulation in Greek) as well as speech rate and speaker-specific patterns (Lubker & Gay, 1982). The introduction of the *movement expansion* model in order to account for highly variable data on lip kinematics attempts to bring together speaker-dependent strategies and general patterns based on spatio-temporal constraints (Abry & Lallouache, 1995 as cited in Farnetani & Recasens, 1999).

Based on the aforementioned notions introduced by Bladon and Al-Bamerni, and Stevens and House, as well as Öhman's and Folwer's gestural models, Recasens

(1985, 1987, 2002a) and Recasens and colleagues (e.g., Recasens, Pallarès, & Fontdevila, 1997; Recasens & Pallarès, 2000; Recasens, & Espinosa, 2009) began developing a model that would account for the large amount of variability observed in coarticulatory overlap and that would predict more precisely the magnitude and extent of coarticulatory effects. In his early studies, Recasens investigated electropalatographic (EPG) and acoustic patterns of V-to-C (1984a) and V-to-V (1984b) coarticulation in VCV sequences produced by a Catalan speaker, in which the vowels were /i/, /a/ and /u/ and the consonants, chosen to represent different degrees of tongue-dorsum contact, were the dorsopalatal approximant [j], the alveolopalatal nasal [ɲ], the alveolopalatal lateral [ʎ] and the nasal [n]. The major finding of the studies was that the degree of V-to-C and V-to-V coarticulation (in linguapalatal fronting and F2) varies monotonically and inversely with the degree of tongue-dorsum contact. Hence, the more resistant the intervening consonant the smaller the V-to-C and V-to-V effects. Additionally, the increased degree of tongue-dorsum contact also limits the temporal extent of coarticulation, with a greater decrease on anticipatory than carryover effects.

This model of coarticulation was named the *DAC* model (Recasens et al., 1997; Recasens, 2002a) as it assigns different Degrees of Articulatory Constraint, or DAC values, to consonants and vowels based on the involvement of the tongue dorsum in their constriction or formation and on their additional articulatory properties. Thus it makes predictions about the magnitude, temporal extent and direction of lingual coarticulation on the basis of the requirements placed on the tongue by the production of vowels and consonants (Farnetani & Recasens, 2010). According to the DAC model (Recasens et al., 1997), high front vowels (e.g., [i]) are more constrained than low or back rounded vowels (e.g., [a] or [u]), as the formation of the former requires raising and fronting of the tongue dorsum and are thus assigned a high DAC value (=3). Schwa is assigned the lowest DAC value (=1) as it lacks articulatory target and places no constraints on the articulators. Likewise, highly constrained consonants that require considerable tongue dorsum involvement (e.g., alveolopalatals [ʃ], [ɲ], velar /k/ and dark /l/) or whose formation involves high articulatory precision (i.e., the production of frication or trilling) are assigned a maximal DAC value (=3). Minimally constrained consonants with no involvement of the tongue in their production (e.g., [p] or [b]) are given a DAC value of 1, while there is also an intermediate category of consonants and vowels which are assigned a DAC value of 2. These are segments that require partial tongue dorsum involvement due to coupling effects (e.g., [n], [t], clear /l/) or are formed with a low and inactive tongue dorsum (e.g., [a] and [u]). Data mainly on English, German and Catalan vowel-dependent effects confirm that the degree of variability at the tongue front of dentoalveolars, laminal fricatives and apicals decreases as follows: [n] > [l] > [d] > [t] > [s] (Recasens, 1999:84).

A pivotal prediction of the model is that segments with a high DAC value will exhibit little coarticulatory variability or context-sensitivity and, at the same time, induce strong coarticulatory effects on adjacent segments (Farnetani & Recasens, 2010). Thus, in a VCV utterance, a highly constrained consonant will allow little V-to-C and V-to-V effects, while causing considerable C-to-V effects on the adjacent vowel. Moreover, C-to-V effects become maximal when adjacent gestures are both highly constrained and antagonistic, e.g., more effects are observed from dark /l/ (DAC=3) on /i/ (DAC=3) than on /a/ (DAC=2).

Moreover, the DAC model makes predictions about coarticulatory directionality. Regarding C-to-V effects, highly constrained consonants (DAC=3) favour a specific direction, i.e., the dark /l/ favours the anticipatory direction due to the tongue tip raising anticipation during the tongue dorsum lowering and retraction, whereas alveolopalatals, palatals and velars show a preference to the carryover component because of the inertia associated with the slow lowering motion of the tongue dorsum at constriction release. The prediction of the model for C-to-V effects from consonants with an intermediate degree of constraint (DAC=2), e.g., dentals and alveolars, is two-fold depending on the vowel; effects on /a/ are more prominent in the anticipatory direction because it allows apical anticipation, while effects on /i/ occur mostly in the carryover direction due to inertia (Recasens, 2002a). Studies on Japanese and Catalan have demonstrated dominance of the carryover over anticipatory effects when the intervening consonant is not very highly constrained (e.g., bilabial, alveolar and velar for Japanese; Kiritani, Itoh, Hirose & Sawashima, 1977) due to inertia originating from the sluggishness of the tongue dorsum. Conversely, highly constrained consonants like the alveolar trill [r] or velarized lateral /l/ show larger anticipation on [i] as a result of the high demands that must be met for their production (Recasens, 1999).

The above predictions regarding the direction of C-to-V effects are also assumed to account for the direction of vowel-dependent effects (V-to-C and V-to-V). The DAC model predicts that the degree of preference for a certain direction of vowel-dependent effects is inversely related to that of C-to-V effects, due to the conflict between vocalic and consonantal gestures. Hence, vocalic anticipatory effects are prominent when C-to-V carryover effects are weak and vowel-dependent carryover effects are favoured when C-to-V anticipation is low. More specifically, vocalic effects are more salient in the carryover than the anticipatory direction when the intervening consonant is highly constrained (e.g., dorsal), because large biomechanical constraints associated with the consonant's production inhibit vowel anticipation. When the intervocalic consonant is less constrained, vowel-related effects can favour either direction depending on the degree of tongue dorsum raising, stress and speech rate (Recasens, 1999). Farnetani and Recasens (2010) comment that greater attention need to be paid to manner requirements and tongue-body configuration characteristics, so as to predict directionality of vowel-dependent effects when the corresponding C-to-V patterns are unclear.

In addition to coarticulatory direction, the DAC model makes predictions about the temporal extent of consonant- and vowel-dependent effects in each direction, an issue also associated with the nature of the coarticulatory effects. As opposed to the time-locked model proposed by Bell-Berti and Harris (1981) and the claim for a fixed onset of anticipatory coarticulation put forth by Fowler and Saltzman (1993), examination of long range coarticulation effects in VCVCV sequences showed that the degree of gestural conflict plays a role in the temporal extent of coarticulation in both directions (Recasens, 1989). In addition, discontinuous V-to-V effects were found in specific contexts, suggesting that "speakers accommodate the occurrence of coarticulation to context and thus plan the upcoming phonemes according to the articulatory requirements for the ongoing phonetic segments" (Recasens, 2002a:2840). Thus, anticipatory effects do not start invariably, instead they occur earlier when the gestures are relatively unconstrained. Nevertheless, the onset of anticipatory effects has been found to vary less than the offset of carryover effects. A possible explanation is that anticipation is associated with planning as well as contextual influence, whereas carryover coarticulation is mostly determined by biomechanical requirements, i.e., inertia of the involved articulators and articulatory overshoot (Recasens, 1989, 1999, 2002, 2010).

Although the coproduction model and articulatory phonology constitute a fairly detailed account of how speech is produced through the blending of gestures as units of articulatory action and have done “wonderful work in relating high level descriptions of languages in abstract terms to low level observable phonetic facts” (Ladefoged, 2004:7), they have been criticized for focusing primarily on production, neglecting the role of the listener. Lindblom’s theory of *Adaptive Variability* and *Hyper-Hypo Speech* (1983, 1989, 1990) is based on the teleological nature of speech and focuses on how communication between speaker and listener can succeed with a minimum amount of effort on the part of the speaker. This schema effectively introduces two different kinds of demands that need to be met simultaneously, an *input* or speaker requirement for economy of effort and an *output* or listener requirement for successful communication. The output is regulated by the needs of the communicative situation; when the need for perceptual clarity is highlighted, the speaker tends to *hyper-articulate*, whereas when the message can be easily received, the speaker chooses to *hypo-articulate* to save energy. Thus a continuum from hypo- to hyper- speech is formed (Lindblom, 1990).

Within the H&H framework coarticulation is viewed as “a low-cost motor behaviour” (Farnetani, 1999:381). According to the first version of the theory (Lindblom, 1963), the speech mechanism may not always have enough time to complete trajectories moving from one articulatory target to the next, e.g., in running speech or as speech tempo increases, resorting to *undershoot*, i.e., not reaching the intended target. In his acoustic study of eight Swedish vowels in /bVb/, /dVd/ and /gVg/ sequences produced under varying timing conditions, Lindblom (1963) observed that as duration decreases, formant movements are reduced and vowels fall short of their acoustic targets. Hence, vowel reduction is a manifestation of undershoot. A revised version of the theory (Moon & Lindblom, 1994) attempts to accommodate findings of more recent studies that looked into the relation of additional variables other than duration to vowel reduction and undershoot. Reduced articulatory movements are not always the outcome of a decrease in duration (Kuehn & Moll, 1976; Gay, 1978b; Engstrand, 1988) and vowel reduction has been observed at fast as well as at slow rates (Nord, 1986). Peak velocity of lingual movement has been associated with undershoot to a greater degree than duration (Flege, 1988). Additionally, speech style, communicative requirements as well as individual articulatory strategies play a significant role in the degree of undershoot (Kuehn & Moll, 1976; Krull, 1989; Lindblom, Brownlee, Davis & Moon, 1992). Thus, even in fast tempo, undershoot can be avoided if the speaker decides to increase articulatory force in order to optimize communicative functionality with articulatory precision. Speech production is, therefore, a continuously adaptive process, maintaining a sensitive balance between economy of articulatory effort on the part of the speaker and the perceptual demands on the part of the listener, so that the ultimate goal of communication between the two parties is reached.

H&H theory can be viewed as an attempt to shift part of the focus to the listener, in contrast to the theory of coproduction and the task dynamic model which concentrate on the way phonetic entities are planned as vocal tract gestures by the speaker and implemented so as to reach the listener. More recently, attempts have been made towards the formulation of a theory that combines both elements, i.e., the concept of overlapping gestures as well as the role of audition in the speech production process. To that end, some researchers propose auditory speech targets as speakers' goals instead of gestural targets (Guenther, Hampson & Johnson, 1998).

Hence, speech movements are programmed to achieve auditory/acoustic goals rather than articulatory goals.

Based on this proposition, a new theory of speech motor control was developed by Perkell, Guenther and colleagues (Perkell et al., 2000), supported by data from speakers with normal hearing as well as with profound hearing loss. The idea is based on a neural network model of speech production (Guenther, 1995) after recent findings of mirror neurons in the human brain “matching action observation and action execution” (Fadiga, Fogazzi, Pavesi & Rizzolatti, 1995:2609). Brain imaging studies have shown that motor areas and auditory areas of the brain are active during speech perception and speech production respectively (Rizzolatti & Arbib, 1998; Hickok & Poeppel, 2000), suggesting a close connection between the two processes (Hickock, 2001). The Directions Into Velocities of Articulators (DIVA) model of speech motor planning (Guenther, 1995; Guenther et al., 1998; Perkell et al., 2000; Guenther & Perkell, 2004; Guenther, Gosh & Tourville, 2006) is based on the assumption that segments are represented in the nervous system as spatio-temporal auditory goal regions which are equated to acoustic goals for the production of speech. It is essentially composed of an internal model that correlates vocal tract shapes with acoustic signals. This model does not rely on continuous auditory feedback after the system’s maturation, especially since saturation effects, e.g., stabilization of articulatory position through contact of articulators, play an important role in determining acoustic goals and help calibrate the system. The system’s function is influenced by biomechanical constraints as early as the planning level so that speech is concurrently produced with minimal effort and adequate perceptual distinctness.

In order to demonstrate the intimate relationship between production and perception, Perkell and colleagues measured phoneme contrast and auditory discrimination between the vowel pairs /ɑ/-/ʌ/ and /u/-/ʊ/ (Perkell, Guenther et al., 2004) and between the sibilants /s/ and /ʃ/ (Perkell, Matthies et al., 2004) and found that articulatory contrast distance correlates with auditory discrimination in both the vowel and the sibilant study. They conclude that “speakers who have relatively sensitive perceptual capabilities produce more distinct sound contrasts” (Perkell, Guenther et al., 2003:439). Additionally, contrast correlates with contact of the tongue tip with the lower incisors for /s/. Their findings are compatible with the DIVA model of speech motor planning which hypothesizes that phonemic goals are in auditory and somatosensory spaces (Perkell, Matthies et al., 2003).

A significant element of DIVA is that its internal model must be learnt during speech acquisition. Auditory, somatosensory and perhaps visual feedback is used for tuning and updating the internal model. Once the relations between motor commands and acoustic output are learnt, they are stored in a feedforward subsystem that becomes increasingly skilled with practice, so that, to a large extent, it does not have to depend on sensory feedback for speech production. The foregoing hypotheses have been tested with various experiments. One of the studies investigated the effects of hearing status and bite blocks on vowel production. Eight postlingually deaf and ten normal hearing adults produced /hVd/ syllables with and without bite blocks and auditory feedback. The results showed that long-term absence of auditory feedback caused vowel dispersion, while auditory experience with a prosthesis reduced vowel dispersion and expanded the vowel space for the deaf both with and without bite blocks (Lane et al., 2005). A perception and production study assessing short- and long-term changes in auditory feedback was also conducted. Vowel and sibilant contrasts were measured in eight postlingually deafened adults at three different times, i.e., before activating their cochlear implant speech processors, one month and one year after activation. It was revealed that their phonemic contrasts worsened one month after activation, as their feedforward mechanism had not had the time to calibrate according to the new auditory feedback, while their contrasts improved one year later (Lane et al., 2007).

These findings underline the importance of the role of auditory feedback in keeping the feedforward component of the DIVA model attuned and up-to-date. The researchers suggest that "models of speech production must assign a role to auditory feedback in error-based correction of feedforward commands for subsequent articulatory gestures" (Lane et al., 2005). As mentioned above, in comparison with the task dynamic model, which uses articulatory actions as targets, the DIVA model utilizes acoustic/auditory targets for phonemic planning (Perkell et al., 2000). In order to investigate the planning and control of vowel-to-vowel (V-V) sequences, acoustic data of such sequences from a male subject and simulation results of the movements corresponding to the same sequences obtained from a computer model of his vocal tract were compared (Zandipour, Guenther, Perkell, Perrier, Payan & Badin, 2004). It was shown that both schemes produced comparable results. Hence, the planning of a V-V sequence in acoustic/auditory space and in motor/muscle space renders similar formant trajectories. This finding unifies the auditory and the motor component involved in learning and planning speech sequences.

DIVA is currently among the most advanced models of speech motor skill acquisition and speech production. It satisfactorily accounts for contextual variability, motor equivalence, coarticulation and speaking rate effects in a wide range of data (Guenther, 2001) and has been computationally implemented to generate articulatory and acoustic data that can be compared to behavioural data. Some of its applications include modeling the effect of lack of auditory feedback on hearing impaired speech (Perkell et al., 2000; Lane et al., 2005; Lane et al., 2007) as well as deriving predictions in cases of neuromotor deficits that underlie CAS (Childhood Apraxia of Speech) and SSD (Speech Sound Disorders) in general, aiming to deduct new angles for clinical intervention (Maasen, Nijland & Terband, 2010; Terband, 2011).

2.1.2. Speech Perception Theories

The central question of early research in the perception of speech regarded the transformation of the acoustic signal into phonetic segments and most studies revolved around the issues of invariance, constancy and perceptual units (Jusczyk & Luce, 2002). The mapping between the properties of the acoustic signal and phonemes or distinctive features proved to be more complex than originally thought and three major theoretical perspectives were expounded and will be briefly reviewed here: the *motor theory*, the *direct realist theory* and the *general approach* or *auditory theory* of speech perception. These theories are narrowly construed, in that they focus on the categorization and discrimination of phonetic segments. In the 1970s the focus was shifted from segments to words and a different category of theories arose, the broadly construed theories of speech perception, according to which, a complete understanding of speech perception entails the examination of the effect of long-term knowledge, and especially lexical knowledge, on early sensory processes. Among them are the *top-down*, *bottom-up* and *Bayesian* theories (Mattys, in press). We will not dwell on this type of theories here[3].

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[3] Among the recent models that belong to the broadly construed framework is the *Fuzzy Logical Model of Perception* (FLMP) (Massaro, 1989; Massaro & Chen, 2008) which suggests that listeners remember descriptions of the perceptual units of language, called prototypes, and perceive speech through a process of matching the acoustic signal with values of the prototypes. Other models include the *TRACE Model* (McClelland & Elman, 1986), *ART* (*Adaptive Resonance Theory*, Grossberg, 1986 as cited in

As discussed previously, the existence of neuronal perceptuomotor couplings indicated by experimental findings (Rizzolatti & Arbib, 1998) provided ground for the development of the DIVA model. In addition, it presented evidence for the claim that the speech motor system participates in speech perception. This claim constitutes a central notion in the *motor theory of speech perception* first postulated by Liberman and colleagues (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Liberman & Mattingly, 1985). According to this theory, “the objects of speech perception are articulatory events rather than acoustic or auditory events” (Diehl, Lotto & Holt, 2004:150). Firstly, it was hypothesized that listeners recover relatively invariant *intended gestures*, i.e., neuromotor commands to the articulators rather than actual gestures. It was assumed that coarticulatory effects complicate the mapping between phonemes and speech sounds, as the temporal and spatial overlap of adjacent phonemes eliminates the one-to-one relation between vocal tract shapes and acoustic signals. Perception experiments with synthetic stimuli of formant transitions demonstrated that speech percepts track articulation in a way that suggests the motor recruitment of gesture perception (Liberman, 1996). In one of the earliest experiments, Liberman, Delattre and Cooper (1954) presented synthetic two-formant stimuli that the listeners identified as /di/ or /du/, despite the fact that the formant transitions are different physically. It was concluded that although the transitions are dissimilar due to coarticulatory effects from the vowel, the listener perceives the same consonant; hence perception tracks articulation. Secondly, the motor theory attributed speech perception to “a specialized decoder, (…) speech-specific, unique to humans, (…) innately organised and part of the larger biological specialization for language”

Mattys, in press), the *Merge Model* (Norris, McQueen & Cutler, 2000), *Shortlist B Model* (Norris & McQueen, 2008), the *Neurocomputational Model* (Kröger, Kannampuzha & Neuschaefer-Rube, 2009), the *Dual Stream Model* (Hickok and Poeppel, 2007), and others.

(Diehl, Lotto & Holt, 2004:152), shifting the weight away from general mechanisms of audition and perceptual learning.

A second theoretical perspective on speech perception, the *direct realist theory*, was developed by Fowler (1981a; 1986; 1990; 1991; 1996). A main point that the direct realist theory and the motor theory have in common is that the objects of speech perception are claimed to be articulatory rather than acoustic events. The foregoing early experiments investigating acoustic cues for consonants via coarticulatory effects from different vowels (Liberman et al., 1952; Liberman et al., 1954) and the investigation of the McGurk effect, which associates hearing and vision with speech perception (McGurk & MacDonald, 1976), suggested that perceptual objects are gestural and not acoustic. More recently, Fowler and colleagues carried out a number of experiments (Fowler, Brown, Sabadini & Weihing, 2003; Fowler, 2006) to further support the claim that perceiving speech entails perceiving gestures (Galantucci, Fowler & Turvey, 2006; Galantucci, Fowler & Goldstein, 2009).

However, a difference between the two theories is that the direct realist theory maintains that listeners perceive actual vocal tract movements and not intended gestures. This view is in keeping with the coproduction theory expounded above (section 2.1.1.), according to which gestures are coproduced and not merged. Therefore, the listener should be able to recover them without requiring a medium such as neuromotor commands, hence the term *direct realism*. Additionally, this theory differs from the motor theory concerning the human-specific mechanism for speech perception; in contrast, it is postulated that “[p]erceptual systems have a universal function. They constitute the sole means by which animals can know their niches” (Fowler, 1996:1732).

The motor theory of speech perception has been criticized by researchers who are sceptical about the motor character of speech percepts (Sussman, 1989; Ohala, 1996) and maintain that no account is given of how listeners translate acoustic signals into intended gestures. Moreover, several empirical findings, such as similarities in perception of nonspeech and speech stimuli (Stevens & Klatt, 1974; Pisoni, 1977) and speech perceptual performance by nonhuman animals (Kuhl & Miller, 1975; Kluender, Diehl & Killeen, 1987), suggesting a general auditory mechanism not specific to humans, provided ground for the development of an alternative theory, a general auditory and learning approach to speech perception, referred to as the *general approach* (Diehl, Lotto & Holt, 2004:154). This approach differs from the motor theory, in that it does not consider speech perception unique to humans nor as a process requiring any special modules. It also contrasts with both the motor and the direct realism theory regarding the implication of actual or intended gestures in speech perception. It is hypothesized that the perceiver utilizes "multiple imperfect cues to categorize complex stimuli" (Diehl, Lotto & Holt, 2004:154). Although this theory does not invoke special mechanisms for perception, there have been claims of specialized processes working in tandem with general perceptual mechanisms, e.g., the attentional or learning bias observed in acquiring native phoneme categories by human infants (Jusczyk, Pisoni, Walley & Murray, 1980; Kuhl, 1991).

As mentioned above, a challenging phenomenon accounted for differentially by theoretical perspectives is that of coarticulation. Experiments have shown that, in ambiguous cases, perception seems to compensate for coarticulatory effects (Liberman et al., 1954; Lindblom & Studdert-Kennedy, 1967; Fowler, 1981a; Holt, Lotto & Kluender, 2000). Since the acoustics are variable, the two perception theories that rely on invariant gestures, intended or actual, as opposed to acoustic pattern recognition, present a stronger case. The *general approach*, based on experiments with birds and humans, postulates that perceptual compensation for coarticulation lies in spectral contrast. In addition, Holt et al. (2000) have provided evidence for the existence of nonspeech context effects and propose a general perceptual function that plays an important role in human production and perception of phoneme coarticulation.

Proponents of the gestural theory (see Galantucci, Fowler & Turvey, 2006, for a review) have challenged the spectral contrast account. Experiments of synchronized auditory and visual interactions (the *McGurk effect*) (Fowler, Brown & Mann, 2000) initially rendered support to the motor and articulatory-gesture theories, as the integration of the visual component in speech perception would require a gestural account. However, McGurk-type findings have proven divisive theoretically as advocates of auditory theories call upon *experience* to interpret the link between visual information with corresponding auditory primitives (Rosenblum, 2005:53). Nevertheless, more recent experiments, using continua hybridized from natural speech (Fowler, 2006) and examining tone analogues vs. natural formants (Viswanathan, Fowler & Magnuson, 2009) cast doubt on the role of spectral contrast in natural speech.

Overall, the *general approach* or *auditory theory* has been criticized for inadequacy in theoretical content. This theory seems to have evolved as a counter-argument to the gestural approach without developing an autonomous identity based on the auditory representation of natural speech. Although the popularity of the original version of the motor theory has waned over the years, in their recent paper, confirming the results of Kerzel and Bekkering (2000) which indicate that the perception of syllables affects their production, Galantucci, Fowler and Goldstein (2009:1148) state that:

> "the claim of the motor theory that the motor system is recruited for perceiving speech represents today a simple unifying explanation for a large number of empirical results related to speech perception (…) [and] appears to be an expected consequence of a much broader design feature of cognition."

Despite the disagreement about the process underlying the extraction of linguistic elements or distinctive features from the acoustic signal by listeners, there is consensus among theorists that "regularities in speech production (e.g., context dependencies in the realization of successive phonemes) should be highly correlated with listeners' perceptual judgments" (Diehl et al., 2004:167). The difference in theoretical positions lies in the explanation of the correlation.

According to the *general approach* or *auditory theory*, the correlation between production and perception is twofold. Firstly, production follows perception, in that a speaker manipulates his production so as to achieve auditory distinctiveness. A representative example is a principle followed by the sound systems of languages, the principle of dispersion, which maximizes the distances between phonemes so as to ensure intelligibility. Speakers implement the dispersion principle by selecting that gestural correlate of a phoneme which will make it maximally distinctive, i.e., acoustically and auditorily most distant from others (*auditory enhancement hypothesis*, Diehl & Kluender, 1989). Secondly, perception follows production; listeners do not recover gestures, but rather perceive their acoustic corollaries, assisted by general mechanisms of perceptual learning. The use of visual and auditory cues in speech perception (McGurk effect) has been utilized as support for the gestural theories, but the mapping between visual or auditory cues and phonemes could also be attributed to perceptual learning and serve as evidence for the auditory theory.

The *motor theory* and the *direct realism theory* of speech perception both postulate that the only way to avoid the much discussed in the literature discrepancy between the language forms of phonological competence and the actions that produce them is the employment of gestures, i.e., “linguistically significant actions of the vocal tract” (Fowler & Galantucci, 2005:636). It is maintained that, in order to achieve *parity*, that is, “a relation of sufficient equivalence between phonological messages sent and received” (Fowler & Galantucci, 2005:636), two conditions must be met; first, the forms of linguistic messages should be the actual forms of the actions producing them or should be isomorphic with them, and second, language forms should be preserved throughout a communicative exchange. Proponents of this theory consider unrealistic the idea that language forms exist in the mind of the listener. The signal itself contains articulatory information that the listener can recover, so as to reconstruct the gestures of the speaker, in spite of the mismatch caused by coarticulation. If listeners perceive gestures, as experimental evidence cited above seems to suggest, both conditions for parity are met. Parity in speech “requires the use of a common currency between talkers and listeners” (Fowler, Galantucci & Saltzman, 2003:707). The employment of gestures as the common currency warrants the link between production and perception, and fosters successful communication.

2.2. Coarticulation Studies -Production of Normal Speech

In this section we provide a review of recent studies on coarticulation phenomena in normal speech. We will focus on factors influencing coarticulatory effects which are within the scope of this thesis, i.e., context, stress and gender, with special reference to the segments examined in the present study.

2.2.1. Contextual Variability

A central question posed by Fowler and Saltzman (1993) is why speakers follow a speech production strategy that permits flexible achievement of phonetic goals instead of choosing one context-free route. Although the latter may initially seem simpler, it would entail the existence of a countless list of allophones ready for use in the corresponding context. In contrast, the invariance in phonetic goal achievement calls for the existence of context-sensitive phonemes, each characterized by a blending strength depending on its articulatory requirements. In accordance with the task-dynamic modeling, "[b]lending strength (…) captures in a formal sense both the coarticulatory *resistance* and *aggression* of phonetic gestures…" (Fowler & Saltzman, 1993:183). A phoneme displays coarticulatory variations depending on the degree of spatial overlap, that is, the degree to which it shares articulators with adjacent phonemes (Farnetani, 1999). When competing demands are made on the same articulators simultaneously, the constraints imposed on the competing gestures will play an important role in the temporal and spatial overlap of the gestures (Farnetani & Recasens, 1999).

The degree and extent of coarticulatory effects in association with the coarticulatory resistance and aggression displayed by segments during gestural coordination have been extensively examined by researchers over the years using various techniques, e.g., acoustic analysis, cinefluorography, EPG (electropalatography), EMMA/EMA (Electromagnetic Midsagittal Articulometry), MRI (Magnetic Resonance Imaging), Ultrasound. We will cite major findings, focusing on vocalic and consonantal segments selected for the current study, namely, vowels [i, a, u] and consonants [p, t, s]. We will be paying particular attention to the DAC model studies (section 2.1.1.) carried out by Recasens and colleagues, as they are associated with the research questions of the current thesis (section 2.5.2).

2.2.1.1. Vowels

The three vowels [i, a, u] are among the most studied vowels in the literature. According to the *Quantal Theory* (Stevens, 1989), these vowels, namely the *quantal vowels*, are more stable acoustically, in that their acoustic properties are not as affected by articulatory variation. They appear in the inventory of the vast majority of languages and, as supported by the *Adaptive Dispersion Theory* (Liljencrants & Lindblom, 1972), they are situated at the extremes of a physiologically possible vowel space which makes them maximally acoustically distinct. However, variability has been observed in their production (Pisoni, 1980) and their stability has been questioned, as invariance in one vocal tract parameter does not preclude variation in others (Diehl, 2008). The DAC model claims that vowel coarticulability varies inversely with the involvement of the tongue dorsum in vowel production in much the same way as is the case with consonants (Recasens et al., 1997; Recasens, 2002).

For the production of the high front vowel [i], the tongue is positioned forward and high in the oral cavity. Additionally, “the sides of the tongue blade are pushed against and restrained by the hard palate” (Perkell & Nelson, 1985:1893). The simultaneous fronting and raising for the formation of a constriction between the tongue dorsum and the hard palate make this vowel highly constrained and resistant to coarticulatory effects, while, at the same time, able to induce more V-to-C and V-to-V effects in comparison to other vowels in most languages (American English: Gay, 1977b; Butcher & Weir, 1976; Catalan and Spanish: Recasens, 1985, 1987; Italian: Farnettani, Vagges & Magno-Caldognetto, 1985; Scottish English: Zharkova, 2007). Nevertheless, variability has been reported for this vowel at regions located behind the palatal constriction when adjacent to velars (MacNeilage & DeClark, 1969; Kiritani, Itoh, Hirose & Sawashima, 1977) and alveolar fricatives (Farnetani & Recasens, 1993). Moreover, an EPG study conducted by Nicolaidis (1997), investigating coarticulatory variability in VCV sequences containing vowels [i, a] and consonants [p, t, s] produced by two male speakers of Greek, showed increased variability in the production of [i] which was attributed to its possessing a relatively larger area in the Greek vowel space. Asteriadou (2008), in an acoustic study of V-to-V coarticulation in VCV sequences with vowels [i, a] and consonants [k, n, ɲ, p, t] produced by five male speakers, also found Greek [i] more sensitive to coarticulatory effects than [a] at vowel midpoint in the F1 dimension. In addition, an earlier glossometry study of German vowels revealed a rather surprising tendency for high and tense vowels to show more coarticulation (Bohn, Flege & Dagenais, 1991).

However, more coarticulatory variability has been generally reported in the literature for low and back vowels (Butcher & Weir, 1976; Farnetani & Recasens, 1993). For the production of vowel [a], the tongue is slightly back and low in the oral cavity and the mandible is lowered. Hence the retracted tongue dorsum allows variation at the anterior tongue region (Perkell & Nelson, 1985; Perkell, 1990). A recent EMA study of symmetrical VCV sequences with the consonants [p, n, l, s, ʃ, ɲ, k] and the vowels [i, a, u] produced by three Catalan male speakers is in support of this observation. Recasens and Espinosa (2009) demonstrated that C-to-V effects on [a] and [u] occur mostly at the tongue tip and blade. Effects from alveolopalatals and dentoalveolars are evident in tongue height for [a] and tongue fronting for [u] (also Recasens, 1985). Lower jaw position for [a] has been related to coarticulation susceptibility in jaw height in English and Swedish (Keating, Lindblom, Lubker, & Kreiman, 1994), although Hoole and Kühnert (1995:444), in their EMA study of tense-lax German vowels, argue that "increasing variability with decreasing tongue height is not completely warranted" and thus, "the question of high vs. low vowels may be wrongly posed". Instead they propose a palatal vs. non-palatal distinction in variability and underline the importance of investigating entire vowel systems rather than selected vowels. As mentioned above, less variability for the Greek [a] vs. [i] was also found by Nicolaidis (1997) in an EPG study and acoustically by Asteriadou (2008) in the F1 axis, which may indicate a constrained retracted tongue dorsum and a more context-sensitive anterior tongue region for [a] as suggested by Perkell and Nelson (1985).

In producing the high back vowel [u], the tongue is elevated into a high and back position forming a narrow constriction in the velo-palatal region while the lips are rounded and protruded. This vowel has been reported as more variable than [i] because of the trading relationship between the tongue and the lips; more lip rounding can compensate for less tongue raising and vice versa (Perkell, 2006; Brunner, Hoole & Perrier, 2007). Overall, coarticulation resistance has been documented to vary in the order [i] > [a] > [u] in Catalan (Recasens, 1985; Recasens & Espinosa, 2009) and German (Hoole & Kühnert, 1995). Nevertheless, in a cinefluorographic study of vowels [i, a, u] in VCV combinations with the consonants [p, t, k], Gay (1974) observed that both vowels [i] and [u] were relatively insensitive to consonantal and vocalic effects, whereas [a] displayed a strong tendency for variability. However, these observations could not be confirmed acoustically which he attributed either to articulatory compensation for the open vowel's perturbations not measured in the study or to the more gross movement of the massive jaw during the production of [a] in comparison to that of the tongue for [i] and [u].

In contrast, Heuvel, Cranen and Rietveld (1996) examined coarticulation effects on Dutch vowels [i, a, u] in /C_1VC_2ə/ pseudo-words containing the consonants [p, t, k, d, s, m, n, r] produced by fifteen male speakers and found the largest amount of coarticulation on [u] especially from nasals and alveolars. Its increased coarticulation with alveolars (apicalization) relative to [i] and [a] may be accounted for by the sluggishness of the tongue tip that dwells at the alveolar ridge during its production. These results are in agreement with Recasens and Espinosa (2009) who find [u] less resistant than [a]. Mok (2011), however, in an acoustic examination of V-to-V coarticulation with Thai long and short vowels produced in the bilabial context /pV_1pV_2paː/ by three male and three female speakers, reports that [a] is more susceptible to vocalic effects than [i] and [u]. The DAC model assigns the maximal value of 3 to [i] and the intermediate value of 2 to both [a] and [u] (see also section 2.1.1). Perhaps data from more vowels of different languages are needed in order to make more accurate predictions regarding vocalic resistance and aggression.

2.2.1.2. Consonants

According to the DAC model, coarticulatory resistance and aggression displayed by a consonant increases with the degree of its articulatory constraint and depends on the involvement of the region under study in the consonantal closure and constriction formation as well as on manner requirements (Recasens & Espinosa, 2009). As far as lingual coarticulation is concerned, the degree of tongue involvement in the consonant's production is a major determinant of its resistance. Overall, alveolopalatals, palatals and laminal fricatives, such as [s], [z], [ʃ] and [ʒ], are more resistant than apicals, dentals and alveolars, such as [t], [d], [n] and [l], while labials are the most sensitive due to an unconstricted tongue dorsum (Recasens, 1999).

Regarding the production of the three consonants of the current study, for [p] the lips are brought together to obstruct the oral cavity, while the tongue position may vary depending on phonetic context. As a result, contextual effects spanning this consonant are large (Carney & Moll, 1971; Recasens, 1985, Recasens et al., 1995, 1997). For an alveolar stop such as [t], on the other hand, the front and sides of the tongue must contact the alveolar ridge anteriorily and laterally. Therefore it is more constrained and hence more coarticulation resistant than [p]. Regarding the Greek [t], EPG data shows "an advanced lingual placement (…) with possible constriction further forward in the dental area" (Nicolaidis, 1994:230) and very small articulatory variability at the tip/blade region (Nicolaidis, 1997). Although less variability has been generally reported for dentoalveolars than bilabials (Gay, 1974), the coupling between the tongue front and dorsum does not preclude the occurrence of contextual effects (Recasens, 1999). The constriction at the dentoalveolar region allows the rest of the tongue to adjust to context as Recasens (2002) has demonstrated with the production of [n]. In addition, evidence from an ultrasound study, that captures movements of the whole tongue contour as opposed to EPG and EMA which provide information for only parts of the tongue, shows that the tongue contour during the production of [t] is three times more influenced by context than that of [a] (Zharkova & Hewlett, 2009).

Besides tongue involvement, jaw position has also been related to the higher coarticulatory resistance of [t] as compared with [p]. The alveolar stop is produced with a higher jaw position than [p], as the tongue has to be positioned higher in order to direct airflow at the teeth. Consequently, these production requirements instigate a fairly stable position for [t] and contribute in increasing its resistance to vocalic influence in height, as opposed to [p] which seems to vary more according to vowel context (Perkell, 1969; Tuller, Harris & Gross, 1981; Keating et al., 1994).

For the production of the fricative [s], the apex and blade of the tongue are elevated into contact with the post-alveolar area while a short midsagittal groove is formed in anterior tongue blade. The blade is positioned against the alveolar ridge so as to produce a narrow constriction, and air is forced through so that turbulent frictional noise is generated (Shadle, 1985 as cited in Perkell et al., 2000). Due to its manner of articulation placing increased demands on the tongue, [s] often allows for less tongue dorsum coarticulation than homorganic stops such as [t], which is why the former has been assigned a DAC value of 3, and more recently a value of 4 (Recasens, 2005), and the latter a value of 2 (Recasens, 1999). The alveolar stop has been found slightly more variable than [s] in several languages, e.g., German (Hoole, Gfoerer & Tillmann, 1990 as cited in Recasens & Espinosa, 2009) and Scottish English (Zharkova, 2007). Additionally, according to recent EMA evidence, frication possibly places more demands on the tongue dorsum than laterality and possibly darkness, contributing to an increase in articulatory constraint for fricatives compared to laterals (Recasens & Espinosa, 2009:2297; Zharkova, 2007:243, see Table 1). However, less variability for [s] than clear [l] has been found for German (Hoole, Gfoerer & Tillmann, 1990 as cited in Recasens & Espinosa, 2009).

In addition to increased tongue dorsum requirements, the high position of the jaw during [s] production intensifies its coarticulatory resistance. The characteristic high-frequency noise during sibilant production is enhanced by the upper and lower incisors[4] which poses additional demands on the jaw (Howe & McGowan, 2005). The high and invariant position of the jaw, despite a lower tongue tip height for sibilants was also corroborated by Mooshammer, Hoole & Geumann (2007) in an EMMA examination of German coronal consonants. These results are in line with Lindblom's (1983) *sonority hierarchy* that places sibilants at the lower end due to their high jaw position, and consequently underlining their incompatibility with vowels, traditionally related with lower jaw positions. High jaw position is thus an additional parameter to the high degree of coarticulatory resistance attributed to frication.

Nevertheless, [s] may display coarticulatory sensitivity at unconstricted lingual regions, e.g., the tongue back. A study employing the parallel use of EPG and ultrasound techniques revealed that vocalic influence on Scottish English [s] is registered in the tongue root with ultrasound but not with EPG (Zharkova, 2008). Additionally, EPG data on the Greek [s] show that "there is relative freedom in the articulation of the fricative which can range from retracted alveolar to advanced postalveolar and occasionally postalveolar" (Nicolaidis, 1994:229). The absence of a contrastive fricative in Greek articulated in the same region on the one hand, and the lingual bracing with the hard palate for the production of the alveolar stop on the other, may account for the greater overall sensitivity of the Greek [s] vs. [t] to coarticulatory effects from neighbouring segments (Nicolaidis, 1997). Furthermore, an EMMA and EPG study of German alveolar stops vs. fricatives provides evidence for a significantly greater percentage of maximal anterior contact during stop closure than fricative constriction (Fuchs, Perrier, Geng & Mooshammer, 2006). The authors attribute the high amount of contact during the alveolar stop to the tongue's collision with the palate for the formation of the closure, and explain the reduced contact

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[4] According to a new aeroacoustic theory postulated by Howe & McGowan (2005:1025), "the sibilant fricative [s] is produced by a jet of air striking the upper incisors (…) [and this] jet is deflected downwards to pass through the gap between the upper and lower incisors".

during the sibilant on the basis of the tongue grooving that prevents more contact with the palate. Thus, more palate contact for the alveolar stop could account for its higher coarticulatory resistance when compared with the fricative. Moreover, [s] has been documented to allow coarticulatory effects from [i], exhibited in increased tongue dorsum contact (Stone, Faber, Raphael & Shawker, 1992; Nicolaidis, 1994, 1997; Recasens, 1999) and from [u] due to lip rounding, demonstrated in its acoustics and aerodynamics (Shadle & Scully, 1995).

2.2.1.3. Consonant-to-Vowel Effects

As expounded above, consonants that display strong coarticulatory resistance will also exert considerable influence on the adjacent vowel, depending on the degree of articulatory constraint (DAC) for the vowel as well as on the two segments' trajectory distance. Thus, the size of C-to-V effects depends on the relative DAC specification for the two adjacent segments as well as on whether their articulatory trajectories are synergistic or antagonistic, that is, whether the constraints involved in their production are compatible or opposing (Recasens, et al., 1997:559).

Thus, C-to-V effects are negligible (a) when the vowel has a higher DAC value than the consonant, e.g., /pi/, /pa/, and (b) when the consonant and the vowel are specified for the same DAC value and their trajectories are synergistic, e.g., /ɲi/. C-to-V effects are more prominent (a) when the consonant is specified for a higher DAC value than the vowel, e.g., /ɲa/ > /na/, and (b) as the degree of gestural antagonism increases, e.g., /łi/ > /si/. According to the DAC model, maximal C-to-V articulation occurs with maximal antagonism so as to ensure successful realization of the consonant. The temporal extent of C-to-V effects has been found to correlate highly with coarticulatory size. In particular, large effects are usually longer (e.g., /li/, /ɲa/), while small effects are often shorter (e.g., /pa/, /la/) (Recasens et al., 1997:559).

More specifically, the consonants related to the current study, i.e., the alveolar stop [t] and the fricative [s], are likely to cause some coarticulatory effects on vowel [i] and considerable effects on vowels [a] and [u]. Tongue dorsum raising and stretching has been reported for [a] (Gay, 1974, 1977a; Recasens, 1990) and [u] (Butcher & Weir, 1976; Kiritani et al., 1977; Recasens, 1990) when adjacent to dental and alveolar consonants, while [i] is fairly constrained due to tongue dorsum involvement in the palatal constriction (Recasens, 1985, 1990, 1999; Recasens & Espinosa, 2009). However, lowering of the tongue predorsum has been documented during the production of the fricative [s] as well as the alveolar [n] in the [i] context, due to manner requirements and language-specific constraints for [s] and [n] respectively (Recasens et al., 1997:550).

Regarding the coarticulatory aggression of the two alveolars, an EPG and acoustic study of C-to-V effects in Catalan (Recasens, 1990) showed that the fricative [s] causes a lower F2 than the stop [t] on [i], because of the lowering of the tongue dorsum along the mediopalatal region of [i] due to frication (also Farnetani & Recasens, 1993, for Italian). In the same way, [s] tends to cause a higher F2 on back vowels than [t] (also Stevens & House, 1963, for American English). As more research is being conducted, the DAC value of the fricative [s] is found higher. In early studies, [s] along with [t, d, z] were characterized as dentoalveolars, less constrained than [l] and [r] (Recasens, 1985:106). Progressively, more data on Catalan indicated that [s] is more constrained than other alveolars and was assigned a DAC value of 3 (Recasens et al., 1997:545). More recently, [s] was specified for a DAC value of 4 (Recasens, 2005), and Recasens & Espinosa (2009:2296) claim that "frication contributes more than laterality and possibly darkness to an increase in degree of articulatory constraint". However, as mentioned above, differences in languages and instrumental techniques have rendered differential results regarding the relative coarticulatory resistance and aggression of [t] versus [s], and consequently the relative strength of their coarticulatory effects on vowels (cf. Farnetani, Hardcastle & Marchal, 1989, for Italian; Nicolaidis, 1997, for Greek; Fuchs et al., 2006, for German).

2.2.1.4. Vowel-to-Vowel Effects

Coarticulatory Magnitude

The first model attempting to account for V-to-V coarticulation across bilabial, alveolar and velar stops was proposed by Öhman (1966). According to the tongue system of independent articulators for consonants and vowels (section 2.1.1.), tongue regions that are not constrained by consonantal commands during a VCV sequence can be conditioned by the underlying diphthongal gesture and allow for V-to-V effects. A lot of articulation studies since then have shown that the production of a vowel is influenced by a vowel in an adjacent syllable across a consonant (Gay, 1974, 1977a&b; Butcher & Weir, 1976; Alfonso & Baer, 1982; Farnetani et al., 1985; Huffman, 1986; Butcher, 1989; Magen, 1997; Cho, 2004; Fletcher, 2004).

In his study of V-to-V coarticulation in Catalan VCV sequences, Recasens (1984b:1624) found that "the degree of V-to-V coarticulation in linguapalatal fronting and F2 frequency varies monotonically and inversely with the degree of tongue-dorsum contact of the intervening consonant". Non-dorsal consonants allow more transconsonantal effects than dorsal consonants. However, he also points out that articulatory mechanisms involved in the production of the entire VCV sequence come into play. The DAC model can make predictions about V-to-V effects but *both* the constraints of the intervocalic consonant *and* that of the fixed vowel[5] need to be taken into account (Recasens, 1997). Hence, when a fixed vowel is not highly constrained, e.g., [a], V-to-V effects should be larger across a bilabial than an alveolopalatal, whereas this difference may be cancelled out when the fixed vowel has a maximal DAC value, e.g., [i]. Predictions about V-to-V effects based on coarticulatory sensitivity of consonants and vowels become even more complex with segments assigned intermediate DAC values.

In their acoustic study of V-to-V coarticulation, Cole, Linebaugh, Munson and McMurray (2010) name [i], [a] and [æ] *trigger* vowels, as they cause variability in [ʌ] and [ɛ], the *target* vowels; [i] triggers fronting and raising, [a] backing and lowering and [æ] fronting and lowering. Most studies use vowels that occupy the extremes of vowel space as triggers and central, unaccented vowels as targets. Vowels [ə] and [ʌ] are selected as targets in a large number of studies. Effects on these vowels are bound to be larger and longer than on the rest of the vowels (Whalen, 1990; Fowler & Brancazio, 2000; Beddor, Harnsberger & Lindemann, 2002; Fowler, 2005). As many studies have shown, consonant-dependent effects can affect the magnitude and extent of V-to-V effects (Öhman, 1966; Recasens et al., 1997; Fowler & Brancazio, 2000; Fowler, 2005); however vowel identity also plays an important role. In their experiment, Cole et al. (2010) used voiced and voiceless consonants with a bilabial, alveolar and velar place of articulation and observed that, despite the significant consonantal effects, speaker and target vowel identity alone accounted for 80% of the total variance in F1 and F2, underlining the contributing role of the target vowel in V-to-V coarticulation effects. Variable results have been reported regarding V-to-V

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[5] Fixed is the vowel viewed as the ‘target’ receiving the contextual influence and kept constant when comparing VCV pairs, e.g., in /ata/-/ati/ pairs V1=[a] is the fixed vowel.

coarticulation across different consonantal contexts in Greek. Nicolaidis (1997) reports bidirectional V-to-V effects over the bilabial [p], less effects over [s] and negligible or negative effects over [t]. Koenig and Okalidou (2003), in a comparative acoustic V-to-V coarticulation study in English and Greek, observe greater V-to-V coarticulation across [t] than [p] in both languages, in opposition with the DAC model predictions. The different technique used for the analysis of the data, i.e., EPG in the former and acoustic measurements in the latter study, as well as other differences in the methodology may account in part for the diverse results. Asteriadou (2008) also found overall greater F2 V-to-V effects over [p] than [t], but carryover [a]-to-[i] effects were larger over [t]. Thus, fixed vowel context and coarticulatory direction are two additional factors that need to be taken into account along with consonant identity.

Besides consonant and vowel identity or degree of constraint, the vowel inventory of a language can also influence the degree and extent of V-to-V coarticulation. Manuel and Krakow's (1984) seminal study of V-to-V coarticulation in English, which has a relatively crowded vowel system, and two Bantu languages, Shona and Swahili with five-vowel systems, showed larger V-to-V effects in the second case, which the authors associated with a higher tolerance for variability in systems with more spread apart vowels since it would not compromise distinctiveness. Similar results were reported from Magen (1984a) regarding V-to-V effects in English and Japanese, also a language with five phonemic vowels. Okalidou and Koenig (1999) also report greater V-to-V coarticulation along the F2 in Greek, a five vowel system, than in English. The aforementioned studies as well as Manuel's subsequent work with Ndebele, Shona and Sotho (1987, 1990), provided support to the idea that the degree and extent of coarticulation "respects output constraints determined by the distribution of contrastive segments in the phonetic space" (Manuel, 1999:186).

Phonemic vowel density, however, does not seem to be the sole criterion for predicting V-to-V coarticulatory patterns in a language. Choi and Keating (1991) compared V-to-V coarticulation in English and in three Slavic languages with five or six vowel phonemes and found more effects in English. These results, in line with Öhman's explanation for the lack of coarticulation in Russian (1966), were attributed to contrastive palatalization in these languages which interacts crucially with vowel variability. Thus, consonant contrast, along with vowel contrast, may be another factor conditioning coarticulation. However, Beddor, Harnsberger and Lindemann, (2002), do not confirm the expected larger V-to-V effects in Shona versus English, regardless of the fact that the former is a language with a sparser vowel space. Han (2007), testing the role of contrast in V-to-V coarticulation in Korean and Japanese, whose vowels differ in number and distribution, located no cross-linguistic coarticulatory differences. His findings are in line Disner (1983) who, after examining the vowel systems of different languages, claims that the precise phonetic quality of vowels is specified in the grammar of a language. Consistent with this notion, Bradlow (1995), following a comparative acoustic study between English and Spanish vowels, maintains that "vowel categories are determined by a language-specific base of articulation property" (p. 1923). For these researchers, contrast cannot adequately explain coarticulatory patterns.

In agreement with Bradlow (1995), Mok (2006), subsequent to a V-to-V coarticulation study in Cantonese (eight vowels) and Mandarin (five vowels), assigns a more important role to syllable structure than phonemic vowel density. Her comparative V-to-V study in English and Thai demonstrates that the former, a language with complex syllable structure, allows for more V-to-V effects than the latter, a language with simple syllable structure albeit with a less crowded vowel system (Mok, 2007). Additionally, she found that closed syllables (VC#V) allow slightly more V-to-V effects than open syllables (V#CV) for [i] in Thai (Mok, 2010). These findings corroborate the importance of syllable structure on language-specific V-to-V coarticulation.

Coarticulatory Extent and Direction

The extent of V-to-V effects, in much the same way as their magnitude, is related to the requirements made upon the tongue dorsum for the intervening consonant as well as for the transconsonantal vowel (Recasens, 1999). Temporal aspects of coarticulation have been typically examined in relation to coarticulatory directionality.

The existence of anticipatory transconsonantal V-to-V effects was incompatible with the look-ahead model (Henke, 1966), as all vowels except [ə] are specified, and also conflicted with the notion that the C_nV syllable is the primary unit of speech restricting coarticulatory effects within its boundaries (Kozhevnikov & Chistovich, 1965 as cited in Kent & Minifie, 1977) (section 2.1.1). In early studies, V-to-V effects were not found to extend beyond consonantal closure (Gay, 1974, 1977a) or the transitions of the transconsonantal vowel (Öhman, 1966; Carney & Moll, 1971), but various V-to-V coarticulation studies in Japanese (Magen, 1984a), Bantu languages (Manuel, 1990), English (Magen, 1989; Whalen, 1990) and Catalan (Recasens, 1984; 1987) demonstrated the existence of such effects in the steady-state period of the transconsonantal vowel and even beyond adjacent syllables. Fowler and Saltzman (1993), however, after calculating segmental durations in Magen's work (1989), maintain that the temporal extent of vowel's influence in English is about

200-250 ms at a comfortable rate, which is in line with the predictions of the time-locked model (Bell-Berti & Harris, 1981).

An acoustic analysis of V-to-V coarticulatory effects in Catalan and Spanish showed that transconsonantal effects in both the anticipatory and the carryover direction can last until the onset of V_1 and the offset of V_2 correspondingly (Recasens, 1987). Regarding long range coarticulation, a study of coarticulatory effects in VCVCV sequences carried out by Recasens (1989) revealed no coarticulatory effects exceeding the VCV domain. In this study, the vowels in initial and final position were [i] and [a], the consonants were [t] and [ʃ], while the medial vowel was [ə]. He found that V-to-V anticipatory effects were blocked by the highly constrained [ʃ], whereas they appeared during [ə] over [t]. On the other hand, the offset of the carryover effects was more variable, depending to a large extent on the articulatory demands of contextual gestures. This temporal aspect of anticipatory and carryover articulation unveiled a difference in their nature, suggesting that anticipation onset is preprogrammed, whereas the extent of the carryover effects depends on contextual requirements and could be sensitive to mechanico-inertial factors (Recasens, 1999). That is not to say that anticipatory effects start invariably at the same point in time. In a V_1CV_2 sequence, when the gestures involved in the production of the intervening consonant and/or transconsonantal vowel are relatively unconstrained, then V_2 anticipation is expected to start earlier in V_1 (Farnetani & Recasens, 2010).

Recent data from an acoustic study of interspeaker variation in the extent and perception of long-distance vowel-to-vowel coarticulation (Grosvald, 2009) showed that such effects may last over at least three vowels' distance and across as many as five intervening segments. The material consisted of two sentences containing real words: "It's fun to look up at a key" and "It's fun to look up at a car". The "trigger" vowels [a] and [i] at the end of the two sentences were found to induce anticipatory V-to-V effects up to vowel [ʌ] in “up” over consonants [k] and [t]. These results seem inconsistent with the limited temporal duration proposed by the coproduction theory and more in line with the window model. A crucial parameter of the experiment was the use of the highly susceptible schwa or the lax back vowel [ʌ] as a target vowel in the context of natural-sounding sentences.

The DAC model predicts trends in V_1-to-V_2 coarticulatory direction based on the degree of constraint for the intervocalic consonant and the prominence of C-to-V effects. That is to say, “the extent to which vowel-dependent tongue dorsum activity may be anticipated is closely linked to the mechanico-inertial constraints associated with the tongue dorsum during consonantal production” (Recasens et al., 1997:544). Consonants exerting more carryover than anticipatory C-to-V coarticulation will allow more vowel-dependent carryover than anticipatory effects across them. Hence, vocalic anticipation varies inversely with the salience of C-to-V_2 carryover effects and vocalic carryover effects become weaker as C-to-V_1 anticipation strengthens (Recasens, 2002a&b). The clearer the patterns of C-to-V direction are, the more robust the V-to-V direction patterns appear. Consonants with less anterior places of constriction, such as alveolopalatals, palatals and velars favour C-to-V_2 carryover effects due to the inertia of the tongue dorsum; vocalic anticipation is blocked whereas carryover vowel-dependent effects are predominant, especially in the fixed [i] context (Recasens et al., 1997, 2010).

Concerning less constrained consonants, coarticulatory direction predictions are less consistent (Recasens, 2002a). More anterior dental and alveolar consonants do not exert such large carryover effects (Recasens, 2010). In the case of dentoalveolars and labials, the quality of the fixed vowel seems to play a determining role. In a lingual coarticulation study in Catalan (Recasens et al., 1997), results showed that when [n], [ʃ] and in some cases [ɲ] are adjacent to [i], vowel-dependent effects are prominent at the carryover level, whereas when adjacent to [a], the anticipatory component is more salient (p. 560). A possible explanation was offered; vocalic anticipation is blocked when raising of the tongue dorsum during the consonant is enhanced in the fixed [i] context, while less anterior tongue dorsum positioning for [a] permits unencumbered apical anticipation. Regarding [s], no clear directionality pattern for vocalic effects was detected in either vowel context which was attributed to the high requirements for its production. As far as the temporal extent of V-to-V effects is concerned, consonants specified for a high DAC value (e.g., [ɲ], [ʃ], [s]) allow shorter anticipation in F2 than consonants requiring lesser tongue-dorsum involvement (e.g., [p], [n]) (Recasens et al., 1997:553).

In the previous subsection (see *Coarticulatory Magnitude*) we discussed that there is evidence that syllable structure influences the size of V-to-V coarticulation in some languages; in Thai, closed syllables allow more coarticulation than open syllables (Mok, 2010). Besides coarticulation magnitude, syllable structure has been found to influence direction and extent of V-to-V coarticulation. An acoustic analysis of the bidirectionality of coarticulation in VCV utterances in American English was carried out by Modarresi, Sussman, Lindblom and Burlingame (2004). In this study the syllable structure was found to be a determining factor in controlling coarticulatory direction and extent. The influence of [i] and [ɔ] on [i, ɔ, e, u] was measured in the F2 frequency across the stops [b, d, g, p, t, k]. It was demonstrated that closed (VC.V) syllable shapes facilitate carryover effects across all stops. In open (V.CV) syllables, anticipatory exceed carryover effects across labial and velar stops, while the carryover direction is favoured by alveolar contexts. The prominence of anticipatory effects in open syllables was associated with the CV_2 syllabification that induces significant effects on V_1. On the other hand, in closed syllables there was shorter temporal separation between V_1 and V_2 and a possible V_1C affiliation that caused overwhelmingly greater carryover than anticipatory coarticulation.

Variable directionality trends for vocalic effects have been reported in different experiments cross-linguistically. For instance, larger carryover than anticipatory vowel-dependent effects have been reported over bilabials in some experiments (Bell-Berti & Harris, 1979; Manuel & Krakow, 1984, for English; Recasens, 1987), while in others, the anticipatory component is favoured (Manuel & Krakow, 1984, for Swahili and Shona; Magen, 1984a, for Japanese; Hoole, Gfoerer & Tillman, 1990, for German as cited in Recasens, 1999; Butcher, 1989; Magen, 1997, for English; Recasens, 2002, for Catalan). Asteriadou (2008) reports that the carryover component is systematically preferred in V-to-V coarticulation over the Greek consonants [p, t, n, ɲ, k]. As discussed above, cross-linguistic variation in magnitude and extent of coarticulatory directionality may be attributable to variables such as phonemic inventory, prosody, syllable structure and output constraints related to communication requirements (Manuel & Krakow, 1984; Manuel, 1990; Manuel, 1999; Han, 2007; Tilsen, 2007; Mok, 2010).

2.2.1.5. C- and V-dependent effects in F1

The majority of coarticulation studies have concentrated on EPG and F2 acoustic data, although F1 data can enhance our understanding of interarticulatory coordination during the production of vowels and consonants. F1 reflects oral opening and is thus correlated with tongue dorsum and jaw height.

An investigation of jaw height variability during the production of English and Swedish consonants and vowels in VCV sequences was conducted by Keating, Lindblom, Lubker and Kreiman (1994) using magnetometry. Vowels were found more open and more variable than consonants in jaw height. However, although significant V-to-C effects in jaw height were located, C-to-V effects did not reach statistical significance and hence, consonantal height was not established as a statistically significant factor for vowel height. The researchers concluded that the results support Lindblom's proposal (1983) that consonantal jaw height adapts to vocalic context. Additionally, alveolar consonants, such as [s], [t] and [n], and to a lesser extent [b, l, k] and [f], were less susceptible to vocalic influence than [h].

An EPG and acoustical study of F1 coarticulation in VCV sequences composed of the seven consonants [p], [n], dark alveolar lateral /l/, [s], alveolopalatals [ʃ] and [ɲ], and [k], and the two vowels [i] and [a], uttered by five Catalan speakers, was conducted by Recasens and Pallarès (2000). They report that C-to-V effects on [i] are very small in size in relation to corresponding effects on [a] and do not differ significantly as a function of consonant identity. In the temporal domain, C-to-V effects on [i] are longest from alveolopalatals [ʃ] and [ɲ] and alveolars [n] and [l]. Regarding [a] they are more prominent from alveolopalatals and velars than bilabials and alveolars both in size and temporal extent.

Regarding V-to-V effects along the F1, the authors state that their magnitude and duration matches dorsopalatal contact and F2 coarticulation as reported in Recasens et al. (1997). This conclusion is based on results from correlation analyses that revealed good correspondence between the magnitude and the duration of V-to-V effects and between their overall prominence and magnitude during the intervocalic consonantal period (Recasens & Pallarès, 2000:511). More specifically, F1 V-to-V effects on [i] were found small in size but long in extent across [p] and [ɫ] and short across [s], alveolopalatals and velars. V-to-V size effects on [a] were also small but relatively larger than those on [i], while temporally they are longest across [l] and [k], less across [n] and [s] and least across alveolopalatals and [p] (Recasens & Pallarès, 2000). Concerning V-to-V coarticulatory direction in the fixed [i] context, [s] favours anticipation in both size and time, [n] favours the carryover component in both size and time, and [p] prefers the carryover direction in size and the anticipatory direction in time. In the fixed [a] context, all consonants favour the V-to-V carryover coarticulation component in both size and time. According to the authors, the general preference for the carryover component in F1 vocalic effects indicates slow jaw movements and provides additional evidence that V-to-V gestures are controlled by the mandible.

Mok (2011) also reports larger F1 V-to-V effects along the F1 over [p] on [a] in comparison with [i] and [u] in Thai. She maintains that high jaw and tongue body position for [i] and [u] renders these high vowels least susceptible to coarticulation. Small F1 V-to-V size effects on both [i] and [a] are also reported for Greek, although larger for [i] than for [a] (Asteriadou, 2008). In that study, consonants [k] and [n] were found to allow the largest [i]-to-[a] F1 effects which was attributed to the velar's high adaptability to vowel height (Tuller et al., 1981; Keating et al., 1994). As far as coarticulatory direction is concerned, (Recasens & Pallarès, 2000) found that in the fixed [i] context, the carryover direction is preferred by dark /l/, [k], and to some extent [p], [ɲ] and [n], while [s] and [ʃ] favour the anticipatory direction due to manner requirements. In the fixed [a] context, carryover effects were predominant across all consonants under study. The salience of the carryover component in F1 coarticulation has been related to the relatively slow motion of the mandible in speech (Recasens, 2002b), although several studies have located strong anticipatory lowering of the jaw during bilabials (Fletcher & Harrington, 1999).

An EMA study of jaw V-to-V effects in Catalan VCV sequences with vowels [i, a, u] and seven consonants (as above) was carried out by Recasens (2002b) and results were paralleled with the aforementioned study (Recasens & Pallarès, 2000). Directionality patterns in jaw height coarticulation were found to relate to DAC specifications for highly constrained consonants, that is, similar coarticulatory duration and direction trends in tongue dorsum and jaw height were detected for dorsal consonants [ɲ] and [k] and lingual fricatives [s] and [ʃ] in sequences without [i]. In particular, the carryover component is favoured by [ɲ], while [k] and the fricatives prefer the anticipatory direction in both jaw and tongue dorsum vertical coarticulation. Conversely, less constrained consonants, produced with the tongue front and a lower jaw, such as [l] and [n], display differences in coarticulatory direction and duration between tongue dorsum and jaw height coarticulation trends. An interpretation adduced by the author is that for consonants produced with a close interaction between tongue dorsum and mandible, e.g., dorsals, the two articulators are linked and similar coarticulatory behaviours may be displayed, whereas for consonants involving a relatively independent tongue dorsum and jaw activity, e.g., dentoalveolars, coarticulatory behaviours may differ due to less cooperation demanded of the two articulatory structures (Recasens, 2002b:91).

In addition, V-to-V effects in jaw vertical displacement were not always longer in the carryover direction in the fixed [a] context as found in F1 coarticulation data (Recasens & Pallarès, 2000, see above), as fricatives and, to some extent, [p] and [l] were found to favour anticipation. Regarding the fixed [i] context, fricatives favour anticipation in accordance with F1 data, but differential trends are observed for other consonants. These differences between F1 coarticulation and jaw height coarticulation effects could be partly due to differences in material but could also suggest that coarticulatory effects along the F1 are associated with more articulatory factors than jaw vertical displacement.

2.2.2. Stress

The influence of stress on coarticulation has been explored extensively over the years. Stress is one way of marking prominence in a segment or syllable (de Jong, 1995). A stressed syllable in English has been documented to have higher intensity, longer duration, a prominent fundamental frequency (F0) pattern and a different formant structure than an unstressed counterpart (Fry, 1955, 1958, 1965; Lehiste, 1970). Longer duration and a higher F1 that results from a lower jaw position during vowel production have been reported for accented syllables (Summers, 1987; Edwards, Beckman & Fletcher, 1991).

The observation that the aforementioned lower jaw positions were not accompanied by lower tongue dorsum positions led to the development of the *jaw expansion model* (Macchi, 1985 as cited in de Jong, 1995) that accounted for stress in terms of jaw movement. A more general model encompassing the jaw opening as well as other changes, such as movements of the tongue tip and the lips altering the amount of vocal tract opening due to stress is the *sonority expansion model* (Edwards et al., 1991). This model integrates a temporal component as well, according to which, the aforementioned vocal tract opening modifications occur in longer durations resulting in less temporal overlap between vocalic and consonantal gestures in accented syllables (Beckman, Edwards & Fletcher, 1992). Thus, a stressed vowel coarticulates less with the neighbouring sounds to guarantee its prominence. This can be viewed as a “syntagmatic enhancement strategy” (Mooshammer & Geng, 2008:118). Besides delayed gestural phasing resulting in less temporal overlap, an alternative way of lengthening a stressed syllable suggested by the gestural theory of speech production is reducing gestural stiffness (Brownman & Goldstein, 1986; Saltzman & Munhall, 1989). Stressed syllables are not as stiff as their unstressed counterparts (Kelso, Vatikiotis-Bateson, Saltzman & Kay, 1985).

A different approach to the articulation of stress is that of localized *hyperarticulation* proposed by de Jong (1995). Subsequent to a microbeam analysis of jaw and tongue kinematics varying with stress, he maintains that only the hyperarticulation model can account for the whole body of the results, many of which being nonsonority features, e.g., increased constriction in stressed back vowels, increased lip protrusion in rounded vowels and elimination of coarticulatory effects on a stressed stop. Drawing from Lindblom's hyper-hypo theory (1983), he postulates that hyperarticulation of stressed vowels enhances their distinctness and ensures intelligibility. In order to distinguish a vowel from others that can occur in the same position, the talker uses hyperarticulation as a "paradigmatic enhancement strategy" (Mooshammer & Geng, 2008:118). Thus, stressed vowels are found in more peripheral positions in the vowel space, while unstressed vowels are more centralized (Rietveld & Koopmans-van Beinum, 1987; Palethorpe, Beckman, Fletcher & Harrington, 1999).

The paradigmatic and the syntagmatic vowel reduction accounts conjoin in an attempt to explain what seems like contradictory evidence of the articulatory production of stress. For instance, a prominent low vowel, e.g., [a], is articulated with a low jaw, as expected (Stone, 1981; Beckman et al., 1992; Erickson, 1998). The same is observed, however, by Harrington, Fletcher and Beckman (2000) for accented high vowels, that is, they are also produced with a lower jaw in comparison with their unaccented counterparts, but at the same time the tongue dorsum constriction is increased. The lower mandible position suggests syntagmatic dissimilation (increased sonority) and the increased degree of constriction denotes paradigmatic enhancement (hyperarticulation). In a different study, Erickson (2002) made formant, jaw and tongue dorsum measurements using X-ray microbeam in emphasized vs. unemphasized high-front, mid-front and low vowels. She observed that jaw position was lower in emphasized vowels regardless of height, while the tongue dorsum had a differential position for low vs. high vowels; emphasized low vowels were produced with a lower tongue dorsum, while for high and mid-front vowels the tongue dorsum assumed a more forward position. Her account differs from that of Harrington et al. (2000), in that, both the jaw and the tongue dorsum are hyperarticulated to increase contrastiveness, in line with Lindblom (1990), but results are also interpreted to provide support to the Converter and Distributor (C/D) model, a generative description of articulatory gesture organization for utterances (Fujimura, 2000), that links emphatic stress with the magnitude of a syllable pulse, thus calling attention to the role of the underlying metrical structure/prosody unit in regulating articulation and acoustic output.

Regardless of the theory behind vowel hyperarticulation or reduction, the absence of stress usually results in the shrinkage of the overall vowel space (Tiffany, 1959; Miller, 1981; Fourakis, 1991, for American English; Fourakis, Botinis & Katsaiti, 1999 and Nicolaidis & Sfakianaki, 2007, for Greek; Chiang & Chiang, 2005, for Truku; Mooshammer & Geng, 2008, for German; Beňuš & Mády, 2010, for Slovak), although lack of stress effects on the size of the vowel space have also been reported (cf. Orr, 2005, for Danish[6]). Recent evidence on the combined influence of stress, accent and corrective contrast on the whole vowel inventory of a language was obtained from measurements of the F1 and F2 frequencies and the tongue positions

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[6] Orr (2005) observes hyperarticulation of [a] in unstressed syllables, attributable to maintenance of contrast in the crowded 10-vowel-system of Danish.

with the use of EMMA at the midpoint of all fifteen German stressed and unstressed vowels in CVC sequences uttered by seven speakers (Mooshammer & Geng, 2008). The sequences were embedded in the carrier phrase “I said /ˈtVtɐ/, not /tVˈta:l/” so that the first syllable /tV/ in the first test word was always stressed and pitch accented and the first syllable in the second test word was always unstressed and deaccented. A normalization procedure (Generalized Procrustes Analysis) was applied to eliminate anatomically induced differences. Unstressed vowels displayed a greater degree of consonantal influence, with low vowels being more susceptible than high vowels. This resulted in a vertical shrinkage of the vowel space, elevating the low vowels (lower F1). Centralization along the F2 axis was also observed, albeit to a lesser extent than that along the F1 axis in the acoustic data, whereas the reduction along horizontal and vertical directions in articulatory measurements was more symmetrical. Front vowels were backed and back vowels were fronted. The researchers noticed that lax vowels were not as shortened when unstressed as tense vowels (*lax vowel incompressibility*). The lax vowel space did not undergo significant reduction, although it did shift upwards because of the alveolar stop. Since vowel reduction is not temporally based in their data, they attempt to provide an alternative interpretation associated with articulatory effort. They claim that during the production of unstressed vowels there is sustained muscle activity of the tongue muscles that keeps the tongue blade elevated towards the consonantal place of articulation; this sustained activity ultimately results in energy conservation. Conversely, during stressed vowels the muscles involved in consonant production deactivate leading to a lower tongue tip position and activate again for the vowel. This extra articulatory effort ensures a lessened assimilation of stressed vowels with adjacent consonants.

Concerning V-to-V coarticulation in particular, stressed vowels have been found less inclined to coarticulatory effects from neighbouring segments than their unstressed counterparts (Nord, 1974; de Jong, 1995). Bell-Berti and Harris (1979) studied coarticulation phenomena in [pəCVCəp] utterances (C = [p, t, k] and V = [i, a, u]) and located large carryover effects from the stressed vowel on the schwa, but no anticipatory influence. Large bidirectional coarticulation effects are reported by Fowler (1981a) on unstressed medial [ʌ] from both initial and final vowels in sequences [VbəbV] (V = [i, a, u]) with the carryover component being more prevalent. On the other hand, smaller symmetrical bidirectional effects were detected on [ʌ] when stressed. Fowler comments that the asymmetry between anticipatory and carryover effects on unstressed vowels is related to compensatory shortening. When an unstressed vowel is added next to a stressed vowel, strong anticipatory shortening of the stressed vowel occurs with simultaneous strong carryover coarticulation on the unstressed vowel. The two occurrences are two sides of the same coin, namely coproduction or gestural overlap.

The effect of stress on V-to-V coarticulation in VCV utterances in English has also been studied by Magen (1984b). Her analysis showed that the extent of both anticipatory and carryover effects was more restricted when vowels are in the stressed vs. the unstressed condition. In a later study, Magen (1997) examined the extent of V-to-V effects on primary and secondary stressed vowels in trisyllabic utterances of the form [bV_1bəbV_3b]. Although primary stressed vowels were expected to show stronger effects on the secondary stressed vowels, it only occurred in one of the four speakers, denoting the existence of a speaker-specific strategy regarding coarticulatory directionality in primary vs. secondary stressed vowels.

Greek vowels have also been found to exert more coarticulatory effects when stressed. Nicolaidis (1997, 1999) investigated the effect of stress on V-to-V coarticulation in [pV_1CV_2] sequences. In agreement with Fowler (1981a), greater anticipatory effects are exerted when stress is on V_2, while carryover effects are significant when V_1 is stressed. This interaction between stress and syllable position is more systematic over [p]; the effect of stress on coarticulation in [t] and [s] contexts is more variable. Lindblom, Agwuele, Sussman and Cortes (2007) provide an explanation for the differential effect of emphatic stress on coarticulation involving labial vs. lingual stops, i.e., the *deeper contact hypothesis*. “[T]here is a greater degree of tongue tissue compression and hence larger contact areas on the alveolar ridge/hard palate during longer occlusion interval of emphatically stressed relative to nonemphatic lingual consonants” (p. 3811). In order to maintain an airtight seal, lingual stops are realized with more forceful closure movements impeding the anticipatory activity related to the succeeding stressed vowel. Emphatically produced labial consonants are also hypothesized to involve greater tissue compression at the lips, but coarticulatory effects are not as encumbered due to the fairly unconstrained activity of tongue dorsum. Koenig and Okalidou (2003) carried out a comparative study of stress effects on V-to-V coarticulation in English and Greek in VCV utterances including all five Greek vowels and their closest English counterparts in a bilabial and alveolar context. The results show that the stressed vowel induces larger effects on the unstressed vowel in both languages, although in Greek this is more pronounced in the first syllable position, i.e., in ˈVCV sequences. Concerning C-to-V effects, they are consistently larger on unstressed vowels in Greek, while back and central vowels receive more consonantal influence in English.

According to the foregoing, stressed vowels have been documented to be less conducive to contextual influence, undergoing less reduction and blending. In few cases, though, prominent coarticulatory effects have been detected on stressed vowels. The results of a locus equation study in [V_1#CV_2] sequences in English carried out by Agwuele (2005) revealed that significant coarticulatory effects from unstressed V_1 transcended the syllabic boundary and persisted into the stressed V_2, in opposition with Öhman (1966) and Cho (2004). Greater coarticulatory effects from an unstressed V_2 on a stressed V_1 were also located in Greek and in Italian across [t] (Nicolaidis, 1997; Farnetani et al., 1985). Moreover, stress does not always play a significant role in V-to-V coarticulation. Huffman (1986) investigated the influence of stress on V-to-V coarticulation in VCV and [bVCəCVb] sequences including the consonants [d] and [l] and the vowels [i, a, u]. The results revealed small stress effects, so that context rather than stress was a more significant factor in V-to-V coarticulation. A similar observation about the greater relative importance of context as compared with stress and other prosodic factors concerning vowel reduction has been made by other researchers (Engstrand, 1988; Fourakis, 1991).

2.2.3. Gender

Male and female speakers have a number of biological differences that influence the sounds they produce. After the onset of puberty, male speakers begin to develop longer and thicker vocal folds and a longer vocal tract. Moreover, speakers adopt speech patterns appropriate to their gender through imitation and learning. These differences pertaining to anatomy as well as learned behaviour result in acoustic differences between productions of the two genders.

One of the most noticeable gender differences in acoustics concerns the size of the F1xF2 plane. Across different languages, the female vowel system has a larger acoustic area than that of the male due to the higher F1 and F2 values of female vowels (Fant, 1966, 1975; Nordström, 1977; Goldstein, 1980). However, the gender difference in vowel space is non-uniform, that is, the difference is more pronounced in low vowels than in back rounded vowels. An explanation for the non-uniformity suggested by Fant (1966) is that female speakers attempt to compensate for these differences by making tighter and longer strictures at the lips and the tongue hump that cause an F1 and F2 drop in [o] and [u]. Traunmüller (1984) proposes that, although the male larynx descends after puberty, neural commands to the male articulators remain unchanged, therefore causing a non-uniform decrease of male formant values relative to female values. These non-uniform differences in formant values require different constants for each formant in order to normalize male and female vowel spaces, i.e., to map the set of vowels of one gender onto that of the other. Normalization procedures that combine information from different vowels (vowel extrinsic) and operate on individual formants (formant intrinsic) have been found more successful in reducing anatomical/physical variation (Adank, Smits & van Hout, 2004; Flynn & Foulkes, 2011)[7]. Although the majority of studies report greater vowel dispersion in female speech even after normalization (Henton, 1995; Bradlow et al., 1996; Yang, 1996; Pierrehumbert, Bent, Munson, Bradlow & Bailey, 2004; Heffernan, 2007), some researchers observe reduction or elimination of gender differences in vowel space size after normalization (Jacewicz, Fox & Salmons, 2007; Zee & Lee, 2011).

Gender differences in vowel space have also been interpreted in connection with pitch. Due to the higher fundamental frequency of the female voice, harmonic spacing is broader, leading to a poorer definition of female vowel quality. A wider

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[7] For the normalization procedure utilized in this thesis, see section 3.2.5.3.

dispersion of female vowels in the acoustic space could be interpreted as a compensation aiming at improving vowel identification (Goldstein, 1980; Ryalls & Lieberman, 1982; Diehl, Lindblom, Hoemeke & Fahey, 1996). Nevertheless, the relationship between pitch and vowel space area is still elusive. Although an experiment involving identification of synthesized vowels [ɪ] and [ʊ] at different fundamental frequencies carried out by Diehl et al. (1996) led to the suggestion that fundamental frequency is inversely related to vowel recognition, only a weak correlation was found between fundamental frequency and acoustic space size, and consequently vowel identification, in more recent studies (Simpson & Ericsdotter, 2007; Simpson, 2011).

In addition to a larger acoustic space, female speakers have also been found to produce longer vowel durations (Hillenbrand, Getty, Clark & Wheeler, 1995, for American English; Simpson, 1998, for German; Ericsdotter & Ericsson, 2001, for Swedish; Simpson, 2001, for American English diphthongs and Simpson, 2002, for American English vowel sequences), longer utterance durations (Byrd, 1992; Whiteside, 1996), and to exhibit greater durational differences between long and short vowel pairs (Johnson & Martin, 2001, for Creek[8]) and between stressed and unstressed vowels (Ericsdotter & Ericsson, 2001, for Swedish). In addition, male speakers have been found to speak faster than female in spontaneous talks of two distinct varieties of American English (Jacewicz, Fox & Wei, 2010). However, contradictory results have also been reported; no significant duration differences were found between male and female French back vowels (Martin, 1998 as cited in Simpson & Ericsdotter, 2003). Additionally, although female vowels were found slightly longer in two of three American English dialects, gender-related duration

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[8] Creek is a Muskogean language spoken by several thousand individuals in eastern Oklahoma and central Florida.

differences were not overall significant (Jacewicz, Fox & Salmonsand, 2007). Moreover, no significant utterance length differences were found between the two genders in American English and Swedish (Simpson, 2001, 2002; Simpson & Ericsdotter, 2003).

Many researchers note greater distinctiveness and higher intelligibility in female speech (Labov, 1970; Henton, 1983, 1992; Bradlow, Torretta & Pisoni, 1996). A more recent study by Hazan and Markham (2004) did not find a strong correlation between gender and speech intelligibility, although women as a group were still more intelligible than men. Faster speaking rates, vowel reduction and centralization, vowel nasalization, production of glottal stops and laryngealization, alveolar flapping and reduced frequency of stop releases have been detected in male speech more frequently than in female speech in English (Byrd, 1994). Greater vowel durations, durational contrasts as well as increased articulatory precision for female speakers have been attributed mainly to sociophonetic reasons. Clarity in female speech has been related to the role of the primary care-giver more often assigned to women (Labov, 1990) and as an attempt on women's part to guard standard or prestige forms (Henton, 1995).

Besides the role of social and cultural stereotypes in speech production by male and female talkers, gender-specific durational and acoustic patterns have also been interpreted in the light of articulatory dynamics by Simpson (2000). He reasons that, given the difference in vocal tract dimensions, male speakers need to travel greater articulatory distances than female speakers to reach analogous phonetic targets. Since size of articulatory spaces is different, size of acoustic products, i.e., acoustic space, both linear and nonlinear, will also be different. For Simpson (2000:212), "phonetic correlates of clarity, often attributed to female speakers, such as more widely distributed acoustic vowel spaces and greater vowel duration, may be nothing more than by-products of reconciling differences in articulatory dimension". In addition, Simpson and Ericsdotter (2003) found longer durations in female stressed vowels, but greater durations for male consonants and no significant differences between genders in utterance length. They propose that clarity may be restricted to places of prominence in female speech and shorter durations of other segments in the utterance could compensate so that overall durational differences between the two genders are leveled out.

Drawing from the mass-spring model of Articulatory Phonology (Browman & Goldstein, 1986), Simpson (2001) hypothesizes that different degrees of stiffness are employed by male and female speakers in order to execute the same gesture, resulting in different temporal extent and speed of movement. Thus, despite being spatially larger, stiffer male tongue body movements are bound to be carried out in less time than corresponding female tongue body movements. However, an investigation of acoustic and articulatory patterns with the use of lingual pellets in interword vowel sequences (Simpson, 2002) revealed that, despite having to displace the tongue dorsum further, male speakers had a significantly shorter stretch duration. Thus, a higher speed of tongue dorsum movement was hypothesized for male speakers. Opposite to expectations, a subsequent experiment showed that male tongue body movements are on average slightly longer than that of the female (Simpson, 2003). The difference between male and female speakers was found to lie in the synchronization of tongue body and tongue tip movements, i.e., the male tongue body movement begins earlier, leading to shorter durations located in male stretches. Based on the statistical analyses of tongue displacement measurements, this finding was interpreted by the author as an indication of a gender-specific strategy employed to bring about a different acoustic duration and not as a mechanical byproduct of articulatory interactions (Simpson, 2003:266).

Although certain aspects of acoustic and durational differences between genders may indeed be related to dynamic consequences of anatomical differences, by no means can such an approach account for all differences in male vs. female speech. Comparisons of vowel systems in many languages have shown that the size of gender differences in vowel space size varies from language to language (Henton, 1995; Johnson, 2006). In addition, sexual orientation has been found to have a significant influence on vowel production (Pierrehumbert et al., 2004). These studies highlight the importance of the sociophonetic component in gender speech patterns. Even taking both the biophysical and the social approach into account, the relative contribution of one or the other to gender-specific differences in speech is still not clear (Simpson, 2009).

2.2.4. Developmental Aspects of Coarticulation

An important accomplishment during language acquisition is the production of combinatorial sequences of consonants and vowels that will constitute the syllables of a child's first words. Two different approaches to the development of coarticulation in child speech have been put forth. The first is a *segmental approach* (Kent, 1983; Sharkey & Folkins, 1985) suggesting that children initially produce utterances on a segment-by-segment basis hence their gestures are less coarticulated or overlapped. Coarticulation increases with maturation and speech becomes more efficient. According to the second account, the *holistic approach* (Nittrouer, 1993; Nittrouer, Studdert-Kennedy & Neely, 1996), during babbling the infant rhythmically alternates closed and open positions of the vocal tract, producing sequences sounding like regularly timed CV syllables that will gradually develop into autonomous segments.

These first syllables are “undifferentiated entities” (Nittrouer, 1993), largely overlapped, that will be narrowed to smaller, more independent phonetic units characterized by less influence from neighbouring sounds (Goodell & Studdert-Kennedy, 1993). Thus, coarticulation decreases with age and patterns become temporally precise and adult-like.

A clear picture has proved difficult to emerge as results from earlier studies on child speech are contradictory, some of them reporting more, others less and others similar coarticulation in comparison to that found in adult speech. Research concentrates on anticipatory coarticulation, as this component is thought to reflect preplanning. Nittrouer and Studdert-Kennedy (1987) and Nittrouer, Studdert-Kennedy and McGowan (1989) examined anticipatory labial coarticulation in fricative-vowel syllables and observed a decrease of V-to-C effects with age, suggesting that “the initial domain of perceptuomotor organization is a meaningful unit of one or a few syllables” that begins to precipitate gradually into phonetic segments as the child’s lexicon increases (Nittrouer et al., 1989:131). On the other hand, less coarticulation in children’s speech (Kent, 1983; Sharkey & Folkins, 1985) or roughly equal coarticulatory effects for adults and children have been documented (Repp, 1986; Sereno, Baum, Marean & Lieberman, 1987; Sereno & Lieberman, 1987; Katz, Kripke & Tallal, 1991). In their study of anticipatory labial coarticulation, Sereno et al. (1987) found that listeners can satisfactorily utilize coarticulatory cues in children’s [t] tokens but not in [d] or [s] tokens. They discuss that although a robust acoustic effect may be present in the children’s stimuli, it does not necessarily mean that it is perceptually salient, whereas acoustic and perceptual effects were congruent in adults’ stimuli.

Furthermore, results from a number of more recent studies show that the development of a coarticulatory pattern depends on place of consonant articulation hence, no uniform characterization can be assigned to the development of coarticulation across consonants. Sussman, Duder, Dalston and Cacciatore (1999) analyzed stop consonant-vowel productions of a monolingual English female child from age 7 months to 40 months using locus equations. They found that, during the initial months of babbling, labial and alveolar syllables exhibited large changes albeit in opposite directions. Coarticulation of labial + vowel productions was initially small and increased sharply across months 10 to 13, whereas the degree of coarticulation of alveolar + vowel sequences started off high and declined across months 7 to 12. Both changes, however, led to a more adult-like pattern of coarticulation. Regarding the interpretation of the developmental pattern for labial consonants, coarticulation is initially small as the child merely oscillates the mandible while the tongue lies in a ‘resting’ position. Coarticulation increases as the child gradually learns to move the tongue according to vowel type with a concurrent and independent lip constriction for the labial consonant. The increase is dramatic as labials allow maximal temporal overlap with the vowel.

The production of alveolars, on the other hand, requires articulatory differentiation between two parts of the same articulator, i.e. the tongue. The tongue tip must remain fixed for the alveolar whilst the tongue body moves to contribute to the vocal tract shape corresponding to the vowel. Research has shown a preference for the production of front vowels after alveolars, mid central vowels after bilabials and mid/low back vowels after velars during early speech acquisition (Davis & MacNeilage, 1995). During the first months productions consisting of alveolar + vowel (most frequently high front) are extensively coarticulated. As the child begins to gain control of independent tongue body and tongue tip/blade movement, the degree of coarticulation drops and becomes more adult-like. Interestingly, Sussman et al. (1999) observed that during the second and third year child coarticulation in [dV] sequences was even less than that of the adult. Similarly, an exaggerated resistance to vowel context effects at 21 months displayed by the child examined by Sussman, Minifie, Buder, Stoel-Gammon and Smith (1996), may suggest that the fine tuning of coarticulation decrease is harder than that of coarticulation increase. Knowing when coarticulatory degree in the production of alveolar + vowel syllables is not “too much” or “too little” but “just right” seems to be a very difficult task to master for children, causing the production of [dV] syllables to be the hardest in comparison to [bV] or [gV] syllables (Sussman et al., 1999:1093). Concerning the last, the child coarticulatory pattern very soon became adult-like. The biomechanical limitations for utterances involving a consonant and a vowel produced by exactly the same articulator, i.e., the tongue body, in one gesture seem to accelerate the learning of the proper degree of overlap between velar + vowel combinations.

A more recent study of coarticulation across voiced stop consonant place of articulation in 10 English-speaking children aged 17 to 22 months also using F2 locus equations was carried out by Gibson and Ohde (2007). In adult speech, the most coarticulated consonant was the voiced bilabial whereas the voiced alveolar was the least coarticulated. The alveolar was also the least articulated in child speech, but the consonant showing the most coarticulation effects was the velar. The velar consonant displayed overall a holistic pattern of production with great consistency, while neither a pattern of holistic nor of segmental nature could be specified for the bilabial or the alveolar, leading the authors to the conclusion that “coarticulation during early speech production is place of articulation specific” (p. 105).

Ultrasound is currently being used to investigate differences in lingual coarticulation between children and adults. Many researchers note that older studies attempted to make inferences about articulatory movements solely from acoustic measures of the speech signal, while more robust interpretations can be made on the basis of articulatory data such as ultrasound imaging of tongue movement. An ultrasound investigation of Scottish English syllables [ʃi, ʃu, ʃa] spoken by four adults and four children aged 6 to 9 years conducted by Zharkova, Hewlett and Hardcastle (2008) revealed that children show significantly more anticipatory lingual coarticulation than adults. In addition, within-group and within-speaker variability was greater for children than for adults. The authors note that child-adult difference was better reflected in within-speaker variability than in amount of coarticulation.

A subsequent ultrasound study including CV combinations with [s] as well as [ʃ] (Zharkova, 2010) displayed that, in adults coarticulation is significantly different for the two fricatives, that is, consonant contours for [ʃ] as a function of vowel are closer to each other than those of [s], whereas in children this difference is smaller, indicating less precise control of different parts of the tongue. Thus this type of lingual constraint seems to increase with age due to motor control improvement. The developmental pattern of coarticulation of the two fricatives in terms of temporal extent has been examined by Katz and Bharadwaj (2001) through kinematic analysis (EMA) of [si, su, ʃi, ʃu] syllables produced by eight adults, six 7-year-old and three 5-year-old American English speaking children. Children exhibited more anticipatory coarticulation in temporal extent than adults in [sV] syllables, while child [ʃV] syllables were equally or less coarticulated than those of adults. Although only preliminary, these results suggest an earlier emergence of the palatal fricative, as [ʃV] stimuli may be simpler in terms of gesture coordination and thus coarticulated in a more adult-like fashion than [sV] stimuli.

Coarticulatory patterns in child speech beyond the boundaries of the syllable are also under study. Mènard, Toupin, Thibeault, Noiray, Giroux and Rousseau (2010) explored lingual coarticulation in [V_1bV_2] syllables with vowels [i, u, a, y] spoken by six 4-year-old children and six adult speakers of French using ultrasound imaging. Children demonstrated more anticipatory V_2-to-V_1 effects than adults with the magnitude varying according to vowel. Unrounded vowels were less coarticulated than rounded vowels. Moreover, Noiray and Mènard (2010), using locus equations and ultrasound, conducted a parallel examination of vocalic coarticulatory influences on consonants in symmetrical VCV sequences (V = [i, a, u] and C = [p, t, k]) uttered by four adults and six 4- to 5-year-old children speaking Canadian French. In line with previous studies, locus equation data showed that adults and children display similar coarticulatory patterns, i.e., larger coarticulatory degree in labial and velar contexts and smaller in alveolar contexts. Ultrasound lingual data were found congruent with locus equation measures, both leading to similar results on coarticulation degree in adults and children. An important point underlined by the researchers is that coarticulation degree as a function of consonant place of articulation in children does not only indicate coarticulatory maturation, but also relates to articulatory constraints imposed on the tongue (Recasens & Espinosa, 2009) and reveals possible synergies between lingual functional subparts. Synergies such as the recruitment of the tongue back to assist the tongue tip during the alveolar constriction of [t] were located in the ultrasound articulatory patterns of 4-year-old children.

Going beyond the disyllable, Goffman, Smith, Heisler and Ho (2008) performed a kinematic analysis in order to examine the temporal extent of anticipatory lip rounding in child and adult speakers of American English. Upper and lower lip movements were recorded during the production of three word pairs contrasting in lip rounding, embedded in the medial position of 7-word/7-syllable sentences, by eight young adults and eight 4- to 5-year-old children. For both adults and children broad coarticulatory effects that crossed word and even phrase boundaries were found. The effects were similar for children and adults in absolute anterior/posterior displacement and temporal extent, although articulatory movement variability was greater for children. As commented by the authors, the lack of a substantial difference in magnitude and extent of coarticulation between adults and children, contrary to older studies (e.g., Nittrouer et al., 1989) could be related to the different method used. Kinematic measurement of lip rounding focuses on a single component, whereas acoustic analysis reflects the interplay among multiple articulators. Also, the increased coarticulatory variability found in child speech denotes an immaturity in automatized speech motor control which is attributed to both representational and performance factors. Moreover, compatibly with previous research (Jusczyk, 1997; Soderstrom, Seidl, Kemler & Jusczyk, 2003), these findings provide evidence for multiple production units in child speech indicating that, possibly, units even bigger than syllables, such as phrases or clauses, come first or co-occur with smaller units in infant perceptual processing.

In addition to consonant place of articulation or syllable composition in general, the acquisitional process of coarticulation may also depend on language. Although many studies report nonsignificant differences between child and adult anticipatory lip rounding before [u] in English, Abelin, Landberg and Persson (1980) found a difference in the temporal extent of labial coarticulation between children and adults in Swedish. They report that children's coarticulatory behaviour seems to be time-locked, whereas adults adopt a more look-ahead strategy. In line with Lubker and Gay (1982) who advocate the importance of language-specific factors in labial coarticulation, the authors discuss that since lip rounding is more essential for maintaining contrast in Swedish than in English, labial anticipation undergoes different maturation stages in the two languages.

The theories and studies expounded above are of interest in the present study, as it has been suggested that coarticulatory patterns found in mature HI speech present similarities with patterns located in normally developing speech. In an acoustic study of symmetrical [ə#CVC] disyllables with consonants [b, d] and vowels [i, a, u] uttered by HI adult speakers of American English, Okalidou and Harris (1999) have detected greater degree of anticipatory V-to-V coarticulation in alveolar vs. bilabial contexts in HI than NH adult speech, a pattern reminiscent of that located in early speech acquisition (Nittrouer, 1985; Nittrouer et al., 1989; Goodell & Studdert-Kennedy, 1993; Sussman et al., 1999). The authors interpreted the findings on the basis of a different gestural organization in deaf versus NH speakers resembling in part that of children (section 2.3.4).

2.3. Hearing Impaired (HI) Speech

Hearing impaired speakers are, to a greater or lesser extent, deprived of auditory feedback. If hearing loss occurs prelingually, that is, before the speaker has managed to acquire speech and language, then all aspects of speech production are susceptible to delay or disorder (Pratt, 2005). Without audition the use of the articulators towards production of the sounds of a language cannot be learnt and refined over time. The extent to which HI speech will differ from that of normally hearing (NH) speakers depends on a large number of factors, including the age of hearing loss onset, the type and degree of hearing loss and the amount of residual hearing, the onset and consistency of use of sensory aids or the age of cochlear implantation, the speech/language training program (age of onset, frequency of attendance and overall approach), the communication orientation of the learning environment (oral or total) and the parental involvement.

2.3.1. Hearing Loss Classification

Hearing impairment is a symptom of variable etiology and has been classified in many ways such as “prelingual vs. postlingual, conductive vs. sensorineural, syndromal vs. nonspecific, and genetic vs. acquired” (Morton, 1991:16). Pure Tone Average (PTA) which refers to Pure Tone Thresholds (PTT) computed over three or four frequencies[9] has been used traditionally as a measure to categorize individuals as mildly, moderately, severely and profoundly hearing impaired (HI) or severely, profoundly and totally deaf, although “there are no definitive criteria for each category and these labels can often be misleading” (Northern & Downs, 2002:20).

Different researchers provide slightly different average hearing levels to categorize hearing loss according to PTTs. According to Morton (1991:16), an

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[9] Typically over the frequencies 500, 1000 & 2000 Hz.

individual is considered hearing impaired when loss exceeds 25 decibels (dB), and profoundly deaf if hearing loss is at least 80 dB bilaterally which, if untreated, “interferes with speech and may lead to the condition formerly known as deaf mutism”. Boothroyd (1988:83) uses the aforementioned qualifiers to classify hearing loss as mild for ranges of 15-30 dB, moderate for 31-60 dB, severe for 61-90 dB and profound for losses exceeding 90 dB, while the last category is further subdivided into three others depending on both degree of hearing loss and residual hearing level above 1000 Hz: (1) considerable residual hearing: 91-100 dB HL with thresholds above 1000 Hz of 105 dB HL or less, (2) little residual hearing: 101-110 dB HL with thresholds above 1000 Hz of 110 dB or more, and (3) no residual hearing: PTA in excess of 110 dB.

Stach (1998:106) describes a hearing loss of 11-25 dB as minimal, 25-40 dB as mild, 40-55 dB as moderate, 55-70 dB as moderately severe, 70-90 dB as severe and above 90 dB as profound[10]. Northern and Downs (2002:21) state that, in children, a hearing loss of 15-25 dB can be characterized as slight, 25-30 dB as mild, 30-50 dB as moderate, 50-70 dB as severe and 70+ dB as profound. Despite the different categorizations, there is consensus on the fact that such labels are not indicative of the degree of dysfunction or delay in speech development, as the correlation between pure tone threshold and potential contribution of hearing to spoken language development is imperfect (Boothroyd, 1984:135; 1988:82; Northern & Downs, 2002:20, Roeser & Downs, 2004:3).

Regarding the classification of hearing impairment as pre- or post-lingual, according to Sander (1972) and Stoel-Gammon and Dunn (1985) children stabilize their phonology after the age of four. The age of four is used as a criterion for early

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[10] Goodman had used a similar classification of mild to profound hearing loss with adult population (Goodman, 1965, as cited in Roeser & Downs 2004) differing only in the “minimal” category; according to Goodman, -10 to 25 dB HL is within normal limits.

onset deafness by Osberger, Maso and Sam (1993). Staller, Belter, Brimacombe, Mecklenburg and Arndt (1991) classify children of two or three years of age as prelingually deafened.

The present study focuses on prelingual profound hearing loss in adults, treated from a young age with hearing aids and speech/language therapy, not including intervention via cochlear implantation (section 3.2.1.1). Bearing this in mind, our literature report concentrates on research of a related context.

2.3.2. Problem Areas in HI Speech

2.3.2.1. Segmental Production

Vowels

Vowels have been reported as less distorted than consonants in HI speech (McGarr, Raphael, Kollia, Vorperian & Harris, 2004; McNeil, 2009), although listener tolerance for vowel errors is greater and part of consonant information lies in the vocalic part which, if erroneous, implicates the neighbouring consonant (Osberger & McGarr, 1982). Vowel errors include substitution of one vowel for another, neutralization, diphthongization, nasalization, as well as diphthong splitting (into its vowel components) or simplification (omission of the final part of the diphthong) (Hudgins & Numbers, 1942; Markides, 1970; Smith, 1975; Osberger & McGarr, 1982).

Different vowel error patterns have been observed by various researchers, i.e., low vowels are reported as more correctly produced than high and mid vowels (Nober, 1967; Smith 1975; Geffner, 1980), while others report the opposite (Angelloci et al., 1964; McGarr & Gelfer, 1983). A speech intelligibility evaluation with the SPINE test correlated with measures of tongue deviancy computed from formant frequencies revealed that, in speakers with severe-to-profound hearing loss, the front vowel [i] shows the most deviation from the normative tongue position, the back vowel [u] the least and the low-back vowel [a] a deviation value between the two (Wold, Evans, Montague & Dancer, 1994:354). The authors interpret the low deviation observed for [u] in terms of its more intense lower F2 frequency energy and requirement for less precise tongue placement than that of high [i]. More centralization for vowel [i] as compared to [u] and [a] was also observed by Ryalls et al. (2003:111). In other studies, front vowels are reported as produced more correctly than back vowels (Hudgins & Numbers, 1942; Rubin, 1985). McGarr and Gelfer (1983) observe that front vowels produced by speakers with HI receive better identification scores by listeners than back vowels, although they note that other studies give opposing evidence (Boone, 1966; Smith, 1975; Geffner, 1980). The variability of error patterns in the literature may be due to the recruitment of different subjects (degree of hearing loss, age, etc) and use of different materials (syllables, structured utterances, spontaneous speech), but also because of the lack of a "generic deaf speech pattern" (McGarr & Harris, 1980:309) which would indicate a uniformity in production. Finally, errors in vowel place (front vs. back) have been reported as more frequent than those in height (Angelocci et al., 1964), the occurrence of the latter increasing with severity of hearing loss (McCaffrey & Sussman, 1994).

Vowel neutralization is very common in HI speech and leads to a more central and lax vowel (e.g., Hudgins & Numbers, 1942; Pratt & Tye-Murray, 2009). A great number of HI vowel production studies in English come to the conclusion that F1 and F2 formant values tend towards a neutral /ə/ which results in a reduced phonological space (Angelocci et al., 1964; Monsen, 1976a; 1978; McGarr & Gelfer, 1983; Okalidou, 1996; Ryalls, Larouche & Giroux, 2003, for French; Shukla, 1989, for Kannada; Ozbič & Kogovšek, 2008, 2010 for Slovene). Angelocci et al. (1964)

observed greater fundamental frequency variability in HI vowels compared to NH vowels, and suggested that speakers with HI may attempt vowel differentiation through fundamental frequency and not formant frequency variation.

Phonological space reduction has been attributed to a characteristic immobility of the second formant that has been described in the literature (Monsen, 1976a, 1976c; Rothman, 1976). The F2 contour represents tongue activity along the front-back dimension which the HI cannot track visually and therefore find more difficult to master (McGarr & Harris, 1980). Boone (1966) observed a lower F2 for English deaf children in relation to NH children that was attributed to a misplacement of the tongue too far back in the oral cavity. On the other hand, inappropriately high F2 values have been reported for back vowels (Angelocci et al., 1964; McGarr & Gelfer, 1983). More specifically, the high back vowel [u] was realized as the French high front rounded vowel [y]. This error was interpreted as an attempt to produce front-back distinction by solely using lip rounding (visible cue) and not tongue position (invisible gesture) (McGarr & Gelfer, 1983). Conversely, [i] productions were perceived as [y] in [ʃi] syllables (McGarr et al., 2004). The lip rounding of [ʃ] was carried onto the high front vowel [i], lowering its F2 and leading to a perception of [y] by the listeners.

The first formant is also restricted in range, although it is considered, along with F0, to be one of the main factors contributing to HI vowel differentiation (Angelocci et al., 1964; Martony, 1968; Monsen, 1976a, Rubin, 1985; Stevens, Nickerson & Rollins, 1983). The movement of the jaw is a visible cue that the HI can exploit to make the high-low distinction that relates to the F1 dimension (McGarr & Gelfer, 1983). Moreover, residual hearing is most often located at the low frequencies which promotes F0 and F1 audibility. Thus the reduction of the HI phonological space is largely explained by the restricted F2 rather than F1 range (Monsen, 1976a; Van

Tassel, 1980; Metz, Samar, Schavetti, Sitler & Whitehead, 1985; Zimmermann & Rettaliata, 1981; Shukla, 1989).

Regarding Greek, a study carried out by Nicolaidis and Sfakianaki (2007) examining formant frequencies F1, F2 and duration of all five Greek vowels in [ˈpVCV] disyllables (C = [p, t, k, s]) uttered by six speakers with profound HI and six speakers with NH, showed clearly defined vowel categories but substantial vowel space reduction for speakers with HI. The reduction was mostly attributed to a restricted F2 range in agreement with aforementioned studies. In addition, absence of stress caused a similar lowering of the F1 frequency for NH and speakers with HI, while the stress effect on F2 was more prominent in NH vowels. A large-scale investigation of Greek vowel production and recognition in hearing loss was conducted by Vakalos (2009). Seventy nine speakers with mild-to-severe hearing loss of varying etiology and 23 speakers with normal hearing took part in the experiment. The age range was 9 to 81 and the groups were balanced for sex. Subjects were recorded reading a sentence containing all five Greek vowels and a list of five [pVs] words. A vowel recognition test ensued. Vowel spaces and dispersion were calculated on the basis of F0, F1 and F2 formant measurements. No statistically significant differences were found in terms of vowel area and dispersion between speakers with NH and HI and no correlation was detected between these measures and degree of hearing loss. Thus no remarkable distortions regarding vowel production for the speakers with HI were noted. As far as vowel recognition is concerned, performance tended to decrease with an increase in hearing loss but only a weak statistical correlation was found between the two factors. Identification was significantly higher for front vowels [i] and [e] and lowest for the high back vowel [u].

The integrity of various acoustic aspects of speech produced by talkers with less than profound hearing loss has been examined by other researchers as well. An acoustic study of basic syllables containing vowels [i, a, u] and consonants [p, b, t, d, k, g] was carried out in French by Ryalls and Larouche (1992). No statistically significant differences between children with moderate-to-severe HI (MHI) and children with NH regarding total duration of CV syllables, VOT, F0 and formants F1, F2 and F3 at vowel midpoint were detected. In a follow-up study, Ryalls, Larouche and Giroux (2003) performed the same measurements in a group of children with profound hearing impairment (PHI), matched for size and sex, so as to compare them with those found for children with MHI. The PHI group showed significant differences in all aforementioned measures from both NH and MHI groups. Moreover, in their investigation of vowel organization, McCaffrey and Sussman (1994) observed that the NH group displayed more similarities with the severely HI group in terms of F0, F1, F2, F3 and percent vowel intelligibility than with the profoundly HI group. Speakers with severe HI demonstrated difficulty with vowel place (F3-F2 dimension), while speakers with profound HI had problems both with vowel place and height (F3-F2 and F0-F1 dimension). As hearing loss increased from severe to profound, vowel differentiation in terms of height deteriorated especially among high vowels [i], [u] and [ɪ]. Nevertheless, the authors underline that speakers with profound HI level showed a variable performance level that, in some cases, approached the severely HI one or even the NH one.

Consonants

A less accurate production of consonants relative to vowels has been reported in isolated words as well as spontaneous speech (Hudgins & Numbers, 1942; Brannon

1966; Markides, 1970; Smith, 1975; Geffner & Rothman Freeman, 1980)[11]. The most common consonantal errors involve omissions, distortions and substitutions (Pratt & Tye-Murray, 2009). Omissions usually occur to final consonants and especially final velars (Nober, 1967; Markides, 1970; 1983; Smith, 1975; Osberger, Robins, Lybolt, Kent & Peters, 1986). Smith (1975) reports that fricatives show a high rate of substitution to, but not from, plosives. Clusters are frequently simplified into stops (Hudgins & Numbers, 1942; Calvert & Silverman, 1983). Other types of errors involve the production of glottal stops in the place of other sounds (Smith, 1980) and the addition of adventitious phonemes, e.g., the epenthesis of a vowel in abutting consonants so that CCV sequences become CVCV (Osberger & McGarr, 1982).

Regarding place of articulation, front consonants are usually produced better than back consonants possibly due to their higher visibility (Nober, 1967; Oller, Jensen & Lafayette, 1978). Consonants formed in the middle of the mouth are often susceptible to errors in production (Smith, 1975; Gold, 1978). Huntington, Harris, Shankweiler and Sholes (1968) claim that visibility is not the sole crucial factor contributing to better articulation. Bilabials and velars both have a higher rate of correct production than lingual consonants due to the difficulty speakers with HI face with tongue movements. Barzaghi and Madureira (2005) also report better production and perception of bilabial as well as velar Brazilian Portuguese consonants.

An exceptionally problematic area in HI articulation is sibilant production. Concerning the articulation of the two voiceless fricatives [s] and [ʃ] in English, the shape of the tongue groove needs to be narrow and near the front of the alveolar ridge for the former, whereas for the latter it must be wider and in the post-alveolar region (Fletcher & Newman, 1991). In addition, two different types of turbulence are

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[11] Although, as noted in the previous section, vowels are louder and easier to hear (Brannon, 1966) and correct identification of consonants depends largely on vowel transitions (Monsen, 1976c).

employed during sibilant production; the channel turbulence which “occurs when air stream is generated through the grooved portion of the tongue” and the wake turbulence which “occurs when the air stream strikes the teeth” (Shadle, Dobelke & Scully, 1992; Shadle & Scully, 1995; Shadle, 1997 as cited in McGarr et al., 2004:120). Consequently, speakers with HI have to face two daunting tasks in order to achieve an adequate production of the two fricatives, one related to correct shape and placement of the tongue and another related to appropriate aerodynamic balance between the two types of turbulence described above.

Looking more closely at the fricative production issues of the HI, McGarr, Raphael, Kollia, Vorperian and Harris (2004) investigated tongue-palate contact during sibilant contrasts in English using CV syllables (C=[s] and [ʃ], V=[i] and [u]) produced by four severe-to-profound ‘oral deaf’ adults. They found that identification scores for [ʃ] were higher than those for [s] and that the HI linguapalatal contact patterns differed from those of the NH as regards temporal organization. Their tongue-palate contact was not as differentiated as the NH one and their tongue movements were slower than normal.

Consonant articulation of Greek speakers with HI has been studied by Nicolaidis (2004) using EPG. Lingual-palatal contact patterns of consonants [t, k, s, x, n, l, ɾ] produced by four speakers with profound hearing loss and differing levels of intelligibility were examined. Substitutions, distortions and epenthesis of segments were amongst the most frequent errors resulting in deviant consonantal patterns and, in some cases, neutralization of contrasts. Concerning the two alveolar consonants of interest in the present study, [t] was found less problematic and less variable than most consonants, a finding possibly attributed to the stability required for the complete occlusion during its production (Stone, 1990), while [s] deviated from normal for all speakers along with the palatals [c] and [ç] (allophones of /k/ and /x/ respectively). The fricative [s] was realized with a large variety of gestures (open, closed, front, back or grooved) indicating decreased articulatory precision which could be related both to the fact that there is no contrastive sibilant in the alveolar region for Greek and to its invisibility and difficulty of formation for speakers with HI. Nicolaidis (2004:430) underlines that, although variability in its constriction location may be expected for Greek (as opposed to English), certain limits have to be maintained so as not to neutralize its contrast with [x] and [ç]. A subsequent study looking into aspects of spatio-temporal variability during the production of the aforementioned Greek consonants was also carried out (Nicolaidis, 2007). Consonant variability in terms of tongue-palate contact was found to be inversely related to consonant duration, that is, consonants with short duration displayed the highest degree of variability. These two parameters seemed to relate to speech intelligibility, although not in a straight-forward way, since short consonantal duration and high variability was observed for a speaker with moderate intelligibility, while long consonantal duration and low variability was noted for two speakers with significantly different intelligibility levels.

2.3.2.2. Theories on Vowel Production in HI Speech

In an attempt to account for the perceptual, physiological and acoustic data gathered from HI vowel productions, two theories were put forth, the *absent target theory* and the *deviant phonology theory*. The *absent target theory* was postulated by Angelocci et al. (1964) and is based on insufficient vowel differentiation. After the acoustic analysis of 10 vowels in /hVd/ sequences produced by normal hearing and deaf 11-to-14-year-old boys, Angelocci and colleagues found that HI vowels displayed wider ranges of F1 and F2 formant frequencies and extensive overlap between vowel areas in an F1xF2 plane as opposed to NH vowels. They conclude that speakers with HI have not formed differentiated auditory vowel categories and consequently their articulatory movements are highly unstable, resulting in a restricted formant range and, at the same time, variable vowel production. As mentioned in a previous section, they claim that speakers with HI differentiate vowel targets on the basis of F0 variation.

According to the *deviant phonology theory* put forward by Monsen (1976a), HI vowels are deviant from normal but in a consistent way. Monsen measured formants F1 and F2 of vowels [i], [a] and [ɔ] in the speech of 36 deaf and 4 NH adolescents and, in partial agreement with Angelocci et al. (1964), found a reduced phonological space due to a relative immobility of the F2, while F1 varied within a normal range for some deaf adolescents. The researcher attributed this difference to the visibility of the articulators related to F1, i.e., the lips and jaw, and the auditory prominence of the first formant which is lower in frequency as opposed to the second formant that reaches to higher frequencies. Based on these two parameters that constitute only a subset of those needed for a normal production, deaf speakers formulate a deviant phonology. Within the limits of their phonology, vowels are well defined, albeit not in the same way as NH vowels.

The two aforementioned theories share a common principle; speakers with HI differentiate their vowels according to parameters different than those employed by NH speakers, i.e., F0 in the case of the *absent target theory* and F1 in the case of the *deviant phonology theory*. Thus, an experienced listener should be capable of utilizing these cues and identify HI vowels to a greater extent than an inexperienced listener. Additionally, according to the *deviant phonology theory*, HI vowel production should be as variable as NH vowel production, since both are governed by a phonological system, albeit with different rules. Both these postulations were challenged by Rubin (1984) who measured F0, F1 and F2 of seven vowels in /bVb/ sequences uttered in a carrier phrase by six orally trained adolescents with HI. Each stimulus was repeated 15 times so as to examine token-to-token variability and hence articulatory stability in HI speech. Three different styles of HI vowel production were identified: (a) the 'point vowel' talkers showed greater stability for point vowels and higher variability for intermediate vowels; overlap was greater along the F2 than the F1 dimension, (b) the 'front/back' talkers produced sufficiently differentiated front and back vowels, but not high and low vowels, resulting in overlap along the F1 dimension, and (c) the 'overlapped' talkers displayed extensive overlap along both formant dimensions. Therefore, speakers with HI were not able to differentiate as many vowel categories as NH speakers, which led to the postulation of the *reduced target hypothesis*. Moreover, an intelligibility test revealed that intelligibility level varied according to style of production, that is, speakers in the first category scored highest in the intelligibility test, followed by speakers in the second category, while speakers in the third category came last. An important finding is that no significant differences were located in vowel identification between the experienced and inexperienced listeners. This result contests Monsen's theory of deviant phonology, according to which experienced listeners are expected to perform better since they should be able to trace systematic elements in HI productions assisting them in the recognition of their vowels. Moreover, the intra- and inter-speaker variability found in HI vowels challenges both the deviant phonology and the absent target theory, as they are based on the utilization of a relatively consistent F0 or F1 in HI vowel production. Rubin suggests that HI speech is based on the same principles as NH speech and can resemble it to a lesser or greater degree depending on individual characteristics and idiosyncratic strategies.

Subsequent research has also challenged the claims of the first two theories. Although neutralization of vowels and restricted tongue movement have been documented in acoustic and physiological studies (McGarr & Gelfer, 1983; Rubin, 1985; McGarr & Harris, 1980; Tye-Murray, 1992), a hypothesis implying the uniform absence or imprecision of articulatory and acoustic representations of vowels because of hearing loss has never been sufficiently substantiated. McGarr and Whitehead (1992:39) maintain that research has shown a correlation between quantity of errors and degree of hearing loss but no systematic error patterns according to certain factors such as degree of hearing loss, age of loss, speech therapy onset and educational placement. Thus, no generic pattern in HI vowel production due to one distorted acoustic dimension has been established.

The observed variability in HI speech further weakens claims of the existence of one pattern applying to HI speech in general. Harris, Rubin-Spitz and McGarr (1985:51) state that "[a] deviant phonology would be indicated by normal production variability, co-occurring with failure to differentiate pairs of sounds, or an abnormally based distinction". However, acoustic, physiological and EPG studies have found speakers with HI highly variable in repeated tokens production and no HI stereotypical performance has ever been established (Harris, Rubin-Spitz & McGarr, 1985; Dagenais & Critz-Crosby, 1991; Okalidou, 1996, 2002; Nicolaidis, 2004, 2007). Although variability is also found in NH repeated productions (Nicolaidis, 1997; McAuliffe, Ward & Murdoch, 2001; Dromey & Sanders, 2009), NH speakers are very consistent in producing intelligible speech under a variety of adverse conditions (e.g., pipe smoking, novocaine, bite-blocks) and show extraordinary stability of interarticulator timing (Tuller & Kelso, 1984). Physiological studies have shown that speakers with HI are also capable of compensating for jaw restriction (Tye, Zimmermann & Kelso, 1983) and for bite-block conditions (Campbell, Boothroyd, McGarr & Harris, 1992), albeit in different ways and not as consistently as the NH. Although the role of auditory feedback is quintessential while learning a language and maintaining the motor patterning of speech, the achievement of a compensatory behaviour on part of the HI in these experiments indicates that this type of equilibrium configuration is largely owed to the dynamic characteristics of the muscle-joint system (Tye et al., 1983) and not to a specific strategy associated with planning.

2.3.2.2. Suprasegmental Production

Duration, Stress and Suprasegmentals

Research in NH production mainly in English has shown that each phonetic segment has its own intrinsic or inherent phonological duration. More specifically, vowel durations tend to vary inversely with vocalic height (Lehiste, 1970), schwa is shorter than other vowels (Peterson & Lehiste, 1960; House, 1961), voiceless fricatives are 40 ms longer on average than voiced fricatives, the occlusion and VOT phase are shorter for voiced stops [b, d, g] than voiceless stops [p, t, k], and labial closures are longer than alveolar closures (Klatt, 1976). Context dependent effects have been documented on NH segmental durations by various researchers. Vowels have been found shorter in voiceless consonant environments (Peterson & Lehiste, 1960; Di Simoni, 1974; Klatt, 1976; Van Santen, 1992) and 20-25% longer when followed by a fricative than a stop (Peterson & Lehiste, 1960). Consonant durations have been found longer before [i] regardless of the identity of the preceding vowel (Schwartz, 1969), [p] and [s] are shortened in a [sp] cluster, while [r] is lengthened by about 30 ms in consonant clusters with [p, t, k] than with [b, d, g] (Umeda, 1977). Additionally, the number of syllables in a word or the number of words in an utterance can influence segmental duration. In general, vowel and consonant duration vary inversely with the number of syllables in a word (Lindblom, 1968; Harris & Umeda, 1974; Klatt, 1973; Port, 1981). The closure duration of word-initial [p] when located in the first word of an utterance decreases as the number of words in the utterance increases (Schwartz, 1972). Effects related to utterance length on duration have been observed in children as young as 3 years old (Di Simoni, 1974).

It is, therefore, evident that NH speakers from a very young age develop a “forward scan” or “anticipatory mechanism” regarding segmental duration (Schwartz, 1969:481). Evidence for the existence of such a mechanism has also been reported for speakers with HI, albeit it does not seem to incorporate all the learned principles of coarticulation located in normal speech. For example, following the normal pattern, vowels produced by adults with HI were found significantly longer in a voiced than in a voiceless consonant context (Whitehead & Jones, 1976) and also longer in a fricative than a stop consonant environment (Whitehead & Jones, 1978). However, contrary to expectations, Whitehead and Jones (1978) note that HI fricative duration is longer when situated in the low vowel [a] context rather than that of the high vowel [i]. Moreover, in an earlier study on the inherent durational difference between [i] and [ɪ] and the influence of the following consonant on their duration, Monsen (1974) found that severely HI and profoundly deaf adolescents do not vary the duration of the vowels in a normal manner in relation to the tenseness of the following consonant. Hence, although certain vowel duration patterns are found in HI speech, they often are not manifested systematically, while other patterns seem to be missing altogether.

Generally, longer segmental and utterance durations have been reported by a large number of studies on HI speech (e.g., Calvert, 1961; Osberger & Levitt, 1979; Okalidou, 1996; Nicolaidis & Sfakianaki, 2007; Vandam, Ide-Helvie & Moeller, 2011; Coimbra, Jesus & Couto, 2011) and many researchers have noted that HI differentiation between tense and lax vowels or between voiced and voiceless stops in terms of duration is insufficient (Monsen, 1974, 1976b; Gilbert & Campbell, 1978; Leeper, Perez & Mencke, 1980; McGarr & Löfqvist, 1982; Ryalls et al., 2003, for French; Barzaghi & Madureira, 2005, for Brazilian Portuguese; Khouw & Ciocca, 2007, for Cantonese) leading, as a result, to lower speech intelligibility. In addition, Leeper, Perez and Mencke (1987) noted that VOT duration does not vary according to utterance length in HI speech. In an EPG study of Greek consonants produced by four speakers with profound HI, Nicolaidis (2007) found that only two of the four speakers showed significantly longer consonants than normal but their intelligibility level differed significantly, indicating that the relationship between segmental duration and speech intelligibility is not a straight-forward one. Moreover, in the same study, speakers with NH demonstrated differences in duration according to consonant type, i.e., [s] was the longest and [ɾ] the shortest, whereas speakers with HI frequently produced similar durations across consonants.

Segmental duration in NH speech is also influenced by position and stress. Stressed vowels are longer than their unstressed counterparts (section 2.2.2). Word-final vowels are lengthened in many languages (Klatt, 1975; Beckman & Edwards, 1990), while vowel and word durations shorten as more syllables or words are added after them (Fowler, 1981b; Lehiste, 1972; Port, 1981). Consonants in pre-stressed syllables have been reported as longer than consonants in unstressed or post-stressed syllables (Klatt, 1976). In HI speech, duration is not used consistently to mark a syllable with primary stress. In their study of syllabic stress in English words, Ando and Canter (1969) observed that listeners were able to distinguish between stressed and unstressed syllables produced by deaf speakers only by 20% as opposed to 81% for NH syllables. The authors suggest that this failure may be related to the use of excessively long internal open junctures by the HI subjects that distorted their rhythm and slowed down their speech rate. Moreover, speakers with HI may not utilize the same correlates as NH speakers to convey stress. NH speakers use intensity, duration and fundamental frequency cues to mark syllables with primary stress (Ando & Canter, 1969). Speakers with HI may not use all these cues which potentially compromises stress identification by listeners (Most, 1999; O'Halpin, 1997). Even after cochlear implantation, such problems persist. An investigation of the ability of 11 cochlear implanted children (CI), 10 children with hearing aids (HA) and 90 NH children to convey stress in Dutch revealed that a large number of children with CI could not reproduce the target stress pattern and had a poorer overall performance when compared with HA and NH children. Their stressed syllables were less accentuated, i.e., they displayed pitch rises of restricted degree, while pitch falls were longer in duration (Hide, Gillis, Verhoeven, Govaerts & De Maeyer, 2010).

Durational shortening in unstressed vs. stressed syllables, has been documented in various HI speech studies, albeit to a smaller degree on average in comparison to NH speech (Stevens, Nickerson & Rollins, 1978; Osberger & Levitt, 1979). Longer vowel durations than normal of stressed and unstressed HI vowels, but also evidence of durational shortening in HI vowels was also found for Greek in the study conducted by Nicolaidis and Sfakianaki (2007). Data from that study showed that, in terms of formant frequency, absence of stress was mainly marked by F1 lowering, while changes in F2 were less than half in comparison to those observed in

NH speech. Barzaghi and Mendes (2008) investigated acoustic parameters of the stressed Brazilian Portuguese vowel [a] in [Cata] disyllables with the initial consonant [p, b, t, d, k, g] uttered by two speakers with moderate and one speaker with severe hearing loss. They also report shortening for unstressed vs. stressed [a], but the highest stressed-to-unstressed duration ratio was found for the speaker with severe HI that exceed even that found in NH speech. The researchers attribute this contradictory finding of increased HI vs. NH shortening for this one subject to compensation for the extreme lengthening of her stressed vowels. Additionally, they found a higher F1 frequency for stressed [a] in all contexts and speakers, although the speaker with severe HI again demonstrated the highest values indicating excessive jaw opening in stressed position. Concerning the duration reduction of segments in derived forms, Tye-Murray and Woodworth (1989) note that deaf speakers in their study do demonstrate reduction, albeit inconsistently and to a lesser extent in comparison with NH speakers. Additionally, the reduction displayed by the deaf speakers did not affect vowels proportionately more than consonants as occurring in NH speech, but vice versa.

In addition to the differences between HI and NH speech in segmental and syllable duration and suprasegmental timing, HI intonation patterns have also been reported as diverging from those of the NH speakers. Many researchers observe that speakers with HI cannot use F0 sufficiently to mark intonation, probably due to its limited range (Hood & Dixon, 1969; but see Angelocci et al., 1964) which makes their speech sound “monotonous” and “devoid of melody” (Osberger & McGarr, 1982). Abnormally high pitch has been detected at the beginning of their productions and pitch breaks and pausing have been located between words and syllables (Willemain & Lee, 1971; Martony, 1968; Hood & Dixon, 1969; Ando & Canter, 1969; Monsen, 1979; Tobey, 1993; Allen & Andorfer, 2000). Prolongation of segments, syllables and words, pausing and aberrant timing lead to a decrease in speaking rate. HI speech is on average 1.5 to 2 times slower than NH speech and sounds laboured (Boone, 1966; John & Howarth, 1965; Osberger & McGarr, 1982).

Respiration, Voice and Nasality

Problems with appropriate VOT production and failure to make voice/voiceless distinctions, as well as difficulties with duration and relative timing seem to relate to an inability to regulate aerodynamic events. Inappropriate or inconsistent gestures reflecting poor coordination and timing between oral articulator movement and vocal fold adjustment have been detected in HI speech. The characteristic breathy quality of voice is also associated with improper adjustment of the vocal cords (Stevens et al., 1978).

An explanation in terms of physiology was put forth by McGarr and Löfqvist (1982) who studied the organization of laryngeal control and interarticulator timing in the production of voiceless obstruents by three speakers with severe-to-profound HI using transillumination in combination with an electrical transconductance technique. They concluded that interarticulator coordination was different from the NH and variable among the HI. Plosive production demands precise coordination between the glottis and the upper articulators, as well as accurate airstream management. On the other hand, voiceless fricatives may not demand such fine interarticulator timing, but require accurate placement of the upper articulators which are invisible and inaudible due to their high-frequency energy to speakers with HI. Nevertheless, the study showed that, in some cases, speakers with HI did manage to execute appropriate glottal gestures, which contrasts with the notion of complete failure of interarticulator coordination; this finding is explicable along the lines that such gestures do not only require auditory monitoring but are also depending on "intrinsic factors of the speech production system" (McGarr & Löfqvist, 1982:41). Lane and Perkell (2005:1339) maintain that "lack of an appropriate phonemic representation in the first place, an inability to establish an internal neural model of the relations between speech movements and their acoustic consequences, and possible influences of speech therapy" play a potential contributing part in a problematic management of the voicing contrast among speakers with prelingual HI.

Problems with duration, timing and prosody are also related to respiration. According to McGarr and Whitehead (1992:33-34), a breakdown in the complex and sophisticated interaction between the respiratory system, the larynx and the structures contained in the oral cavity may result in biomechanical and/or aeromechanical aberrations. A large number of studies concentrate on respiratory problems in HI speech. Excessive amount of air expenditure as well as lack of coordination between respiration and articulation has been observed (Hudgins, 1934; Rawlings, 1935). Forner and Hixon (1977) and Whitehead (1983) note that the HI initiate phonation with inadequate air volumes and thus manage only a reduced number of syllables per breath, frequently having to stop for inhalation at linguistically inappropriate places in the sentence (Hudgins, 1946; Tye-Murray, 1987). In addition, the inhaled volume of air is mismanaged by inappropriate valving at the glottis. The abnormally high airflow rates during obstruent production (Whitehead, 1983) combined with the unusually low airflow observed during voiceless fricatives in VCV syllable contexts (Whitehead & Barefoot, 1983), as well as the wastage of air through an open glottis during pauses between words[12] (McGarr & Löfqvist, 1982) provide evidence towards air mismanagement. Breathy voice quality or hoarseness is another byproduct of

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[12] But see Stevens, Nickerson & Rollins (1983) who maintain that the glottis is closed during pauses between words produced by the HI.

problematic respiration during speech (Rawlings, 1935; Hudgins, 1937; Hudgins & Numbers, 1942; Forner & Hixon, 1977; Monsen, Engebretson & Vemula, 1978; Stevens, Nickerson & Rollins, 1983, Zimmermann & Rettaliata, 1981).

Nasality problems are also observed in the speech of the HI which could be attributed to improper velopharyngeal timing caused by poor auditory feedback (Pratt & Tye-Murray, 2009). Accelerometer measurements of nasality in the speech of 25 deaf children showed that they present more instances of vowel nasalization than NH children and that their nasal consonants are often denasalized and nonnasal consonants nasalized (Stevens, Nickerson, Boothroyd & Rollins, 1976). Evidence of hyper- or hypo-nasality in HI speech exists in other studies as well (Gilbert, 1975; Fletcher & Daly, 1976), although normal levels of nasalance have also been detected in the utterances of highly intelligible speakers with HI (Higgins, Carney & Schulte, 1994). Okalidou (2002:101) notes that excess nasality may be a prominent characteristic in HI speech, but one that can be restored to normal levels subsequent to appropriate intervention and timely residual hearing amplification.

Overall, HI speech displays errors whose physiological correlates may span entire utterances due to the interplay between segmental and suprasegmental aspects of speech. “Inappropriate respiratory control, glottal abduction/adduction gestures, vocal fold tension and mass, tongue position and range of movements, velopharyngeal posture and movements” are *postural errors* that influence the function of the speech production mechanism over time and can lead to a breakdown in interarticulator coordination, substantial variation in production and reduced intelligibility (Osberger & McGarr, 1982).

2.3.3. Intelligibility of HI Speech

Speech intelligibility refers to the accuracy with which a normal listener can understand a spoken word or phrase. As expounded in the sections above, HI speech presents various types of segmental and suprasegmental errors which can compromise its 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.

The degree of hearing loss is among the determining factors of HI speech intelligibility (Elliot, 1967; Boothroyd, 1969; Markides, 1970; Smith, 1975; Levitt, Smith & Stromberg, 1976). Speakers with severe or mild HI have been documented to achieve higher intelligibility scores than speakers with profound HI (Gold, 1978; Markides, 1970). In Boothroyd's study (1969), children with an intelligibility score of above 70% had a hearing loss of less than 90 dB at 1000 Hz, while when hearing loss exceeded that level, the median intelligibility score fell rapidly. Other researchers mention a similar PTA 'threshold' up to which speech was intelligible (Smith, 1975, about 85 dB; Monsen, 1978, about 95 dB) but no direct relationship between hearing level and intelligibility over that was identified. 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 carried out by Metz, Samar, Schiavetti, Sitler and Whitehead (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 (Smith, 1975; Monsen, 1978; 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, e.g., 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, Maso and Sam (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 vary significantly 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 19-40% (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 influences significantly 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, Ochsner & Testut, 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 of listener experience with intelligibility has been investigated by various researchers. “Intelligibility is rooted in characteristics of a speaker-listener dyad” (Kent, Miolo & Bloedel, 1994:81), therefore the listener’s characteristics are bound to affect the intelligibility score (McGarr, 1983; Monsen, 1983a; Boothroyd, 1983, 1985). 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). It has been hypothesized that the consistency of segmental errors found in HI speech relative to the irregularities of errors reported in other speech disorders, e.g., cerebral palsy (Carlson & Bernstein, 1988), plays a role in the improved performance of listeners with skills and experience who are able to factor out deviant characteristics in HI speech and ultimately reach a higher identification percentage (Kent et al., 1994:91).

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 it seems to be an advantage quickly and easily acquired.

Intelligibility has also been examined in relation to segmental errors. Unintelligible speech usually displays a high number of segmental errors, although the two measures are not directly correlated. As expounded above (section 2.2.3.1.), different results have been reported regarding the most frequent errors in vowels and consonants by various researchers, depending on methods, materials and the subject characteristics of the studies. Different correlation values have been documented for various phoneme errors in the literature. Hudgins and Numbers (1942) found that the total number of consonant and vowel errors significantly reduce speech intelligibility, the former to a greater extent than the latter. However, vowel errors are reported to correlate more with intelligibility than consonant errors in Smith’s study (1975). Gold (1980) comments that although consonantal errors show a higher frequency of occurrence in the literature, the high frequency of an error does not necessarily pertain a higher negative correlation with intelligibility in comparison with a less frequent but graver error (e.g., vowel omission).

Monsen (1978) reports 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. In an attempt 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. They 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. Nicolaidis (2004) observes an inverse relationship between number of articulation errors in consonant production and intelligibility in two of the four Greek speakers with profound HI participating in the study. Furthermore, production variability and contrast neutralization were indicative of reduced intelligibility. However, two speakers with HI and differing levels of intelligibility had error profiles of a similar size, suggesting that errors of a different type, such as prosodic errors, also play an important part in speech intelligibility.

Suprasegmental errors include prolonged durations, aberrant timing, rhythm errors, slow speech rate, intrusive sounds, pauses, inappropriate intonation patterns, inappropriate pitch and intensity level, insufficient stress marking, hyper- or hypo-nasality, poor phonation control and voice quality. Errors in rhythm (Hudgins & Numbers, 1942), frequent inter- and intra-word pausing (Hudgins, 1946; Levitt, Smith

& Stromberg, 1976), excessive variation and breaks in pitch (Parkhurst & Levitt, 1978), erroneous prosody and abnormal phonation (Smith, 1975; McGarr & Osberger, 1978) have been found quite detrimental to overall speech intelligibility. Nevertheless, the correction of timing errors via speech synthesis (Osberger & Levitt, 1979) only brought about 4% average improvement of intelligibility. Additionally, severely deviant pitch levels have been detected in intelligible HI speech (McGarr & Osberger, 1978; Monsen, 1978). In an EPG study of duration and variability in Greek consonant contact patterns, Nicolaidis (2007) observes that two of the speakers who produced prolonged consonants of a similar duration, differed significantly in intelligibility level, one being highly intelligible and the other unintelligible. In addition, a third speaker displayed short durations, variable patterns and reduced intelligibility. The researcher concludes that duration and contact pattern variability cannot sufficiently account for variation in HI intelligibility.

An experiment investigating the relative effect of segmental and suprasegmental corrections on deaf speech intelligibility (Maasen & Povel, 1985) showed that suprasegmental correction improved intelligibility by 10%, while segmental correction approached a 50% improvement. The authors maintain that segmental errors are more important determiners of intelligibility than suprasegmental errors. Phonation errors and poor breath control have the highest negative correlation with intelligibility, while the correction of overall pitch level and variation causes significant improvement only if segmental aspects of speech are relatively intact. Their view is in accordance with Monsen (1978) who claims that only the intelligibility of speakers with well-developed articulatory skills can benefit from an improvement in duration. Moreover, pauses were found to aid intelligibility as the listener may require additional time to process HI speech (Boothroyd, Nickerson & Stevens, 1974; Parkhurst & Levitt, 1978; Osberger, 1978).

2.3.4. Coarticulation in HI Speech

As expounded in previous sections, HI speech manifests segmental and suprasegmental deviancies that negatively affect intelligibility. Articulation errors, aberrant rhythm due to duration prolongation and pausing, interarticulator timing errors, restricted formant ranges and "flat" formants led researchers to the assumption that "deaf speakers treat phonemes, syllables and words as isolated events rather than as integrated parts of an event of substantially greater magnitude" (Rothman, 1976:129). Evidence indicating that HI speech did not demonstrate certain contextual influences to the same degree as NH speech (e.g., variation in vowel duration as a function of consonant type or utterance length, flat and relatively shorter or longer formant transitions (sections 2.3.2.1. and 2.3.2.2.), revealed differential implementation of coarticulation patterns. As Monsen (1976c:279) points out, low intelligibility in HI speech may involve not only a sum of segmental or suprasegmental errors, but also more fundamental characteristics of speech, such as "an aberrant generation of the glottal source, or a difference in the dynamics involved in combining phonemes into syllable form". Thus, formant transitions and other manifestations of coarticulatory effects in HI speech became the focus of phonetic research.

Monsen (1976c) investigated F2 formant transitions in consonant-vowel sequences in the speech of six adolescents with NH and six adolescents with HI. Hearing loss was prelingual and varied from severe to profound (65.6 to 103.9 dB HL PTA). The material consisted of 20 CV(C) monosyllabic words repeated 5 times, with vowels [i] and [u], initial consonants [f, b, d] and final consonants [n] or [d]. F2 measurements were made at the onset and at 20-ms intervals up to the first 120 ms of the vowel. The bandwidth was doubled so as to improve formant display, as the fundamental frequency of the speakers was quite high due to their age. Transition range and duration were calculated on the basis of measurements at the onset and the 120 ms point. The analysis showed that the speakers with HI differentiated much less between [i] and [u], mainly because of a lower mean F2 value for [i]. Transition durations were found variable, in some cases too short and in others quite long. Moreover, the extent of F2 change was substantially reduced and transition patterns were variable among speakers with HI. The author suggests that the diminished transitions may be caused by articulatory inactivity during consonantal occlusion that minimizes the acoustic effects of the movement from the consonant to the vowel. Finally, he proposes that the increased occurrence of consonantal errors in deaf speech reported in the literature may be related to lack of consonantal cues in vowels, rather than poor consonantal articulation per se.

Rothman (1976)[13] carried out a spectrographic study of consonant-vowel transitions in the speech of four NH male adults and four intelligible, orally-trained deaf male adults with a profound bilateral hearing loss. The material consisted of minimally different pairs of monosyllabic nonsense words of the type [CVt] (C = [t, k, l, s] and V = [i, a, u]) embedded in the utterance “Take a _____ aside”. Each utterance was repeated 10 times and 5 of them were chosen for analysis. Duration measurements of intervocalic closures and vowels were made as well as F2 and F3 frequency measurements at three points in the utterance, between [ei] and [k] in “take”, between [ə] of the article before the key word and [C] of the key word, and

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[13] An earlier abstract publication by the author was made in 1972 in the Journal of the Acoustical Society of America (vol. 52) with the title “An acoustic and Electromyographic Investigation of Consonant-Vowel Transitions in the Speech of Deaf Adults”.

between [ə] and [s] of "aside". The data were treated on a group basis. Results showed a restricted range of F2 and F3 variation at transition start and end, and minimal coarticulatory effects on [ə]. The author observed a "stereotyped articulation" (p. 134) in deaf speech, that is, deaf speakers began all articulatory sequences in the same manner regardless of context. He attributes lack of coarticulatory effects to long closure durations that allow time for the treatment of segments as isolated events and stresses the importance of speech rhythm training so as to promote allophonic variation in deaf speech.

Coarticulation in HI speech in relation to direction of influence was first examined in two studies carried out by Waldstein and Baum (1991) and Baum and Waldstein (1991) that investigated anticipatory and perseveratory (carryover) effects respectively in the speech of profoundly HI and NH children. The participants were nine intelligible children with profound prelingual HI and nine NH children, divided into two age groups: five children were 6-7 years of age and four children were 9-10 years of age. The stimuli were ten tokens of CV syllables [ʃi, ʃu, ti, tu, ki, ku] for the investigation of anticipatory effects and 10 tokens of VC syllables [iʃ, uʃ, it, ut, ik, uk] for carryover coarticulation. Temporal and spectral measurements were made. Regarding spectral measurements, the researchers employed the measure of *consonantal centroid frequency* or *centre of gravity*, thought to "reflect details concerning the front cavity size and constriction shape" (Nittrouer, Studdert-Kennedy & McGowan, 1989:122). It is associated especially with the presence of lip rounding, but also constriction location. Centroid measurements were made at two consonantal points, an early one located nearer the vowel and a late one farther from the vowel. An additional measurement of F2 peak was made to capture consonantal spectral energy at a 20 ms distance from the vowel so as to infer presence of lingual coarticulation.

The results showed that, overall, V-to-C anticipatory effects were present in HI speech, although they were less robust than in NH speech. Temporal effects were small in magnitude and inconsistent for children with HI, in agreement with Whitehead and Jones (1978). However, such effects formed a trend and did not reach significance for NH children either. Early and late centroid measurements revealed that anticipation gestures may start later for children with HI when compared with NH children. Additionally, low centroid measure values for HI speech suggested either more lip protrusion or a more back place of constriction. The former is in agreement with the lip rounding findings of an electromyographic study conducted by Huntington, Harris and Sholes (1968) and the latter is in accordance with Subtelny, Li, Whitehead and Subtelny (1989) who found consistent retraction of the tongue root and lowered tongue body position for speakers with HI in relation to NH speakers. Differences in F2 calculated on the basis of pairs such as [Ci]/[Cu], indicating anticipatory tongue movement for the upcoming vowel, showed a smaller magnitude of F2 difference for HI children in the [ʃ] and [k] context but not in the context of the alveolar [t]. An interesting finding concerning NH coarticulation is that younger NH children exhibited less evidence of anticipatory effects. This result along with the fewer anticipatory effects in HI speech seems to be in contrast with the proposal put forth by Nittrouer et al. (1989) regarding increased coarticulatory influences in young children’s or generally undeveloped speech as opposed to in mature adult speech.

Concerning carryover coarticulation, there was evidence of V-to-C effects for both NH and HI children, although the magnitude of effects was smaller for the latter at consonant onset, while 50 ms into the consonant both groups displayed comparable coarticulatory magnitude. Thus, the temporal extent of perseveratory coarticulation was found similar for both groups, whereas that of anticipatory coarticulation had been shorter for children with HI (see above). This finding was associated by the authors with the different nature of the two types of coarticulation, i.e., anticipatory reflecting planning while carryover indicating mechanical constraints (section 2.1.1.). Regarding NH speech, greater degree of carryover vs. anticipatory coarticulation was observed. The overall smaller magnitude of HI carryover effects was partially attributed to the decreased differentiation of HI vowels. Lower centroid frequencies were observed in both studies for HI children, denoting less precise articulatory targets and, in this case, accounting for the smaller magnitude of carryover effects in terms of mechanical properties being sensitive to subtle changes in articulation.

A study designed to parallel Waldstein and Baum (1991) is the investigation of anticipatory coarticulation in the speech of young normal and hearing impaired French Canadians conducted by Ryalls, Baum, Samuel, Larouche, Lacoursière and Garceau (1993). This research added two more factors to be explored in relation to coarticulation, namely, the degree of HI and the nature of the language. Regarding the first, in addition to 10 NH children and 10 children with profound HI (PHI) a third group consisting of 10 children with moderate-to-severe HI (MHI) was included (30 to 90 dB HL PTA) so as to examine the effect of degree of hearing loss on coarticulation. Regarding the language, a comparison between French, examined in this study, and English in the Waldstein and Baum study would demonstrate whether HI coarticulation is influenced by language-specific factors, such as vowel inventory. The children were from 6;10 to 10;9 years of age and the three subgroups were balanced for sex. Children with MHI were oral communicators, while children with PHI used both sign and oral language. The stimuli were syllables [ki, ku, ti, tu] read five times from cards. The analyses included early and late centroid frequencies as in the Waldstein and Baum study (see above), as well as early and late LPC analysis for locating F2 formant frequency peak values.

Children with NH and MHI showed strong anticipatory effects in both [t] and [k] consonantal environments, while children with PHI demonstrated smaller F2 differences, suggesting less adequate vowel differentiation. Centroid values were similar for children with NH and MHI in the [t] but not in the [k] context, indicating that the latter could not achieve an appropriate target for velars, probably due to their invisibility. For children with PHI no statistical analyses were conducted due to the great number of consonant substitution errors related especially with velars. Despite being incomplete, the overall analysis did show anticipatory coarticulation for children with PHI, albeit of a lesser magnitude. The decreased magnitude of PHI effects was attributed to deviant place of constriction, probably further back in the vocal tract, in line with Waldstein and Baum (1991). As far as the comparison between the two languages is concerned, French-speaking children of all hearing groups demonstrated larger coarticulatory effects than English-speaking children. This finding was interpreted on the basis of the larger number of rounded vowels in the French phonemic inventory which was hypothesized to cause increased labial coarticulation for French speakers.

As pointed out by Okalidou (1996) and Okalidou and Harris (1999) certain methodological limitations in the foregoing studies do not allow a clear interpretation of the phenomenon of coarticulation in HI speech. In Monsen's study (1976c), these limitations refer to the recruitment of a heterogeneous subject group in terms of PTA range and a disadvantageous choice regarding the age of the participants, as the acoustic analysis of adolescent voices is quite challenging. Additionally, all formant measurements were made on the basis of a 120 ms interval regardless of duration and syllable type. A panel of three linguists selected only stimuli that demonstrated “reasonable articulatory proficiency” in Rothman’s study (1976:130), thus excluding tokens that might have made a difference in the overall result. Moreover, data were averaged across subjects, contexts or, in some cases, measurement points, possibly obscuring important aspects of the phenomenon. Okalidou and Harris (1999) stress the point that previous studies did not take into account the smaller distance between [i] and [u] found in HI speech, consequently basing their conclusions of reduced HI coarticulation on a direct comparison to that of NH speakers who display more separation along the front/back axis. Such a comparison results in factitious differences in coarticulation as they are not related to differential articulatory strategies, but to more superficial acoustic characteristics such as vowel differentiation, consonant articulation, speech rate and segmental duration (Okalidou, 2002:194). In addition, early studies did not distinguish anticipatory from carryover influence and examined a narrow portion of the acoustic signal, i.e., CV or VC syllables, which could not account for a phenomenon extending over syllable boundaries, as proposed by Öhman (1966), Recasens (1985, 1989) and others.

Thus, Okalidou (1996) and Okalidou and Harris (1999) propose a methodology that looks into both intra- and inter-syllabic coarticulation. In addition, the influence of speaking rate on HI coarticulation, a factor that had not been examined previously, is included in the experimental design. Several studies on NH speech report increased coproduction of gestures with an increase in speaking rate (Gay, 1978b, 1981; Bell-Berti & Krakow, 1991; Munhall & Löfqvist, 1992; Zsiga, 1994). It was, therefore, hypothesized that the reduced coarticulation in HI speech is related to their slow speaking rate, and that an increase in speaking rate would cause an increase in coarticulation. The language under study was American English. Two male and one female NH adults and two male and one female deaf adults with stable, bilateral, sensorineural, prelingual hearing losses of above 106 db HL PTA participated in the study. The deaf subjects were 39, 54 and 61 years old and their intelligibility scores were 46%, 23% and 16% based on Boothroyd's (1984, 1985) isophonemic word lists. The material consisted of symmetrical CVC (C = [b, d] and V = [i, a, u]) nonsense syllables embedded in a carrier phrase "a _____ again". Ten tokens of each utterance were produced at two speaking rates, normal and fast (25% rate increase). Five durational measurements were made in each utterance: the schwa, the first consonant closure, the CVC syllable, the stressed vowel and the phrase. F2 formant frequency measurements were made using broad spectrography and DFT at five locations throughout the disyllable [ə#CVC]: schwa onset, midpoint and offset, and stressed vowel onset and midpoint. The data were treated separately for each speaker and comparisons were made within-speaker. Anticipatory V-to-V coarticulatory effects were examined on the basis of comparisons among F2 means of disyllable pairs differing in stressed vowel, e.g., [ə#bib]-[ə#bub] for anticipatory influence of [u] on the schwa in a bilabial context, while for anticipatory and carryover C-to-V coarticulatory effects disyllable pairs differing in consonant were used, e.g., [ə#bib]-[ə#did] for influence of bilabial vs. alveolar context on the schwa anticipatorily and on the stressed vowel bidirectionally. NH disyllables produced at normal rate were compared with corresponding HI disyllables produced (a) at normal rate and (b) at fast rate.

Results showed that deaf speakers' vowels are somewhat centralized and their consonant production is compromised. An important finding is that deaf speakers show more or less intervocalic coarticulatory effects than NH speakers depending on context which is not in agreement with the results of previous studies reporting a consistently smaller coarticulation magnitude of speakers with HI vs. NH speakers (Monsen, 1976c; Rothman, 1976; Waldstein & Baum, 1991). Results from this study revealed that, in comparison to NH speakers, deaf speakers display more effects from the stressed vowel on the schwa across the alveolar consonant [d] and less effects across the bilabial consonant [b]. In contrast, increased V-to-V effects on the schwa in the bilabial rather than in the alveolar context were found in NH subjects.

Regarding C-to-V effects, the deaf speakers demonstrated less coarticulation than NH speakers on both the schwa and the stressed vowel. The hypothesis concerning increased HI coarticulation in faster speech was not validated in general hence differences in coarticulation between NH and deaf speakers do not seem to originate from a difference in speaking rate. However, the calculation of relative durational patterns for NH speakers at normal rate and deaf speakers at fast rate revealed that (a) the relative duration of the CVC syllable is comparable for NH and deaf speakers, (b) the relative duration of the schwa is longer for deaf speakers and (c) the relative duration of the consonant closure is longer for NH speakers. Longer closure duration may account for the decreased NH V-to-V coarticulatory effects across the alveolar, and relatively shorter stressed vowel durations may explain the increased C-to-V coarticulation for the NH speakers when compared with that of the deaf speakers.

The authors maintain that the evidence of V-to-V effects in certain contexts as early as schwa onset with concurrent reduced C-to-V effects indicates an aberrant coarticulatory pattern in HI speech which is in disagreement with coarticulation models based on NH speech (Bell-Berti & Harris, 1982) that predict stronger influences from neighbouring segments, such as the consonant, in relation to segments at a longer distance, e.g., transconsonantal vowel. The authors suggest that such patterns can only be interpreted on the basis of Öhman's (1966) theory about the V-to-V diphthongal gesture. They claim that increased coarticulation in [ə#dVd] vs. [ə#bVb] disyllables is interpreted in the light of patterns found in developing speech. In child speech, CV sequences where the production of both the vowel and the consonant involve anatomically linked articulators, i.e., tongue tip and tongue body as in /dV/, have been found more coarticulated than CV syllables where vowel and consonant are articulated by independent articulators, i.e. tongue and jaw as in /bV/ (Goodell & Studdert-Kenndy, 1993). The latter type of CV syllable has been found less overlapped in children than in adults as is the case in deaf vs. NH speech in Okalidou and Harris (1999) (section 2.2.4). Thus, larger V-to-V vs. C-to-V effects in deaf speech denote greater inter- vs. intrasyllabic cohesion leading to the assumption that deaf speech is based on gestural patterns involving more than one phoneme, in line with postulations about developing speech. Finally, the researchers maintain that coarticulation is an array of phenomena encompassing heterogeneous articulatory patterns that make various combinations in deaf speech, normal speech or developing speech. The notion that "a general process called coarticulation" may not exist has also been put forth by Repp (1986:1618) while studying the development of anticipatory coarticulation.

A subsequent study by Okalidou (2002) examined acoustic and coarticulatory variability in HI speech in relation to speaking rate. Although based on a small number of subjects, it constitutes the first empirical investigation of the aforementioned relationship. The study was based on two basic theoretical questions: (a) is acoustic variability the consequence of articulatory instability and imprecision or a strategy manifested in immature speech employed to allow articulatory flexibility? (b) is coarticulation the product of speech maturation or an inherent property of the speech mechanism? One NH male adult and two prelingually deaf adults, one male and one female, took part in the experiment. The deaf man had a PTA of 95 dB HL and his intelligibility score was 87% in a test comprising sentences. The woman had a PTA of 98 dB HL and had been judged as very intelligible by three language therapists. The material that was acoustically analyzed consisted of six American English vowels in isolation, i.e., the tense [i, a, u] and their lax counterparts [ɪ, ʌ, ʊ], repeated 10 times, and ten repetitions of twelve symmetrical CVC disyllables embedded in the phrase “a _____ again” with the aforementioned vowels and the consonants [b] and [d]. Measurements of vowel duration and of formant frequencies F1 and F2 at vowel midpoint were made.

Results showed that vowel differentiation in intelligible deaf speech was sufficient in isolated production as well as in disyllables, in line with Rubin (1985). Lax vowels were less distinguished than tense vowels and demonstrated backing, especially the lax back vowel [ʊ]. Regardless of speaking rate, high back vowels showed more acoustic variability in comparison with the rest of the vowels, in accordance with literature on HI articulatory patterns (McGarr & Harris, 1980; McGarr & Gelfer, 1983; Subtelny et al., 1989; Dagenais & Critz-Crosby, 1992). Both deaf speakers displayed more acoustic token-to-token variability in F1 and F2 values at normal speaking rate when compared with the NH speaker. An important finding was that the increase of speaking rate had a differential effect on the acoustic variability displayed by the NH and the deaf speakers. For the NH speaker an increase in speaking rate brought about an increase in variability. In contrast, acoustic variability decreased for deaf speakers with the exception of vowel [ʊ] of one speaker. Consequently, the increased acoustic variability that characterizes deaf speech at normal rate does not necessarily relate to insufficient neuromotor control but should, in some cases, be attributed to slow speed of production.

Moreover, the degree of HI coarticulation was found variable, i.e., in some cases smaller and in other cases greater than that of NH speakers, in accordance with the results of the foregoing studies by Okalidou (1996) and Okalidou and Harris (1999) which had shown increased HI coarticulation in certain contexts in comparison to normal. Deviant C-to-V coarticulatory patterns were manifested as either dissimilatory influences or lack of influence of the consonant on the vowel. In general, coarticulatory patterns of deaf speech were more similar to normal patterns when produced at a normal rather than at a fast rate. When produced at a fast rate, coarticulation in deaf speech was increased. However, this increase did not lead to more normal patterns, but to reinforcement of existing patterns, some of them deviant and some resembling the NH ones. This finding is important for intervention practices, as it indicates that attempts to increase the speaking rate of a deaf talker will result in more normal coarticulatory patterns only if patterns are not deviant at a slower rate. Finally, an increase in speaking rate caused less coarticulation variability for the NH and the male deaf speaker, whereas the female deaf speaker demonstrated more variability.

In the EPG study of spatio-temporal variability of Greek HI consonants mentioned above (sections 2.3.2.2. and 2.3.3.), Nicolaidis (2007) also examined V-to-C effects induced by vowels [i, a] in terms of amount and location of tongue-palate contact at the temporal midpoint of consonants [t, k, s, x, n, l, ɾ] in the speech of one NH speaker and four speakers with profound hearing loss and differing levels of intelligibility. The NH speaker showed smaller coarticulatory effects on [s] and [t] in comparison with those on the rest of the consonants. The coarticulatory patterns of the two most intelligible speakers with HI resembled the NH pattern the most, displaying small or no effects on consonants [s], [t] and [n]. The third speaker showed large effects on [s] and [t], while for the fourth speaker, who was also unintelligible, there was lack of effects on target /s/ and /ɾ/ and evidence of dissimilatory effects on [n]. This speaker's patterns diverged from those of the rest also in that very small effects were found on [k] and [x], while the other three speakers with HI displayed large effects on these velar consonants. This is probably related to deviant consonant production by this speaker, involving a more anterior constriction with concurrent additional lateral posterior contact.

Overall amount of tongue-palate contact for the first three HI subjects decreased in the order [s > t > n > ɾ > l] and for velars [k > x], while for the least intelligible speaker the order was [t > ɾ > s > n > l]. An interesting observation was that HI consonants displaying short segmental duration were found to be more variable. The researcher notes that larger variability due to temporal compression may denote undershoot and, if surpassing a certain limit, could result in reduced intelligibility, as was the case for one of the speakers with HI. Nevertheless, long segmental durations per se are not associated with coarticulatory patterns closer to normal ones and higher intelligibility, as the two speakers with HI displaying the longest durations showed contrasting V-to-C patterns and differing levels of intelligibility. Articulatory variability has also been found to vary according to consonant type in HI speech (Nicolaidis, 2004) (section 2.3.2.1). More sonorous consonants showed more variability than less sonorous consonants which was interpreted along the lines of gesture precision requirement for obstruents, e.g., [t], as opposed to less stability demanded in the production of consonants with relatively more open gestures, e.g., [s] or [l].

A study of coarticulation in syllables produced by four American English speakers with profound hearing loss was carried out by McCaffrey Morrison (2008). Locus equations that reflect V-to-C coarticulation were derived from CVC syllables initiated by the consonants /b/, /d/ or /g/, followed by the vowels /i, ɪ, ɛ, e, æ, a, ɔ, ʌ/ and terminated with /t/. The results showed reduced separation of consonant stop place categories in acoustic space and, in many cases, different coarticulation patterns from the speakers with normal hearing. More specifically, group data indicated that anticipatory coarticulation is reduced in consonant contexts where high levels of coarticulation was expected, e.g., /bVt/ or velar /gVt/, and increased where it should be low e.g., /dVt/ or palatal /gVt/. However, the investigation of individual production revealed the existence of nearly normal coarticulation patterns for one speaker. Limited coarticulation was attributed to a narrow F2 range or aberrant timing in the execution of CVC syllables. Increased V-to-C coarticulation in /dVt/ and palatal /gVt/ syllables was associated with the predominance of single vowels in early productive patterns of children with hearing loss. The author notes that due to the small number of subjects and large individual variation, further investigation is required to arrive at more general conclusions.

2.4. Acoustic Characteristics of the Greek Sound System

2.4.1. Greek Vowels

Greek has a five-vowel-system consisting of two high vowels, one front unrounded, [i], and one back rounded, [u], two mid vowels, one front, [e], and one back, [o], and one low central vowel, [a] (Eleftheriades, 1985; Philippaki-Warburton, 1992). Vowel [a] has been found higher than British English [ɑ] and in terms of height its precise phonetic transcription is [ɐ] (Nicolaidis, 1991), although the more generic symbol [a] will be used in this thesis for convenience. The formant values of the Greek vowels reported in different acoustic studies are somewhat variable, especially those of mid vowels [e] and [o], a fact possibly attributable to differences in materials (isolated words or sentences vs. running speech), speaking rate and style, measurements of vowels in different stress conditions and/or syllable position, the recruitment of subjects of different genders and from different parts of Greece. Arvaniti (2007) provides a comprehensive report and provides a quadrilateral with the gross position of the Greek vowels.

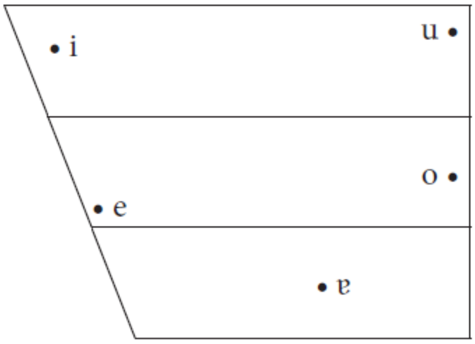


Fig. 2.1. The position of Greek vowels on the vowel quadrilateral. Adopted from Arvaniti (2007:120). Chart reproduced with permission from the International Phonetic Association. http://www.langsci.ucl.ac.uk/ipa/

Regarding the articulatory characteristics of Greek vowels [i] and [a], EPG measurements at the vocalic temporal midpoint in the stressed syllable of [ˈpVpV] symmetrical sequences have shown that “[i] is a front close vowel with major constriction in the palatal region and [a] an open vowel with increased constriction near the postalveolar/velar region” (Nicolaidis, 1997:97).

Some studies document a minimal effect of stress on Greek vowel quality (Dauer, 1980a; Arvaniti, 2000), while others find the effect of stress significant. According to the latter, lack of stress results in a smaller and more central vowel space (Fourakis, Botinis & Katsaiti, 1999; Nicolaidis, 2003; Koenig & Okalidou, 2003; Nicolaidis & Rispoli, 2005; Baltazani, 2007; Nicolaidis & Sfakianaki, 2007; Lengeris, 2011) due to a lowering of F1 which applies to either all vowels or all vowels except the high ones (Nicolaidis & Rispoli, 2005). Overlap of unstressed vowels has been observed especially among [e], [o] and [a] (Nicolaidis, 2003), although speaker-specific patterns of overlap between different neighbouring vowels emerge as well (Baltazani, 2007). Arvaniti (2007) notes that, although similar results have been documented for other languages, the effect of stress on Greek vowels is not as great as that reported for other languages, especially languages in which lack of stress results in vowel quality change, e.g., the English [ə]. Hence vowel quality is not an important correlate of stress in Greek. Moreover, Koenig and Okalidou (2003) observe that in both Greek and American English the vowel space shrinkage due to lack of stress is more extensive in the first rather than in the second syllable, although the difference in magnitude is more substantial in English.

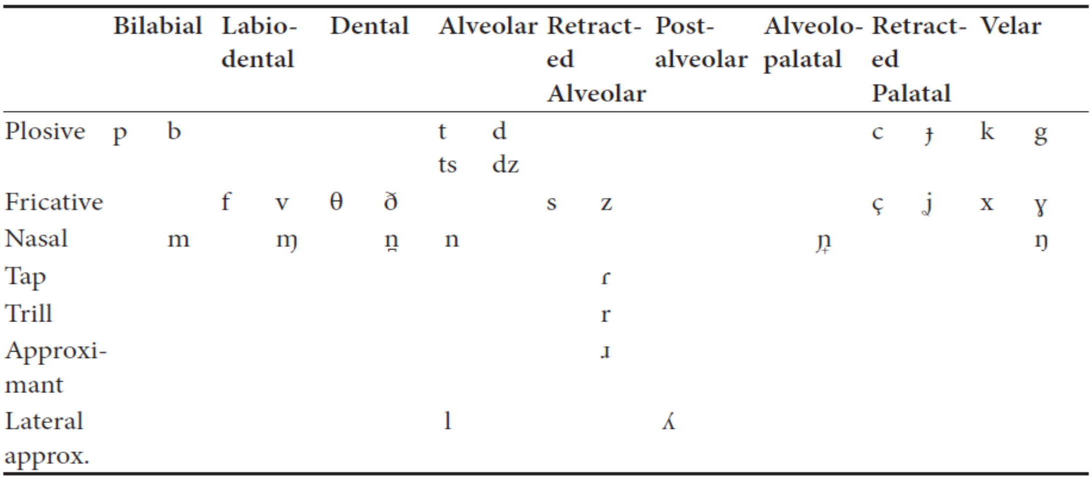
Concerning duration, [a] is consistently reported in acoustic studies as the longest vowel and [i] or [u] the shortest, in line with universal intrinsic vowel duration rules. Vowels are shorter in fast vs. slow speaking tempo (Fourakis et al., 1999), in conversational vs. read speech (Lengeris, 2011), in long vs. short words (Baltazani, 2007) and in unstressed vs. stressed condition (Dauer, 1980a, Botinis, 1989; Arvaniti, 1991, 2000; Nicolaidis, 1997; Fourakis et al., 1999; Nicolaidis & Rispoli, 2005; Nicolaidis & Sfakianaki, 2007; Baltazani, 2007; Lengeris, 2011). Moreover, stressed vowels are longer in stress clash conditions (Arvaniti, 1991, 2000) and when located word-initially (Fourakis, 1986), while unstressed vowels are longer when immediately preceding than following a stressed syllable (Dauer, 1980a; Arvaniti, 1994; Baltazani, 2007). Unstressed high vowels [i] and [u] are often whispered or completely elided when located between two voiceless consonants or after a voiceless consonant at the end of a phrase (Dauer, 1980b; Nicolaidis & Rispoli, 2005; Baltazani 2007). These phenomena are more likely to occur when the vowels are in a post-stressed syllable, while speaking style also plays a role, in that a careful style involves more whispering while a more a casual style promotes elision (Dauer, 1980b). Prosodic position was also found to significantly affect the voicing and duration of high rounded vowel [u] (Tserdanelis, 2003). Regarding coarticulatory effects on Greek vowels (sections 2.2.1.3. and 2.2.1.4).

Consistent with the *dispersion theory* (Liljencrants & Lindblom, 1972; Lindblom, 1986), Greek vowels have been found more central than vowels of languages with larger vowel inventories (Jongman, Fourakis & Sereno, 1989; Bradlow, 1995; Okalidou & Koenig, 1999). However, the five Greek vowels are well separated in the acoustic/auditory space (Kontosopoulos, Ksiromeritis & Tsitsa, 1988; Jongman et al., 1989). Jongman et al. (1989:230) note that Greek [i] and [e] show a lot less variation than expected on the basis of Lindblom's (1986) postulations. Additionally, a comparison between the perceptual vowel space of Greek and that of American English revealed a maximally contrastive organization of the Greek vowels vs. sufficient perceptual differentiation of the more numerous American English vowels (Hawks & Fourakis, 1995). The authors observed that Greek listeners were stricter in recognizing stimuli as belonging to their native language when compared with American listeners. Similarly, Botinis, Fourakis and Hawks (1997) observed that speakers identified as Greek about 36% of the stimuli presented to them and report little or no overlap between perceptual vowel categories. Therefore, the standard versions of Greek vowels seem to be quite limited in dispersion range in Greek listener's minds. The overall tight organization of the Greek auditory space reflected in the high rate of stimuli rejection reported in the foregoing studies may indicate that inventory size is not the foremost factor influencing vowel production and perception.

2.4.2. Greek Consonants

Although consensus has not yet been reached and many aspects of the consonant system of Greek are still under study, a "matrix of phonetic consonantal segments" is provided by Arvaniti (2007:117-118) (see Fig. 2.2.). We provide here a brief description of the three consonants under focus in the present study, [p], [t] and [s].

Consonants [p] and [t] are two of the three voiceless stops of Greek, the third being [k] (Mackridge, 1985; Joseph & Philippaki-Warburton, 1987). Compared with voiced stops, voiceless stops have a shorter occlusion and short-lag VOT (Botinis, Fourakis & Prinou, 2000) and although typically described as voiceless, they have



	Bilabial	Labio-dental	Dental	Alveolar	Retract-ed Alveolar	Post-alveolar	Alveolo-palatal	Retract-ed Palatal	Velar
Plosive	p b			t d ts dz				c ɟ	k g
Fricative		f v	θ ð		s z			ç ʝ	x ɣ
Nasal	m	ɱ	n̪	n			ɲ̟		ŋ
Tap					ɾ				
Trill					r				
Approxi-mant					ɹ				
Lateral approx.				l		ʎ			

Fig. 2.2. The phonetic inventory of Greek consonants (adopted from Arvaniti, 2007:117). Chart reproduced with permission from the International Phonetic Association. http://www.langsci.ucl.ac.uk/ipa/

been found partially or fully voiced in running speech when located in intervocalic position or between a vowel and a voiced consonant (Nicolaidis, 2001, 2002). As far as duration is concerned, [p] and [t] do not demonstrate large differences in occlusion duration, VOT and total duration, although most studies report slightly longer closure duration for [p] vs. [t] and longer VOT for [t] vs. [p] (Arvaniti, 2007:104). Vocalic context has been documented to influence the duration of these consonants. When preceding high vowel [i] vs. low vowel [a], closure duration of [t] and VOT of both [t] and [p] have been found longer (Nicolaidis, 2002). Regarding place of articulation, [p] is a bilabial plosive, while [t] has been traditionally classified as dental or apico-dental (Eleftheriades, 1985; Joseph & Philippaki-Warburton, 1987). EPG studies conducted by Nicolaidis (1994, 1997) show advanced lingual placement with evidence of alveolar contact and a possible constriction further forward in the dental region during the production of [t], suggesting that it would be more precisely described as ‘dentoalveolar’. Its place of constriction is influenced by vocalic context especially when positioned in post-stress syllables. Tongue placement is more posterior in [ata] vs. [iti] sequences, while more lateral contact and thus tongue raising is observed in the latter, although speaker-specific differences in tongue-palate contact are observed (Nicolaidis, 1997:94-95). In running speech, its degree of constriction may vary from complete closure to incomplete closure with either a constricted grooved configuration or a very open articulation at the alveolar region (Nicolaidis, 2001:70).

According to Eleftheriades (1985), consonants [t] and [s] have the same place of articulation, namely apicodental, along with [d], [z], [ts] and [dz] (also Joseph & Philippaki-Warburton, 1987). For Mackridge (1985), however, [s] and [z] are alveolar fricatives, while [t] and [d] are dental stops. A reason he postulates for the retracted location of [s] and [z] is that there are no contrastive postalveolar fricatives in Greek, such as the English [ʃ] and [ʒ], thus larger variability in place of articulation is allowed for the Greek [s] and [z]. EPG measurements carried out by Nicolaidis (1994, 1997) show that the Greek fricative [s] "…is articulated in an area within the alveolar and postalveolar region. On the basis of this data, therefore, the place of articulation of the coronal fricative could be described as 'retracted alveolar' " (Nicolaidis, 1997:93). Additionally, its exact place of articulation and overall lingual contact varies with vocalic context and/or speaker, i.e., its constriction can be fronter in an [i_i] context, while in an [a_a] context it may withdraw to advanced postalveolar or postalveolar depending on speaker. A comparison in groove width between the English and the Greek [s] revealed that the groove width of the Greek [s] could have a value corresponding to either that of English [s] or [ʃ] while its variation is greater than that of the English fricatives (Nicolaidis, 1997).

Considerable variability in place of maximum constriction, groove width and degree of lateral contact in the palatal area were also found in realizations of [s] in spontaneous speech (Nicolaidis, 2001). Moreover, full or partial voicing was observed in some tokens, e.g., occurring intervocalically. Concerning duration, the Greek [s] is slightly longer than the Greek [t] (Nicolaidis, 1997, 2001), but shorter than the English [s] (Panagopoulos, 1991 as cited in Arvaniti, 2007). Nicolaidis (2001) notes that [s] displays nonsignificant duration dependent variability in tongue-palate contact in comparison with [t] in spontaneous speech. The relative invariance of the [s] lingual gesture in relation to consonant duration may be associated with the articulatory and aerodynamic requirements for the production of the fricative which may necessitate temporal incompressibility as opposed to the less demanding articulation of [t]. Regarding Greek consonant variability, see section 2.2.1.2.

2.5. Research Aims, Questions and Hypotheses

The current study constitutes one of the very few investigations of coarticulation in normal Greek speech and the first acoustic investigation of coarticulation phenomena in the speech of Greek talkers with hearing impairment (HI). Variability in Greek HI consonant production has been examined using EPG (Nicolaidis, 2004, 2007) and a preliminary acoustic description of HI vowels has been given (Nicolaidis & Sfakianaki, 2007), but, to the best of our knowledge, no acoustic study of coarticulatory effects in Greek HI speech has been carried out to this date. Therefore, the acoustic study of coarticulation in the speech of Greek talkers with HI constitutes the basic aim of the current study. In addition, a parallel examination is also conducted in normal-hearing (NH) Greek speech so as to obtain a baseline for comparison, but also to complement existing knowledge about the variability and coarticulation patterns of normal Greek vowels acquired through the method of electropalatography (Nicolaidis, 1991, 1994, 1997, 1999, 2001, 2002, 2003) and previous acoustic findings on coarticulation in normal Greek speech (Okalidou & Koenig, 1999; Koenig & Okalidou, 2003; Asteriadou, 2008).

2.5.1. Research Aims

In particular, the main aims of the study are the following:

1. To provide an acoustic description of the point vowels [i, a, u] in symmetrical bilabial disyllables of the form [VpV] in terms of vowel space and variability (vowel distribution) based on F1 and F2 formant frequencies (Hz) in relation to the following factors
    a. Hearing level (speakers with HI vs. speakers with NH)
    b. Gender (male vs. female speakers within the two hearing groups)
    c. Intelligibility level of speakers with HI (very high, high, medium)

    d. Stress (stressed vs. unstressed syllable)
    e. Syllable position (first/initial vs. second/final)

2. To report the duration (ms) of the point vowels [i, a, u] according to the factors
    a. Hearing
    b. Gender
    c. Intelligibility level
    d. Stress
    e. Syllable position
    f. Consonantal context [p, t, s]
    g. Vocalic context [i, a, u]
3. To examine C-to-V coarticulatory effects on F1 and F2 formant frequencies at the midpoint of the three point vowels [i, a, u] from the alveolar consonants [t] and [s] in disyllables of the form [VtV] and [VsV], taking the bilabial context [VpV] as a base for comparison, in relation to the following factors
    a. Hearing
    b. Stress
    c. Coarticulatory direction (anticipatory vs. carryover)
4. To examine V-to-V coarticulatory effects on F1 and F2 formant frequencies of the three point vowels [i, a, u] in relation to the following factors
    a. Hearing
    b. Gender
    c. Intelligibility level
    d. Transconsonantal vowel [i, a, u]
    e. Consonantal context [p, t, s]

    f. Coarticulatory direction
    g. Stress
    h. Temporal extent (vowel onset, midpoint, offset)

5. To relate results regarding NH and especially HI speech to findings reported in studies on other languages.
6. To explain results within current theories of coarticulation and in particular the gestural framework of speech production (Browman & Goldstein, 1986), and to test the predictions of the DAC model of coarticulation (Recasens et al., 1997) with reference to Greek NH and HI speech.

2.5.2. Research Questions and Hypotheses/Expectations

Based on the literature reviewed earlier and the main aims stated above, the following research questions and hypotheses are formulated.

Aim 1: Examination of point vowel acoustic characteristics, vowel space and acoustic variability in HI vs. NH speech

Questions

1. What are the acoustic characteristics (F1 and F2) of the three point vowels [i, a, u] in HI vs. NH speech?
2. What are the main differences in vowel area and acoustic variability of the point vowels between the HI and the NH group before and after normalization?
3. Are there gender differences regarding the aforementioned acoustic characteristics in the two hearing groups?
4. Does gender influence the acoustic characteristics differently in the two hearing groups?

5. Does speech intelligibility level influence the acoustic characteristics of vowels of the individuals with HI?
6. Does stress have an effect on the acoustic characteristics of vowels of the two hearing groups?
7. Is the effect of stress similar in the two hearing groups?
8. How does stress interact with syllable position in the two hearing groups?

Hypotheses and Expectations

Questions 1-4

Based on the literature on HI speech (section 2.3.) and the postulations of the DIVA model regarding the correlation existing between vowel contrast discrimination and production (section 2.1.1.), we expect that vowel space will be reduced and vowel contrastiveness limited for speakers with HI, while their vowel variability is expected to be higher than that of NH vowels. Female vowel spaces are expected to be larger than male ones in both NH and HI speech due to gender anatomical differences, but perhaps the difference will not be as pronounced for HI genders. We will also look into these gender differences in both NH and HI speech after normalization.

Question 5

In order to examine whether speech intelligibility level influences the acoustic characteristics of vowels for the speakers with HI, an intelligibility experiment will be conducted (section 3.4.) and intelligibility groups will be created. More intelligible speakers are expected to display better vowel differentiation than less intelligible speakers.

Questions 6-8

Regarding stress, different studies have found variable effects of stress on NH Greek vowels regarding its relative influence on the F1 and F2 axis (section 2.4.1.), hence it is of interest to investigate the effects of stress on NH vowels as well as HI vowels. Preliminary results on Greek HI vs. NH vowels have shown a similar stress effect on F1 and a more pronounced effect in F2 for the NH (section 2.3.2.1). Additionally, the effect of stress in association with the position of the vowel in the syllable will be examined in both NH and HI speech. In NH speech, the first syllable has been reported as more stable, especially when stressed, than the final syllable where reduction is more extensive. Thus, differential influence of stress is expected in the two syllable positions for the NH vowels. Conversely, HI vowels are usually longer than normal which might lead to less final vowel reduction. Hence stress and syllable position may interact differently for the HI vowels.

Aim 2: Examination of the duration of the point vowels in HI vs. NH speech

Questions

1. What is the duration of the point vowels in the two hearing groups?
2. Are there any gender differences concerning vowel duration in the two hearing groups?
3. Does speech intelligibility level influence point vowel duration in HI speech?
4. Does stress cause a similar effect on point vowel duration in both hearing groups?
5. Are there any gender differences regarding stress effects on vowel duration in the two hearing groups?
6. Does stress influence the duration of the point vowels differently in the two syllable positions for the HI and the NH group?

7. What is the effect of consonant type (bilabial stop, alveolar stop, alveolar fricative) on the duration of the preceding and the following vowel in symmetrical [pVCV] disyllables produced by the two hearing groups?
8. What is the effect of the transconsonantal vowel [i, a, u] on point vowel duration in [pV_1pV_2] disyllables produced by the two hearing groups?

Hypotheses and Expectations

Although patterns of intrinsic vowel duration should be observed for both the NH and the HI, vowels in HI speech are overall expected to be longer compared with NH vowels (section 2.3.2.2). Longer durations may also be expected for female than male speakers in both groups and more pronounced stress effects on female vowels, as reported in the literature (section 2.2.3). We do not have strong predictions about vowel duration vs. intelligibility level, as research in Greek and other languages has shown that they do not have a straightforward relationship (section 2.3.3). Regarding stress and syllable position, we expect to find reported trends in NH speech, such as durational shortening in the absence of stress and stressed-vowel-lengthening in final position. Moreover, based on previous studies, contextual effects due to consonant type are expected to influence NH vowel duration, although vowel quality is also of importance. In addition, low vowel lengthening is expected in the context of high vowels. The range of such context and stress effects is claimed to be limited in HI speech (section 2.3.2.2.). Thus, less pronounced patterns of durational effects are hypothesized for the HI group.

Aim 3: Investigation of C-to-V coarticulatory patterns in HI vs. NH speech

Questions

1. Is the overall C-to-V coarticulatory pattern different for the two hearing groups, as illustrated through the effects of the two alveolars, [t] and [s], on the three point vowels [i, a, u] in height (F1) and fronting/backing (F2)?
2. Which one of the two alveolars, [t] or [s], displays more coarticulatory aggression in HI and NH speech?
3. Which point vowel is more resistant to consonantal coarticulatory effects in HI and NH speech?
4. Does C-to-V coarticulation favour the same direction (anticipatory vs. carryover) in HI and NH speech?
5. Does stress influence C-to-V coarticulation similarly for the two hearing groups?

Hypotheses and Expectations

Questions 1-3

Regarding C-to-V effects, predictions are different for the two formant dimensions. In F1, consistent with Keating et al. (1994), where it was shown that C-to-V effects in jaw height were not significant, we do not expect substantial effects on vowel height (section 2.2.1.5). In F2, the DAC model provides different scenarios depending on the constraint of the consonant and the vowel as well as the antagonism/synergy between the two kinds of gestures (section 2.2.1.3). More specifically, the bilabial [p] is expected to cause minimal C-to-V effects regardless of vowel identity and is therefore taken as a baseline for comparison. The two alveolar consonants are expected to cause relatively small C-to-V effects on [i], as it is a constrained vowel and does not involve an antagonistic gesture in relation to the alveolars. On the other hand, large C-to-V effects are predicted for the alveolars on [a] and [u], as they are less constrained and antagonistic gestures are required for their production relative to those of the alveolars. If the Greek fricative [s] is more constrained than the stop [t], then it is expected to induce larger C-to-V effects than [t].

In relation to HI speech, the range of F1 has been examined and found limited, although not to the same degree as that of F2 (section 2.3.2.). However, to the best of our knowledge, coarticulation in terms of C-to-V effects in the F1 dimension has not been investigated acoustically. Coarticulation is usually measured on the basis of centroid frequencies, F2 peak values and locus equations. Therefore, the investigation of C-to-V effects in F1 may offer an important perspective and add to the existing knowledge about HI coarticulation. C-to-V effects for the HI group are generally expected to follow NH trends in both F1 and F2, although deviations from the NH pattern are likely to occur. Smaller C-to-V effects are commonly reported for HI in comparison with NH speech. (section 2.3.4). Since jaw opening is documented as less problematic than tongue positioning in HI speech, coarticulation patterns closer to normal could be expected in F1 than F2.

Question 4

Concerning C-to-V coarticulatory directionality, according to the DAC model, the more constrained the consonant the more specific the preference for a certain direction. No clear coarticulatory direction pattern has been established for the alveolars [s] and [n] in the fixed [i] context, while in the fixed [a] context the fricative has shown strong gestural anticipation in previous research on Catalan. Thus, no specific directionality preference is expected to manifest in the NH data. C-to-V anticipation is assumed to prevail when highly constrained consonants are produced especially in cases of gestural antagonism between consonant and vowel, e.g., [s] and

[a] or [u]. If HI alveolars are more constrained than normal, then a preference to the anticipatory component is expected in the non-front fixed vowel contexts.

Question 5

C-to-V effects are expected to be more prominent on unstressed vowels, in line with previous findings (section 2.2.2), although the lack of stress may influence consonant-dependent coarticulation more in the F2 axis, as C-to-V effects are expected to be substantial along this dimension in NH speech. However, if stress influences HI vowels more along the F1 dimension, then stress effects on C-to-V coarticulation may be more pronounced in F1 for the HI than the NH group, while stress effects in F2 may be more salient in C-to-V coarticulation for the NH group as compared with the HI group.

Aim 4: Investigation of V-to-V coarticulatory patterns in HI vs. NH speech

Questions

1. Is the overall V-to-V coarticulatory pattern different for the two hearing groups, as illustrated through the effects of the transconsonantal vowel across the three consonants [p], [t] and [s] on the fixed vowel in height (F1) and fronting/backing (F2)?
2. Which consonantal context, the bilabial plosive [p], the alveolar plosive [t] or the alveolar fricative [s], allows for more V-to-V effects in HI vs. NH speech?
3. Which point vowel is more coarticulation resistant and coarticulation aggressive in height (F1) and fronting/backing (F2)?
4. What is the temporal extent of anticipatory and carryover V-to-V coarticulation in the consonantal and vocalic contexts under study in HI vs. NH speech?

5. Which coarticulatory direction is favoured by V-to-V effects in HI vs. NH speech?
6. Does stress influence anticipatory and carryover V-to-V effects in the vocalic and consonantal contexts under study similarly in NH vs. HI speech?
7. Are there significant differences in anticipatory and carryover V-to-V effects in the selected vocalic and consonantal contexts between the two genders in NH vs. HI speech?
8. Does intelligibility level of HI speech play an important part in the manifestation of anticipatory and carryover V-to-V effects in the vocalic and consonantal contexts under study?

Hypotheses and Expectations

Based on the articulatory phonology framework (Browman & Goldstein, 1986, 1993) and the DAC model of coarticulation (Recasens et al., 1997) we have expectations/predictions concerning the magnitude, temporal extent and preferred direction of coarticulatory effects in NH speech depending on context. However, we also take under consideration Manuel and Krakow's (1984) hypothesis about the role of contrast in coarticulation and attempt to modify our expectations according to the Greek sound system.

Questions 1-3

According to the DAC model, highly constrained segments, such as high front vowels or fricatives, are expected to be resistant to coarticulation and at the same time coarticulation aggressive. Thus, [i] is expected to resist V-to-V effects more than the other two vowels. Nevertheless, we also bear in mind that Greek [i] may display differential coarticulatory behaviour in comparison with its counterpart in other languages due to differences in the number and distribution of vowels. Similarly, the bilabial [p] is expected to allow more V-to-V effects than the two alveolars [t] and [s] due to the fact that the tongue is unconstrained during its production. However, variable patterns depending on flanking vowel and coarticulatory direction may be expected as shown in previous acoustic studies on Greek (section 2.2.1.4).

Of particular interest in this study is the relative coarticulatory resistance/aggression displayed by vowels [a] vs. [u] and consonants [t] vs. [s]. Differential results are reported in the literature regarding which segment in each pair shows more coarticulatory aggression/resistance (section 2.2.1.1). As far as Greek is concerned, our knowledge about acoustic V-to-V effects on [u] in NH speech is fairly limited. Most studies concentrate on [i] vs. [a] effects due to their contrast in both F1 and F2 dimensions. The high back rounded [u] is a vowel difficult to measure acoustically due to its low intensity and close location of the first two formants. It is frequently omitted in final position or hard to establish spectrographically. However, as noted in the literature, more data on this vowel is needed in order to clarify its coarticulatory resistance/aggression in relation to [a]. Regarding the two alveolar consonants [t] and [s], although the DAC model predicts that the fricative will display greater coarticulatory resistance/aggression, contradictory reports have been provided for Greek in EPG studies (section 2.2.1.2.). To the best of our knowledge, acoustic data on V-to-V coarticulation across the Greek [p] and [t] come from two studies (Okalidou & Koenig, 1999; Asteriadou, 2008), while there is no acoustic data in the Greek [s] context. Thus, the investigation of the coarticulatory behaviour of the aforementioned segments in NH speech, i.e., the vowel [u] and the fricative [s], constitutes an original contribution of the present study.

Coarticulation in HI speech is expected to show similarities as well as differences compared with NH coarticulation. Predictions concerning coarticulation in

Greek HI speech, as produced by the speakers with HI of our study, are based on the aforementioned models and theories about NH speech but also on findings and postulations from studies on HI speech in other languages, mainly English (section 2.3.4.), as well as articulatory data on Greek HI speech obtained with EPG (section 2.3.2.1). As expounded earlier in this chapter, differences in the articulation of consonants and vowels have been documented between HI and NH speech in different languages. Some studies report reduced coarticulation in HI speech primarily owing to a limited F2 range. Subsequent studies, however, report either reduced or increased coarticulatory effects compared with that of NH speakers; the consonantal and vocalic context as well as individual strategies seem to play a significant role and contribute to the variable results.

Coarticulation has been studied mainly within the syllable, either in the form of C-to-V or V-to-C effects. V-to-V coarticulation has not been examined to the same extent, although it is equally important in gaining a better understanding of the gestural organization of HI vs. NH speech in longer utterances. The present study examines bidirectional C-to-V and V-to-V coarticulation in CVCV disyllables, placing the main research focus on the latter. Based on the literature, we do not expect to find reduced effects uniformly across consonantal contexts in HI speech. Unlike the NH coarticulatory pattern, more anticipatory V-to-V effects have been located in the alveolar /d/ than the bilabial /b/ context (Okalidou & Harris, 1999) and more V-to-C effects have been observed in the alveolar /d/ and the palatal /g/ than the bilabial /b/ context in HI speech (McCaffrey Morrison, 2008). However, these results are based on a small number of subjects in one language, namely American English. Hence the present study attempts to broaden the current knowledge-base by examining the phenomenon in the speech of more participants as well as in a different language.

Question 4

Concerning the temporal extent of coarticulatory effects, the DAC model predicts a longer span of V-to-V coarticulatory effects across less constrained consonants. Highly constrained consonants induce longer C-to-V effects and allow shorter V-to-V effects. However, direction of effects is also of relevance since anticipatory effects have been documented as less affected by context, i.e., they are more temporally fixed, than carryover effects (section 2.2.1.4). According to the frame or time-locked model proposed by Bell-Berti and Harris (1981), the composition of the disyllables should not influence the onset of anticipatory effects. One of the goals of the present study is to investigate the bidirectional temporal span of V-to-V coarticulatory effects in the three consonantal contexts, [p], [t] and [s]. In HI coarticulation, a more restricted temporal extent in the anticipatory direction of V-to-C has been reported by some researchers (Waldstein & Baum, 1991; McCaffrey Morisson, 2008), while others document an early appearance of anticipatory V-to-V effects (Okalidou, 1996; Okalidou & Harris, 1999). By measuring effects at the onset, midpoint and offset of the vowel, we attempt to define the temporal span of the anticipatory and the carryover V-to-V effects in Greek NH and HI speech. If the temporal span is influenced by context in NH speech, then support will be lent to the DAC model. Additionally, we will investigate whether HI coarticulation is more limited temporally in comparison with NH coarticulation.

Question 5

Concerning coarticulatory directionality, the carryover component has been found more prominent in NH speech in the majority of languages examined. The predictions of the DAC model concerning V-to-V coarticulatory direction are associated with consonantal degree of constraint and prominence of C-to-V effects (section 2.2.1.4).

However, V-to-V direction trends across less constrained consonants, such as dentals and labials, are not clear; in such cases, vocalic context is an important factor. In the bilabial context, the carryover direction has been found more salient in vocalic effects induced by [i] and the anticipatory direction by [a] (Recasens et al., 1997:560). No consistent directionality pattern has been reported across the fricative [s]. Therefore, we will attempt to further elucidate preferences in coarticulation directionality in the various contexts. Regarding HI speech, directionality trends in V-to-V HI coarticulation have not been previously investigated using the point vowels in both directions. Hence, the examination of this question constitutes an original contribution of the current thesis. Based on previous studies, it can be hypothesized that speakers with HI will show reduced anticipatory coarticulation in the bilabial context and increased anticipation in the alveolar contexts.

Question 6

Regarding stress, greater effects are predicted by the theory of coproduction from the stressed on the unstressed vowel. However, the effect of stress on Greek vowels may not be as substantial as that documented in stress-timed languages, e.g., English (section 2.4.1). According to the literature, the differences between stressed vs. unstressed vowels are even less emphasized in HI speech (see 2.3.2.2.); hence, stress may play a different and probably less significant role in HI coarticulation.

Question 7

Although several studies have provided evidence of greater female vowel dispersion due to anatomical and/or sociophonetic factors and higher intelligibility of female vs. male speech (section 2.2.3.), the role of gender in the degree of coarticulation has not been systematically investigated. Greater coarticulation could be hypothesized for female speakers, if degree of coarticulation depends on total vowel space area or higher acoustic variability expected of female vowels. However, speaker-specific strategies also come into play. We attempt to explore if gender affects V-to-V coarticulation in the NH and the HI group of our study, but results are interpreted with caution. Regarding HI speech, high speaker-specific variability could interfere with gender influence, thus a differential coarticulatory pattern according to gender may emerge relative to the NH group.

Question 8

Intelligibility level has been found to correlate with various segmental and suprasegmental characteristics of HI speech (section 2.3.3). Highly intelligible speakers with HI make less segmental errors and their F1 and F2 ranges are closer to the normal ones. It can be hypothesized that the HI subgroup displaying coarticulation patterns more similar to the NH ones will also be composed of highly intelligible speakers, although close to normal coarticulation patterns have not been reported to translate to fully intelligible speech (McCaffrey Morrison, 2008). The investigation of the relationship between HI speech intelligibility and coarticulation constitutes an original contribution of this study as, to our knowledge, it has not been examined before in Greek or any other language.

Chapter 3

Methodology

3.1. Introduction to the experimental design

The Main Study is divided into two parts, Part 1 and Part 2. Part 1 attempts to give an acoustic description via vowel space calculation and distribution in the F1 by F2 plane of the three vowels [i, a, u] produced by the hearing impaired as opposed to the normal hearing speakers, as well as factors that influence their production for each group, such as gender, intelligibility, stress, syllable position and consonantal context (C-to-V effects). Therefore, Part 1 concentrates on acoustic characteristics which are related to Formant 1 & Formant 2 at the midpoint of each vowel, and vowel Duration.

Part 2 concentrates on the main question of our study which regards vowel-to-vowel coarticulation in the speech of the hearing impaired vs. the normal hearing, and factors that influence this phenomenon. In order to study V-to-V coarticulation, that is, the influence of one vowel on the transconsonantal vowel, we chose three vowels ([i, a, u]) and three consonantal contexts ([p, t, s]) in which to study vowel-to-vowel effects. Stress was an additional parameter.

In addition to the Acoustic Experiment, an Intelligibility Experiment was also conducted so as to include the intelligibility factor in our design and study its effect on the coarticulation of the hearing impaired (section 3.4). As already mentioned, concerning the English language, there has been a lot of research on the correlation between hearing level and speech intelligibility, as well as between intelligibility and speech production, but, to our knowledge, the relationship between intelligibility and coarticulation has not been investigated. The sections below give a detailed account of the techniques and materials used, as well as the characteristics of the speakers and listeners that participated in the two experiments.

Furthermore, the final selection of the HI speakers was made on the basis of a pilot analysis of the data. A concise report of the setup and results of the Pilot Study is thus provided below (section 3.3.).

3.2. The Acoustic Experiment

3.2.1. The subjects

3.2.1.1. The hearing impaired (HI) group

Originally, eighteen (18) adults with varying degrees of hearing impairment were contacted through the Association of Parents and Guardians of Hard of Hearing Children of Thessaloniki[14]. The Association supports oral communication and inclusive education for children with hearing impairment, hence we were able to ensure that all subjects came from a similar educational background.

An appointment for an interview was scheduled with each subject so as to make certain that he/she meets specific criteria for the study. The criteria were the following:

1. Age range: 20-35 years old.
2. Language variety: Standard Greek; place of origin: Northern Greece.
3. Hearing impairment characteristics: bilateral, stable; onset before 2.5 years of age (Staller, Belter, Brimacombe, Mecklenburg & Arndt, 1991).
4. No additional illnesses diagnosed.
5. Oral communication used exclusively or in addition to sign language.
6. No cochlear implants received.

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[14] This Association is now called Association of Parents & Guardians of Deaf & Hard of Hearing Children of Central Macedonia (Σύλλογος Γονέων & Κηδεμόνων Κωφών & Βαρήκοων Παιδιών Κεντρικής Μακεδονίας, http://www.varikoos.gr/75892D3E.el.aspx)

The interview also contained questions about their school and university education, their profession, hearing impairment etiology, and age of diagnosis, use of hearing aids, onset, duration and frequency of speech training, use of oral speech and/or sign language and level of comfort using oral speech (see Appendix 1.1. and 1.2.). A recent audiogram was also requested. After careful screening, fourteen (14) subjects with HI were recorded.

Based on the audiograms, hearing level for each subject was calculated for the better ear by averaging over the 500, 1000 and 2000 Hz frequencies (Boothroyd, 1988). A hearing loss is characterized as severe when the hearing loss range is 71 to 90 dB and profound when it is above 91 dB (Clark, 1981). Hearing levels ranged from +76 dB to +105 dB, hence subjects were categorized into 3 groups:

Group A:	6 subjects with a hearing loss of more than 100 dB
Group B:	4 subjects with a hearing loss of 91 to 99 dB
Group C:	4 subjects with a hearing loss of 76 to 90 dB.

In an effort to create one hearing impaired group based on hearing level as homogeneous as possible, we conducted a pilot study (see Section 3.3.), and following analysis of the data, Group C (severely hearing impaired) was excluded, as statistically significant differences were found between this group and the other two, while its coarticulatory patterns resembled that of the control group (normal hearing). In addition, subjects in Group A & B (profoundly hearing impaired) were merged into one group, as their coarticulatory behaviour was similar and statistically different from that of the control group. Hence, this group of 10 subjects, 5 male and 5 female, with a hearing loss of more than 91 dB became the HI group of our study.

Besides averaging over the three aforementioned frequencies, we also studied the pattern of the subjects' audiograms, as a visual inspection of an audiogram is necessary in addition to the average hearing loss level, to examine the hearing loss pattern across frequencies. Thus, Fig. 3.1. presents audiogram information about the 10 HI subjects, concentrating on responses at frequencies 500, 1000 & 2000 Hz. We observe that subjects HI_01 through 08 (with the exception of HI_04) display a similar line of hearing loss which starts higher at the low frequencies and gradually declines at higher frequencies. Subject HI_09 diverges slightly from the group, showing a fairly better response at 1000 Hz, and both subjects HI_09 and 10 show a relatively better response at 2000 Hz than the rest of the group. Thus subjects HI_09 and 10 were specifically chosen for the pilot study and results showed that they could be included in the HI group of the main study.

Besides subjects HI_09 and 10, the hearing loss pattern of subject HI_04 also diverges from that of the majority. Her differences are even more pronounced as she exhibits the lowest response in dB at 1000 Hz and no response at all at 2000 Hz. Therefore, the hearing loss of subject HI_04 differs significantly from that of the other 9 subjects. Further results from the Intelligibility Experiment (Section 3.4.) as well as from the analysis of her acoustic data, led us to the exclusion of subject HI_04 from our statistical analysis. Besides displaying the most profound hearing loss (+105 dB), she differed in many other ways from the rest of the subjects. She had stopped using her hearing aids the last two years. Her intelligibility was rated below 20%, while the other nine subjects scored above 80%. Her preferred way of communication was sign language and she did not feel comfortable using oral communication, as opposed to the rest of the group. Her schooling background was also different; she had attended the School for the Deaf for almost all her primary school years (see Fig. 3.1.). The analysis of her data showed that almost all segmental aspects of her speech (F1, F2, duration) diverged from those of the rest of the group. Hence she was excluded from the study, so as not to compromise the homogeneity of the HI group.

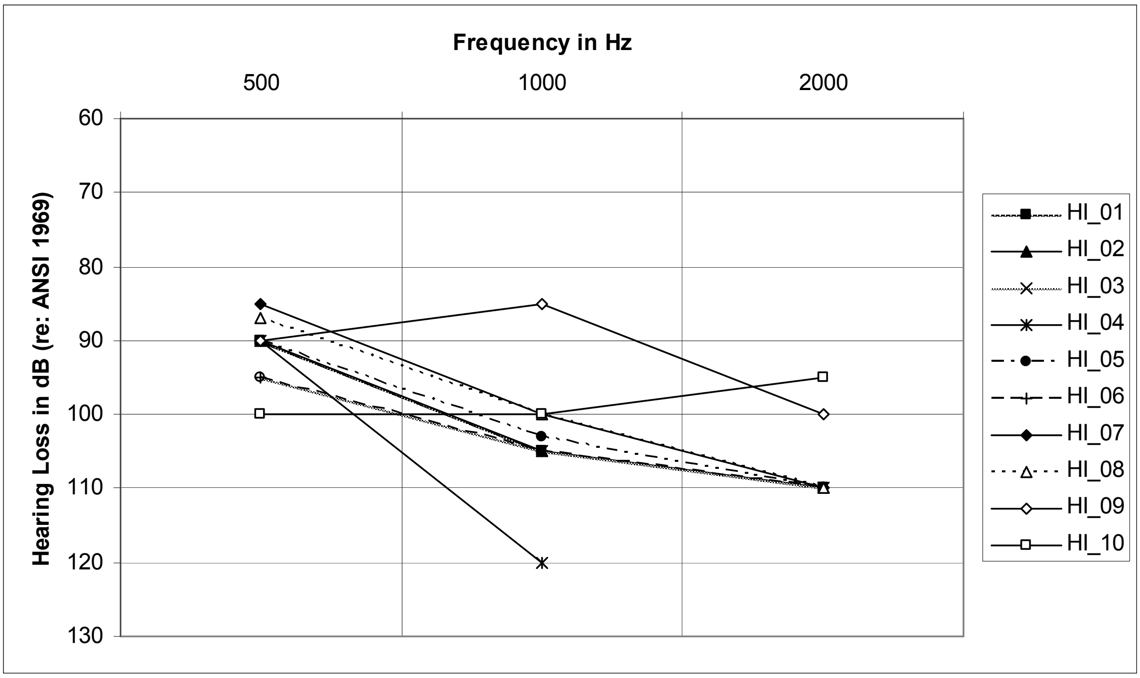

Fig. 3.1. Audiograms (500, 100, 2000 Pure Tone Average) of all 10 HI subjects. Subjects 01-08 present a uniform picture, except for subject HI_04 who displays the most profound hearing loss. Subjects 09 and 10 have a slightly better response at 1000 & 2000 Hz.

Consequently, in this study we report data from 9 HI subjects, 5 male and 4 female, with a hearing loss of 91 to 104 dB. Main information concerning the audiological history, speech training and schooling background, way of preferred communication, third level education and profession of the HI subjects is given in Table 3.1.

In summary, concerning audiological information, subject HI_09 had a hearing level (HL) of 91 dB, while all other subjects had a HL above 95 dB with an average of 96 dB. They were all young adults (below 35 years old). Hearing impairment was diagnosed before 2;5 years of age and is bilateral, but etiology varies; there are 4 cases associated with medication, 1 case of hereditary cause, 2 cases of

Subject	Sex	HL (Better Ear)	Age	Age of diagnosis[15]	Etiology	Age first aided[16]	Speech Training[17]		Knowledge of Sign Language	Way of communication	Type of schooling	University/ college degree	Profession
							Onset[18]	Duration					
HI_01	F	101.7 (L)	23	1;8	medication	3	5	12 yrs (2 times/wk)	very good	oral	mainstream	political science	unemployed
HI_02	F	101.6 (L)	20	2;5	medication or genetic	3	4	2 yrs (2 times/wk)	very good	oral	mainstream	preschool education	university student
HI_03	M	103.3 (R)	21	1;0	genetic (familial)	1	1	10 yrs (4 times/wk)	basic	oral	mainstream	physiotherapy	technological education institute student
HI_04	F	105[19] (L)	25	0;9	meningitis	3	8	7 yrs (2 times/wk)	very good	sign	deaf (1st-5th grade)	logistics	technological education institute student
HI_05	M	101 (L)	25	2;0	medication	4	8	4 yrs (5 times/wk)	basic	oral	a)deaf: 1st grade b)mainstream	physiotherapy	private college student

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[15] In years;months.

[16] In years.

[17] As well as attending formal therapy, many subjects trained at home with the help of their parents.

[18] In years.

[19] For subject HI_04 there was no response at 2kHz.

Subject	Sex	HL (Better Ear)	Age	Age of diagnosis	Etiology	Age first aided	Speech Training		Knowledge of Sign Language	Way of communication	Type of primary school	University/ College education	Profession
							Onset	Duration					
HI_06	F	103.3 (L)	26	2;6	medication (RTA[20])	3	6	10 yrs (3 times/wk)	basic	oral	mainstream	psychology	university student
HI_07	M	98.3 (L)	24	2;0	complications at birth	2	4	20 yrs (3 times/wk)	none	oral	mainstream	architecture	university student
HI_08	M	99 (L)	21	0;9	complications at birth	4	6	3 yrs (2 times/wk)	basic	oral	mainstream	electronics	unemployed
HI_09	F	91.7 (L)	26	0;6	unknown	2	8	4 yrs (3 times/wk)	good	oral	a)deaf: 1st-3rd grade b)mainstream	primary education	special needs teacher
HI_10	M	98.3 (L)	35	1;5	medication	3	26	10 yrs (2 times/wk)	none	oral	mainstream	physiotherapy/ arts	art college student

Table 3.1. Information about audiological history, educational background and communication practices of the HI group subjects. Subject HI_04 was excluded from the study to ensure homogeneity (see text for details).

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[20] Renal Tubular Acidosis

birth complications and 2 cases of unknown etiology. All subjects were aided before the age of 4 and made continuous use of their hearing aid(s)[21].

All subjects had or were still in speech therapy at the time of the experiment. Most subjects started training between 4-8 years of age with the exception of HI_03 who started as early as one year old and HI_10 who had a quite late onset at 26 years of age. We attempt to tackle these differences by introducing the intelligibility factor into our design (Section 3.5.). Thus, if early onset, prolonged duration and/or increased frequency of speech training had an influence on speech development, it should be depicted in the subject's intelligibility score (Section 3.4.6.).

All subjects prefer oral communication with their family and friends, and feel comfortable using speech. Sign language was used only by three subjects with deaf friends who did not communicate orally. The rest of the subjects did not know or had only basic knowledge of sign language, and did not feel comfortable using it. For example, subject HI_09 started to learn sign language three years prior to the study because she had been appointed at a public school as a special needs teacher. Thus she used sign language only in the classroom. Finally, all subjects either had or were in the process of acquiring a college or university degree.

3.2.1.2. The control group (NH)

Five adults, two men and three women, with no history of hearing or speech problems constituted the control or normal hearing (NH) group. They were 18 to 21-year-old undergraduate university students. They were all born and raised in Thessaloniki and spoke standard Greek with no detectable accent.

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[21] Subjects HI_06, HI_08 & HI_10 can only benefit from a hearing aid in their better ear, as reported by the subjects.

3.2.2. The corpus

The stimuli were 54 disyllabic words of the structure [pV_1CV_2], where V=[i, a, u] and C=[p, t, s] in all possible combinations, including symmetrical disyllables (V_1=V_2). Half the words were meaningful and half were nonsense words selected in order to control the material. Vowels [i], [a] and [u] were chosen as they constitute the quantal vowels (Stevens, 1972, 1989); they represent three stable and acoustically non-critical articulatory positions, forming a triangle on the F2-F1 two-dimensional plot. Consonant [p] was chosen at the start of the stimuli, as it does not involve tongue movement and does not interfere with lingual gestures. The three different consonantal contexts were chosen so as to examine V-to-V effects across two articulation places (bilabial and alveolar) and two manners (stop and fricative). Stress also varied position, thus half the stimuli were of the structure [ˈpV_1CV_2] and half [pV_1ˈCV_2]. Table 3.2. presents the complete set of the stimuli.

C	**stressed syllable**	**aCa**	**aCi**	**aCu**	**iCi**	**iCa**	**iCu**	**uCu**	**uCa**	**uCi**
p	**1**	‘papa	‘papi	‘papu	‘pipi	‘pipa	‘pipu	‘pupu	‘pupa	‘pupi
	2	pa’pa	pa’pi	pa’pu	pi’pi	pi’pa	pi’pu	pu’pu	pu’pa	pu’pi
t	**1**	‘pata	‘pati	‘patu	‘piti	‘pita	‘pitu	‘putu	‘puta	‘puti
	2	pa’ta	pa’ti	pa’tu	pi’ti	pi’ta	pi’tu	pu’tu	pu’ta	pu’ti
s	**1**	‘pasa	‘pasi	‘pasu	‘pisi	‘pisa	‘pisu	‘pusu	‘pusa	‘pusi
	2	pa’sa	pa’si	pa’su	pi’si	pi’sa	pi’su	pu’su	pu’sa	pu’si

Table 3.2. The 54 stimuli of the experiment.

The stimuli were placed within the meaningful carrier phrase ‘ˈleʝe _____ ˈpali’ (‘Say ____ again.’) and each sentence was repeated 10 times. The 540 sentences were randomised, keeping the two stress patterns separate, to avoid wrong placement of stress due to confusion. Hence 2 lists were created (Appendix 1.3.); one list with

270 phrases containing stimuli stressed on the 1st syllable, and a second list with 270 phrases with stimuli stressed on the 2nd syllable.

Subsequently, when examining V-to-V coarticulation in Part 2, disyllables were paired according to effect type and direction, e.g., for anticipatory [i]-to-[a] effects over the bilabial, the pair we examined was [apa]-[api] (see Fig. 3.2.), and when examining the effect of stress, the pair [ˈapa]-[ˈapi] would show the anticipatory effects on the stressed [a], while the pair [aˈpa]-[aˈpi] the anticipatory effects on the unstressed [a]. Hence one member of the pair is always symmetrical. All disyllable pairs of the study according to V-to-V effect are listed in Appendix 1.4.

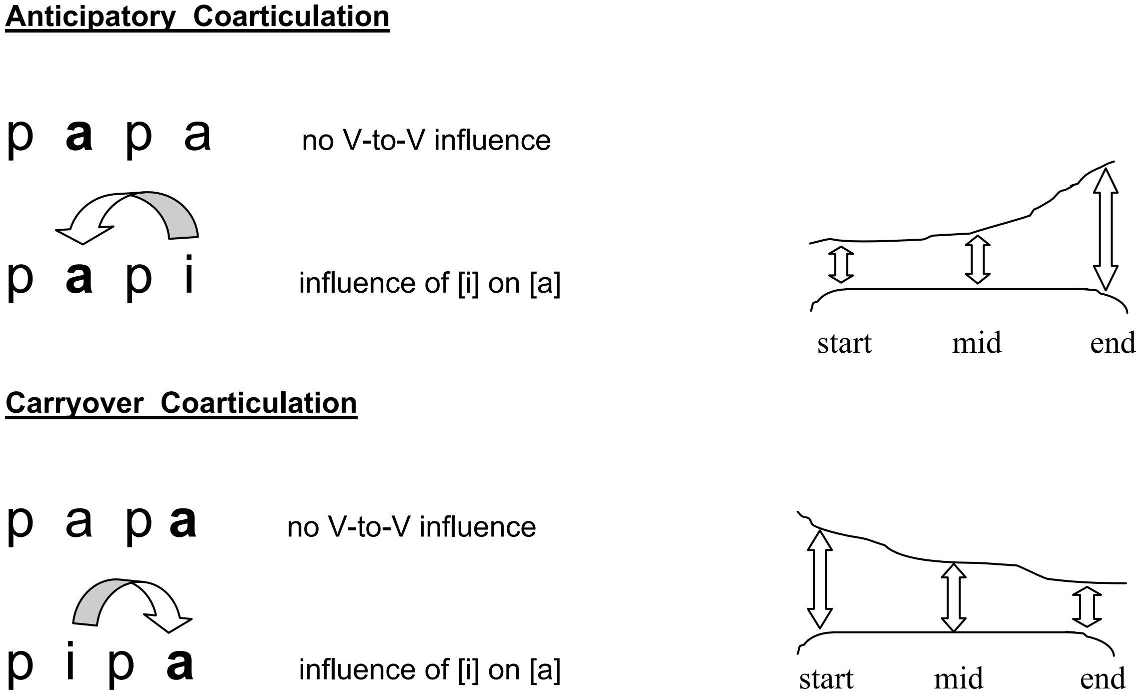

Fig. 3.2. Schematic representation of F2 coarticulation effects in disyllable pairs. Here, for V-to-V anticipatory effects on the F2 of [a], we employ the pair [papa]-[papi] and make measurements at the start, mid and end point of the first [a], while for carryover effects, we measure at the aforementioned points of the second [a] in the pair [papa]-[pipa] The portrayed magnitude and extent of effects (on the right) is arbitrary.

3.2.3. The experimental set-up and the recording procedure

The HI subjects were recorded at the Association's premises after appointment. The recordings took place in a sound proof room used for audiological evaluations that take place regularly for the Association members. The NH subjects were recorded at the Phonetics Laboratory of the School of English Language and Literature of the Aristotle University of Thessaloniki. All subjects were recorded using a YAMAHA external hard disk recording studio[22] connected through a USB port to a laptop and a Shure microphone[23] 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 recording comprised 2 sessions, one for each stress list, with a short break in-between, as the whole procedure lasted close to an hour for each subject. The recordings of the HI subjects had an additional 3rd session which was used for the Intelligibility Experiment (Section 3.4.4.).

Prior to the recording the researcher modelled an utterance at a comfortable speaking rate and subjects were asked to utter a few test phrases which were recorded and checked on the spot to ensure appropriate recording level. The test recordings were not included in the analysis. During the recording subjects were not interrupted while reading, but were asked to repeat tokens that had been omitted or misread by mistake or were not produced at the appropriate level at the end of each session. Such repetitions had a low frequency of occurrence. As mentioned before, fourteen HI subjects were recorded in total, while the data reported here come from nine HI subjects.

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[22] YAMAHA USB Audio/Midi Personal Studio, UW500

[23] SHURE Unidirectional Dynamic Microphone, Model BG3.1

3.2.4. The data annotation

For the Acoustic Experiment, two long wav files were saved for every subject containing the two parts as described above. The editing and analysis was carried out using PRAAT software (Boersma & Weenink, 2011).

The next issue we had to consider carefully was data annotation. Regarding formant measurement, data were annotated at three measurement points, i.e., the start, the middle and the end of each vowel in the disyllable. The measurement at the mid point was computed automatically by the system once the start and end points had been manually placed. Attempting to follow an annotation procedure as consistent as possible while trying to capture coarticulation effects as early as possible too, the start point boundary was set manually 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 set again manually at end of the last cycle where the clear formant structure ended. Measurement markers or "boundaries" are usually placed "at vowel onset at about the zero-crossing which is presumably when the vocal folds start moving and the first pitch pulse starts being formed" (Daniel Recasens, personal communication, 21 February, 2008).

The first and last cycle corresponded well with the beginning and end of F1 & F2 vowel structure for vowels [i] and [a] in many cases (see Fig. 3.3.). There were cases, though, when the onset of formant structure would coincide with the peak of the first cycle instead of its start, or/and the end of formant structure would occur one or more cycles before the last one of the vowel; and these last few cycles that did not correspond to clear formant structure would be more simple in shape and of a much lower amplitude (Fig. 3.4.). In these cases, our boundary placement decisions were based on the beginning and end of clear formant structure rather than on the cycles themselves. In these cases we would place the boundaries where clear formant structure started and ended; hence the start boundary might be placed at the peak of the first cycle instead of the start, and the end boundary at the peak of the last cycle, instead of the end or the end of a cycle not at the very end of the vowel's voicing, but earlier where formants were still well formed. An additional reason for preferring to place boundaries at the peak and not the very start of a cycle is that the analysis window is bilateral and gathers information from both sides of the boundary. Thus, placing the boundary at the peak eliminates analysis of information before or after the actual vowel (Section 3.2.5.1., *Window Length*).

The high back vowel [u] constituted a complicated case of boundary placement, as it often did not have such a full and clear F1 and F2 formant structure, especially when unstressed. In these cases, the boundaries would be set at that point in the cycle which coincided with the beginning and end of clear formant structure. For [u], annotation was based mainly on F1, as the F2 contour usually did not extend to the end of the vowel (see Fig. 3.5.).

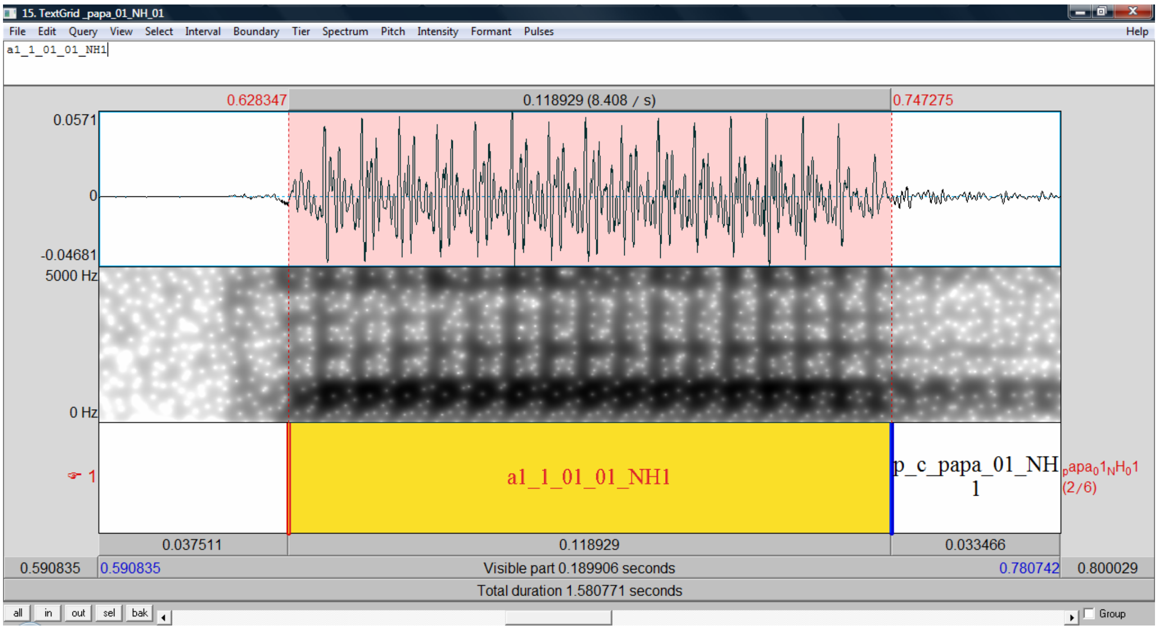


Fig. 3.3. Waveform, wideband spectrogram and annotation Textgrid in Praat for the first vowel [a] in [ˈpapa] produced by a NH male. Boundaries have been placed at the start of the first cycle and the end of last cycle which coincide with the onset and offset of formant structure correspondingly.

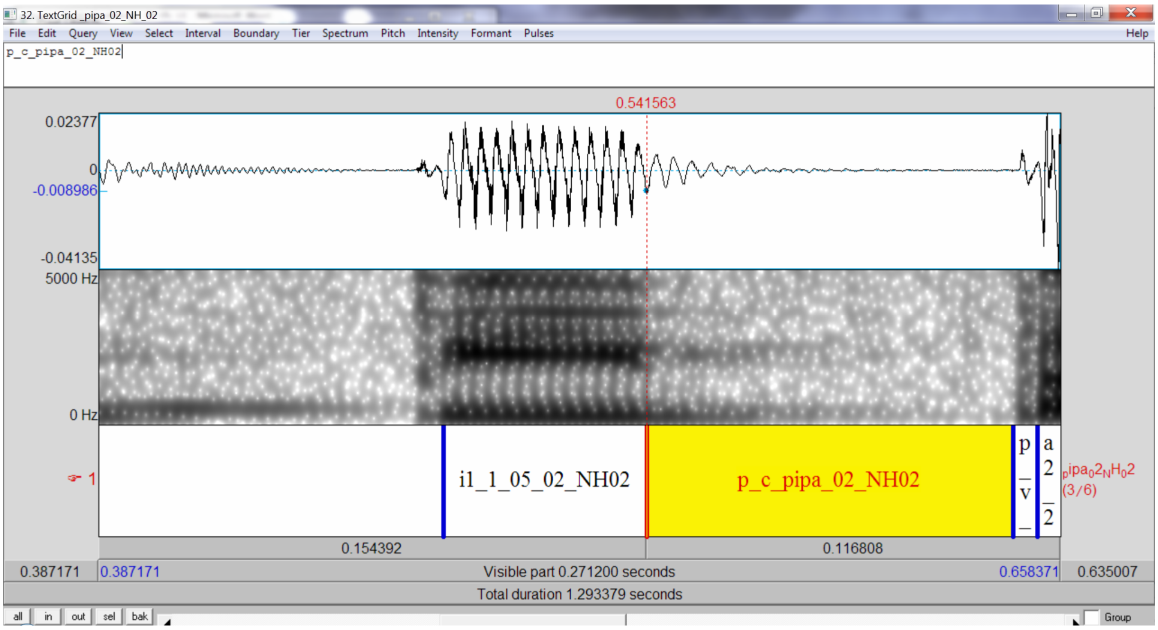


Fig. 3.4. Waveform, wideband spectrogram and annotation Textgrid in Praat for vowel [i] in disyllable [ˈpipa] produced by a NH female. Note that the end boundary of [i] has been placed not at the end of the very last cycle of the vowel, but at the end of the last cycle that corresponds to the end of the formant structure in the spectrogram. From that point on the structure breaks down and the cycles become simpler and faint.

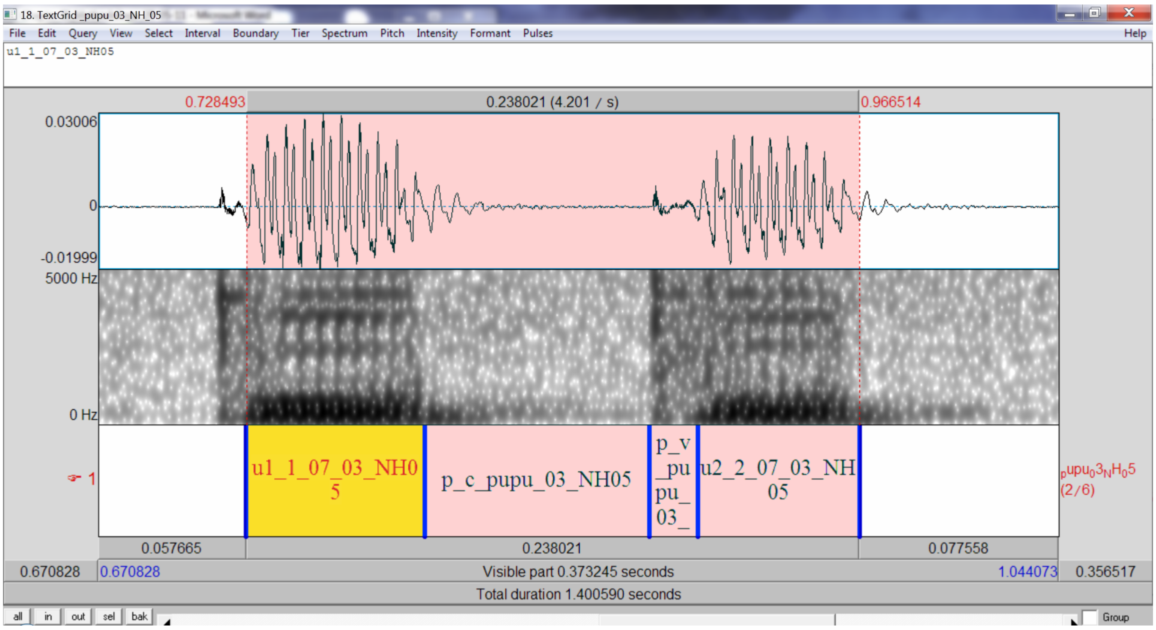


Fig. 3.5. Waveform, wideband spectrogram and annotation Textgrid in Praat for disyllable [ˈpupu] produced by a NH male. Boundaries for both vowels have been placed at the beginning and end of clear formant structure.

Regarding consonants, no additional boundary placement was necessary for the fricative [s], as its start coincided with V_1 end point and its end with V_2 start point. For the plosives [p] and [t] one more boundary was placed at consonant release, creating two parts; the closure and the VOT part (see Fig. 3.6.).

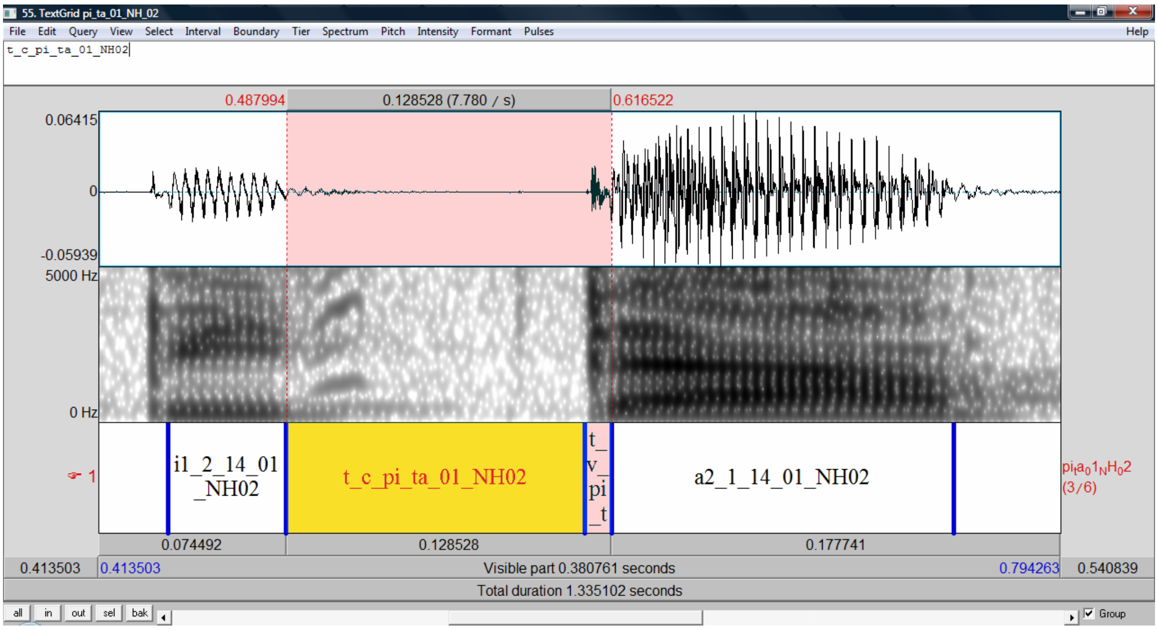


Fig. 3.6. Waveform, wideband spectrogram and annotation Textgrid in Praat for disyllable [piˈta] produced by a NH female. The closure part of the plosive [t] starts at the end boundary of [i] and ends at the next boundary which denotes the start of the release. The release part ends at the start boundary for [a].

The aforementioned boundaries placed in the disyllable were also utilized in measuring the duration of the two vowels and the intervocalic consonant in the [pV_1CV_2] sequence (Section 3.2.5.3.). In cases where voicing for the vowel occurred earlier and/or ended later than its clear formant structure, separate onset and/or offset boundaries were used for the formant and the duration measurements of that vowel.

3.2.5. The data analysis

3.2.5.1. Formant Measurement

As mentioned above, the material consisted of 54 disyllables which were repeated 10 times by each subject. Since we measured F1 and F2 at vowel start, middle and end points and each disyllable contained two vowels, 12 formant measurements were made in each disyllable. This renders a total of 64,800 formant measurements for the 10 subjects (54 x 10 x 12 x 10).

F1 and F2 values were, in a first stage, acquired through AFT (Automatic Formant Tracking) by the program. The program uses LPC for formant analysis. Afterward all values were manually checked or corrected by the researcher by looking at the program-generated formant contour in the wideband spectrograms and locating errors.

A script was written that ran in the Praat program, automatically rendering values for F1 & F2 at the start, mid and end points of the two vowels in each disyllable (Appendix 1.5.). The parameters set for this analysis included:

1. ***Number of Formants.*** Five formants were selected. "The number of formants in formant analysis determines the number of peaks with which the entire spectrum is modelled" (Boersma & Weenink, 2011). The program recommends an analysis of five formants even if our interest is in the first two.
2. ***Maximum Formant.*** For males it was set at 5000 Hz and for females at 5500 Hz.
3. ***Window Length.*** This parameter varied according to measurement point. The type of window we used was Gaussian as recommended by the program. "The Gaussian window is superior as it gives no sidelobes in your spectrogram… the analysis is performed on twice as many samples per frame than other

window shapes" (Boersma & Weenink, 2011). The 25 ms window used traditionally in acoustic analysis was chosen for the mid point measurement, whereas for start and end point measurements a narrower window length of 15 ms was selected, so as to capture coarticulation effects at the beginning and end of a vowel more accurately. An additional reason for using a narrower window is that the analysis window is symmetrical and gets information from both sides of the boundary. Also, Praat uses a Gaussian window with sidelobes beneath -120 dB which actually doubles the size of the window length value. Thus by narrowing the window, we also lessen the superfluous information related to the part in front of the start boundary and after the end boundary. This is also accomplished by placing boundaries at the peak and not at the very start or end of the vowel. Although short window lengths seem ideal for measuring formant transitions, in a window narrower than 15 ms predicted formant values would vary a lot depending on where we measure in the pitch period (Paul Boersma, personal communication, 27 February, 2008), hence the final choice of a 15 ms window.

4. ***preEmphasis.*** A value of 50 Hz was set as suggested by the program for a better formant analysis. Frequencies below 50 Hz are not enhanced thus creating a flatter spectrum and formants match the local peaks rather than the local spectral slope (Boersma & Weenink, 2011).

After acquiring the AFT values, we checked for errors. A first indication of an incorrect AFT value would be an erroneous formant contour in the wideband spectrogram. For example, in Fig. 3.7., we can see that using the default Number of Formants in its analysis, which is five, the program has detected one formant (dots in

Fig. 3.7.) where there should have been two. This occurred very frequently with [u]. The correction procedure involved changing the Number of Formants in the Formant Settings (by 0.5 or 1 point steps) until we got an acceptable formant contour for the vowel. Next, we placed the cursor either on the existing boundary or, if the contour was still not fixed at that point, on the nearest dot we could distinguish as representative of the right contour, and got the formant value from the program automatically (see Fig. 3.8.). We avoided traditional manual measurements which involve clicking on the spectrogram and getting a Y-axis value, as the slightest off-movement resulted in large differences in Hz.

This correcting procedure was implemented on each vowel and each measurement point separately, because the contour depended on vowel type (e.g., AFT for back vowel [u], tended to merge F1 & F2 into one formant, because they are close together, whereas it was less problematic for high front [i]), and on measurement point (e.g., start and end points were more problematic than the mid point).

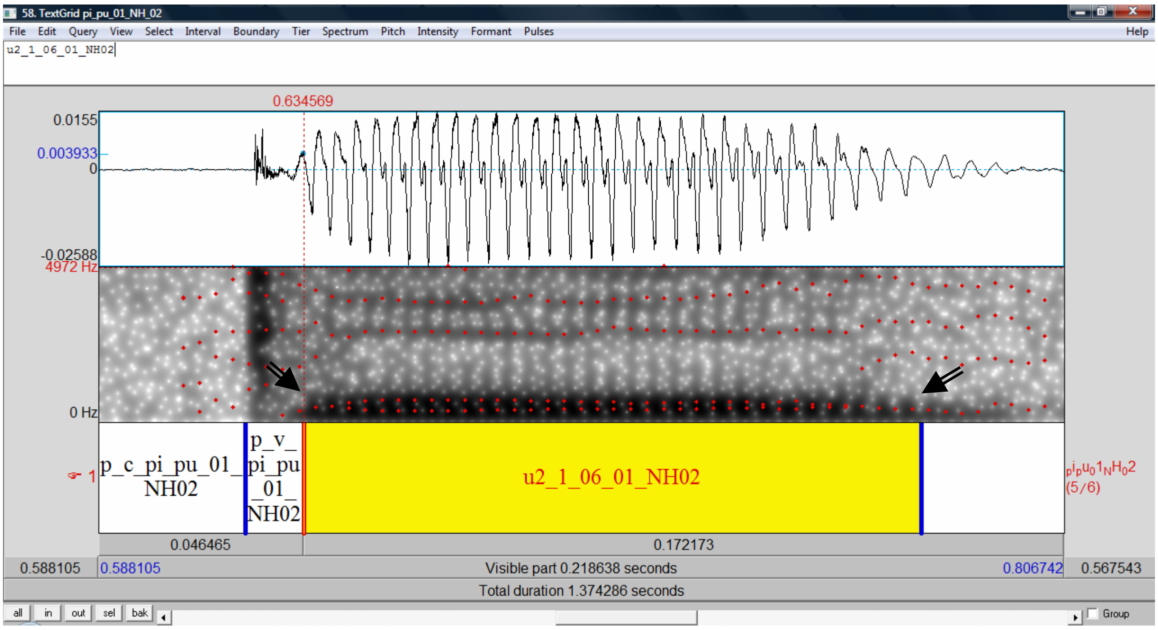

u2_1_06_01_NH02

Fig. 3.7. Erroneous formant contour at vowel [u] start and end, resulting in AFT error. Number of Formants is 5 (default value in script).

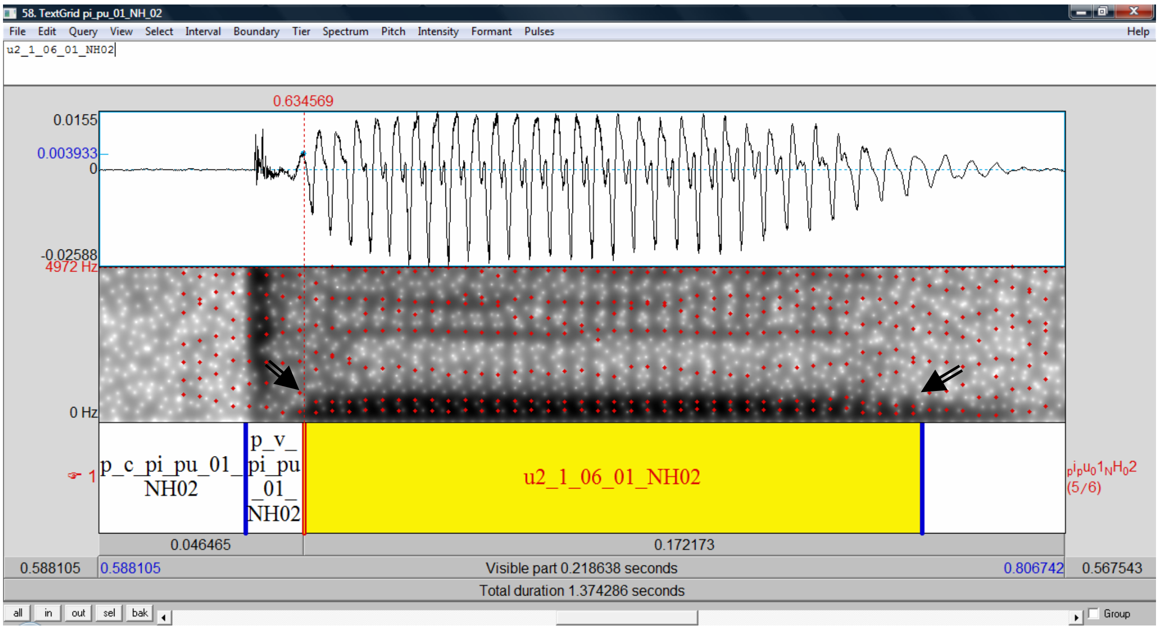


Fig. 3.8. Corrected formant contour by changing Number of Formants to 8 in Menu: Formant > Formant Settings.

3.2.5.2. Problem Areas in Formant Measurement

Having described the procedure followed for formant measurement above, it must be noted that formant location was not always straightforward.

Regarding normal hearing speech, some difficulties concerned female voices which are characterised by higher fundamental frequencies thus making formant location problematical (McGarr & Whitehead, 1992). In other cases, measurement at the start and end points was quite difficult even for normal hearing male voices, as formants at these points are often ambiguous and variable in comparison to the steadier vowel midpoint. Formant trajectories showed differences in each repetition and these differences although subtle on the spectrogram translated into considerable differences in Hz resulting in within-subject formant frequency variability. Such phenomena have been described in the literature (McGarr & Gelfer, 1983; Harris, Rubin-Spitz & McGarr, 1985).

Regarding hearing impaired speakers, additional formant measuring problems were encountered. Such difficulties have been reported to relate to inappropriately high pitch, pitch breaks and other perturbations in the phonatory source such as breathiness, hoarseness or nasalization which "create a mismatch between the source and the bandwidth of the spectrogram filter and obscure important harmonic information" (McGarr & Whitehead, 1992). Moreover, additional variability was introduced depending on each speaker's gender and articulatory behaviour. A summarised description of the problems we encountered during each subject's analysis follows.

Speaker HI_01 spoke slowly and with great deliberation. Her vowels had a lot of harmonics and stressed vowels had more amplitude than NH corresponding vowels. Hence in many cases we observed split formants, as her pitch changed within the long duration of the vowel which was to some degree diphthongised (see Fig. 3.9.). Her unstressed vowels in the plosive alveolar context were very short and almost whispered. Her fricative [s] was produced as the palatal fricative [ʃ] (see low frequency energy in Fig. 3.9.). Her [t] is maybe retracted, causing an increase in the F2 of unstressed [u] which was weak and [y]-like (see Fig. 3.10.).

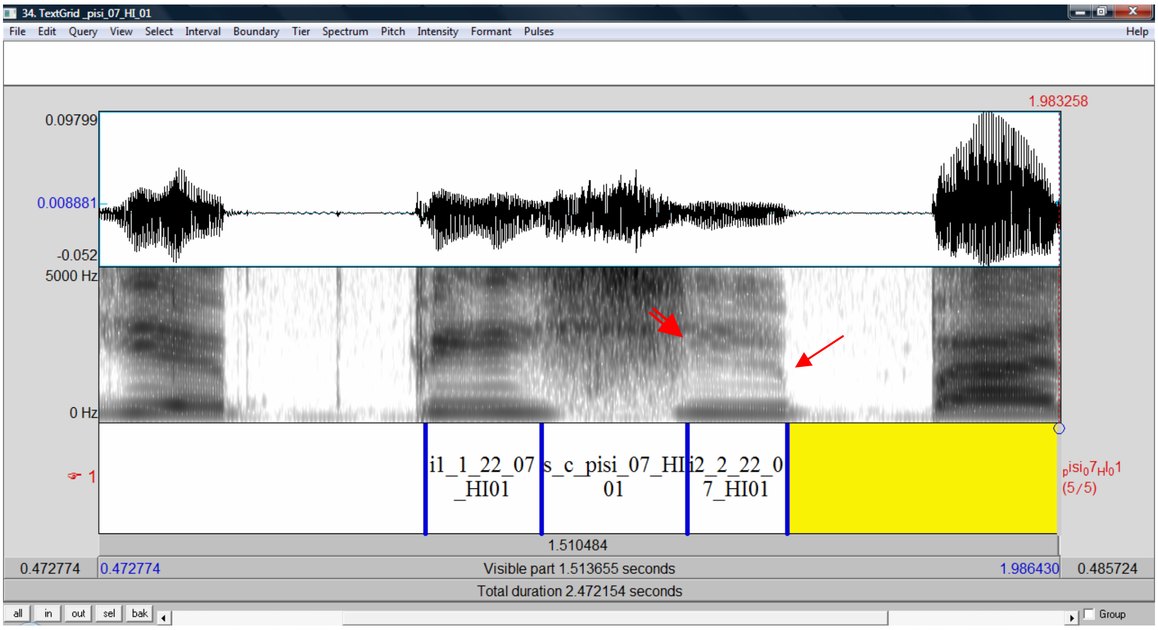


Fig. 3.9. Split F2 of 2nd position vowel [i] in [ˈpisi] produced by speaker HI_01. The thick arrow shows a higher harmonic F2start and the thin arrow points at a lower harmonic F2end.

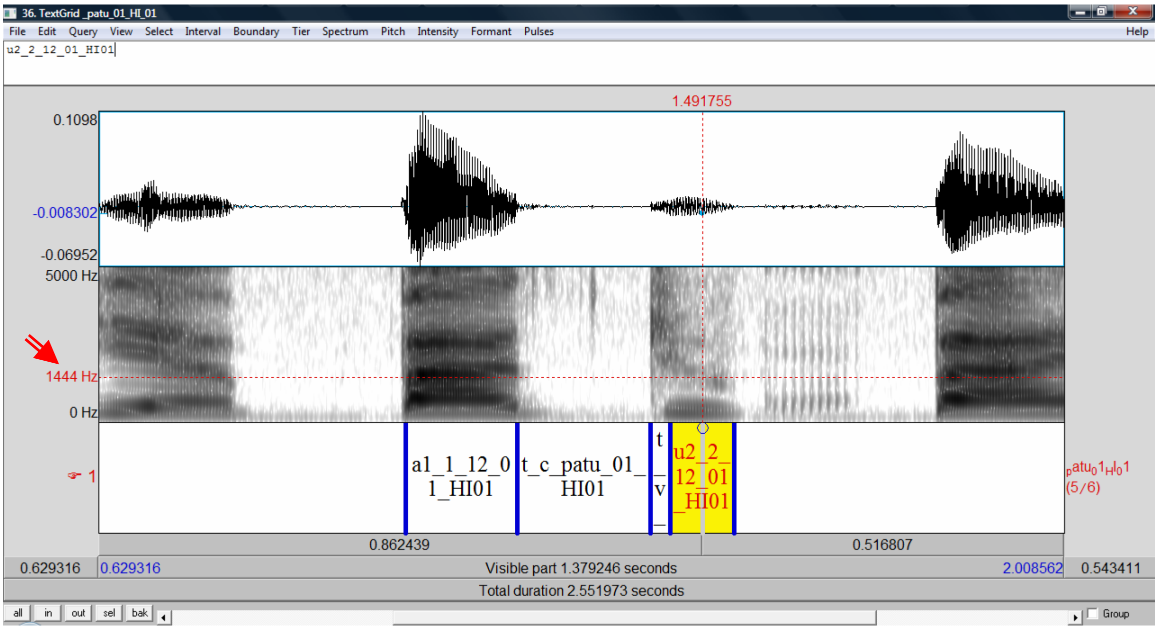
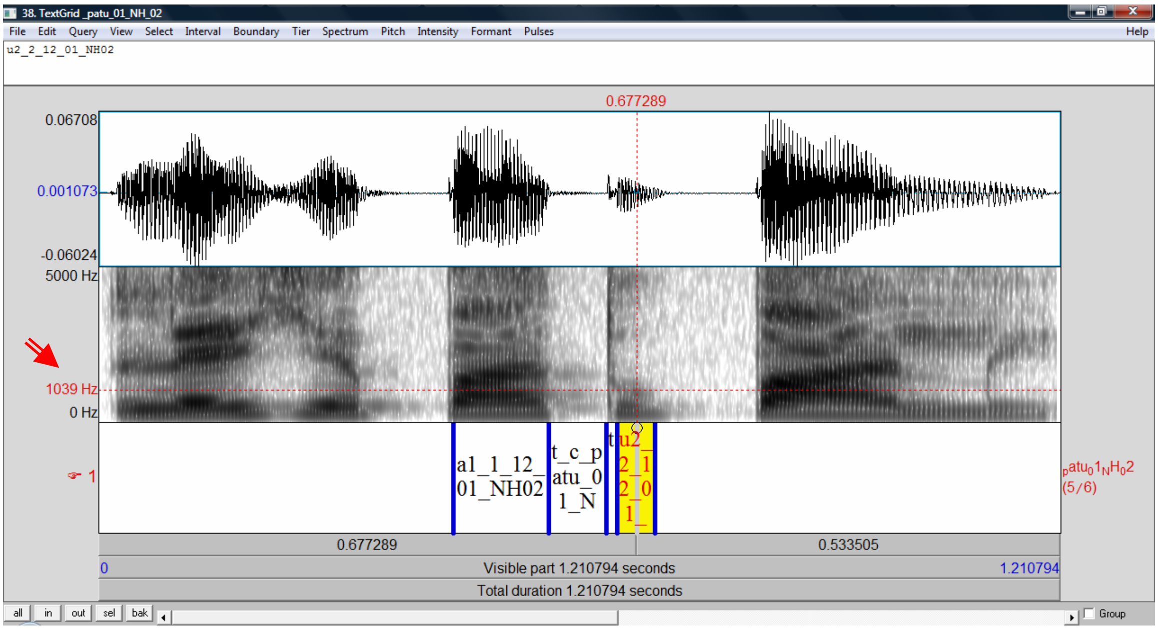
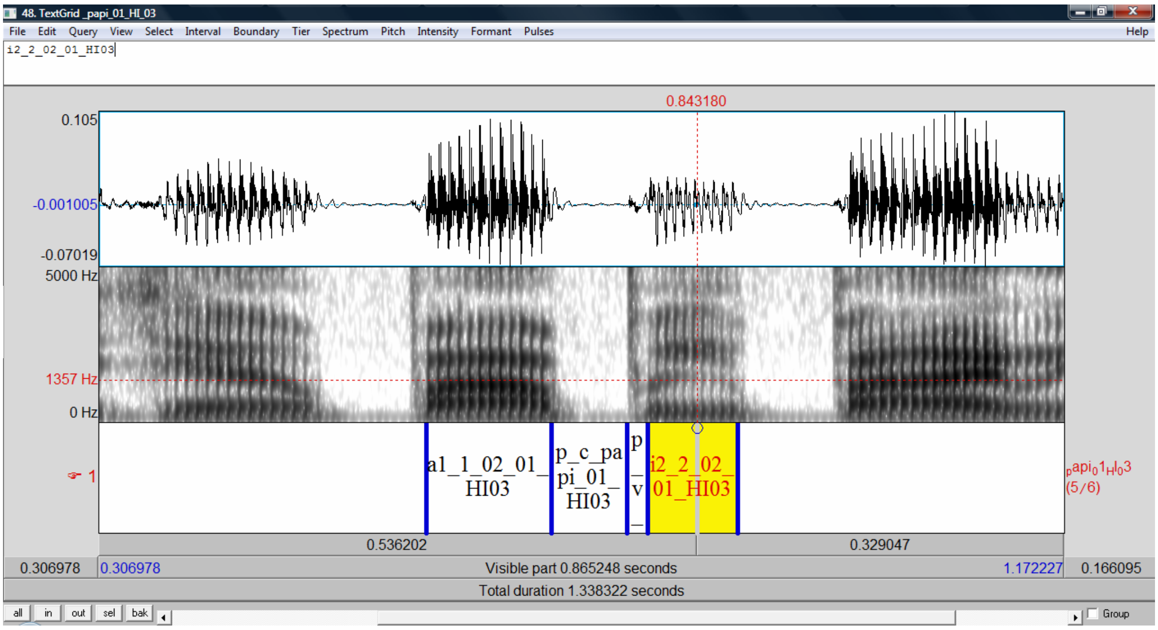


Fig. 3.10. The disyllable [ˈpatu] produced by two female speakers: HI_01 (above) and NH_02 (below). Increased F2 of unstressed [u] by HI_01 in comparison to NH_02 below (see arrows).

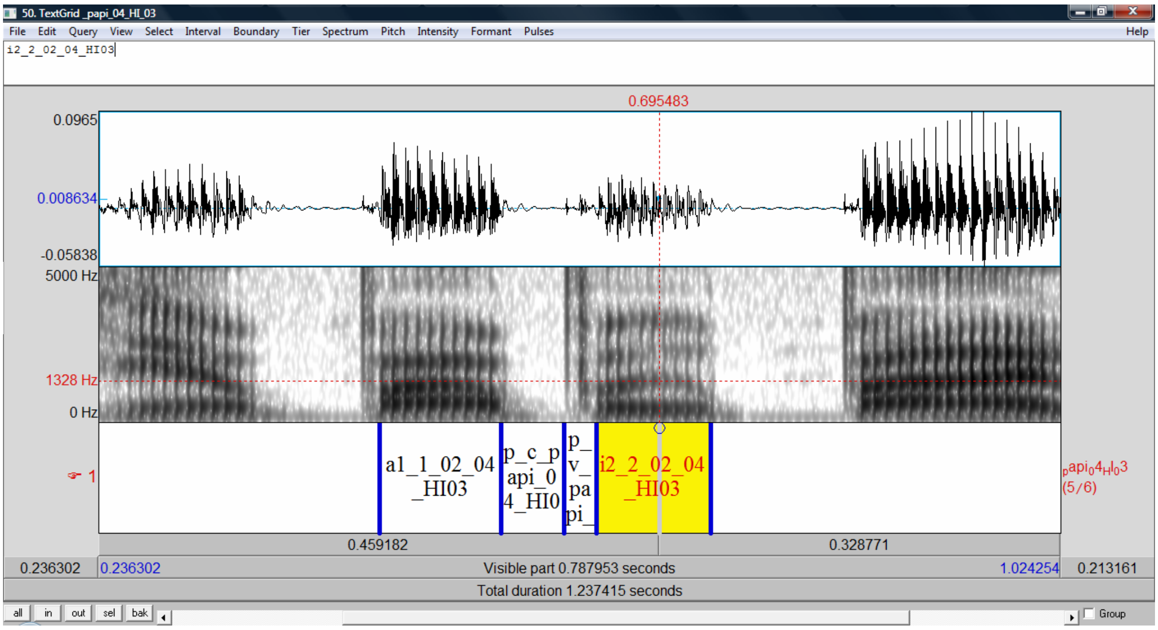


The split formant effect was also found in the [i] vowel of speaker HI_02. In addition, nasal formants were located in her productions, as well as in the productions of speaker HI_03. Concerning the latter, his nasal formant was located around 1200-1500 Hz, hence in [ˈpapi], F2 of [i] was usually the oral formant above the nasal formant (above the horizontal dotted line in Fig. 3.11.a) and the vowel had an [ɨ]-like quality. Nevertheless, in other repetitions of the same disyllable his [i] was a bit higher than a schwa, in which case, F2 of [i] was actually as low as the nasal formant found in other repetitions (see Fig. 3.11.b). A production with no nasal formant is also given for comparison in Fig. 3.11.c. Consequently this subject's formant values were quite variable. Nasality problems in the speech of the HI have been documented in the literature (Stevens, Nickerson, Boothroyd & Rollins, 1976). In other instances, we have observed that speaker HI_03 diphthongized vowel [i] into [iu] and as a consequence F2 started with a high value and ended with a low value.

a



b



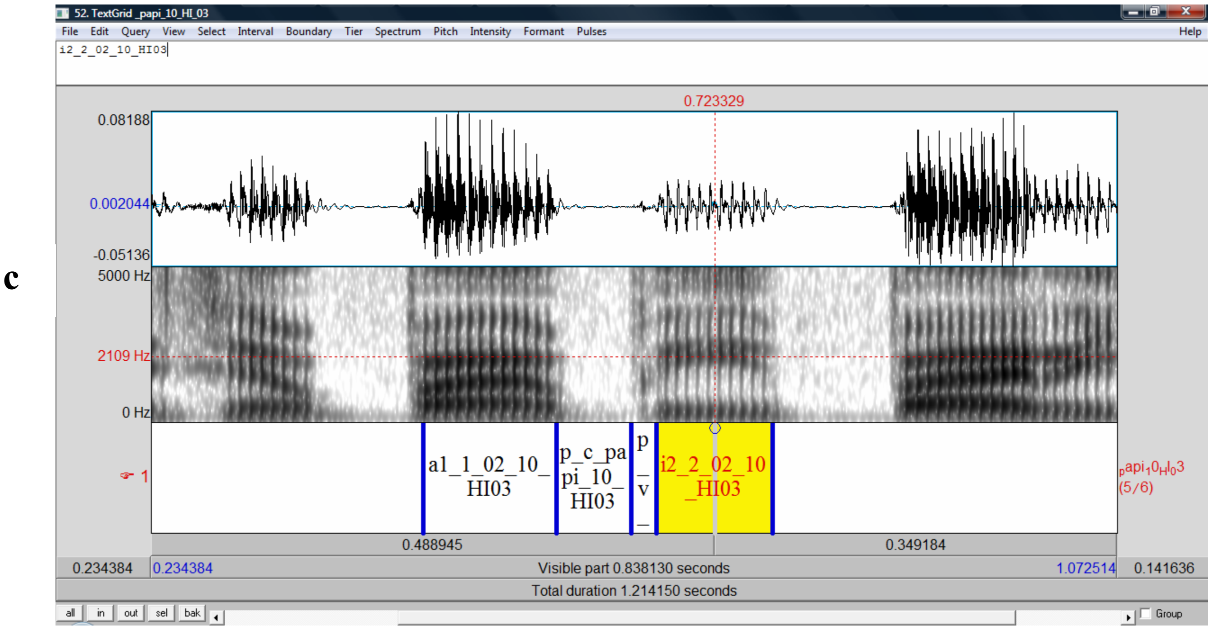


Fig. 3.11. Variability in the F2 value of [i] in three repetitions of [ˈpapi] produced by male speaker HI_03. In repetition (a) [i] is produced as [ɨ], in repetition (b) [i] is pronounced a bit higher than [ə] and finally, in repetition (c), F2 of [i] appears to be within the normal range.

The hoarseness in HI_05[24] speaker's voice created many problems for LPC. Formant contours were uneven, often throughout the vowel, and the first two formants very frequently converged (see Fig. 3.12.). Attempting to increase the Number of Formants for LPC did not always help, especially at the start and end point of unstressed back vowels ([a] and [u]). His [u] was often diphthongized into [ui] especially in the alveolar plosive context (e.g., [ˈputa] → [ˈpuita], [puˈti] → [puiˈti]). Hence there was a lot of F2 variability, since in some cases it was realised as [u] (low F2end) and other times as [ui] (high F2end). His [s] had a more palatal place of constriction (resembling [ç]) and less friction than normal.

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[24] HI_04 speaker's is omitted, as her productions diverged considerably from those of the rest of the subjects. Her vowels were excessively long, the vast majority diphthongized with flat formant transitions and she also had phonatory problems. She was excluded from this group study for homogeneity reasons. For details see Section 3.2.1.1.

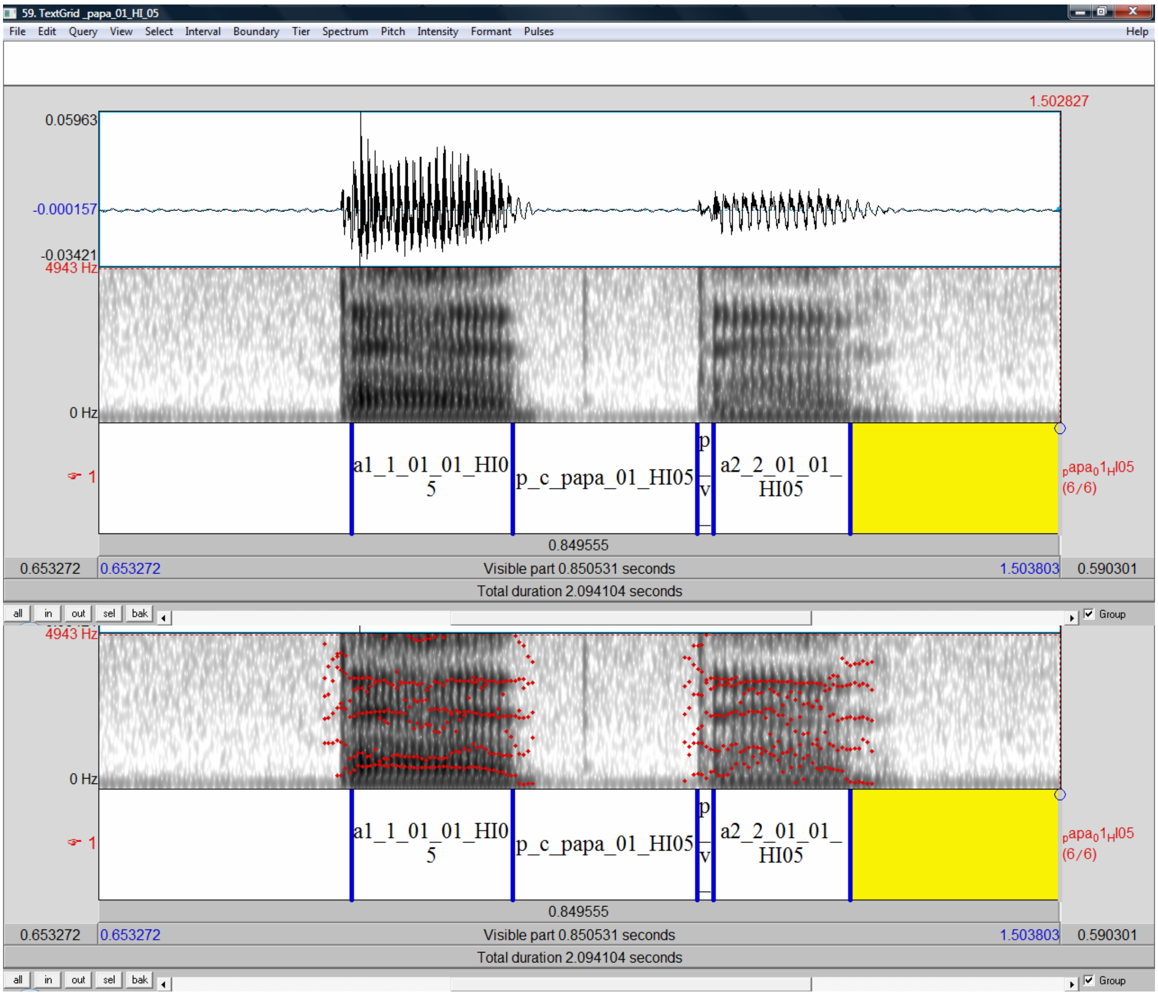


Fig. 3.12. Formant contours for disyllable [ˈpapa] produced by male HI_05. F1 & F2 are not clearly discerned and LPC encounters problems (Number of Formants=6).

A lot of variability was also observed in HI_06 speaker's productions. Although her speaking rate was faster than speaker's HI_01, who presented the longest vowel duration of all subjects, but she displayed, on one hand, elongated stressed vowels and, on the other hand, extremely short, virtually non-existent, unstressed vowels. This was a common occurrence with high vowels [i] and [u]. Her unstressed [i] was either absent or centralized (see Fig. 3.13.a) and her [u] was in many cases too short, making an F2 measurement unfeasible. A vowel so short does not present formant transitions and measurement at three points is a futile if not impossible task. Therefore an increased number of missing values originated from this subject's measurements. Additionally, nasality was evident in her productions and it often continued in the form of additional cycles after the end of the formant structure of the vowel (see Fig. 3.13.b).

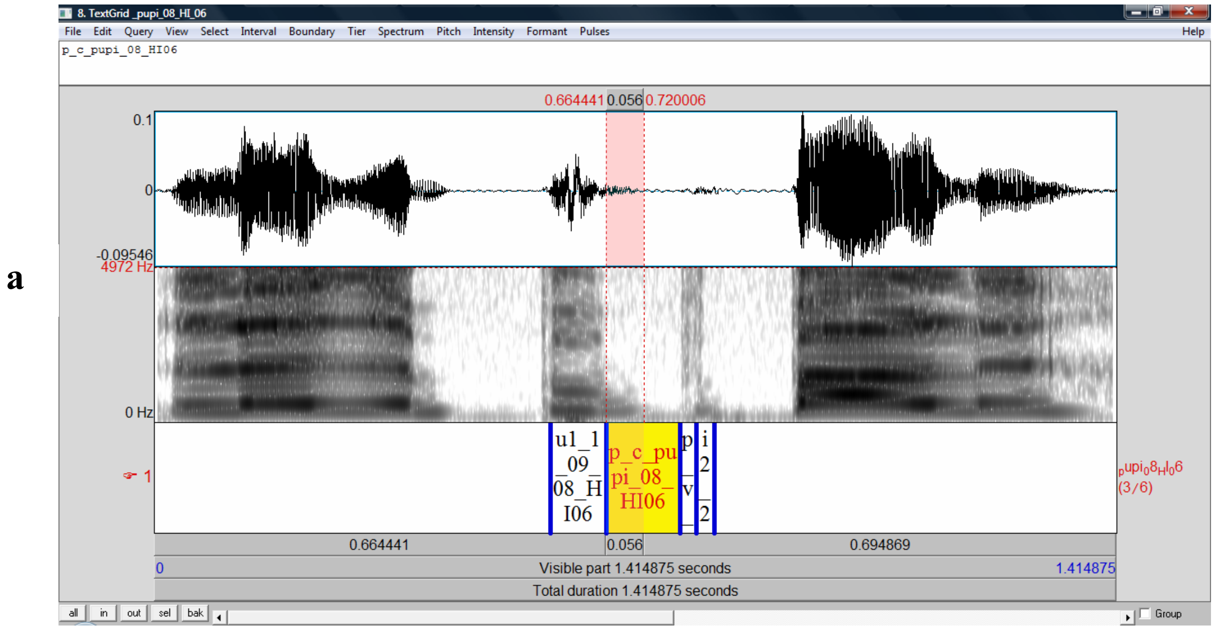
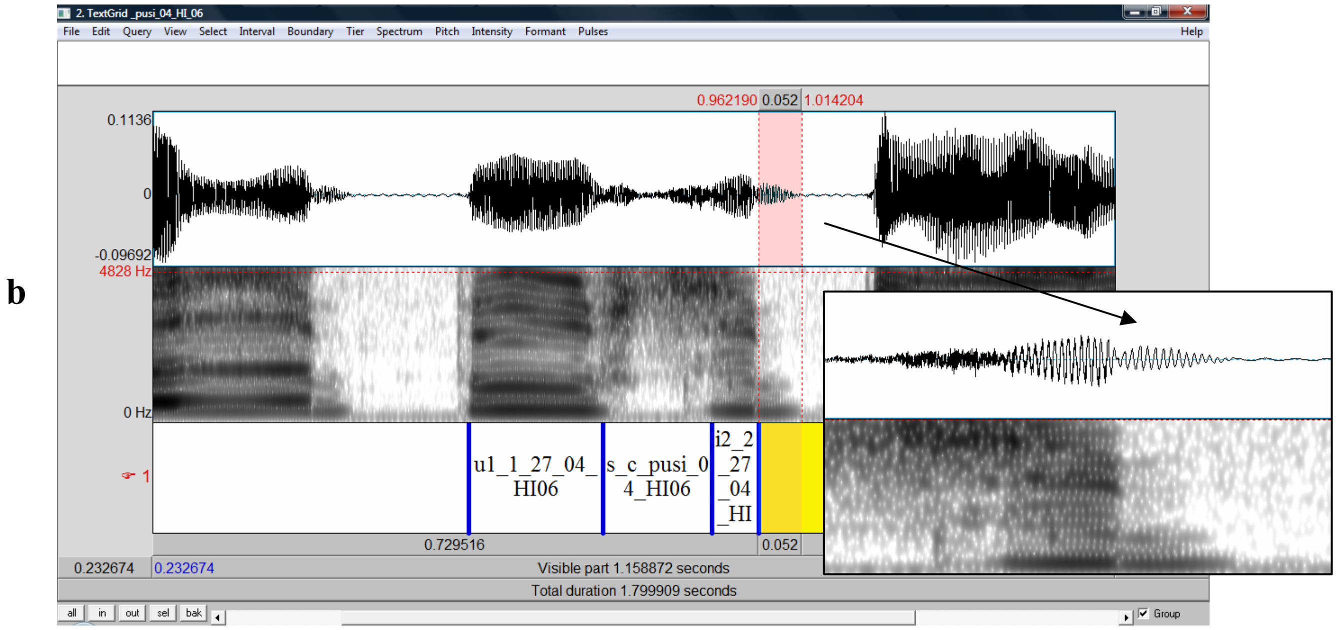


Fig. 3.13. Spectrogram of (a) [ˈpupi] (above) and (b) [ˈpusi] (below) produced by female speaker HI_06. In (a) unstressed high vowel [i] is very faint and in (b) there is an intrusive nasal segment after the vowel [i].



Subject HI_07 produced a central rounded [u] (IPA [ʉ]) which was lowered towards a schwa, hence F2 was higher than normal. His voice intensity was quite low which created difficulties in F1 location for LPC as it frequently converged with F0.

Moreover, nasality made F2 identification for high vowel [i] difficult as it created split formants. When [i] was unstressed, it was frequently, but not always, centralized which contributed to variability in formant values even at the usually more stable vowel midpoint. The alveolar stop was often affricated (e.g., in [puˈta], see Fig. 3.14.).

The [u] vowel sometimes displayed a split F2 formant as well; F2 seems to start on a high harmonic, while it ends in a lower one (see Fig. 3.15.).

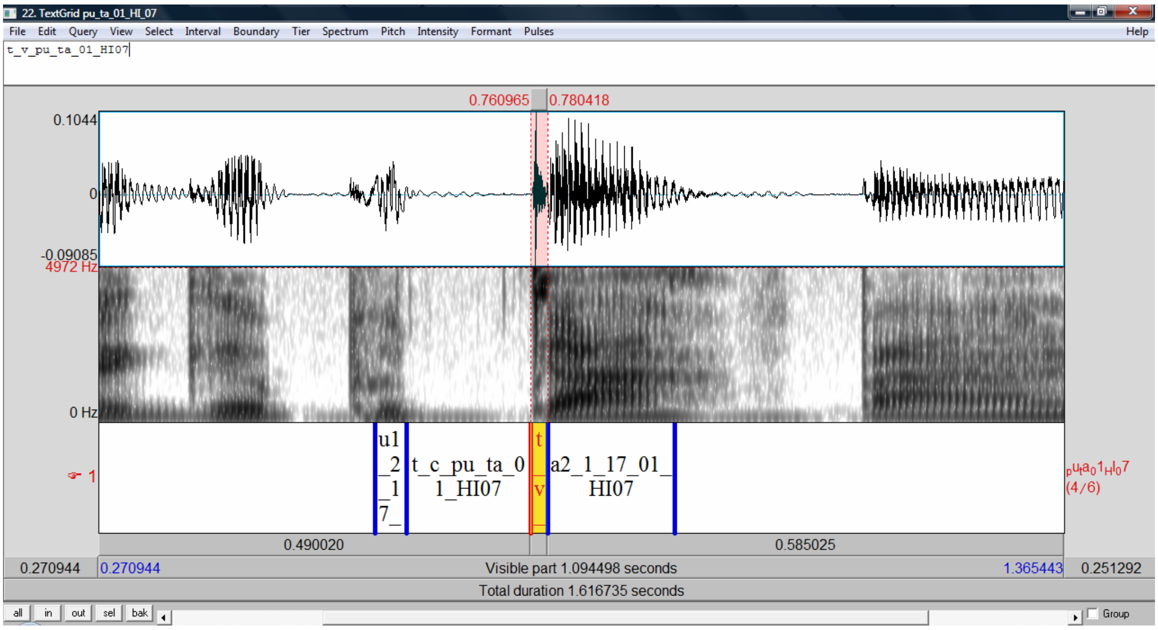


Fig. 3.14. Disyllable [puˈta] produced by male speaker HI_07. We observe a central [ʉ] with a higher F2 than usual and an ejective production of the alveolar [t].

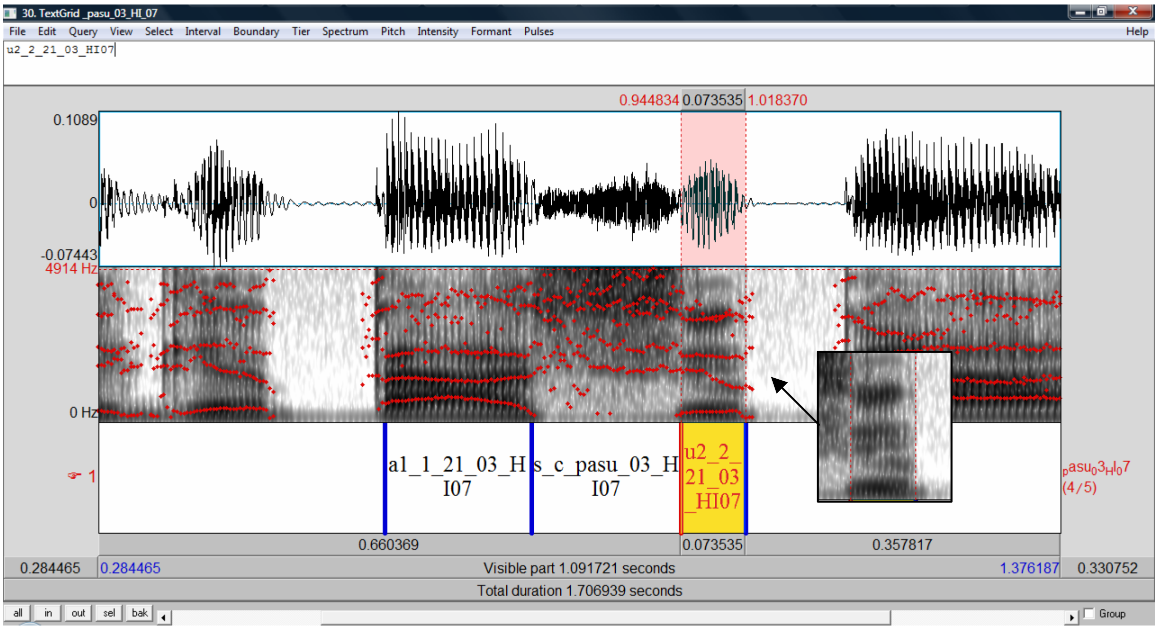


Fig. 3.15. Disyllable [ˈpasu] produced by male speaker HI_07. We see a split F2 formant in [u].

For speaker HI_08, the high front [i] was backed and centralized into [ɨ], thus F2 was located lower than usual (see Fig. 3.16.). His alveolars were both problematic. His [s] did not have enough friction and the constriction often closed completely producing affricate-like sounds. There was evidence of noise suggesting the production of incomplete closure resulting in what was auditorily perceived as a fricative sound between [s] and [ç] (see Fig. 3.17.).

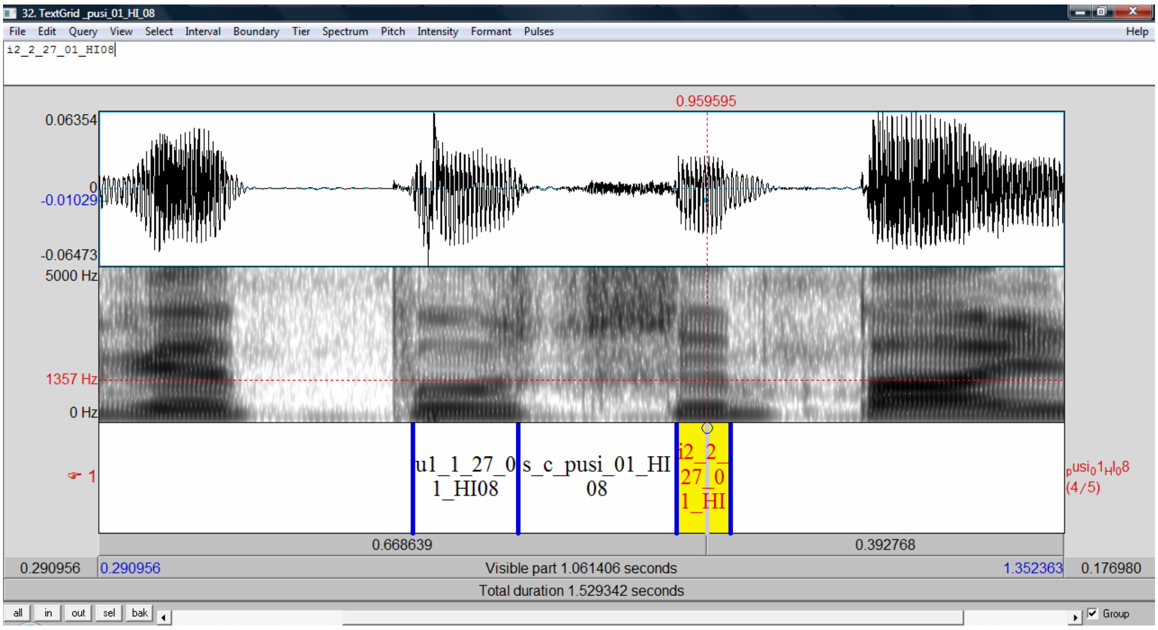


Fig. 3.16. Locating the F2 of [i] (red line) in [ˈpusi] produced by male speaker HI_08. It is backed into a raised [ə], thus presenting a lower F2 than normal.

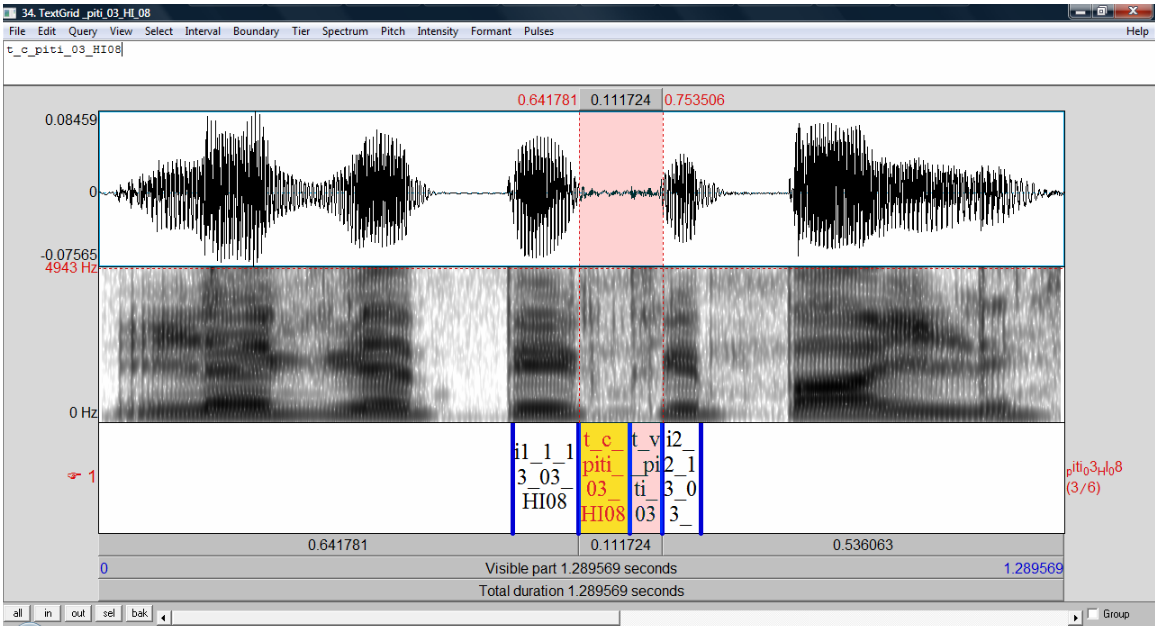


Fig. 3.17. The realization of [t] (highlighted section) in [ˈpiti] by male speaker HI_08. There is evidence of noise during the consonantal interval which indicates incomplete closure.

Formant measurement was quite difficult regarding the productions of female speaker HI_09, as she had a high fundamental frequency and a lot of nasalization. Thus there were a lot of harmonics, and decisions were hard especially at vowel end (see Fig. 3.18. and Fig. 3.19.).

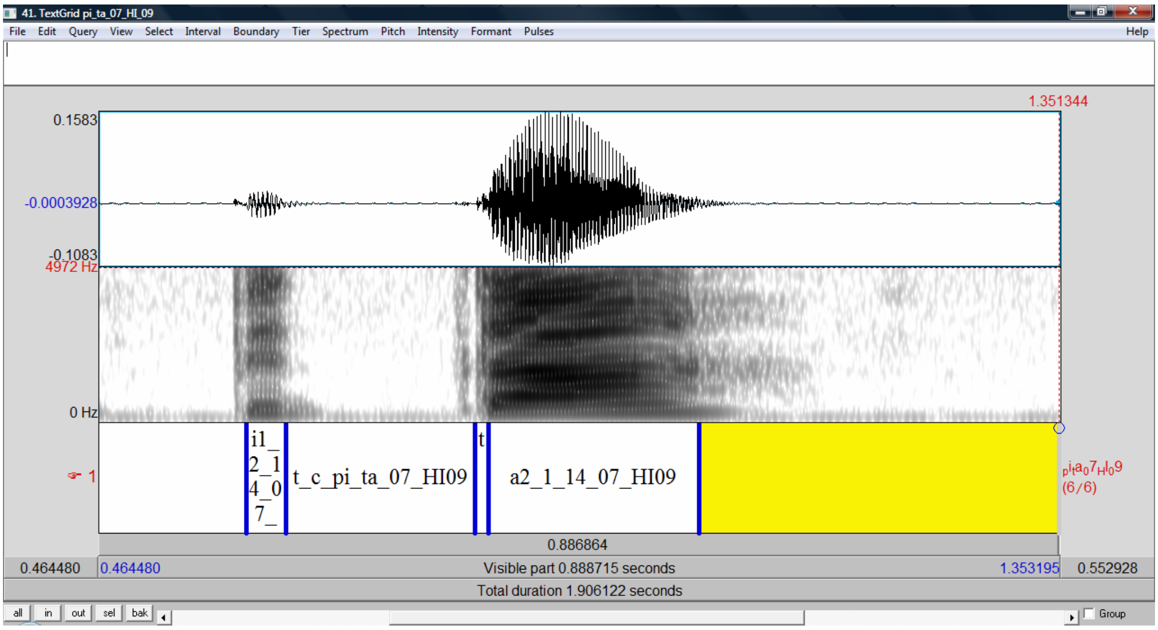


Fig. 3.18. Increased number of harmonics and nasal formants in disyllable [piˈta] produced by female speaker HI_09. Locating formants at vowel end was often challenging.

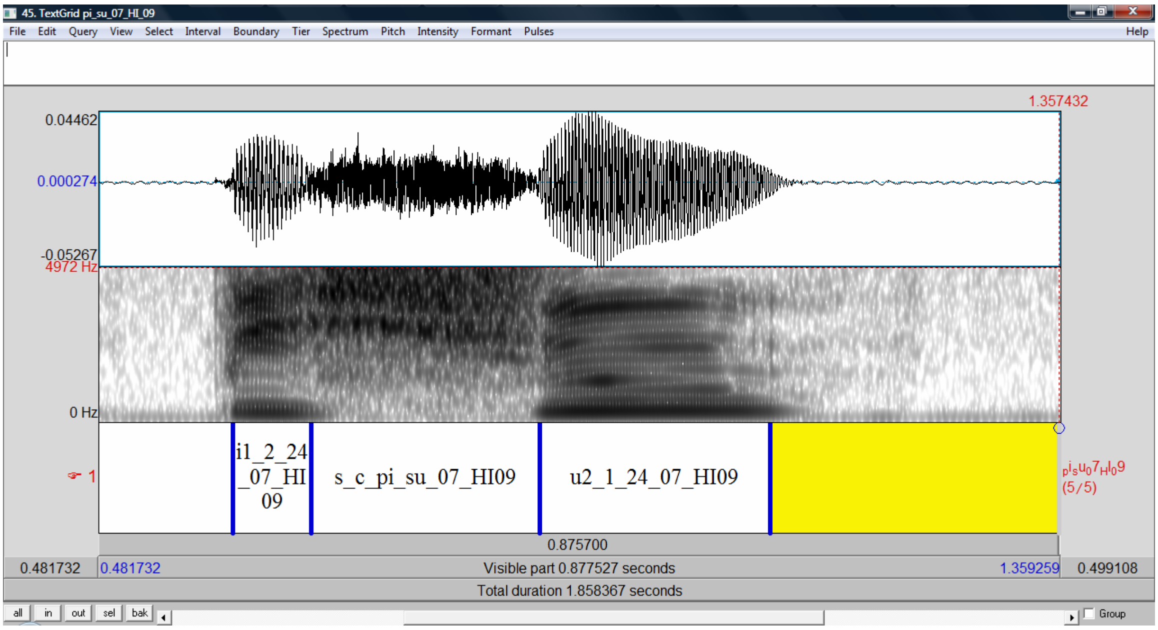


Fig. 3.19. Increased number of harmonics and nasal formants in disyllable [piˈsu] produced by female speaker HI_09.

Difficulties locating formants were encountered for male speaker HI_10 as well. His voice was creaky and his productions were characterised by laryngealization. Due to his abnormal phonation formant tracking encountered difficulties, especially in vowel [u] (see Fig. 3.20.). In addition, his [s] was articulated post-alveolarly and its lower frequency influenced the F2 transition into neighbouring [u].

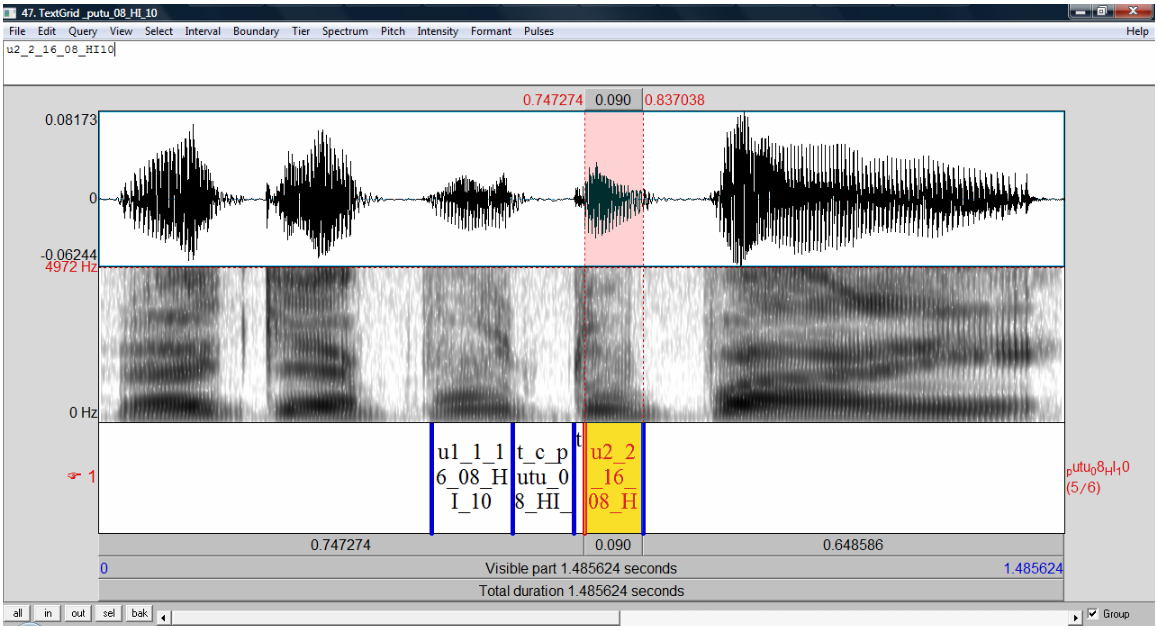


Fig. 3.20. Unclear formant structure of unstressed [u] (highlighted) in disyllable [ˈputu] produced by male HI_10.

3.2.5.3. Calculation and normalization of vowel space and distance

In Chapter IV, Part 1 of the study, the F1 and F2 mean values of the three vowels [i], [a] and [u] are often used in order to create vowel spaces (or more specifically triangles). An example (taken from Part 1, section 4.1.1.) is given below. The third and fourth columns in Table 3.3. below provide the mean F1 and F2 values upon which the NH and HI vowel spaces were computed in Fig. 3.21.

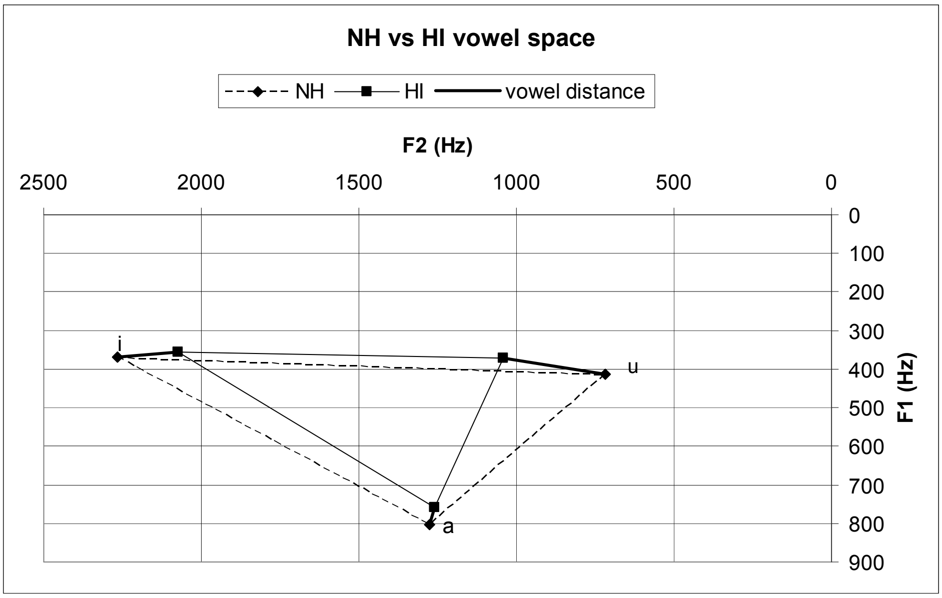


Fig. 3.21. NH (dashed line) and HI (solid line) vowel space and vowel distance (bold line) between the vowels of the two hearing groups.

	vowel	F2mid (Hz)	F1mid (Hz)	**vowel space** (Hz^2)	**Width (i - u)** F2 difference (Hz)	**Height (i - a)** F1 difference (Hz)	F2 difference (Hz)	F1 difference (Hz)	**vowel distance** (Hz)
NH	i	2265	369	312929	1546	433	*192	12	192
	a	1275	802				16	43	46
	u	719	413				*324	*42	327
HI	i	2073	357	201332	1030	402	*Between-hearing-groups comparison*		
	a	1259	759						
	u	1043	371						

Table 3.3. Vowel space, F2 and F1 distance values for the NH and HI groups (left section), and F2 and F1 difference and vowel distance values between the corresponding vowels of the two hearing groups (right section). The asterisk [*] denotes statistically significant difference (p<.05).

The following calculations are performed:

Within group

vowel space: vowel surface or area (in Hz^2) calculated using the formula abs((xB*yA-xA*yB)+(xC*yB-xB*yC)+(xA*yC-xC*yA))/2,

where x=F2mid, y=F1mid, A=[i], B=[a] and C=[u].

width ([i]–[u]) or F2 difference: absolute F2mid difference between [i] and [u] within group

height ([i]–[a]) or F1 difference: absolute F1mid difference between [i] and [a] within group

Between groups

F2 difference: absolute F2mid difference between NH & HI within vowel and the

F1 difference: absolute F1mid difference between NH & HI within vowel

vowel distance: square root of F2 difference raised to the second power plus F1 difference raised to the second power, illustrated in Fig. 3.21. with a bold line.

The F1 and F2 formant values were subsequently normalized using the modified Watt & Fabricius method *(ModWF* or *mW&F),* available via the online normalization 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 very recent study that compared twenty different vowel formant normalization 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). The authors report that vowel-intrinsic methods performed poorly, while the best methods were vowel-extrinsic, formant-intrinsic, speaker-intrinsic. Thus, the mW&F method was selected for our study as it is a vowel-extrinsic, formant-intrinsic, speaker-intrinsic method and was assessed as the most effective in equalizing and aligning vowel spaces along with the Bigham method (Flynn & Foulkes, 2011; Watt & Fabricius, 2011). An advantage of the mW&F method is that it performs well without requiring data from the entire vowel space but rather from the vertices of a triangular vowel space (Fabricius, Watt & Johnson, 2009). In addition, it does not require F3 measurements like the *Bark Difference Metric*.

Thus, besides the vowel distribution and space plots described above, normalized vowel distribution plots are also provided using the Vowel Normalization Suite 1.1. (online tool). Plots demonstrating mean values also include vowel ellipses drawn with radii of two standard deviations. Vowel space plots computed from the means provided by NORM are also created and the triangle areas are calculated by entering the normalized Hz values in the formula abs((xB*yA-xA*yB)+(xC*yB-xB*yC)+(xA*yC-xC*yA))/2, as with un-normalized Hz values.

3.2.5.4. Duration Measurement

Duration measurements in the [pV_1CV_2] sequences were taken for pre and post consonantal vowels and intervocalic consonants. These measurements were taken automatically by the program on the basis of the boundaries placed in the disyllable (as described in Section 3.2.4.). The script rendered one duration measurement for each vowel of the disyllable and one measurement for the fricative or two for the plosive (closure and release phase). Vocalic duration results are reported in this thesis.

3.3. The Pilot Study[25]

The main purpose of the Pilot Study was to analyse part of the data we had recorded from the 5 NH speakers and the 14 HI speakers (see Section 3.2.1.1.), so as to get a preliminary idea on how hearing level influences vowel space, vowel duration and coarticulation degree and extent. In addition, it would provide a basis for the final choice of the subjects that would form the HI group of our main study. Our aim was to create one hearing impaired group based on hearing level as homogeneous as possible. As mentioned in Section 3.2.1.1., the fourteen HI subjects we recorded had been categorized in three groups; in Group A (hearing loss >100 dB) and B (91-99 dB) subjects were profoundly hearing impaired (PHI), and in Group C (76-90 dB) subjects were severely hearing impaired (SHI). We needed to find out whether the SHI group displayed statistically significant differences from the other two groups and whether the subjects of the two PHI groups behaved similarly enough so that they could merge into one group, the HI group of the main study.

3.3.1. The method

For the pilot study we chose to analyse a selection of disyllables produced by half of our subjects. Two NH speakers and six HI speakers from the total number of speakers recorded were chosen. The HI were selected so that three HI subgroups were formed, each containing 2 subjects, one male and one female from Group A and Group B, and two males from Group C, as all four subjects of that group were male.

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[25] This study was presented at the 25th Annual Meeting of the Department of Linguistics of the Aristotle University of Thessaloniki (7-9 May, 2004) with the title “Akoustika haraktiristika ton akreon fonienton [i, a, u] kai i sinarthrotiki epirroi ton simfonon [t] kai [s] analoga me to vathmo varikoias stin omilia 8 Ellinon enilikon” (Acoustic characteristics of quantal vowels [i, a, u] and coarticulatory effects from [t] and [s] according to degree of hearing loss in the speech of 8 Greek adults).

Hence the three HI subgroups were:

Subgroup PHI1: Subjects HI_03 & HI_06 (from Group A)

Subgroup PHI2: Subjects HI_09 & HI_10 (from Group B)

Subgroup SHI: Subjects HI_11 & HI_14 (from Group C)

The control sub-group consisted of one male and one female subject (subjects NH_01 & NH_02) from our original control group.

The material chosen from the original corpus comprised of the selected disyllables [ˈpaCa], [ˈpaCi], [ˈpaCu], [ˈpiCa] and [paˈCa], [paˈCi], [piˈCa], where C= [p, t, s]. Four repetitions out of the original 10 were analysed, hence the total number of disyllables was 672 per subject (see Section 3.2. for recording technique and set-up).

F1 & F2 measurements were made at V_1 and V_2 onset, midpoint and offset and duration measurements of V1 & V2 were also made (see Sections 3.2.4. and 3.2.5.1.). Vowel spaces were measured in Hz^2 (see Section 3.2.5.3.) separately for each individual and comparisons were made between NH and HI subjects of the same gender. Vowel duration was analysed vs. hearing, vowel type and stress. Finally, anticipatory and carryover coarticulatory effects on the F2 were measured at vowel onset, midpoint and offset and statistically significant differences between the control group and each HI group as well as among the three HI groups were investigated using Minitab Statistical Software for ANOVAs and additional SNK post-hoc tests.

3.3.2. The results

Below we present briefly the main results of the pilot study.

Vowel space

- The HI vowels were more centralised resulting in a smaller vowel space in comparison with that of the control group (NH).
- The less the degree of hearing loss, the more expanded and closer to normal was the HI vowel space. In Fig. 3.22. we observe that the vowel area (in Hz^2) sequence from wider to smaller is NH>HI3>HI2>HI1 which coincides with the degree of hearing loss of the speakers in each HI subgroup; for example, the vowel area of speakers in subgroup HI3, who have the lowest degree of hearing loss, is the widest and closest to that of the NH. These results agree with McCaffrey & Sussman (1994:949) who found less difference in F0, F1, F2 and F3 frequency measures between speakers with NH and severe hearing loss than between these two groups and speakers with profound hearing loss.

Duration

- The durations of the three vowels produced by the HI subgroups were longer than the corresponding NH vowel durations (see Fig. 3.23.).
- For both the NH subgroup and all the HI subgroups, stressed vowels ([i] and [a]) were significantly longer than their unstressed counterparts. (Vowel [u] was in the unstressed condition only in the pilot data).
- The difference in duration between a NH vowel and a HI vowel was statically significant regardless of vowel type.

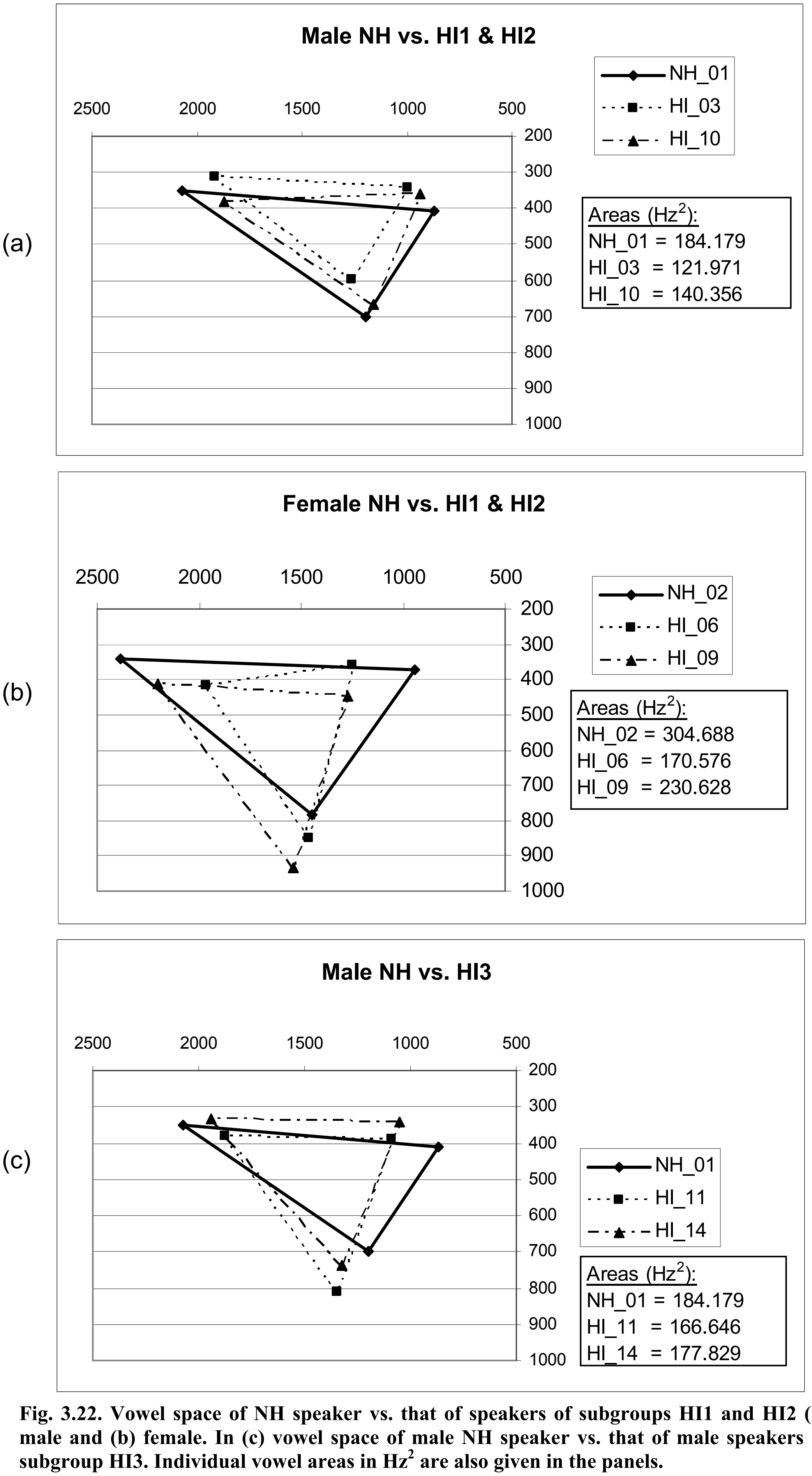

Fig. 3.22. Vowel space of NH speaker vs. that of speakers of subgroups HI1 and HI2 (a) male and (b) female. In (c) vowel space of male NH speaker vs. that of male speakers of subgroup HI3. Individual vowel areas in Hz^2 are also given in the panels.

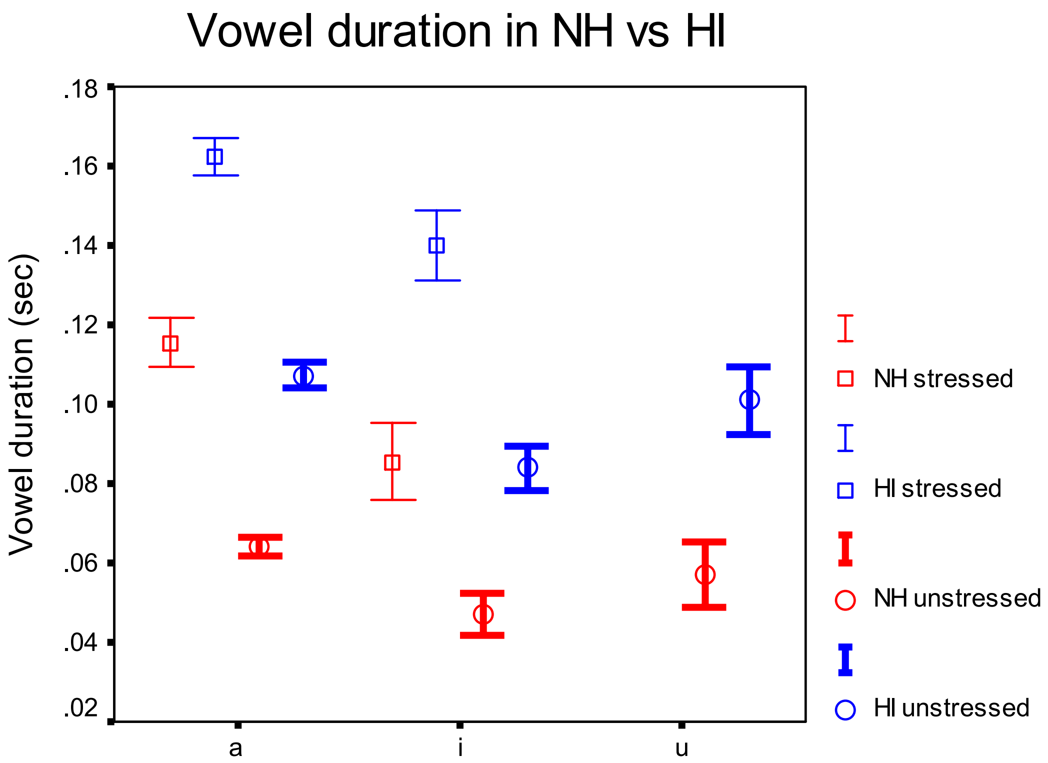

Fig. 3.23. Vowel duration (in sec) of the three vowels [i], [a] and [u] produced by the NH subgroup and the three HI subgroups (mean value).

Coarticulation

- Regarding V1 offset and V2 onset, significant anticipatory and carryover coarticulatory effects respectively were detected for all groups when comparing the bilabial with the alveolar context, both stop and fricative. However, the NH and SHI (severely hearing impaired) subgroups did not show any significant differences between the two alveolar contexts, as opposed to the two profoundly hearing impaired subgroups, PHI1 and PHI2 (see Fig. 3.24. for carryover effects at V2 onset).
- The extent of C-to-V coarticulation was limited to V_1 offset (anticipatory) and V_2 onset (carryover) for subgroups PHI1 & PHI2, whereas for the NH it reached vowel midpoint in both directions and from both consonants, [t] and

[s], and for SHI it extended from V_1 midpoint to V_2 offset regarding [t] and from V_1 offset to V_2 midpoint regarding [s] (see Fig. 3.25).

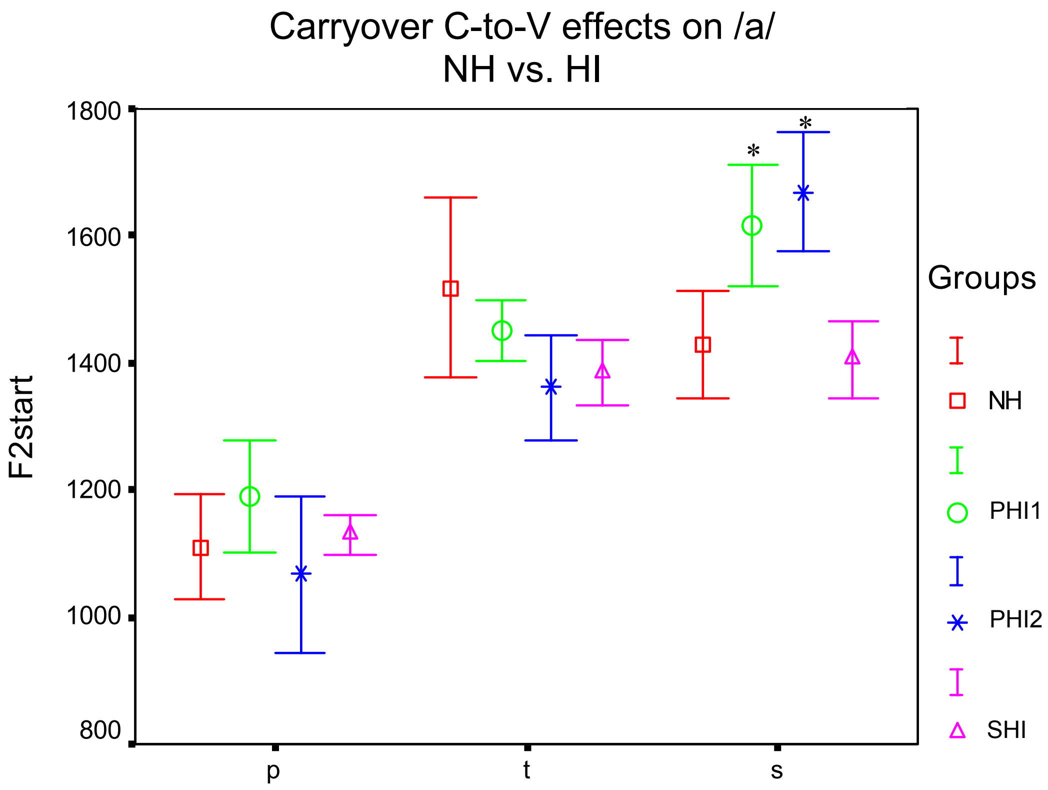

Fig. 3.24. C-to-V carryover effects of consonants [p], [t] and [s] on the F2 formant at the onset of the second [a] in [paCa] as produced by the NH subgroup and the three HI subgroups. The asterisk [*] denotes statistically significant difference between alveolar stop and alveolar fricative (p<.05).

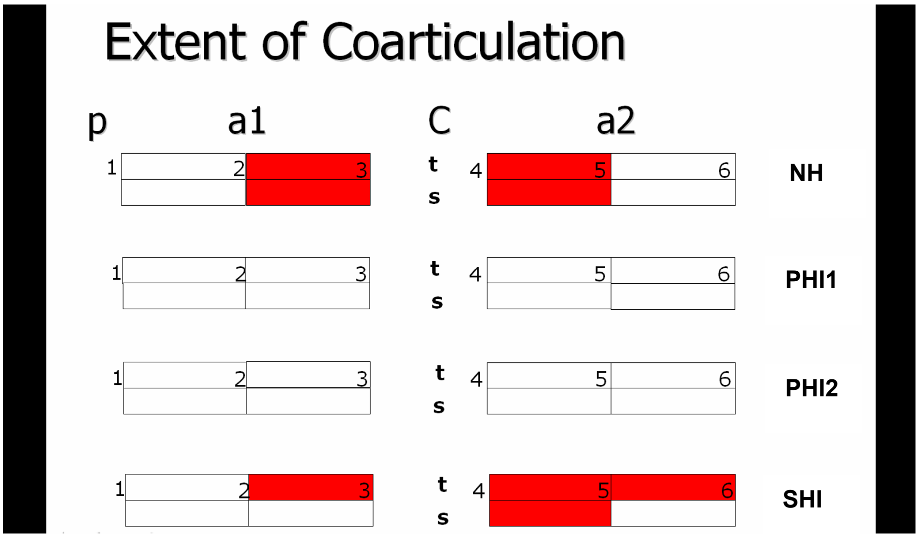

Fig. 3.25. Schematic representation of the extent (highlighted regions) of anticipatory (points 1, 2, 3) and carryover (points 4, 5, 6) coarticulatory effects from [t] and [s] on vowel [a] in symmetrical disyllables [paCa] produced by the NH and the three HI subgroups. Measurements and statistical analyses at six points in the disyllable showed that for the NH, C-to-V effects extend to vowel midpoint (points 2 to 5), whereas for the two PHI groups effects are only significant at vowel onset and offset (points 3 and 4). The SHI display greater coarticulation extent than the PHI resembling up to a point that of the NH.

Consequently, we concluded that subgroup SHI, and therefore the initial Group C (severely hearing impaired), displayed significantly different coarticulatory behaviour from the PHI groups, and therefore the initial Groups A and B (profoundly hearing impaired), and resembled more closely the control group (NH). Subjects in the PHI groups, and therefore in the original Groups A and B, shared a lot of similarities in relation to vowel space area, vowel duration and coarticulatory effects and diverged from the control group. These results are in agreement with Vakalos (2009) for Greek and Ryalls & Larouche (1992) for French speakers with mild or moderate to severe HI (section 2.3.2.). Hence, we concluded that the experimental group of the main study could consist of speakers in Groups A & B but not of speakers in Group C.

3.4. The Intelligibility Experiment

3.4.1. The subjects

The fourteen HI subjects who originally took part in the Acoustic Experiment described in Section 3.2. also participated in an Intelligibility Experiment in order to determine the intelligibility of their speech and include it as a factor in our design. On the basis of the results of the pilot study, the 4 subjects with a severe hearing loss of 76 to 90 dB (Group C) were excluded (Section 3.3.), hence the recordings of the rest of the 10 subjects were rated by 60 listeners. The speech of subject HI_04 (who was later omitted from the main study) was also rated and her intelligibility score was one of the main reasons for her exclusion from the final HI group (see Section 3.4.6.).

3.4.2. The corpus

The corpus consisted of 101 words and 25 sentences (Appendix 1.6.). The words were adopted from the Phonetic and Phonological Development Test developed[26] by the Panhellenic Association of Logopedists and Speech & Language Therapists (PAL). We decided to include a section with sentences as well, because listeners make better judgements when words are in context, as it promotes intelligibility (McGarr, 1981). In addition, 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 subjects' intelligibility level. The sentences were 8 to 14 syllables long and contained all Greek phonemes and frequently used clusters, both in word-initial position.

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[26] 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.

After the end of the recording for the Acoustic Experiment, the HI subjects were asked to read the words and sentences for the Intelligibility Experiment and were recorded following the procedure described in Section 3.2.3.

3.4.3. The listeners

Sixty naïve listeners participated in the experiment. As noted by Okalidou (2002:63), the recruitment of inexperienced listeners for HI speech intelligibility assessment is a widely accepted. Each listener heard the speech of one subject with HI only. Each intelligibility score was an average of six listeners. The listeners were undergraduate and postgraduate students of the School of English of the Aristotle University of Thessaloniki. They had never knowingly heard HI speech prior to the experiment and had normal hearing.

3.4.4. The experimental procedure

After the recording of the material, the words and sentences were cut so as to create 101 word files and 25 sentence files for every subject. A program in DOS language was written so as to play back first the words and then the sentences in random order. The sixty judges were divided into twenty groups of three. Two groups (six listeners in total) listened to the material for each HI subject. The material was randomized once for every subject, so both groups heard the material in the same order.

The listeners were given an answer sheet with two sections, one mandatory and the other optional (Appendix 1.7.). Every item was repeated twice, one playback immediately after the other. The judges listened to both repetitions carefully without writing. Afterwards, if they recognized the item, they were asked to write it down in the first section. Regarding sentences, if they could not understand the whole sentence, they were asked to write down the words they recognized. If an item was not understood, they would leave the corresponding space blank in the first section.

In the second section, if listeners did not recognize an item, they were instructed to write exactly what they heard the subject uttering in Greek spelling[27], if they wished. This section was optional. Our scoring would rely on the first section only. We included the option of the second section after running the intelligibility experiment with three test listeners. We observed that although the test listeners had been instructed to write down what they understood only, they felt they had to also write what they heard, especially when the item was not recognized. Hence we decided to provide two separate sections to clarify the distinction, and only score the first section.

Thus, regarding the first section, if a word/sentence was recognized, the listener would write it down. If not, then the corresponding space in that section would remain blank. The playback of each item was controlled by the researcher so that ample time was given to the listeners after the two repetitions to write down what they had understood, and optionally what they had heard exactly.

3.4.5. The scoring

As mentioned above, the intelligibility test consisted of two parts. The first part included 101 words and the second part 25 sentences. Taking into account scoring systems devised for English intelligibility tests (Monsen, 1978; 1983a;

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[27] The listeners were not required to have training in phonetic transcription.

Picheny, Durlach & Braida, 1985; Osberger et al., 1993), responses were scored as follows.

For both the first and second part of the test, each word was scored as either correct or incorrect, regardless of the number of correct phonemes. For example, ˈvimata (steps) instead of ˈcimata (waves) was allowed no points.

Nevertheless, incorrect tense or person of verb and number of noun were scored as half correct (Monsen, 1978; 1983a; Picheny et al., 1985). Examples:

- 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)

Concerning the second part of the test, as a pilot analysis, subject's HI_03 responses were scored in two different ways described in the literature to see which one would be more appropriate for our data. Subject HI_03 was chosen because his speech was neither highly nor poorly intelligible.

The first method we tried was similar to Monsen's (1978; 1983a). According to this scoring system, all sentences are equal in value regardless of length or difficulty. Words that contribute heavily toward the total message of the sentence are accorded a higher percentage of the total sentence score. Hence, each sentence is assigned a value of 100%, out of which, 70% is accorded to the content words and 30% to the function words of the sentence. Function words include definite articles (o, i, to: the, three genders), indefinite articles (ˈenas, ˈmia: one, male and female), clitics (ton: the, male), pronouns (afˈti: her) prepositions (se, me, ˈmesa: at, with, in), conjunctions (ˈotan: when), negation (min: don’t) and modal verbs (ˈiçe: had, third person).

There is a slight difference between Monsen’s system and our first method. According to Monsen’s weighting system, words can be assigned different values depending on their semantic contribution to the sentence in which they occur. So, in Monsen’s system, not all content words or all function words of a sentence are assigned the same value. For example, “The (5%) coat (30%) was (5%) made (25%) by (5%) hand (30%)” or “Did (20%) you (10%) steal (50%) it (20%)?” Thus, depending on their semantic contribution and their frequency of occurrence in the language, words are assigned slightly different values (Monsen, 1983a: 290). We, on the other hand, decided to keep the fixed percentage 70% for content words and 30% for function words for each sentence. Thus we found that the averaged intelligibility (6 judges) of subject HI_03 is 81%.

For our second method, we followed Osberger et al. (1993), who score the judges’ responses 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. Using this method we found that the average intelligibility of subject HI_03 is 80.8%. Hence, our pilot data also show that weighted and unweighted scores give almost the same result. Hence, we decided to use the Osberger method for simplicity reasons.

The information on listeners’ answer sheets were transferred to the scoring sheet (Appendix 1.8.) of the corresponding subject where answers were scored as described above and then averaged over 6 listeners for each subject.

3.4.6. The results

The scoring procedure rendered the results in Table 3.4. below. The result for each subject is based on an average of 6 listeners. We note that all subjects except HI_04 scored higher in sentences than in isolated words. Subject HI_04 had a very low performance.

Subject	Sex	HL (Better Ear)	Score		Total score
			Words	Sentences	
HI_01	F	101.7 (L)	95%	96%	96%
HI_02	F	101.6 (L)	96%	99%	98%
HI_03	M	103.3 (R)	68%	81%	75%
HI_04	F	105 (L)	16%	14%	15%
HI_05	M	101 (L)	62%	84%	73%
HI_06	F	103.3 (L)	89%	91%	90%
HI_07	M	98.3 (L)	87%	96%	92%
HI_08	M	99 (L)	83%	94%	89%
HI_09	F	91.7 (L)	83%	90%	87%
HI_10	M	98.3 (L)	89%	97%	93%

Table 3.4. The intelligibility score (%) in words, sentences and the average of both (total score) achieved by the HI subjects. Information about gender and hearing level is also provided. Subject HI_04 (highlighted) scored much lower than all other subjects.

On the basis of the above results the HI subjects were divided into 4 groups with intelligibility level ranging from medium to very high (Table 3.5.). It is noteworthy that all subjects except HI_04 scored above 60%, with a mean intelligibility score of 88%, while HI_04 scored below 20%. This notable divergence in intelligibility from that of the rest of the group, as well as significant differences in the acoustic characteristics of her speech, lead to the exclusion of subject HI_04 from the statistical design of the main study. Thus, Fig. 3.26. presents the three final intelligibility groups, very high intelligibility (subjects HI_01 & HI_02, both female), high intelligibility (subjects HI_06, HI_07, HI_08, HI_09, HI_10, 2 female and 3 male) and medium intelligibility (HI_03 & HI_05, both male). The intelligibility scores in our study are generally higher than those found by other researchers (Markides, 1983; Rubin, 1985; Abraham, 1989), probably reflecting differences in materials as well as subject variables such as age of amplification, hearing aid use, intervention type and duration, schooling, etc.

Group	HI Subjects	Intelligibility	
1	HI_01, HI_02	words >90%, sentences >95%	very high
2	HI_06, HI_07, HI_08, HI_09, HI_10	words 80-89%, sentences 85-97%	high
3	HI_03, HI_05	words 60-69%, sentences 81-84%	medium
4	HI_04	both words and sentences <20%	very low

Table 3.5. HI subjects divided into groups according to Intelligibility level based on their word and sentence score (%).

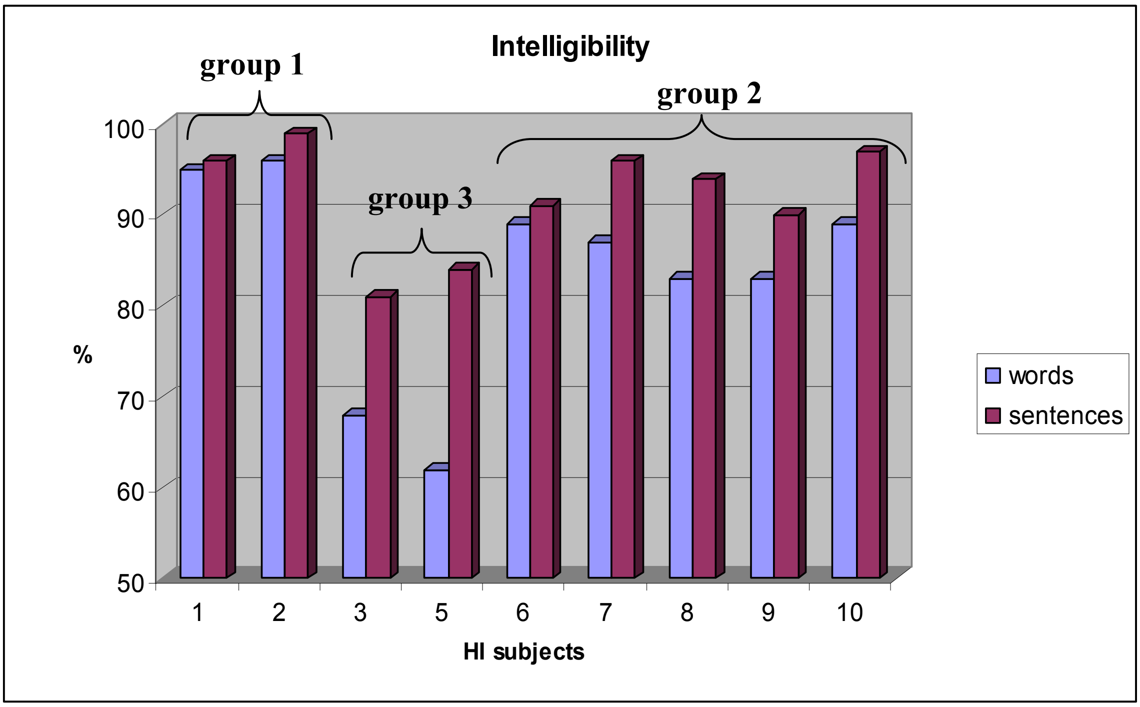

Fig. 3.26. The three intelligibility groups as well as word & sentence score (%) of each subject.

3.5. Statistical Analyses

F1 and F2 measurements as well as duration measurements of the vowels produced by all subjects were inserted in the SPSS Statistics package (version 17) in the form of six formant variables according to type of formant and point of measurement, and one duration variable (Table 3.6.). In addition, six different factors were set according to hearing level, intelligibility level, gender, measured vowel, transconsonantal vowel, consonant identity, stress condition of measured vowel, measured vowel's position in the disyllable (Table 3.7.).

3.5.1. Part 1: Coarticulatory Effects on the F1 and F2 at vowel midpoint and on vowel duration

The aim of this part is to provide an acoustic description of vowels in the F1xF2 plane and determine which of the factors and in what way influence the quality and duration of the measured vowel. Therefore, separate univariate analyses of variance (ANOVAs) were run for variables F1mid, F2mid only, so as to provide a description at the steady state of the vowel, C-to-V effects in symmetrical vowel environments, and Duration, using two models; the first model included all factors except for 'intelligibility' (Appendix 2.2., Tables 2, 5 and 13) and the second model, all factors except for 'hearing'[28] (Appendix 2.2., Tables 8, 11 and 14). We then examined all interactions relative to our research questions and performed post hoc tests to find statistical differences between groups. For example, in order to answer how consonantal environment influences F2mid of the two hearing groups, we looked at hearing * measured vowel * transconsonantal vowel * consonant.

Concerning the second model, we note that interactions including both factors "intelligibility" and "gender" cannot be examined, as two out of the four levels of

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[28] 'Hearing' and 'intelligibility' cannot coexist in the same model because they are nested factors.

intelligibility consist only of one gender. Level 1 (very high intelligibility group) includes two females and level 3 (medium intelligibility group) two males. Thus, not all combinations between the levels of the two factors exist, rendering their interactions statistically invalid. Also, statistical comparisons of F1mid and F2mid values between the intelligibility level 1 (very highly intelligible) and the level 3 (moderately intelligible) groups are not applicable as male and female formants have different ranges. Duration comparisons, though, are valid among all groups.

Variables	Description
F1start	F1 measurement at measured vowel onset
F1mid	F1 measurement at measured vowel midpoint
F1end	F1 measurement at measured vowel offset
F2start	F2 measurement at measured vowel onset
F2mid	F2 measurement at measured vowel midpoint
F2end	F2 measurement at measured vowel offset
Duration	Duration of measured vowel

Table 3.6. Variables for models 1 & 2.

Factors	Levels	Description
hearing	2	1 NH (normal hearing) 2 HI (hearing impaired)
intelligibility	4	1 very high 2 high 3 medium 4 NH (normal hearing)
gender	2	1 male 2 female
measured vowel	3	1 [i] 2 [a] 3 [u]
transconsonantal vowel	3	1 [i] 2 [a] 3 [u]
consonant	3	1 [p] 2 [t] 3 [s]
stress	2	1 stressed measured vowel 2 unstressed measured vowel
position	2	1 measured vowel in 1st syllable 2 measured vowel in 2nd syllable

Table 3.7. Factors for models 1 & 2.

3.5.2. Part 2: V-to-V Coarticulation

3.5.2.1. Effects of Hearing and Context on V-to-V Coarticulation

For this section, the first model (hearing, measured vowel, transconsonantal vowel, consonant, stress, position) was used in univariate ANOVAs for each one of the six formant variables (Appendix 2.2., Tables 1-6). After checking the statistical significance for each factor, we looked at the interaction: hearing* measured vowel* transconsonantal vowel* consonant* position and proceeded with Tukey pairwise comparisons, using Minitab Statistical Package version 15, in order to locate in which vocalic and consonantal contexts coarticulatory effects appeared within each group. This was accomplished by comparing corresponding formant values of the measured vowel in disyllable pairs to find statistical significance.

After locating the contexts where coarticulation was significant for each group, we needed to compare these effects to find out if they differed statistically. To accomplish that, we computed six coarticulation variables based on the variables in Table 3.6. (above). The values of these new variables were the result of the subtraction of the formant value of the fixed vowel of the symmetrical disyllable, e.g., the first [a] in [apa], minus the value of the corresponding vowel in the disyllable containing a different vowel whose influence we wish to examine, e.g., the first [a] in [api], if we wish to measure the anticipatory effect of [i] on [a]).

Table 3.8. presents the coarticulation variables. As a consequence, two of the factors in Table 3.7. merge into one, i.e., measured vowel and transconsonantal vowel become ‘V-to-V’. This is a six level factor ([i]-to-[a], [u]-to-[a], [a]-to-[i], [u]-to-[i], [a]-to-[u] and [i]-to-[u]). Additionally, the factor ‘position’ becomes ‘direction’, as V-to-V effects on the 1st syllable are anticipatory effects and effects on the 2nd syllable are carryover effects.

The aforementioned variables and the factors hearing, gender, V-to-V, consonant, stress and direction (excluding intelligibility) constituted the third model (Table 3.8 & Table 3.9.). Univariate ANOVAs were carried out and the statistical significance of all factors was examined (Appendix 2.2., Tables 15-20). Afterwards, we looked at the interaction hearing * V-to-V * consonant * direction, so as to determine which coarticulatory effects are statistically different between the NH and the HI. This additional examination was performed with Tukey pairwise comparisons only at measurement points where coarticulatory effects had been found significant for the two groups.

CA Variables	Description
ΔF1start	Difference of F1start of fixed vowel at onset
ΔF1mid	Difference of F1mid of fixed vowel at midpoint
ΔF1end	Difference of F1end of fixed vowel at offset
ΔF2start	Difference of F2start of fixed vowel at onset
ΔF2mid	Difference of F2mid of fixed vowel at midpoint
ΔF2end	Difference of F2end of fixed vowel at offset

Table 3.8. Coarticulation variables for model 3, based on the subtraction of corresponding formants of the fixed vowel in disyllable pairs at the same point of measurement.

Factors	Levels	Description
hearing	2	1 NH (normal hearing) 2 HI (hearing impaired)
intelligibility	4	1 very high 2 high 3 medium 4 NH (normal hearing)
gender	2	1 male 2 female
V-to-V	6	1 [i]-to-[a] 2 [u]-to-[a] 3 [a]-to-[i] 4 [u]-to-[i] 5 [a]-to-[u] 6 [i]-to-[u]
consonant	3	1 [p] 2 [t] 3 [s]
stress	2	1 stressed fixed vowel 2 unstressed fixed vowel
direction	2	1 anticipatory 2 carryover

Table 3.9. Factors for Coarticulation Variables used in models 3 & 4.

3.5.2.2. Effects of Stress, Gender and Intelligibility on V-to-V Coarticulation

We examined the effects of stress and gender separately using the following procedure. Firstly, we ran ANOVAs according to the first model (Table 3.6. & Table 3.7.) to find out if stress and gender are significant factors (Appendix 2.2, Tables 1-6). Subsequently, we located the contexts in which significant coarticulation effects existed for the two hearing groups a) in the two stress conditions and b) for the two genders, by performing Tukey pairwise comparisons in the interactions hearing* measured vowel* transconsonantal vowel* consonant* position* stress and hearing* measured vowel* transconsonantal vowel* consonant* position* gender. Finally we examined whether the presence of stress or the type of gender had an influence on coarticulatory effects by running ANOVAs for the coarticulation variables (Table 3.8.) according to the third model (Table 3.9.) (Appendix 2.2., Tables 15-20) and executed Tukey post hoc tests in the interaction hearing* V-to-V* consonant* direction* stress and hearing* V-to-V* consonant* direction* gender.

In order to examine whether intelligibility influences coarticulation, we first had to find out in which contexts coarticulatory effects appeared for each intelligibility group. Hence we ran univariate ANOVAs for the six original variables (Table 3.6.) using the second model: intelligibility, measured vowel, transconsonantal vowel, consonant, stress and position (Table 3.7.) (Appendix 2.2., Tables 7-12). After checking the statistical significance of the factors involved, we looked into the interaction intelligibility* measured vowel* transconsonantal vowel* consonant* position and performed Tukey post hoc tests, in order to detect the effects for each group. Subsequently we ran ANOVAs for the coarticulation variables (Table 3.8.) and used a fourth model including intelligibility, gender, V-to-V, consonant, stress and direction (excluding hearing), in order to see whether intelligibility was a significant factor for coarticulation (Appendix 2.2., Tables 21-26). For those variables that it was, we looked at the interaction intelligibility* V-to-V* consonant* direction and ran Tukey post hoc tests to find out if there were any statistical differences among the intelligibility groups.

In the Results chapter we will be reporting statistical results according to the model used for each section. Table 3.10. below provides a summary of our statistical design. Appendix 2.3. contains V-to-V Coarticulation Tables with information about significant effects according to the major factors.

Subject	Model	Variables	Factors
Acoustic Description (hearing)	1	F1mid, F2mid, Duration	hearing, gender, measured V, transcons. V, C, stress, position
Acoustic Description (intelligibility)	2	F1mid, F2mid, Duration	intelligibility, gender, measured V, transcons. V, C, stress, position
V-to-V Coarticulation in Hearing Groups (Effect of Context)	1	F1start, F1mid, F1end, F2start, F2mid, F2end	hearing, gender, measured V, transcons. V, C, stress, position
Effect of Hearing on V-to-V Coarticulation (between groups differences)	3	ΔF1start, ΔF1mid, ΔF1end, ΔF2start, ΔF2mid, ΔF2end	hearing, gender, V-to-V, C, stress, direction
V-to-V Coarticulation in different Stress conditions & Gender groups	1	F1start, F1mid, F1end, F2start, F2mid, F2end	hearing, gender, measured V, transcons. V, C, stress, position
Effect of Stress and Gender on V-to-V Coarticulation	3	ΔF1start, ΔF1mid, ΔF1end, ΔF2start, ΔF2mid, ΔF2end	hearing, gender, V-to-V, C, stress, direction
V-to-V Coarticulation in Intelligibility Groups (Effect of Context)	2	F1start, F1mid, F1end, F2start, F2mid, F2end	intelligibility, gender, measured V, transcons. V, C, stress, position
Effect of Intelligibility on V-to-V Coarticulation (between groups differences)	4	ΔF1start, ΔF1mid, ΔF1end, ΔF2start, ΔF2mid, ΔF2end	intelligibility, gender, V-to-V, C, stress, direction

Table 3.10. Summarized Statistical Design

Chapter 4

Results –Part 1

Vowel space, Duration and Consonant-to-Vowel Coarticulation

In Part 1 of the study, F1 and F2 measurements at the midpoint (steady state) and duration measurements of the three quantal vowels [i], [a] and [u] are examined statistically, so as to determine which factors influence vowel quality and vowel duration.

Separate GLM ANOVAS were run for F1mid and F2mid vs. the factors hearing, gender, measured vowel, transconsonantal vowel, consonant, stress and position (Appendix 2.2., Tables 2 & 5). Subsequently, additional ANOVAS were run replacing “hearing” with “intelligibility”, as these two are nested factors, and including all the rest (Appendix 2.2., Tables 8 &11). The same procedure was followed for the variable “duration” (Appendix 2.2., Tables 13 & 14). Residual normality and homogeneity were checked for all variables (Appendix 2.2., Plots 2, 5 & 7).

The statistical analyses of F1mid showed that all aforementioned factors are statistically significant [**hearing**: F(1, 15036)=462.173, p<.0001, **gender**: F(1, 15036)=12300.732, p<.0001, **vowel measured**: F(2, 15036)=67536.320, p<.0001, **transconsonantal vowel**: F(2, 15036)=24.286, p<.0001, **consonant**: F(2, 15036)=96.190, p<.0001, **stress**: F(1, 15036)=1608.664, p<.0001, **position**: F(1, 15036)=31.505, p<.0001)]. All factors influencing the F2mid variable were also found statistically significant [**hearing**: F(1, 15045)=156.453, p<.0001, **gender**: F(1, 15045)=9549.159, p<.0001, **vowel measured**: F(2, 15045)=75450.424, p<.0001,

transconsonantal vowel: F(2, 15045)=87.853, p<.0001, **consonant**: F(2, 15045)=872.675, p<.0001, **stress**: F(1, 15045)=50.672, p<.0001, **position**: F(1, 15045)=110.368, p<.0001)].

In the following sections we will look at:

1. vowel space and vowel distribution as a function of hearing, gender and intelligibility.
2. stress and position effects on the vowel space of the NH and the HI group.
3. effect of hearing, gender, intelligibility, stress, syllable position, consonantal and vocalic context on the duration of the three vowels.
4. C-to-V coarticulatory effects in the NH and the HI group[29].
5. stress effects on C-to-V coarticulation in the NH and the HI group.

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[29] V-to-V effects will be presented at all three measurement points of the vowel in Part 2 of the study.

4.1. Vowel Distribution and Vowel Space of Point Vowels

In this section we look at NH and HI mean formant values of the three vowels in symmetrical disyllables of bilabial context which is neutral as far as tongue involvement is concerned. In this way we limit noise in the data from phonetic context, as there are no transconsonantal influences from a different quality vowel and no constraints due to tongue constriction for the production of an intervening lingual consonant.

4.1.1. Hearing

Hearing interacts with measured vowel (hearing*measured vowel: F1mid: F(2, 15036)=61.897, p<.0001, F2mid: F(2, 15045)=2650.994, p<.0001). Using Tukey pairwise comparisons we examine whether F1mid and F2mid of the three vowels are statistically different between the two hearing groups in [pVpV] disyllables (Table 4.1.). Post hoc tests reveal that:

- Both the F1mid and F2mid of vowel [u] are significantly different between the two groups. The HI [u] is characterized by a lower F1mid (by a mean of 42 Hz) and a higher F2mid (by a mean of 324 Hz) in comparison to the NH [u].
- The vowel [i] is significantly different between the two hearing groups only in the F2 axis. The HI [i] has a lower F2mid by a mean of 192 Hz compared with the NH [i].
- Neither F1mid nor F2mid of vowel [a] are significantly different between the two groups, although both HI formant values are lower than the corresponding NH ones.

Measured Vowel	F1mid (StDev) in Hz				F2mid (StDev) in Hz			
	NH		HI		NH		HI	
i	369	(69)	357	(64)	*2265	(211)	*2073	(245)
a	802	(128)	759	(140)	1275	(162)	1259	(169)
u	*413	(73)	*371	(68)	*719	(99)	*1043	(156)

Table 4.1. Mean F1mid and F2mid values and standard deviations (StDev) in Hz of vowels [i], [a], [u] in both syllable positions of symmetrical pVpV disyllables produced by the NH and the HI group. The asterisk [*] denotes statistical significance (p<.05).

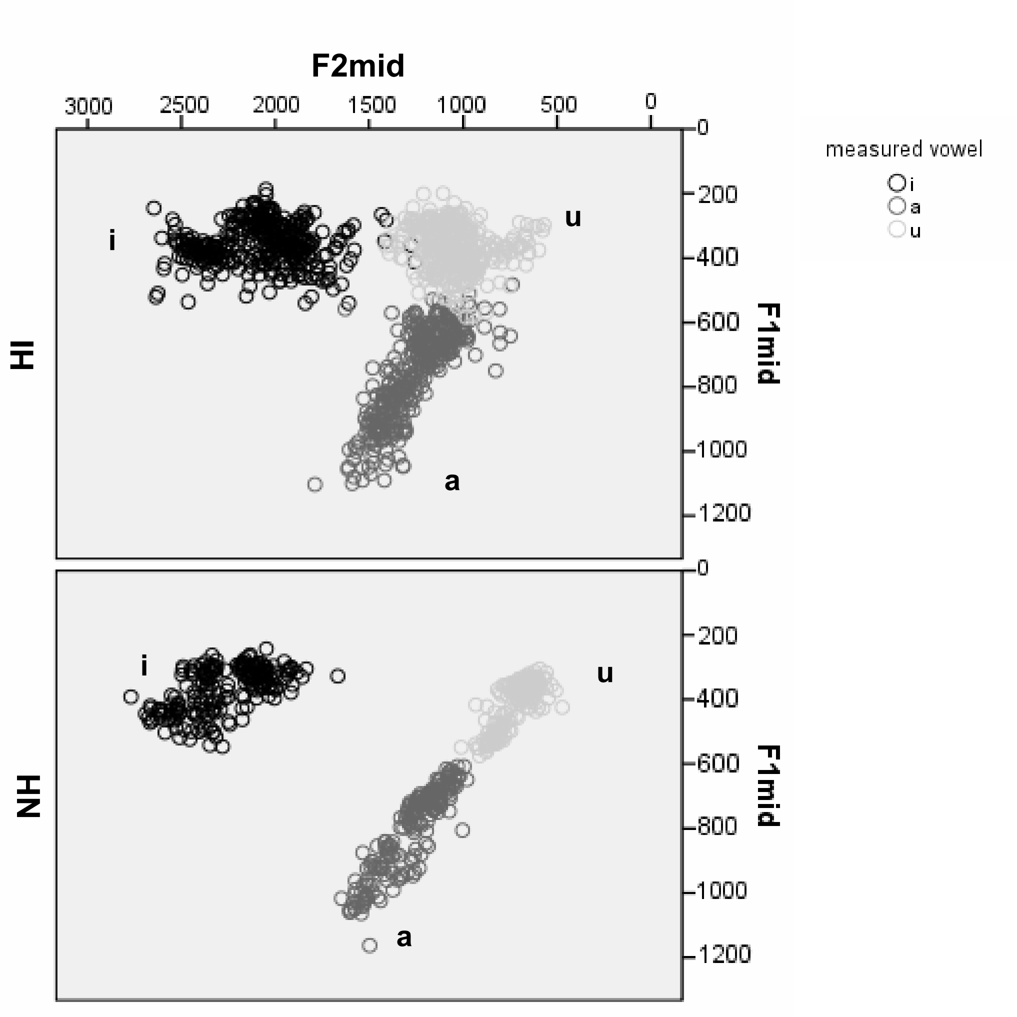


Fig. 4.1. Distribution of all vowel tokens in symmetrical disyllables of bilabial context ([pipi], [papa], [pupu]) produced by 5 NH subjects (bottom panel) and 9 HI subjects (top panel).

Fig. 4.1. demonstrates the distribution of F1mid and F2mid values of each vowel produced by the 5 NH and 9 HI speakers. It is evident that the HI [i] is more backed than the NH [i]. HI [u] is clearly fronted and its mean F1mid is higher in comparison to the corresponding NH values which could be related to a higher jaw and/or tongue position or

less opening of the mouth tract (Delattre, 1951:867). Vowel [a] is more similar between the two groups in terms of range of values and shape of dispersion. As a consequence of all the above, the three vowel sub-areas are distinct as far as the NH are concerned, but for the HI they are closer and show some overlap. The NH [i] is set quite apart from the other two vowels, while [a] and [u] are closer together but still distinct. On the other hand, HI [i] and [u] seem to converge on the F2 axis, and [u] and [a] show overlap on the F1 axis. Although not statistically significantly, F1mid of HI [a] is lower by a mean of 43 Hz in comparison to the NH one, which also plays a role in its overlap with HI [u] on the F1 axis.

Fig. 4.2. displays the normalized F1 and F2 values at the vowel midpoint using the modified Watt & Fabricius method or *ModWF* (section 3.2.5.3). Each symbol corresponds to a speaker mean. The ellipses were drawn with the radii of two standard deviations. A comparison between the NH in Fig. 4.2.(a) and the HI in Fig. 4.2.(b) below reveals that, after normalization, the overlap between [a] and [u] evident for the HI on the F1 axis (see Fig. 4.1. above) is eliminated. However, HI [i] and [u] still overlap partially along the F2 axis even after normalization. Additionally, as manifested by the size of the ellipses, NH vowels are less variable than HI vowels. For the NH, variability seems to decrease in the order [a] > [i] > [u]. For the HI, all vowels show increased variability, particularly observable in the F1 dimension for the low vowel [a] and in the F2 dimension for the high vowels [i] and [u].

(a)

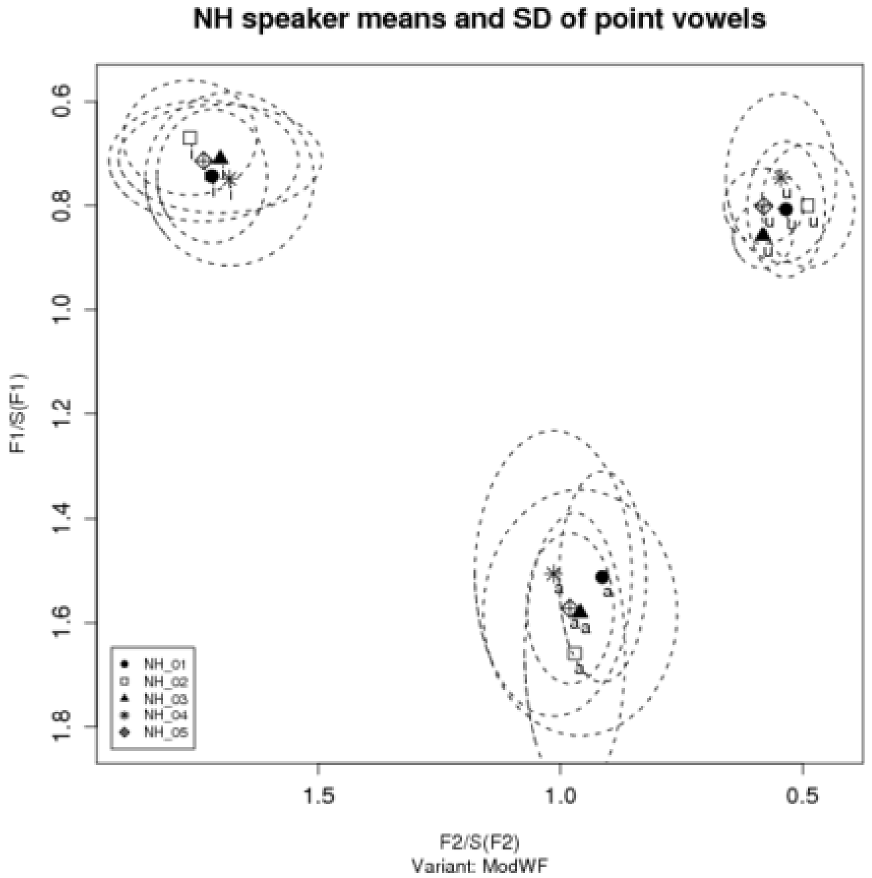
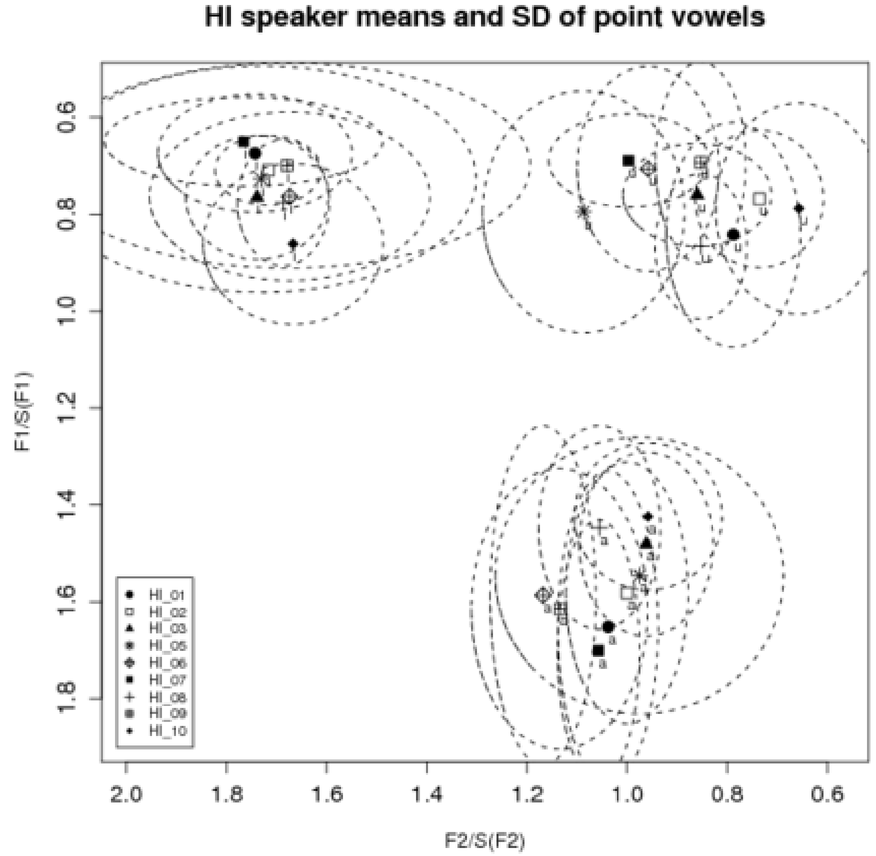


Fig. 4.2. Speaker means of normalized F1mid & F2mid formant values with the method *Watt & Fabricius modified*. All vowel tokens are in symmetrical disyllables of bilabial context ([pipi], [papa], [pupu]) produced by (a) 5 NH subjects (above) and (b) 9 HI subjects (below). The ellipses are drawn with radii of two standard deviations.

(b)



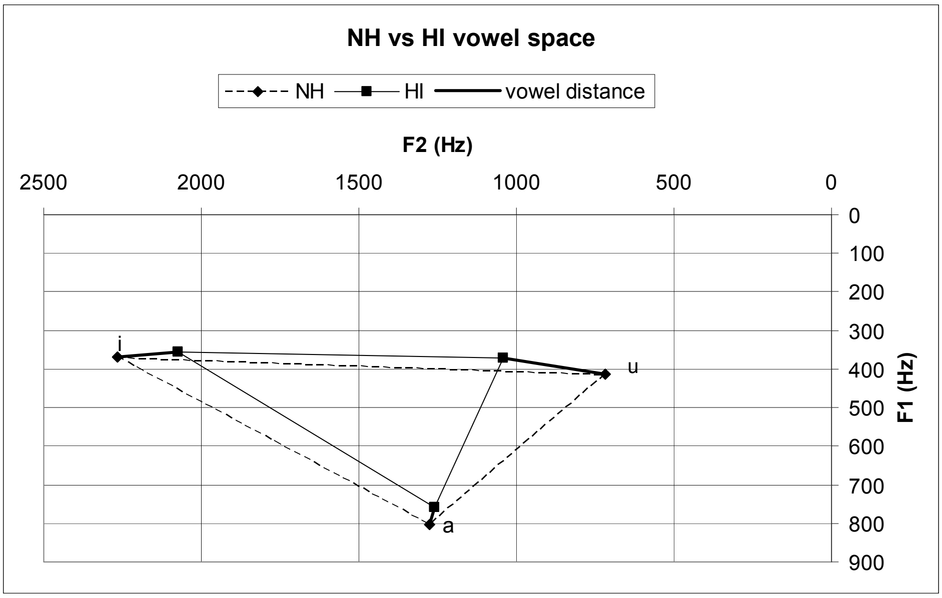


Fig. 4.3. NH (dashed line) and HI (solid line) vowel space and vowel distance (bold line) between the vowels of the two hearing groups.

	vowel	F2mid (Hz)	F1mid (Hz)	**vowel space** (Hz^2)	**Width (i - u)** F2 difference (Hz)	**Height (i - a)** F1 difference (Hz)	vowel	F2 difference (Hz)	F1 difference (Hz)	**vowel distance** (Hz)
NH	i	2265	369	312929	1546	433	i	*192	12	192
	a	1275	802				a	16	43	46
	u	719	413				u	*324	*42	327
HI	i	2073	357	201332	1030	402	*Between-hearing-groups comparison*			
	a	1259	759							
	u	1043	371							

Table 4.2. F2mid and F1mid values, vowel space, F2 (i-u) and F1 (i-a) difference values (width and height) for the NH and HI groups (left section). F2 and F1 difference and vowel distance values between the corresponding vowels of the two hearing groups (right section). The asterisk [*] denotes statistically significant difference (p<.05).

Fig. 4.3. shows the NH and HI vowel triangles based on mean formant values and Table 4.2. presents the vowel spaces (Hz^2) of the two triangles, the width and height of each triangle, as well as a comparison of the two which comprises the F2 and F1 difference of the three vowel points and the *vowel distance*; this is a measure that encompasses the difference in both F1 and F2 of a NH vowel and its HI counterpart (bold lines in Fig. 4.3.) (section 3.2.5.3).

Due to the HI [u] fronting and [i] backing, the HI [i-u] F2 difference (width of the triangle) is 1030 Hz, as opposed to 1546 Hz for the NH. Additionally, owing mostly to an [a] raising, the [i-a] F1 difference (height of the triangle) is 402 Hz for the HI, while for the NH it is 430 Hz. Hence the NH tend to produce more peripheral point vowels and their vowel space occupies a greater surface (312,929 Hz^2), as opposed to the more central and "shrunk" HI vowel space (201,332 Hz^2) which constitutes a 36% surface reduction. As mentioned above, the bold lines of NH and HI vowel distance in Fig. 4.3. as well as the values in the right section of Table 4.2. illustrate that these differences between the two hearing groups' vowel spaces are, for the most part, attributable to [u] fronting and [i] backing.

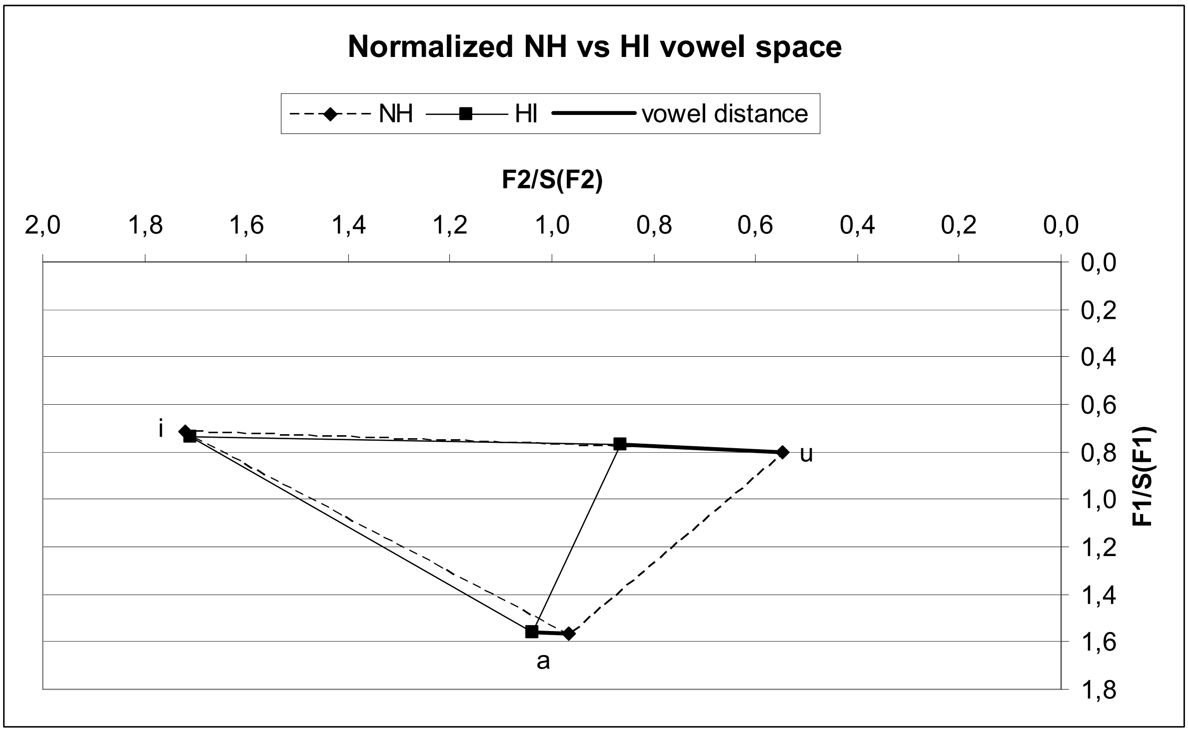


Fig. 4.4. Normalized NH (dashed line) and HI (solid line) vowel space and vowel distance (bold line) between the vowels of the two hearing groups.

Subsequent to ModWF normalization, the picture is somewhat different. The back vowel [u] still undergoes significant fronting for the HI, also observed in the un-normalized vowel space above. The low vowel [a] seems to sustain fronting rather than raising and the front vowel [i] is not more back for the HI as indicated in Fig. 4.3., but rather seems to retain its position in the acoustic space. The normalized surface occupied by the HI vowels is 28% smaller than that covered by the NH vowels, while before normalization it was 36% smaller. Thus, after normalization, HI surface is still reduced in comparison with NH surface, but the reduction is attributed primarily to [u] and secondarily to [a] fronting.

4.1.2. Hearing & gender

Looking at vowel distribution in the two genders of NH speakers in Fig. 4.5., we observe that in male speakers the vowel sub-areas are more concentrated, whereas female speakers show more variability, especially along the F1 axis. Nevertheless, both male and female NH groups have distinct vowel sub-areas. The same tendency for greater dispersion of female vowels can be discerned in the HI group as well. Although there is statistically significant [u] fronting and [i] backing for both male and female HI groups relative to the NH, the female HI speakers display separate vowel sub-areas. On the other hand, [u] and [i] areas partly overlap for male HI speakers. Additionally, HI male [a] is more raised in relation to the NH male [a], although not statistically significantly, whereas HI female [a] has a more similar range with the corresponding female NH [a].

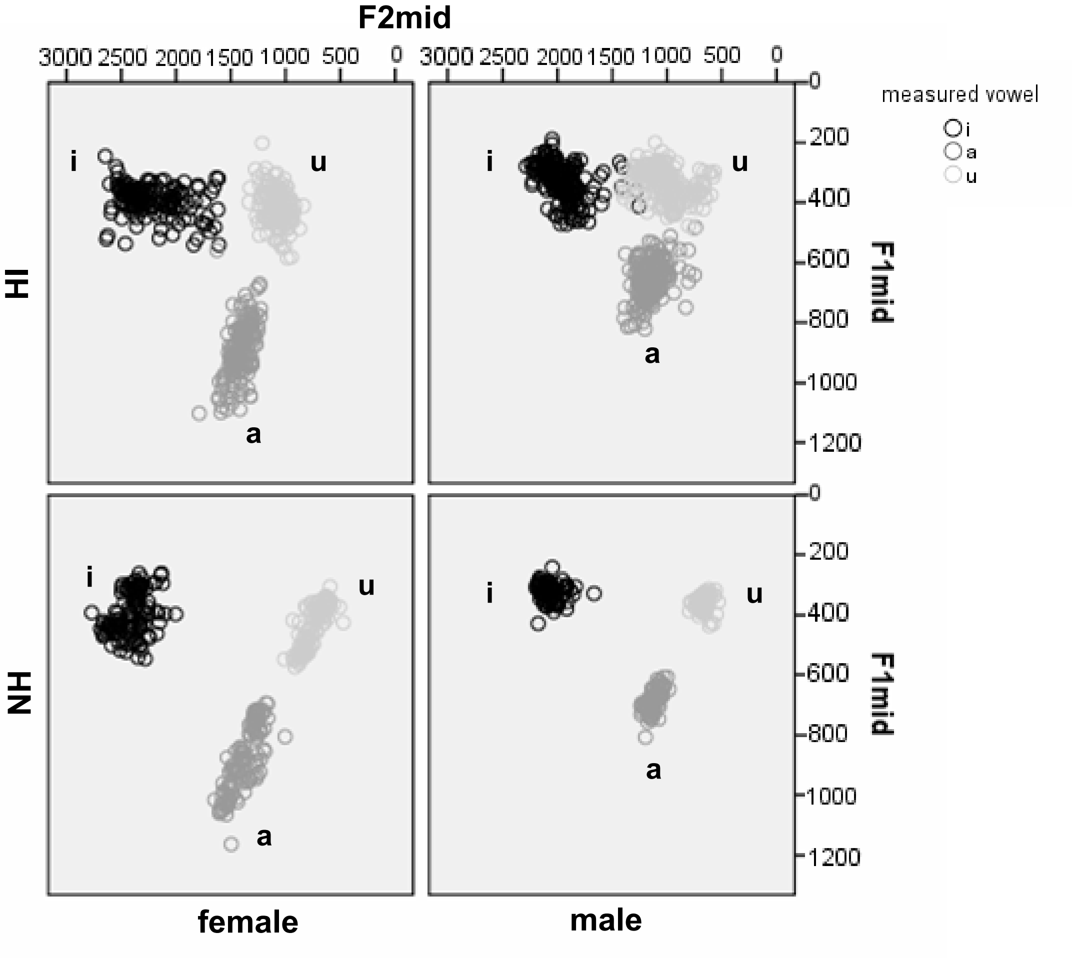


Fig. 4.5. Distribution of all vowel tokens in symmetrical disyllables of bilabial context ([pipi], [papa], [pupu]) produced by 2 male NH speakers (bottom right panel), 3 female NH speakers (bottom left panel), 5 HI male speakers (top right panel) and 4 HI female speakers (top left panel).

Table 4.3. and Fig. 4.6. below provide information about the vowel spaces and vowel distances of male and female NH and HI groups. Female vowel spaces (Fig. 4.6.a) cover a greater surface than male vowel spaces (Fig. 4.6.b) regardless of hearing. The order from largest to smallest vowel space is NH female (370118 Hz^2) > HI female (275452 Hz^2) > NH male (236826 Hz^2) > HI male (150852 Hz^2). This results in a 26% surface reduction for the HI female vowel space and a 36% reduction for the HI male vowel space when compared with the spaces of the corresponding NH genders. Tukey pairwise comparisons of F1 and F2 values between NH and HI male and female groups reveal that, for both HI gender groups, there is significant [i] backing and [u] fronting. In addition, there is statistically significant [u] raising for the female HI group, that is, the F1 of HI female [u] is significantly lower than that of the NH female (see Table 4.3., right section).

Regarding [i], the female HI group displays an F2 difference of 185 Hz from the female NH, and the male HI group an F2 difference of 100 Hz from the male NH. We can compare the NH vs. HI difference between the two genders, if we normalize these values taking into account the differently sized vowel spaces of the NH male vs. female: $100/236826=4.22 \times 10^{-4}$ for the male and $185/370118=5 \times 10^{-4}$ for the female. Thus, the female HI group shows more [i] backing than the male HI group when compared with the corresponding NH gender groups. In the same way, the male HI present slightly more [u] fronting (351 Hz F2 difference; $351/236826=1.48 \times 10^{-3}$) than that of the female HI in relation to the NH (323 Hz F2 difference; $323/370118=0.87 \times 10^{-3}$), while both HI genders show little vowel distance from the NH [a] with the male HI group displaying more [a] raising (31 Hz F1 difference) and the female HI group, more [a] fronting (34 Hz F2 difference).

(a)

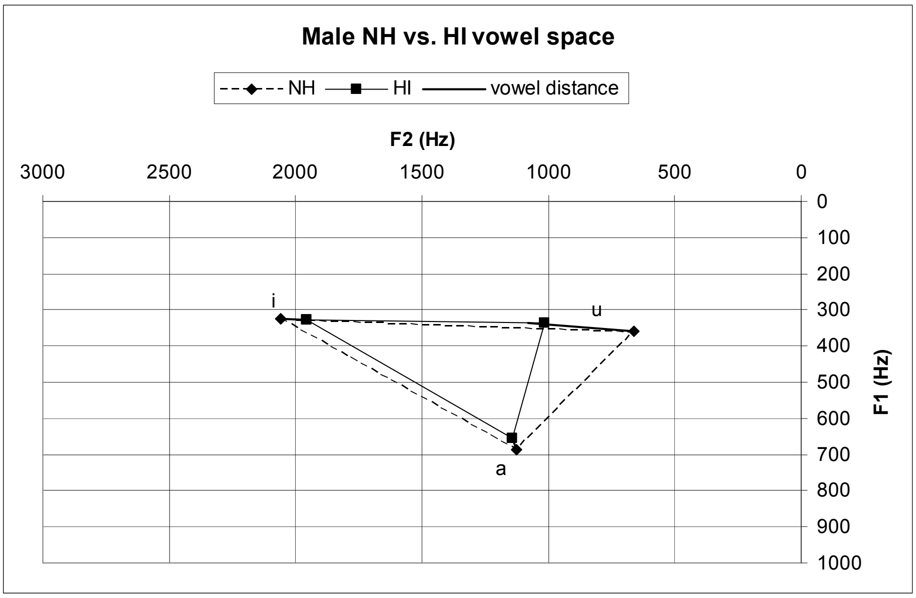
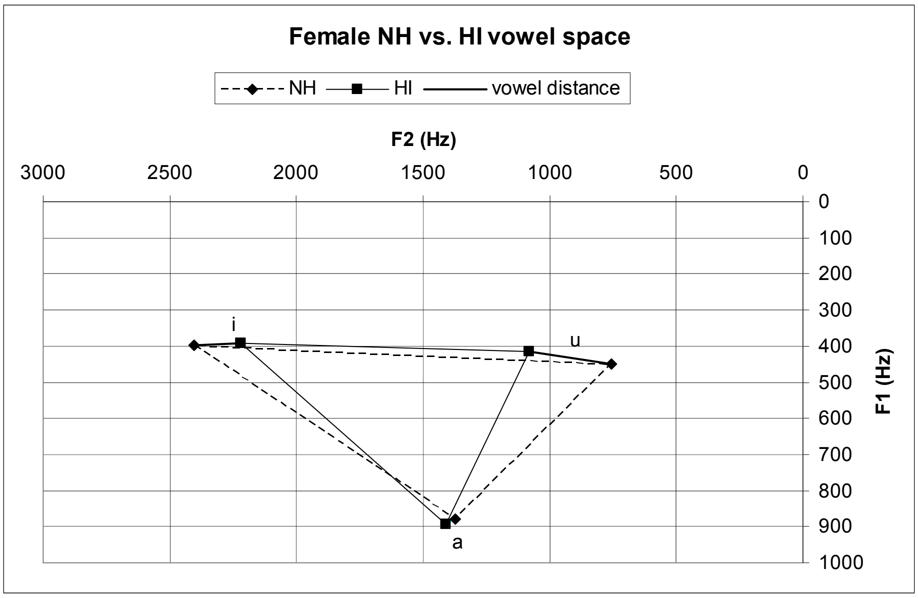


Fig. 4.6. Vowel space and vowel distance (bold line) between the vowels of the (a) male and (b) female NH (dashed line) and HI (solid line) groups.

(b)



hearing & gender	vowel	F2mid (Hz)	F1mid (Hz)	**vowel space** (Hz^2)	**Width (i - u)** F2 difference (Hz)	**Height (i - a)** F1 difference (Hz)	F2 difference (Hz)	F1 difference (Hz)	**vowel distance** (Hz)
NH male	i	2057	325	236826	1394	362	*100	3	100
	a	1127	687				14	31	34
	u	663	358				*351	22	352
HI male	i	1957	328	150852	943	327	*Between-hearing-groups (within-gender) comparison*		
	a	1141	655						
	u	1014	337						
NH female	i	2404	398	370118	1648	480	*185	5	185
	a	1374	879				34	13	36
	u	756	449				*323	*33	325
HI female	i	2219	393	275452	1140	499			
	a	1408	892						
	u	1079	415						

Table 4.3. F2mid and F1mid values, vowel space, F2 (i-u) and F1 (i-a) difference values (width and height) for the male and female NH and HI groups (left section). F2 and F1 difference and vowel distance values between the corresponding vowels of the two hearing groups (right section). The asterisk [*] denotes statistically significant difference (p<.05).

(a)

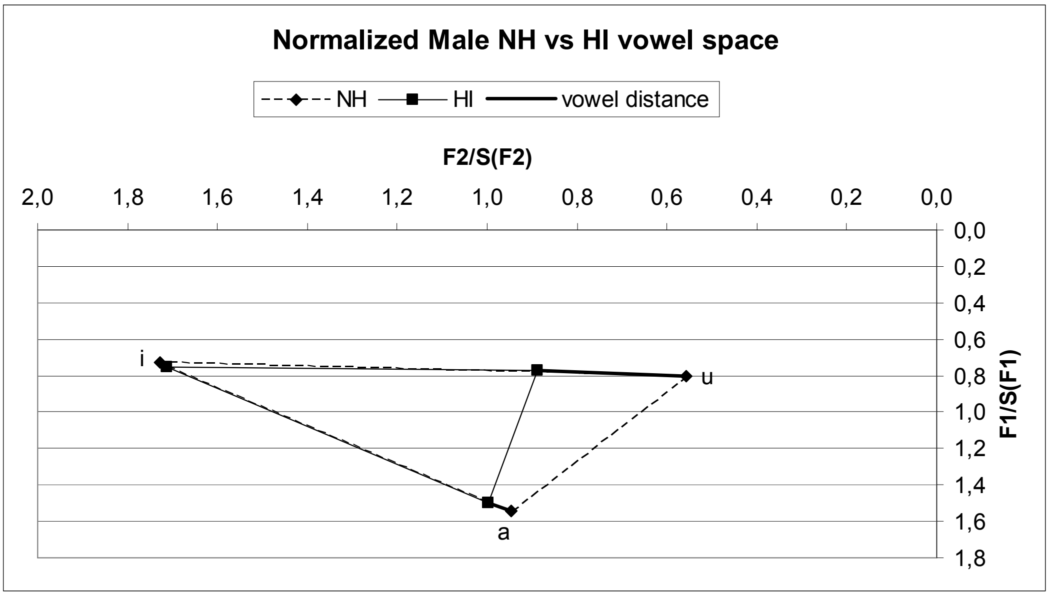


Fig. 4.7. Normalized vowel space and vowel distance (bold line) between the vowels of the (a) male and (b) female NH (dashed line) and HI (solid line) groups.

(b)

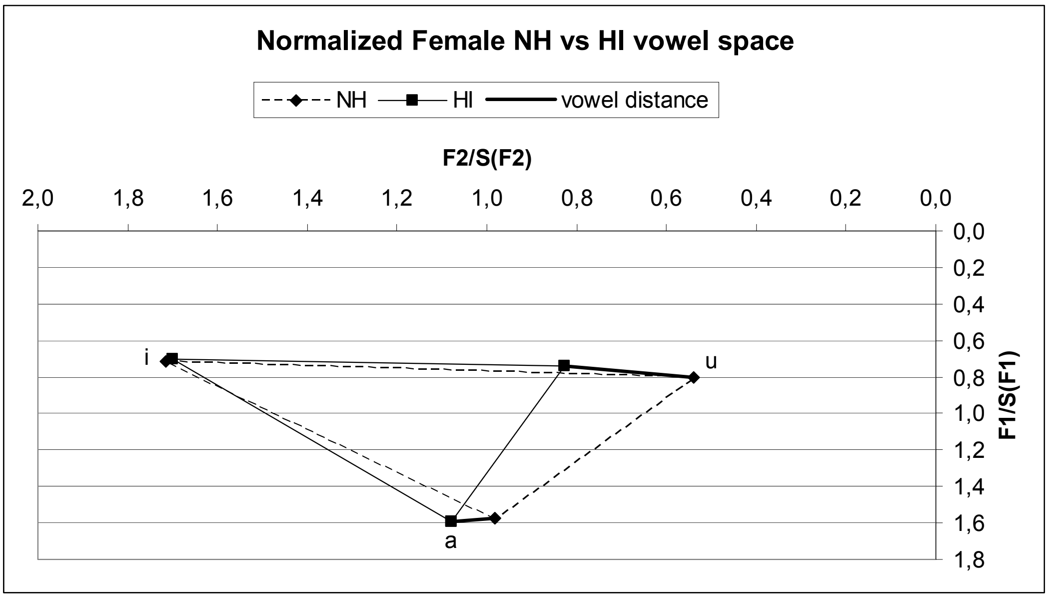


Fig. 4.7.(a) and (b) show the NH and HI male vs. female vowel spaces after ModWF normalization. As mentioned in the previous sub-section, the mean value of vowel [i] remains the same for the two hearing groups (see Fig. 4.4.), an observation also made here for both genders. The back vowel [u] shows significant fronting for both HI genders. The low [a] displays fronting for both genders and additionally relative raising for the male HI group, similarly with the un-normalized vowel spaces. Subsequent to normalization, differences in surface values were found in comparison to un-normalized surfaces. In particular, the order

from largest to smallest vowel space changed, so that NH vowel spaces are larger than HI spaces regardless of gender: NH female > NH male > HI female > HI male. We found that the normalized female HI space is 21% smaller than the female NH space, while the corresponding percentage for the normalized male HI space in comparison with the NH male space is 33%. Hence, the HI male display more vowel space reduction than the HI female, as found with un-normalized spaces.

Fig. 4.8.(a) and (b) demonstrate means and vowel ellipses with radii of two standard deviations of male vs. female group within each hearing group, while Fig. 4.8.(c) and (d) show means and vowel ellipses of NH vs. HI groups of the same gender. In Fig. 4.8.(a) we observe that NH male and female groups display a similar picture for all three vowels, i.e., male and female means are quite close, while vowel variability for the NH female group is always larger than that for the NH male group. In Fig. 4.8.(b) we see that the means of the HI male and female groups are farther apart and that the HI male display slightly greater vowel variability than do the HI female and even more so for the back [u]. Thus, the vowels of the two gender groups do not relate similarly within each hearing group.

In Fig. 4.8.(c) we note that the male NH group shows much less vowel variability than the male HI group. On the other hand, Fig. 4.8.(d) shows that both the NH and HI female groups display a similar degree of variability which may even be relatively higher for NH vowels [a] and [u].

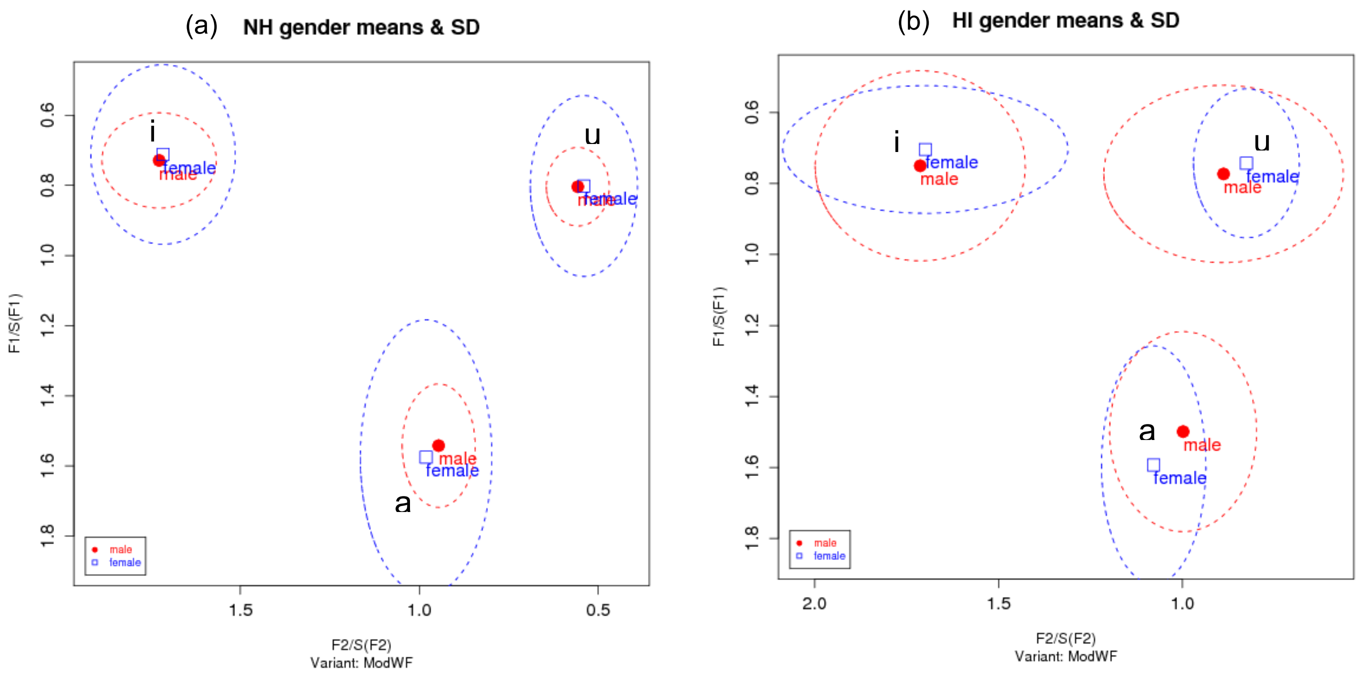
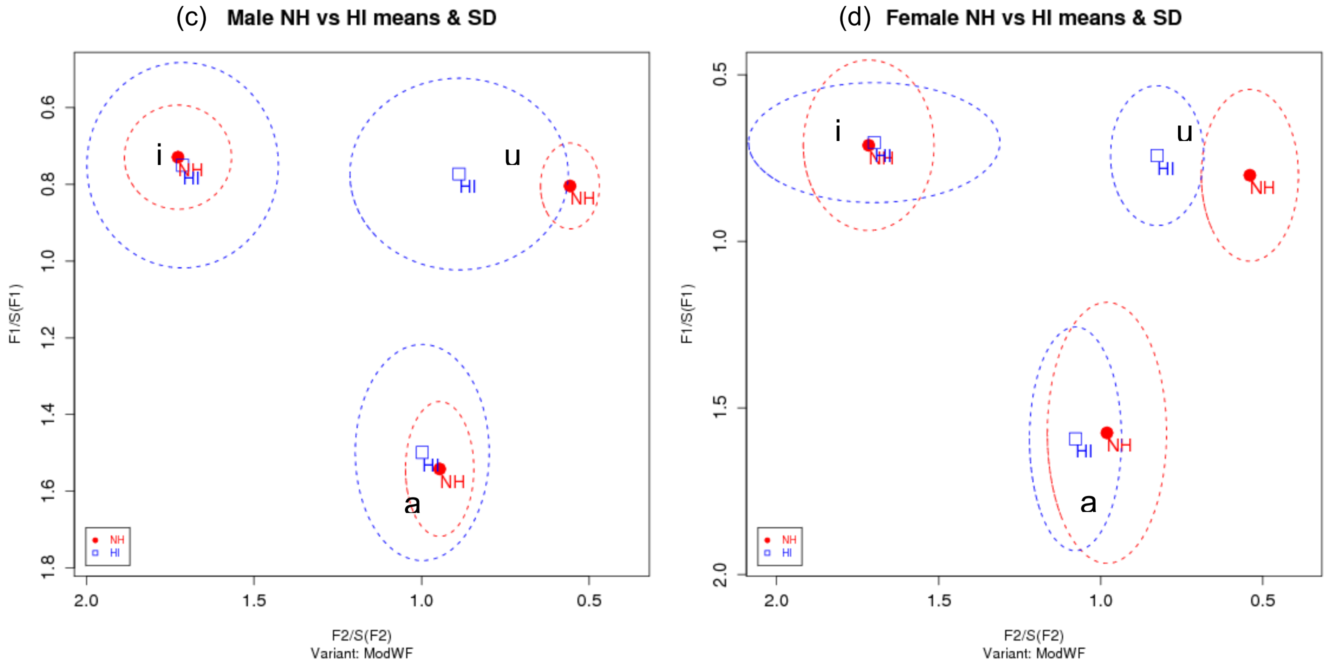


Fig. 4.8. Vowel means and ellipses with radii of two standard deviations of male vs. female speakers with (a) NH and (b) HI (above), and speakers with NH vs. HI of the (c) male and (d) female group (below) computed on the basis of ModWF normalized F1mid and F2mid formant values of point vowels [i], [a], [u] in [pVpV] symmetrical environment.



4.1.3. Intelligibility

F1mid and F2mid distribution vs. intelligibility and gender are illustrated in Fig. 4.9. This figure helps us find out which intelligibility group contributes the most to the vowel space differences between the NH and the HI. Gender had to be included as a factor in order to get an accurate account, as intelligibility groups are not balanced for sex. There are two subjects in the NH male group, three subjects in the NH female group, two female subjects in the very high intelligibility group, two female and three male subjects in the high intelligibility group and two male subjects in the medium intelligibility group (section 3.4.6). We will be looking at the plots vertically in order to focus on the intelligibility factor, that is, to compare the vowel distribution within gender and across intelligibility group. Looking at the plots horizontally, we focus on gender, that is, we compare vowel distribution within intelligibility group and across gender. Since there are no male speakers falling into the category of very high intelligibility and no female speakers of medium intelligibility, the horizontal (gender) comparison is possible only within the high intelligibility group.

We observe that, regardless of gender, the higher the intelligibility the more distinct the vowel areas. The vowel areas of speakers with medium intelligibility manifest the most overlap, while, at the same time taking up the smallest space overall. Regarding the female groups (left panels), comparing the very high intelligibility group and the high intelligibility group to the corresponding NH group, we observe that the very high intelligibility group differs in their [u] which occupies a fronter area, while the high intelligibility group differs in both [u] and [i]; their [u] is quite fronted but their [i] is also a lot more backed and has a much wider F2 range than that of the NH and of the very highly intelligibility group. Thus the high intelligibility group seems to contribute more to the decrease in HI female vowel space.

Regarding the male groups (right panels), both the high and the medium intelligibility groups have a more restricted vowel space compared to the NH male one, but the three vowel regions of the medium intelligibility group are more converged, especially the [u] and [i] areas which overlap the most. The comparison to the NH male group is even more immediate in this case, since both the NH male group and the medium intelligibility group include two subjects each, which factors out any differences in distribution due to total subject number.

In general, regardless of gender and intelligibility group, NH and HI groups seem to differ the most at the production of vowel [u]. In comparison with the NH [u], it displays a pronounced shift towards the center (i.e., higher F2mid) which is largely responsible for the convergence of the [u] and [i] areas and the reduction or centralization of the overall vowel area.

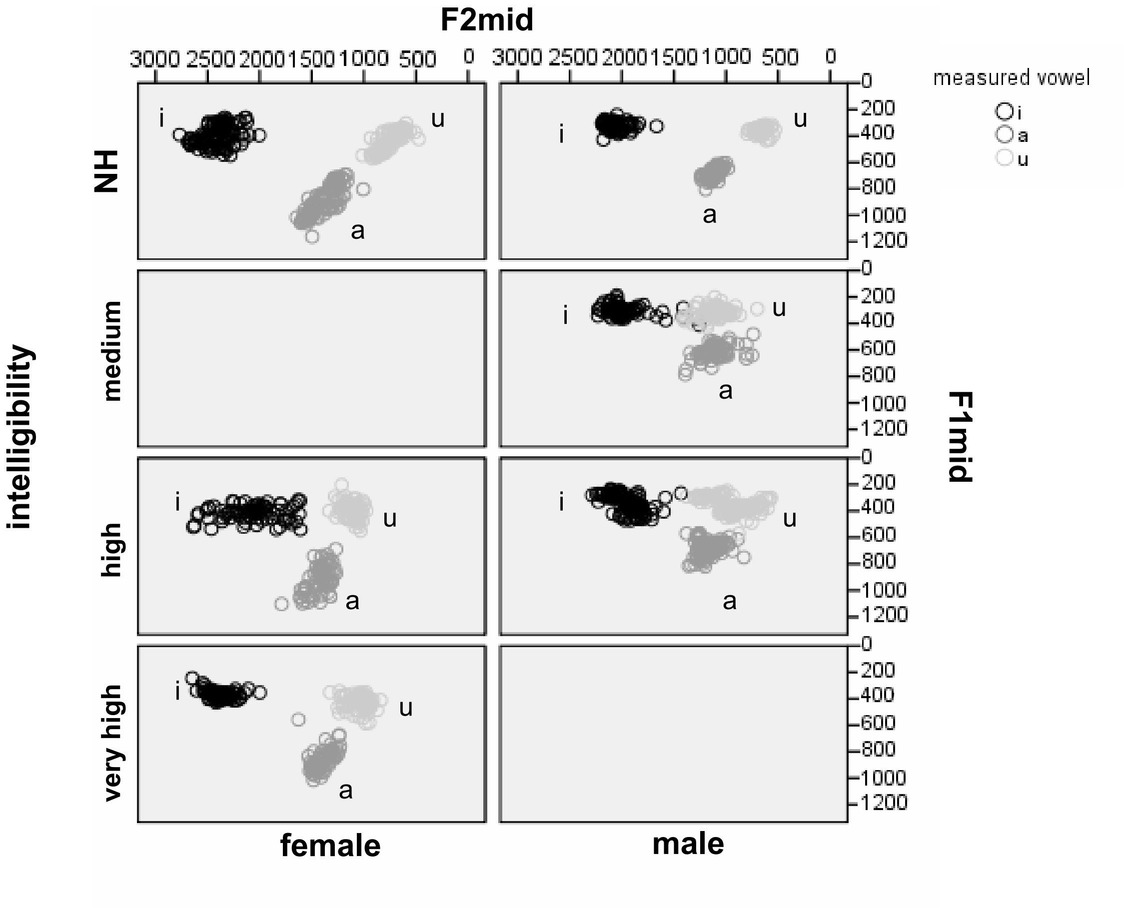


Fig. 4.9. Distribution of all vowel tokens in symmetrical disyllables of bilabial context ([pipi], [papa], [pupu]) produced by the NH gender groups of Fig. 4.5. and the three intelligibility groups according to gender.

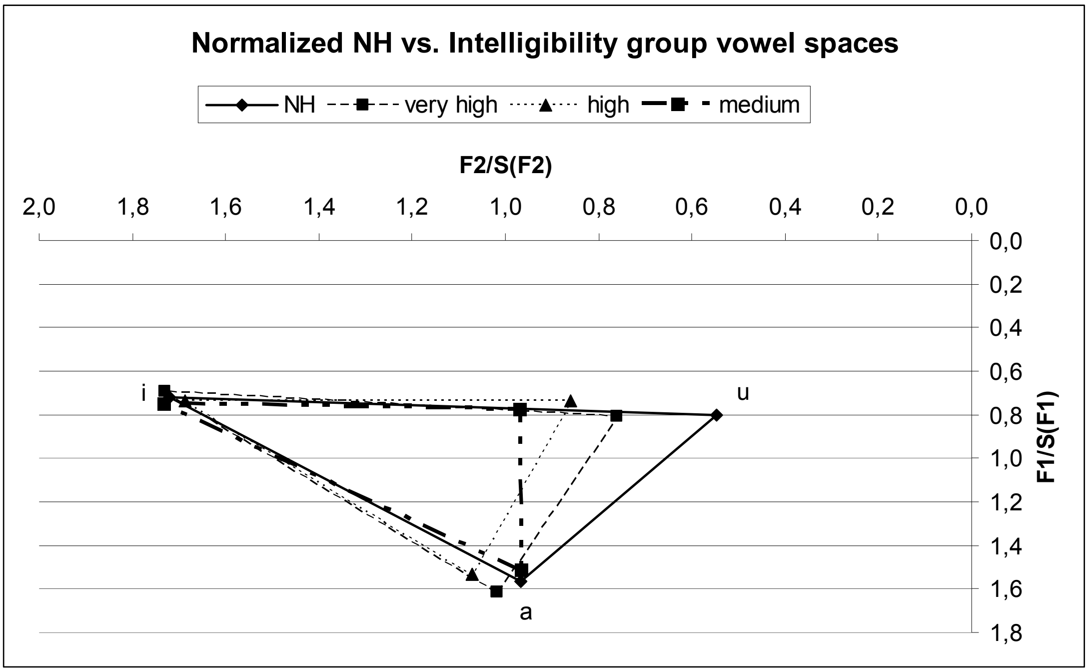


Fig. 4.10. Normalized vowel spaces of the NH and the three intelligibility groups.

Fig. 4.10. above displays the normalized vowel spaces of the NH and the three intelligibility groups. A calculation of the areas revealed that vowel space decreases proportionately with level of intelligibility, that is, the higher the intelligibility the larger the vowel space. Thus the order from largest to smallest vowel space is NH > very high > high > medium intelligibility group.

In Fig. 4.11. below normalized F1mid and F2mid formant values of the NH and the three intelligibility groups are displayed. The vowel ellipses are indicative of the vowel variability within each group as they show two standard deviations. Firstly, we note that after normalization there is no overlap between vowel sub-spaces within each group. As we saw in Fig. 4.9. above there was some convergence of [i] and [u] sub-spaces along the F2 axis for the group with medium intelligibility which is no longer apparent. Secondly, the fronting of [u] decreases for the intelligibility groups in the order medium > high > very high intelligibility. Hence, the lower the intelligibility the more fronting [u] displays.

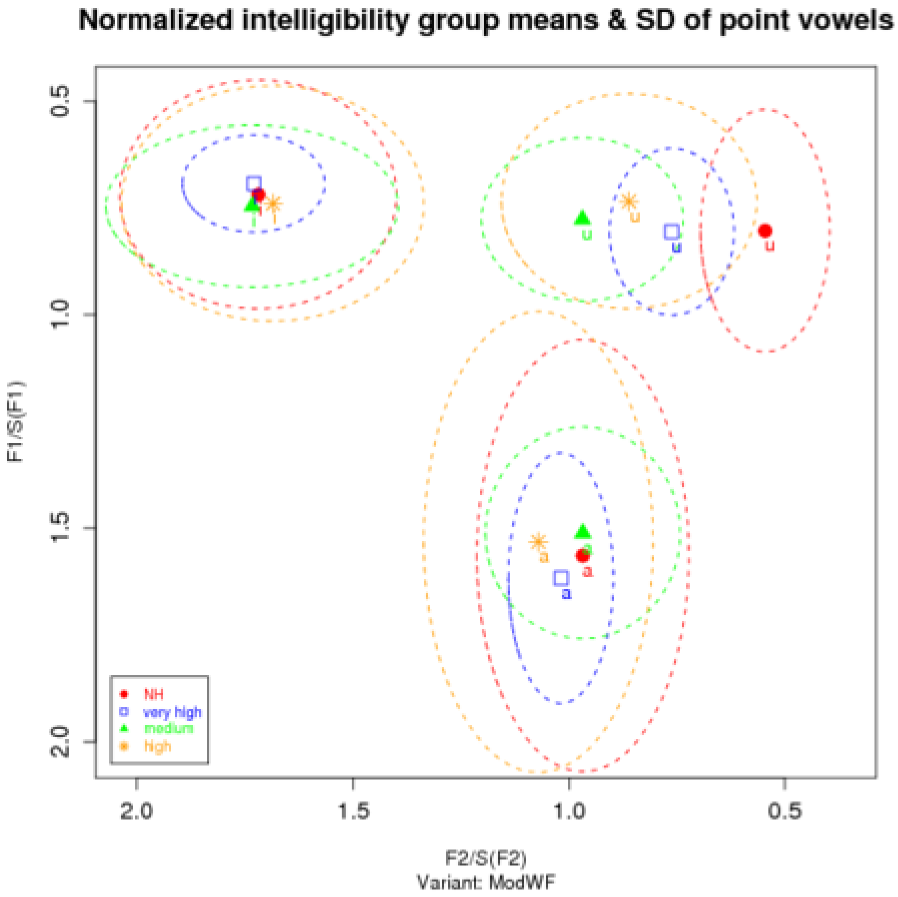


Fig. 4.11. Vowel means and ellipses with radii of two standard deviations of the NH group and the three intelligibility groups computed on the basis of ModWF normalized F1mid and F2mid formant values of point vowels [i], [a], [u] in [pVpV] symmetrical environment.

The high [i] shares similar mean values and standard deviation among groups, except for the very high intelligibility group that displays a lower degree of variability than all other groups. This is the case for all vowels produced by the very high intelligibility group. In general, vowel variability is highest for the NH and the high intelligibility group, lowest for the very high intelligibility group and in-between for the medium intelligibility group. The NH and the high intelligibility group each include five speakers, while the very high and the medium intelligibility group are each composed of two speakers. The difference in variability could be related to number of speakers in each group and/or idiosyncratic strategies of the speakers within each group regardless of their total number. That is, the very high intelligibility group may display low degree of variation either because it consists only of two female speakers and/or because these two female speakers happen to produce less variable vowels. Regarding the low [a], the medium and high intelligibility groups display a more raised vowel in comparison with the NH one, while the very high intelligibility group shows a more open, more sonorous [a]. In addition, the [a] of the high intelligibility group is the most fronted among all groups.

4.2. Stress and Syllable Position Effects on HI vs. NH Vowel Space

Stress was found to be a statistically significant factor for both F1mid (F(1, 15036)=1608.664, p<.0001) and F2mid (F(1, 15045)=50.672, p<.0001). Interaction hearing*stress is statistically significant for both F1mid (F(1, 15036)=42.455, p<.0001) and F2mid (F(1, 15045)=12.154, p<.0001), as well as hearing*measured vowel*stress (F(2, 15036)=7.015, p<.01 for F1mid and F(2, 15045)=8.053, p<.0001 for F2mid correspondingly). Interaction hearing*measured vowel*consonant*stress was found statistically significant for F2mid (F(4, 15045)=6.188, p<.0001).

Syllable position is also a statistically significant factor for F1mid F(1, 15036)=31.505, p<.0001) and F2mid (F(1, 15045)=110.368, p<.0001). Hearing*position is statistically significant for F2mid (F(1, 15045)=76.200, p<.0001) and hearing*stress*position is statistically significant for F1mid (F(1, 15036)=166.638, p<.0001). Hearing*measured vowel*position is significant for both F1mid (F(2, 15036)=8.478, p<.0001) and F2mid (F(2, 15045)=53.268, p<.0001) (see Appendix 2.2., Tables 2 & 7 for a comprehensive list of interactions).

We examined the effect of stress and syllable position on the F1 and F2 of [i], [a] and [u] at the midpoint of the vowel in symmetrical disyllables of bilabial context ([pVpV]) in order to find differences between the NH and the HI and compare their vowel spaces in the two stress conditions and in the two syllable positions. Post hoc tests were carried out in the interaction hearing*measured vowel*transconsonantal vowel*consonant*stress and the interaction hearing*measured vowel*transconsonantal vowel*consonant*stress*position.

Table 4.4. and Fig. 4.12. summarize the results. Stress influences statistically significantly the F1mid of vowel [a] and the F2mid of vowels [i] and [a] for both the NH and the HI. Specifically, the existence of stress causes vowel [a] to be lower and fronter and vowel [i] to be fronter for both groups. Thus stress has a similar impact on the vowel spaces

of the two groups, that is, vowel spaces of stressed vowels are larger than those of their unstressed counterparts. A calculation of stressed vs. unstressed vowel surface in each group shows that lack of stress results in a comparable shrinkage for both groups, i.e., 24.8% vowel space reduction for the NH group and 28.4% reduction for the HI. Regardless of stress, the NH vowel space always covers a greater surface than the HI one. Hence, vowel space decreases as follows: NH stressed > NH unstressed > HI stressed > HI unstressed. Vowel space values (in Hz^2) are given in Table 4.4. below. We also note that the HI stressed [i] and [u] are slightly lowered relative to their unstressed counterparts, although the effect of stress on [u] and [i] along the F1 axis is statistically nonsignificant for both the NH and the HI group.

hearing	stress	vowel	F2mid & StDev (Hz)		F1mid & StDev (Hz)		**vowel space** (Hz^2)
NH	stressed	i	*2337	203	374	71	358787
		a	*1343	166	*842	134	
		u	722	94	413	73	
	unstressed	i	*2194	194	364	67	269668
		a	*1208	125	*762	108	
		u	717	104	412	73	
HI	stressed	i	*2139	220	363	68	236396,5
		a	*1293	174	*802	151	
		u	1028	143	381	69	
	unstressed	i	*2007	251	351	59	169357,5
		a	*1225	158	*717	113	
		u	1058	166	362	65	

Table 4.4. Mean F1 and F2 (Hz), StDev (Hz) and vowel space (Hz^2) of stressed and unstressed point vowels in [pVpV] disyllables produced by the NH and the HI. The asterisk [*] denotes statistically significant difference (p<.05) between a stressed vowel and its unstressed counterpart within group.

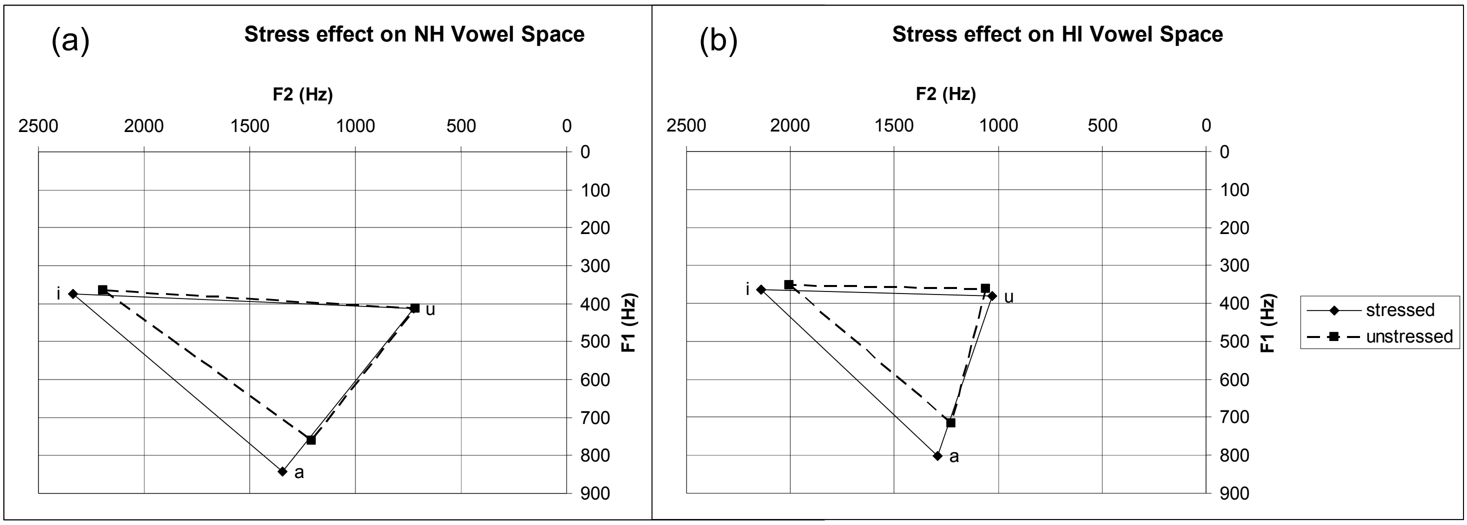


Fig. 4.12. Vowel space of stressed (solid line) and unstressed (dashed line) point vowels produced by (a) the NH (left) and (b) the HI (right) computed from mean F1mid and F2mid values (Hz).

Looking at Fig. 4.13. below which presents both stress and position effects on the vowel space of the two groups, we note that, for both groups, the stressed post-consonantal vowel is the most peripheral one, followed by the stressed pre-consonantal vowel. In the absence of stress, the order is different for the two groups; for the NH, the unstressed pre-consonantal vowels compose a larger vowel space than the unstressed post-consonantal vowels, whereas, for the HI, the opposite is true. Thus, for the NH, the vowel space order from larger to smaller is stressed_position2 > stressed_position1 > unstressed_position1 > unstressed_position2, while for the HI it is stressed_position2 > stressed_position1 > unstressed_position2 > unstressed_position1 (see vowel space values in Table 4.5.).

Within group and within vowel pairwise comparisons between a) stressed and unstressed counterparts either pre- or post-consonantally and b) pre- and post-consonantal counterparts either in the stressed or the unstressed condition revealed that (see Table 4.5.) for the NH, statistically significant differences are found between stressed and unstressed counterparts of vowels [i] and [a] when they are post-consonantal only; for NH [i] this applies only to F2, while for NH [a] to both formants. Conversely, for the HI, we find statistically significant differences between stressed and unstressed counterparts of the aforementioned two vowels in both pre- and post-consonantal locations. Therefore, for the NH, syllable position seems to interact with stress and result in considerable vowel space expansion due to the presence of stress post-consonantally. For the HI, the presence of stress results in more peripheral [i] and [a] vowels both pre- and post-consonantally.

As an example of the last claim, let us observe the change in location of vowel [a] due to stress and syllable position for the two groups. We choose this vowel as it was found accountable for a statistically significant vowel space expansion in both the F1 and F2 axis for both hearing groups (see Table 4.4. above). In Fig. 4.13.(a), in both stress conditions, the pre-consonantal [a] is situated far apart from its post-consonantal counterpart, which means that syllable position is a significant factor in NH [a] location in the vowel chart, while in Fig. 4.13.(b), the two stressed HI [a] counterparts and the two unstressed counterparts form two separate point groups regardless of being pre- or post-consonantal. Consequently, for the NH, vowel position in the disyllable plays a significant role in the vowel's articulation and has an impact on vowel peripherality, whereas we cannot claim the same for the HI.

hearing	stress	position	vowel	F2mid & StDev (Hz)		F1mid & StDev (Hz)		**vowel space** (Hz^2)
NH	stressed	1	i	2319	197	372	71	330980
			a	1321	158	821	134	
			u	748	85	415	67	
		2	i	$^{+}$2355	210	376	71	387075
			a	$^{+}$1365	173	$^{+}$864	132	
			u	696	97	411	80	
	unstressed	1	i	2189	220	376	77	280634
			a	1245	137	786	111	
			u	720	95	420	72	
		2	i	$^{+}$2198	167	353	53	258538
			a	$^{+}$1170	100	$^{+}$737	99	
			u	713	114	404	74	
HI	stressed	1	i	*2124	201	356	55	224339
			a	1276	172	*788	151	
			u	1042	141	379	58	
		2	i	$^{+}$2155	238	370	78	248546
			a	1309	176	$^{+}$815	151	
			u	1014	145	383	79	
	unstressed	1	i	*1992	206	341	52	166278
			a	1194	177	*711	101	
			u	1075	166	379	59	
		2	i	$^{+}$2023	290	361	65	172549
			a	1256	128	$^{+}$723	124	
			u	1042	165	374	69	

Table 4.5. Mean F1 and F2 (Hz), StDev (Hz) and vowel space (Hz^2) of stressed and unstressed point vowels in first and second syllable position in [pVpV] disyllables produced by the NH and the HI. Within group statistically significant difference ($p<.05$) between stressed and unstressed first position vowel is denoted with the symbol [*] and between stressed and unstressed second position vowel with the symbol [$^{+}$].

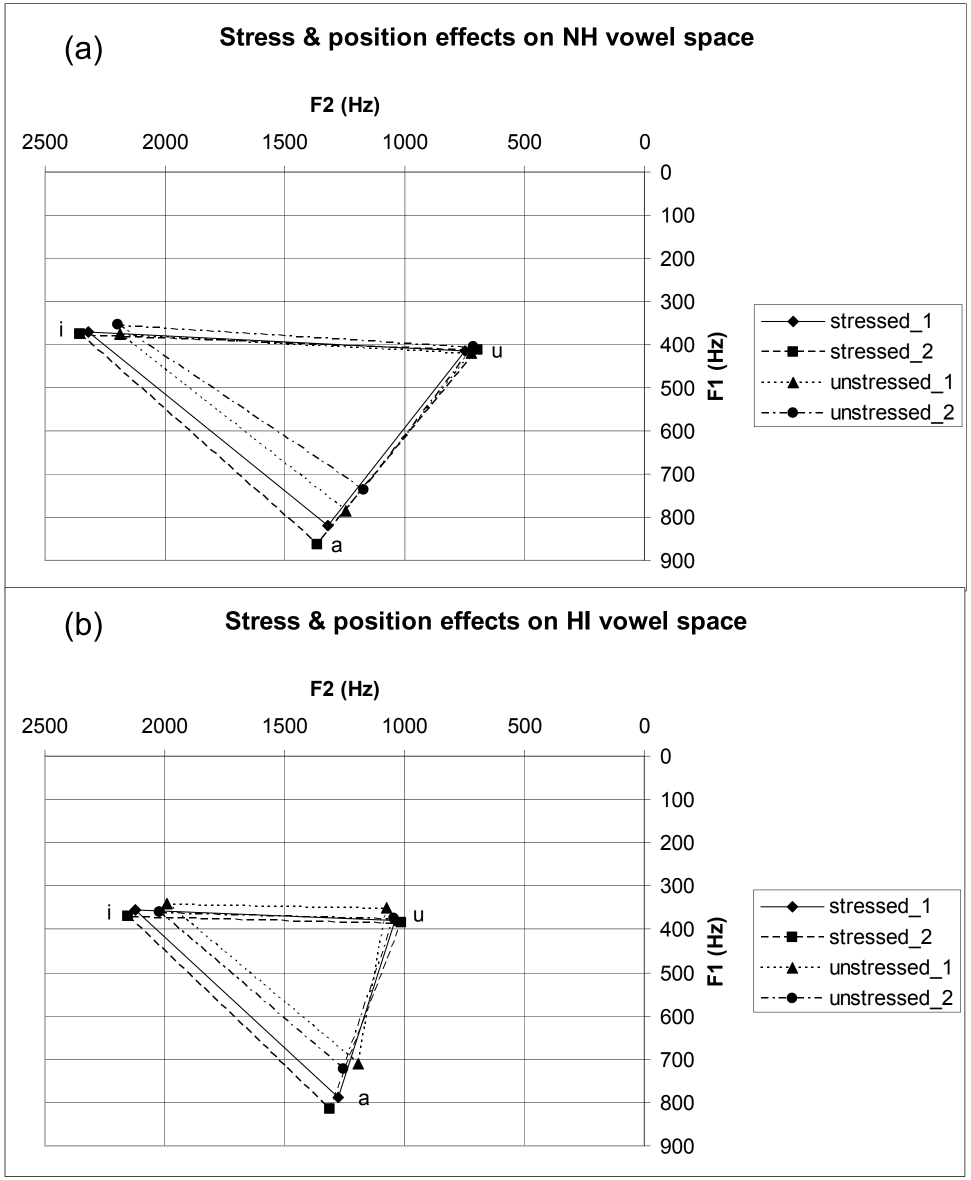


Fig. 4.13. Vowel space of stressed 1st position (rhombus), stressed 2nd position (square), unstressed 1st position (triangle) and unstressed 2nd position (circle) point vowels in [pVpV] disyllables produced by (a) the NH (above) and (b) the HI (below) computed from mean F1mid and F2mid values (Hz).

SYNOPSIS

This section summarizes the main findings regarding the influence of hearing, gender, intelligibility and syllable position on vowel distribution, vowel space from an examination of F1 and F2 formant values at the midpoint of the three vowels [i], [a], [u] in symmetrical disyllables of bilabial context ([pVpV]).

- **hearing**
  - On the basis of the un-normalized F1 and F2 formants of HI vs. NH vowels, we make the following observations:
    - HI vowel [u] is statistically significantly fronted (higher F2mid) and raised (lower F1mid) in comparison with the NH [u].
    - HI vowel [i] is significantly backed (lower F2mid) in relation to NH [i].
    - HI vowel [a] does not differ significantly from the NH [a], although it displays some raising (lower F1mid range).
  - After normalization, significant F1 differences between the NH and the HI are eliminated. The main finding involves fronting of the back vowel [u] and, to a lesser extent, of the low vowel [a].
  - The three un-normalized vowel sub-areas are distinct as far as the NH are concerned, but for the HI they show more overlap. HI [i] and [u] seem to converge on the F2 axis, and [u] and [a] show overlap on the F1 axis. Subsequent to normalization, the overlap observed for the HI is less extensive and refers only to [i] and [u] sub-spaces along the F2 dimension.
  - The HI un-normalized vowel space is about 36% smaller than the NH one, mainly because of HI [u] fronting and [i] backing. The NH tend to produce more peripheral point vowels and their vowel space occupies a greater surface. After

normalization, the relative reduction of the HI vs. the NH vowel surface drops to 28% and is chiefly attributable to HI [u] fronting.

- **hearing and gender**
    - Before normalization, female vowel spaces cover a greater surface than male vowel spaces regardless of hearing. The order from largest to smallest vowel space is NH female > HI female > NH male > HI male. After normalization, NH spaces are found larger than HI spaces regardless of gender. The aforementioned order becomes NH female > NH male > HI female > HI male.
    - For both HI gender groups, before normalization there is significant [i] backing, more so for the female HI, and [u] fronting. As mentioned above, [i] backing is not observed after normalization in either gender group, hence the position of both male and female HI [i] coincides with that of the corresponding NH genders.
    - A few differences are evident between HI male and female speakers:
        - Before normalization the male HI group presents slightly more [u] fronting than that of the female HI group. After normalization both gender groups show comparable [u] fronting, although the male HI group shows more variability in their [u] production.
        - Both HI gender groups show little vowel distance from the NH [a], with the male HI group displaying [a] raising and the female HI group [a] fronting. These observations are still valid after normalization.
    - Concerning male vs. female vowel distribution in the two hearing groups:
        - Both before and after normalization, the NH male vowel sub-areas are more clustered, whereas NH female speakers show more variability, especially along the F1 axis. Nevertheless, both male and female NH groups have distinct vowel sub-areas.

        - The female speakers with HI display separate vowel sub-areas, whereas [u] and [i] areas partly overlap for male speakers with HI. The overlap is largely abated after normalization. The HI male [u] seems to cover a wider F2 area (higher standard deviation) than HI female [u] and overall there is more within-vowel dispersion for the HI male group when compared with the HI female group after normalization. This is in opposition to the more converged NH male vs. female vowel values.

- **intelligibility**
    - The higher the intelligibility the more distinct and set apart the vowel areas and, thus, the larger the vowel space.
    - The vowel areas of speakers with medium intelligibility manifest the most overlap, while at the same time taking up the smallest space overall. Although after normalization the overlap is eliminated, the vowel sub-areas of this group continue to be close together.
    - Regarding female groups, the very high intelligibility group differs in their [u] which occupies a fronter area than that of the NH, while the high intelligibility group differs in both [u] and [i]. Thus the high intelligibility group seems to contribute more to the decrease in HI female vowel space. More [u] fronting for the high intelligibility group is also observed in the normalized vowel spaces; [i], however, occupies a similar position for both high and very high intelligibility groups.
    - Regarding male groups, both the high and the medium intelligibility groups have a more restricted vowel space compared to the NH male one, but the three vowel regions of the medium intelligibility group are more converged.

  - In general, among the three vowels, [u] produced by the intelligibility groups seems to differ the most in comparison with that of the NH. The lower the intelligibility the more fronted [u] appears. The position of the high [i] seems unaffected by intelligibility level, while [a] is more fronted for the high intelligibility group and more open for the very high intelligibility group in comparison with the medium intelligibility group and the NH group.
  - Regarding vowel variability, it was found lowest for the very high intelligibility group. The high intelligibility group displays the highest variability among the three groups which is also comparable to the NH variability. The medium intelligibility group shows a moderate degree of variability.
- **stress & syllable position**
  - The existence of stress causes vowel [a] to be statistically significantly lower and fronter and vowel [i] to be fronter for both groups.
  - Stress seems to have no statistically significant effect on [u] for either group. However, a slight raising of the high vowels [i] and [u] along the F1 axis in the absence of stress is observed for the HI group.
  - Vowel spaces of stressed vowels are larger than those of their unstressed counterparts for both groups.
  - Lack of stress causes a comparable vowel reduction to both groups that amounts to 24.8% for the NH and 28.4% for the HI group.
  - Vowel space decreases as follows: NH stressed > NH unstressed > HI stressed > HI unstressed.
  - When stressed, the post-consonantal vowel is more peripheral than the pre-consonantal vowel, for both groups.

- In the absence of stress, the order is different for the two groups; for the NH, the unstressed pre-consonantal vowels compose a larger vowel space than the unstressed post-consonantal vowels, whereas, for the HI, the opposite occurs.
- For the NH, stressed vowels [i] and [a] are more peripheral than their unstressed counterparts only pre-consonantally, while for the HI, this occurs both pre- and post-consonantally.

4.3. Duration of HI vs. NH Point Vowels

Duration measurements of the three vowels were put into a GLM ANOVA model which, in the same way as for the frequency variables mentioned above, included the factors: hearing, gender, vowel measured, transconsonantal vowel, consonant, stress and position. All of them were found to be statistically significant [**hearing**: F(1, 15055)=2761.851, p<.0001, **gender**: F(1, 15055)=1017.189, p<.0001, **measured vowel**: F(2, 15055)=980.457, p<.0001, **transconsonantal vowel**: F(2, 15055)=102.171, p<.0001, **consonant**: F(2, 15055)=9.239, p<.0001, **stress**: F(1, 15055)=11173.162, p<.0001, **position**: F(1, 15055)=1381.068, p<.0001]. Interactions between hearing and the measured vowel, hearing and the transconsonantal vowel and hearing and stress are *not* statistically significant (Appendix 2.2., Table 13). Hence, HI speakers vary their vowel duration according to the aforementioned factors in essentially the same way as NH speakers. Additionally, an ANOVA was run replacing "hearing" with "intelligibility" (Appendix 2.2., Table 14), which showed that **intelligibility** is also a statistically significant factor (F(3, 15055)=1296.272, p<.0001).

In the following sections, we look at how the aforementioned factors influence the duration of the three vowels [i], [a] and [u] produced in all three consonantal contexts by the two hearing groups. Mean duration and standard deviation values (in ms) are given in Tables 4.6. to 4.23., while in the text, durations of NH vs. HI vowels are provided in percentages to facilitate comparison. For example, in Table 4.6. below, we note that NH [a] has a mean duration of 106 ms while HI [a] a duration of 130 ms. Hence HI [a] is about 23% longer than NH [a]. The mean values are given in the Table, while the percentage is reported in text so as to compare the duration of [a] between the two groups more promptly.

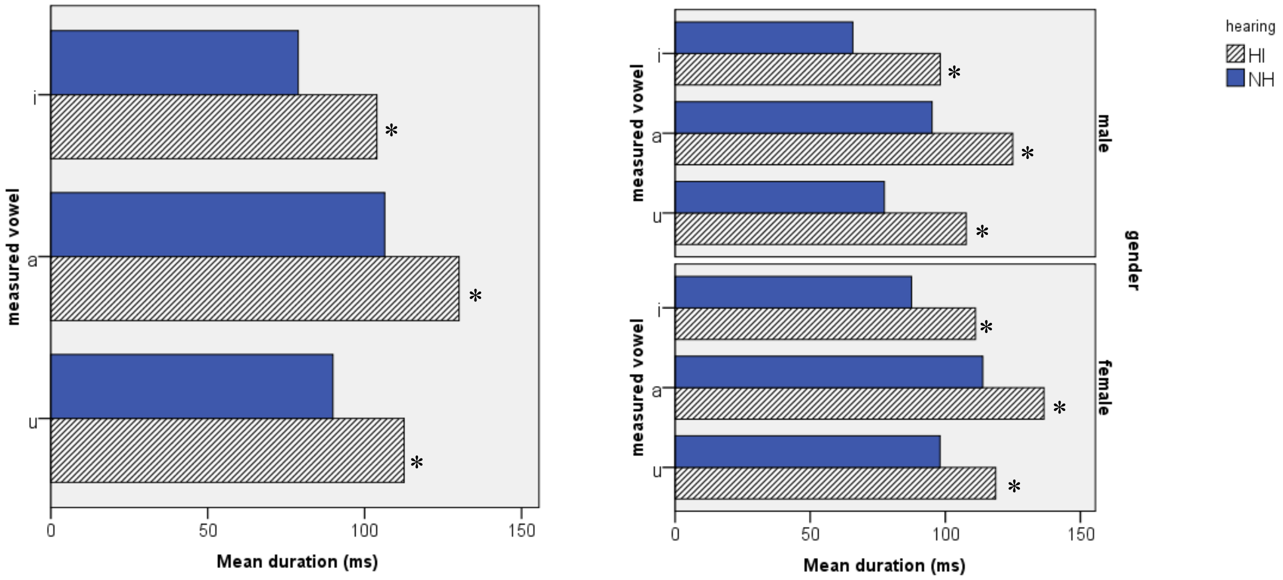
4.3.1. Hearing & gender

Table 4.6. and Fig. 4.14. present the mean duration (ms) of the three vowels in all contexts and in both stress conditions and syllable positions produced by the NH and the HI and by the two gender groups of each hearing group. We note that the vowel duration pattern is [a] > [u] > [i] for both hearing groups. Nevertheless, vowels produced by speakers with HI are significantly longer than those produced by speakers with NH. HI [a] is about 23%, [u] 26% and [i] 32% longer than the corresponding NH vowels.

Looking at the gender factor, female HI vowels are the longest, followed by male HI vowels, female NH and lastly male NH vowels. The mean duration difference between the NH and the HI vowels is slightly more pronounced in male speakers (39% longer as opposed to 22% in female speakers). In addition, female NH speakers produce longer vowels than male NH speakers by 27%, while the corresponding difference in HI speakers is 11%, hence we note a less prominent within group gender related difference than that of the NH.

Gender	Measured Vowel	Duration & St Dev (ms)			
		NH		HI	
	i	79	(46)	104	(46)
	a	106	(47)	130	(45)
	u	90	(47)	113	(45)
male	i	66	(32)	98	(31)
	a	95	(29)	125	(34)
	u	77	(34)	108	(31)
female	i	88	(52)	111	(58)
	a	114	(54)	137	(54)
	u	98	(52)	119	(58)

Table 4.6. Mean duration and StDev (in ms) of vowels [i], [a] and [u] in [pV$_1$CV$_2$] utterances according to hearing and gender.



4.1.14a 4.1.14b

Fig. 4.14. Mean duration (in ms) of vowels [i], [a] and [u] in [pV_1CV_2] utterances (a) produced by speakers with NH vs. HI, and (b) produced by male and female speakers with NH vs. HI. Symbol '*' indicates statistically significant difference of duration between the NH and HI. All within group comparisons were also found statistically significant.

4.3.2. Intelligibility

Duration vs. intelligibility and the rest of the factors was run in an ANOVA (Appendix 2.2., Table 14) which showed that intelligibility is a statistically significant factor (F(3, 15055)=1296.272, p<.0001). Intelligibility interacts with measured vowel (F(6, 15055)=8.125, p<.0001).

Measured Vowel	Duration & St Dev (ms)							
	NH		Intelligibility					
			Very high		High		Medium	
i	79	(46)	119	(45)	96	(48)	109	(35)
a	106	(47)	143	(44)	124	(47)	131	(36)
u	90	(47)	122	(42)	107	(49)	117	(34)

Table 4.7. Mean duration (in ms) of vowels [i], [a] and [u] in [pV_1CV_2] utterances produced by speakers with very high, high, medium intelligibility and NH speakers.

From a first look at Table 4.7. and Fig. 4.15., we note that all intelligibility groups follow the aforementioned pattern of vowel duration, which is [a] > [u] > [i]. We also observe that the very high intelligibility group (consisting of two female speakers) has the highest duration values, while the high intelligibility group has 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 are statistically significant. In addition, within group and between vowels comparisons are also statistically significant, except between [i] and [u] of the very high intelligibility group.

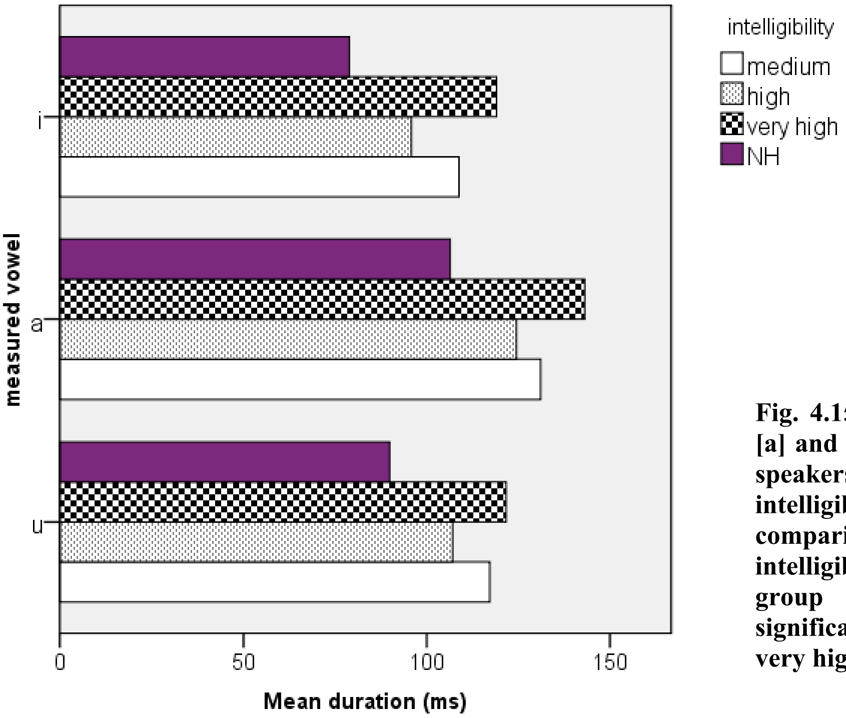


Fig. 4.15. Mean duration (in ms) of vowels [i], [a] and [u] in [pV_1CV_2] utterances produced by speakers with very high, high and medium intelligibility vs. NH speakers. All pairwise comparisons between the NH group and the intelligibility groups, as well as within speaker group and across vowels are statistically significant, except between [i] and [u] of the very high intelligibility group.

4.3.3. Stress and syllable position

All three HI vowels are significantly longer than the corresponding NH vowels in both stress conditions (Table 4.8. and Fig. 4.16.). In addition, vowel quality and stress influence vowel duration in the same way for both groups. Unstressed vowels are significantly shorter than stressed vowels for both groups, although the difference is more pronounced for the NH. Concerning vowel [i], the duration reduction occurring due to absence of stress is 50% for the NH while 39% for the HI. Vowel [u] is shorter by 46% for the NH whereas for the HI by 36%.Unstressed vowel [a] is shorter than its stressed counterpart by 43% for the NH and by 35% for the HI. Hence, for both groups, the pattern of vowel duration sensitivity to stress is [i] > [u] > [a], although the HI present less vowel duration compression due to lack of stress relative to the NH.

Measured Vowel	Stress	Duration & St Dev (ms)			
		NH		HI	
i	stressed	105	(51)	129	(43)
	unstressed	52	(15)	79	(32)
a	stressed	136	(49)	158	(41)
	unstressed	77	(14)	103	(28)
u	stressed	117	(51)	137	(43)
	unstressed	63	(16)	88	(31)

Table 4.8. Mean duration (in ms) of stressed and unstressed vowels [i], [a] and [u] in [pV_1CV_2] utterances produced by speakers with NH and HI.

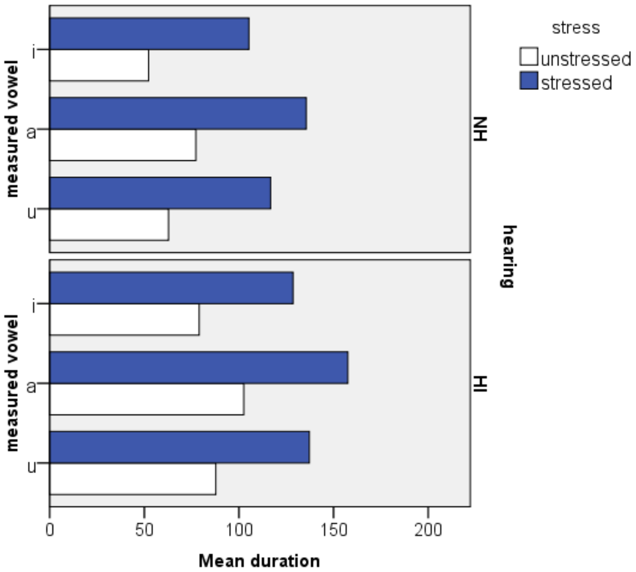


Fig. 4.16. Mean duration (in ms) of stressed and unstressed vowels [i], [a] and [u] in [pV_1CV_2] utterances produced by speakers with NH vs HI. All between group and within group comparisons were found statistically significant (p<.0001).

Syllable position influences vowel duration of the two groups in similar manner (Table 4.9. and Fig. 4.17.). Vowels in second syllable position are always significantly longer for both groups and HI vowels are always significantly longer than NH vowels in both syllable positions. Similarly with the stress factor, the syllable position factor seems to influence NH vowel duration more for than HI vowel duration. Vowel [i] is longer by 32% for the NH as opposed to 19% for the HI when in second syllable position, second position vowel [a] is longer by 20% for the NH and 9% for the HI when compared with its counterpart in the first position, and second position vowel [u] is 34% longer for the NH and 16% longer for the HI. Hence the between group difference is more distinct in vowel [i] and vowel duration sensitivity due to position is [i] > [u] > [a] for both groups, although the difference in duration due to position is more pronounced for the NH than the HI.

Measured Vowel	Position	Duration & St Dev (ms)	
		NH	HI
i	1	68 (19)	95 (31)
	2	90 (60)	113 (55)
a	1	97 (22)	125 (37)
	2	116 (60)	136 (51)
u	1	77 (19)	104 (33)
	2	103 (61)	121 (53)

Table 4.9. Mean duration (in ms) of vowels [i], [a] and [u] in first and second syllable position of [pV$_1$CV$_2$] utterances produced by speakers with NH and HI.

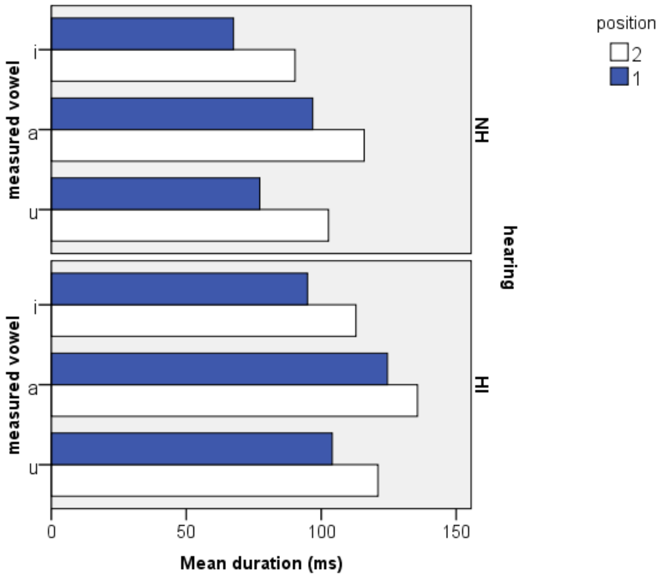


Fig. 4.17. Mean duration (in ms) of vowels [i], [a] and [u] in first and second syllable position of [pV$_1$CV$_2$] utterances produced by speakers with NH vs HI. All between group and within group comparisons were found statistically significant (p<.0001).

The interactions hearing*position (F(1, 15055)=93.261, p<.0001) and hearing*position*stress (F(1, 15055)=146.566, p<.0001) were found statistically significant. Looking at both stress and position (Table 4.10. and Fig. 4.18.), we observe that vowel duration for both the NH and the HI is significantly longer when the vowel is stressed and located in the second syllable rather than stressed and in the first syllable. The difference is more prominent for the NH. Thus, regarding the stressed vowels, [i] is longer when located in the second syllable by 41% for the NH and by 24% for the HI, [a] is longer by 32% for the NH and by 15% for the HI, and [u] is longer by 41% for the NH and 23% for the HI.

When a vowel is unstressed, it is significantly shorter when positioned in the second syllable for the NH, although the difference is not as pronounced as in their stressed vowels. NH unstressed [i], [a] and [u] are 18%, 14% and 13% shorter correspondingly when located in the second than in the first syllable. For the HI, syllable position does not play a statistically significant role in their unstressed vowel duration.

Measured Vowel	Stress	Position	Duration & St Dev (ms)			
			NH		HI	
i	stressed	1	78	(16)	111	(25)
		2	133	(59)	146	(50)
	unstressed	1	57	(15)	79	(29)
		2	47	(14)	79	(36)
a	stressed	1	110	(21)	145	(33)
		2	161	(56)	170	(44)
	unstressed	1	83	(13)	104	(28)
		2	71	(12)	101	(28)
u	stressed	1	87	(17)	119	(28)
		2	147	(57)	155	(48)
	unstressed	1	67	(16)	89	(30)
		2	58	(14)	87	(32)

Table 4.10. Mean duration (in ms) of stressed and unstressed vowels [i], [a] and [u] in first and second syllable position of [pV$_1$CV$_2$] utterances produced by speakers with NH and HI.

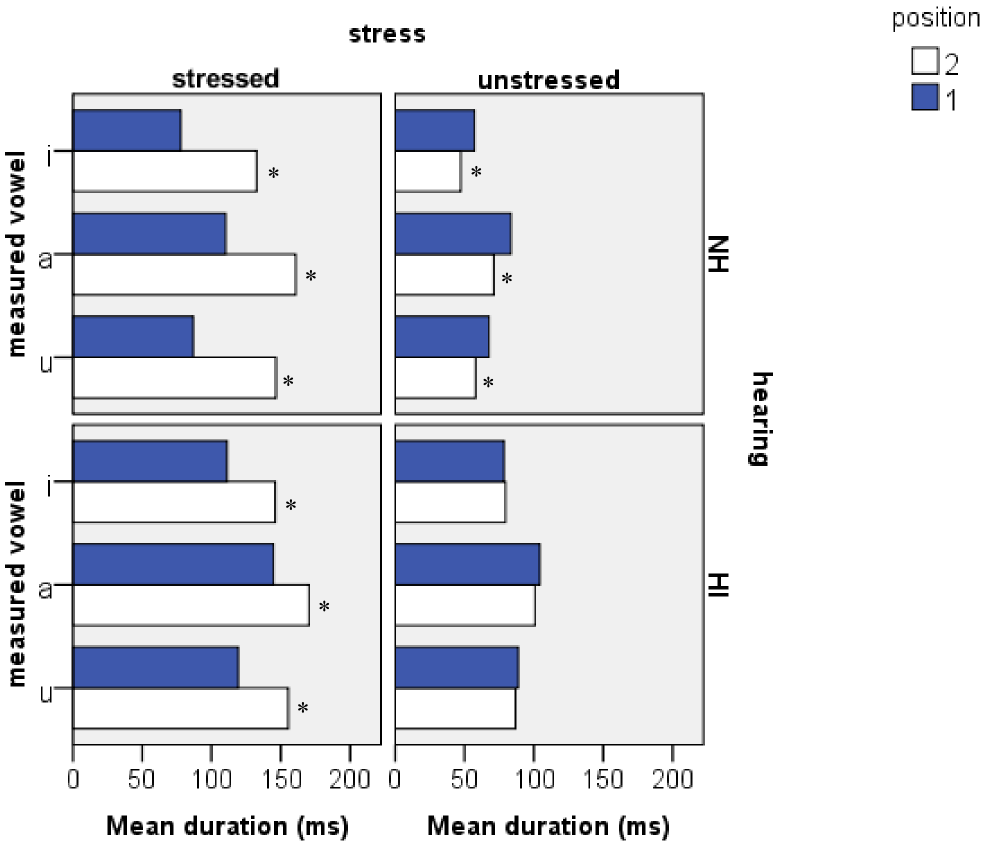


Fig. 4.18. Mean duration (in ms) of stressed and unstressed vowels [i], [a] and [u] in first and second syllable position of [pV$_1$CV$_2$] utterances produced by speakers with NH vs HI. All between group comparisons were found statistically significant. Within group statistically significant comparisons between first and second syllable position vowels of the same stress condition are marked with the symbol [*] (p<.001).

Stress, syllable position and gender

When looking at both hearing status and gender (hearing*gender*stress: F(1, 15055)=120.332, p<.0001), duration values are significantly longer for the female speakers of both groups when vowels are stressed; in the unstressed condition, the female NH vowels are still significantly longer than the male ones, but the female HI vowels are significantly shorter than the HI male vowels (Fig. 4.19.). Moreover, female HI and NH speakers both shorten their unstressed vowels in comparison with their stressed counterparts by 47%, whereas the corresponding percentages for male speakers are 27% for the HI and 44% for the NH. Thus, female HI speakers shorten their unstressed vowels almost twice as much as male HI speakers, while this gender difference is almost negligible for the NH.

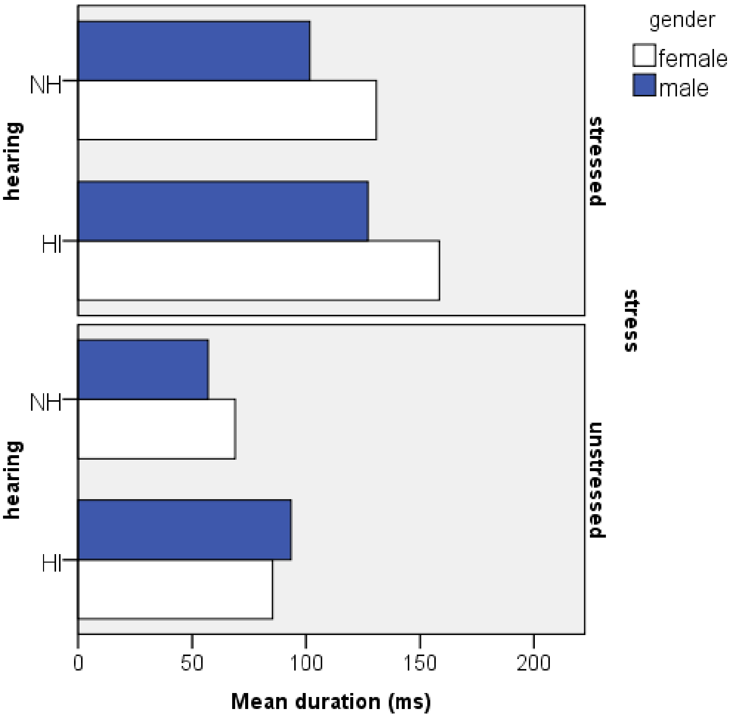


Fig. 4.19. Mean duration (in ms) of all three stressed and unstressed vowels produced by male and female speakers with NH vs HI. All between hearing group and within hearing group (stressed vs. unstressed, male vs. female) comparisons were found statistically significant (p<.01).

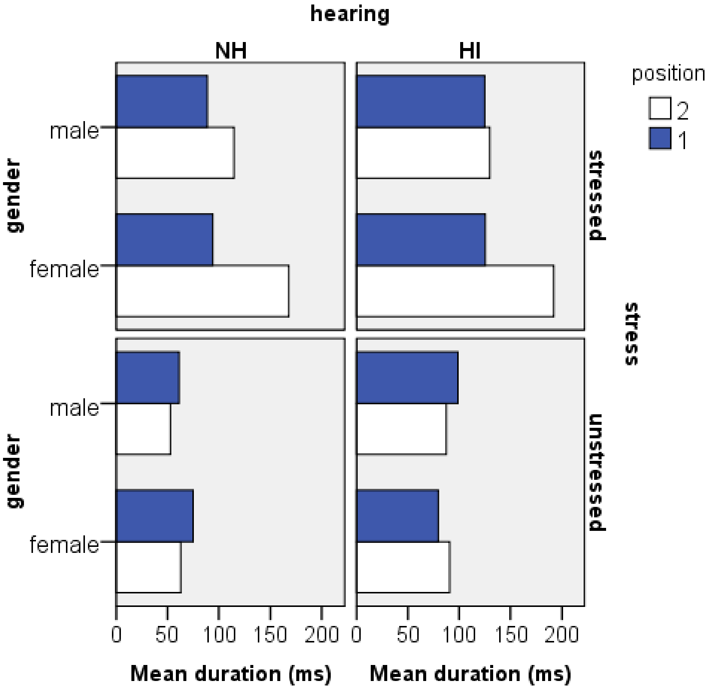


Fig. 4.20. Mean duration (in ms) of all three stressed and unstressed vowels in first and second syllable position of [pV$_1$CV$_2$] utterances produced by male and female speakers with NH vs HI. All between hearing groups comparisons are statistically significant. Comparisons between positions within hearing group and within stress condition are also statistically significant (p<.01).

Examining stress and position interaction with gender (hearing*gender*stress*position: F(1, 15055)=8.318, p<.01), we observe that both NH genders follow a general trend, according to which:

- For both genders, stressed second position vowels are longer than stressed first position vowels (30% for male and 79% female speakers).
- For both genders, unstressed second position vowels are shorter than unstressed first position vowels (13% for male and 16% for female speakers).

The HI genders follow the NH pattern regarding the stressed vowels, albeit their difference is more pronounced than that between the NH genders. However, they do not follow the NH gender unstressed vowel duration pattern. More specifically:

- For both genders, stressed second position vowels are longer than stressed first position vowels, although just by 4% for male and 54% for female speakers.
- For the HI male, unstressed second position vowels are shorter than unstressed first position vowels by 11% which is comparable with the male NH percentage, whereas for the HI female, it is the unstressed first position vowels that are shorter than the unstressed second position vowels by 14%.

This is related to the earlier finding that syllable position does not play a significant role in HI unstressed vowel duration, whereas it does in NH vowel duration, as the two HI genders follow opposing patterns. Thus, the NH pattern regarding gender differences in vowel duration changes due to stress and position is observed only to some extent by the HI group.

4.3.4. Consonantal Context

Hearing and consonant interact (F(2, 15055)=16.081, p<.0001). We examined the influence of consonantal context on the duration of the three vowels produced by the two hearing groups. The consonantal effect is not as robust as that of stress or gender, nevertheless, it is statistically significant in certain contexts. HI vowels are significantly longer than NH vowels in all consonantal contexts (Table 4.11. and Fig. 4.21.).

For the NH group, vowel [i] is significantly longer in the bilabial rather than in the alveolar context, while for the HI group, no significant influences from consonantal context were detected. Vowel [a] was found unaffected from context for the NH, whereas for the HI it is significantly longer in the alveolar context and especially when the intervocalic consonant is the fricative. Finally, for the NH group, the duration of vowel [u] decreases significantly according to context in the order [p] > [s] > [t], while for the HI group, it is significantly longer in the fricative context.

Overall duration patterns according to vowel identity and consonantal context present comparable trends but do not reach statistical significance similarly in the two hearing groups. For the NH group, the high vowels are significantly longer in the bilabial context, while for the HI group, this trend can be discerned but does not reach significance. The low vowel [a] is longer for both groups in the alveolar and especially in the fricative context, but this pattern is statistically significant only for the HI group.

Measured Vowel	**Context**	**Duration & St Dev (ms)**	
		NH	**HI**
i	**p**	84 (46)	106 (46)
	t	77 (47)	102 (46)
	s	76 (45)	104 (44)
a	**p**	104 (45)	124 (43)
	t	106 (48)	130 (45)
	s	109 (47)	136 (45)
u	**p**	94 (45)	113 (47)
	t	87 (47)	110 (42)
	s	88 (47)	114 (45)

Table 4.11. Mean duration (in ms) of vowels [i], [a] and [u] produced in the context of [p], [t] and [s] by speakers with NH and HI.

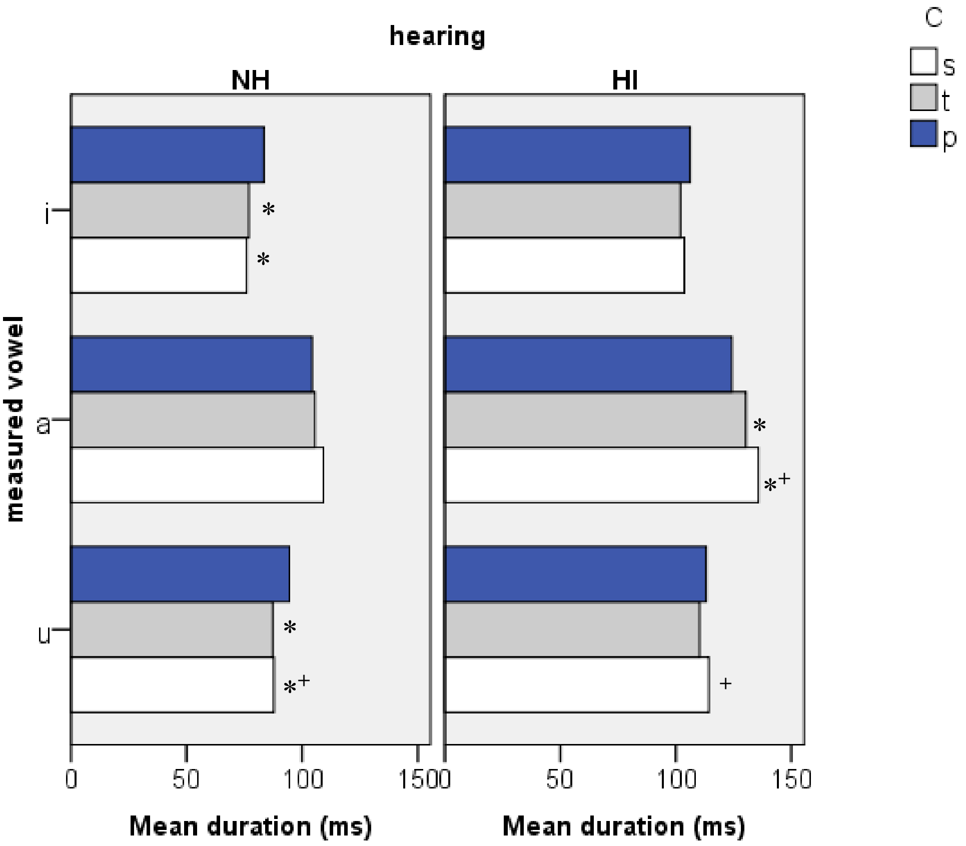


Fig. 4.21. Mean duration (in ms) of vowels [i], [a] and [u] produced in the context of [p], [t] and [s] by speakers with NH and HI. Symbol [*] denotes statistical significance between the bilabial and the alveolar contexts and symbol [$^+$] between the two alveolar contexts within hearing group (p<.05).

Overall, vowels [i] and [u] are significantly shorter in the alveolar context for the NH, while HI vowel [a] becomes significantly longer in the alveolar context and especially due to the fricative. The articulatory distance between an open vowel like [a] and a lingual constriction or narrowing demanded for [t] or [s] may be responsible for the significant lengthening of the HI vowel so that enough time is provided in order to move in and out of the consonantal stricture. This may also be implied by the fact that HI vowels are longest in a fricative context. On the other hand, the proximity of [i] and [u] to the alveolar consonant place of articulation does not produce a significant shortening for the HI as it does for the NH, as the HI take more time in general to coordinate their articulators in relation to the NH.

Consonantal context and syllable position

We subsequently examined the interaction hearing*consonant*position (F(2, 15055)=34.116, p<.0001) and found that consonantal context influences first and second vowel duration differently in the two groups (Table 4.12. and Fig. 4.22. below).

Measured Vowel	Position	Context	Duration & St Dev (ms)	
			NH	HI
i	1	p	69 (16)	88 (27)
		t	65 (18)	95 (30)
		s	68 (21)	102 (35)
	2	p	98 (59)	125 (53)
		t	89 (61)	109 (57)
		s	84 (60)	105 (52)
a	1	p	92 (21)	109 (30)
		t	96 (22)	128 (36)
		s	103 (22)	137 (39)
	2	p	117 (58)	139 (48)
		t	115 (63)	133 (52)
		s	116 (61)	135 (51)
u	1	p	80 (16)	96 (27)
		t	73 (16)	104 (30)
		s	79 (23)	112 (38)
	2	p	109 (59)	130 (56)
		t	102 (62)	116 (51)
		s	97 (62)	117 (51)

Table 4.12. Mean duration (in ms) of vowels [i], [a] and [u] in the first and second syllable position produced in the context of [p], [t] and [s] by speakers with NH and HI.

The main observations are the following.

- Pre-consonantally:
  - For the NH, the open vowel [a] is significantly longer before the fricative than the bilabial stop. The close vowels [i] and [u] are longer before the bilabial stop than the two alveolars but not statistically significantly.
  - For the HI, all three vowels are significantly longer before the alveolars than the bilabial, and also significantly longer before the fricative than the alveolar stop (note symbols [$^{+}$] and [$^{\square}$] in Fig. 4.22.).

- Post-consonantally:
  - For both groups, vowels [i] and [u] are significantly longer after the bilabial than the alveolars, while the duration of vowel [a] is not influenced significantly by consonantal context.
  - For the NH, second position vowels are always significantly longer than first position vowels regardless of consonantal context, whereas, for the HI, we observe that in the context of [s], first and second position [i] and [a] vowels are equally long (note symbol [*] in Fig. 4.22.). Hence, the fricative significantly lengthens the NH vowels in the second position but not HI [i] and [a] vowels.

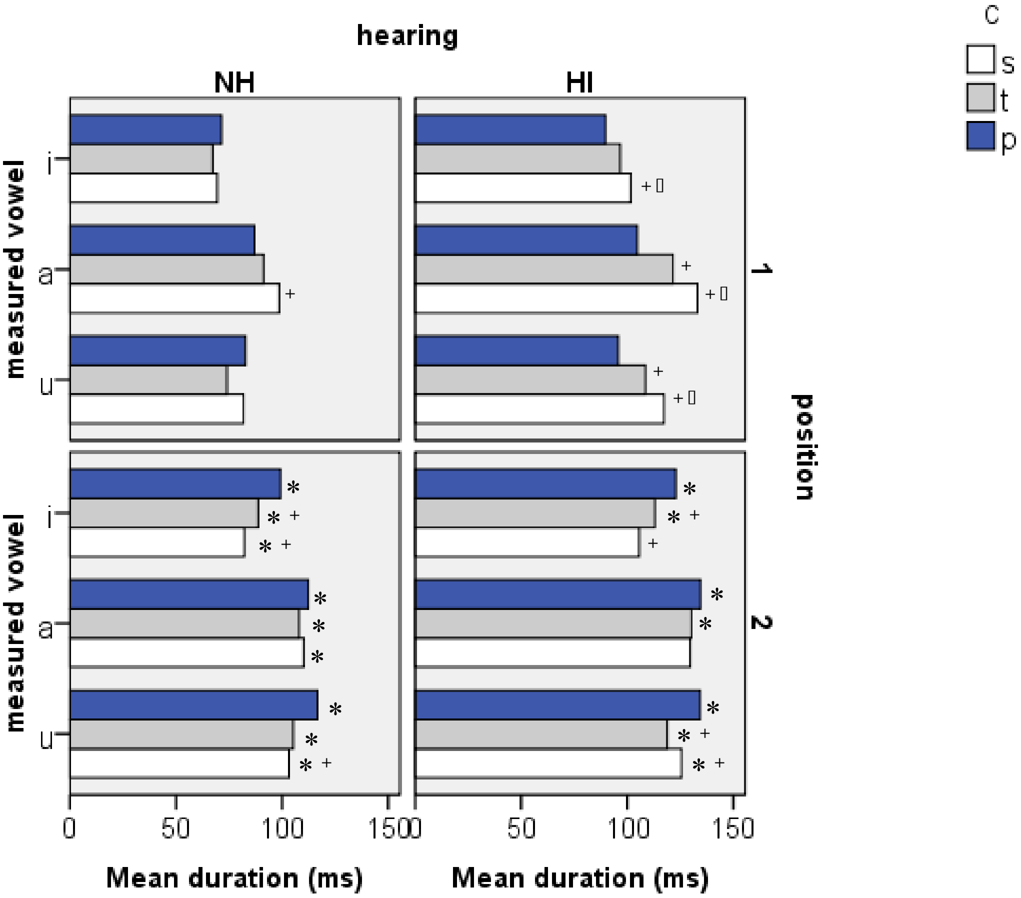


Fig. 4.22. Mean duration (in ms) of vowels [i], [a] and [u] in the first (above) and in the second (below) syllable position, produced in the context of [p], [t] and [s] by speakers with NH and HI. All statistical comparison are made within hearing group (p<.05). Symbol [*] denotes statistical significance between the first and second syllable position within vowel and consonantal context, symbol [$^+$] between the bilabial and the alveolar contexts within vowel and syllable position and symbol [$^{▯}$] between the two alveolar contexts within vowel and syllable position.

In brief, it seems that the fricative significantly lengthens HI vowels pre-consonantally in comparison with the other two contexts. In the second position, the two groups present a similar durational pattern. This significant pre-consonantal lengthening of HI vowels in the alveolar environment and especially in the context of the fricative may be related to the additional time needed in order to satisfy increased demands inflicted by the HI alveolar articulation.

4.3.5. Vocalic Context

As above, the HI display significantly longer vowel durations than the NH in all transconsonantal vocalic contexts. Both groups seem to follow the same duration pattern according to vowel context, although some differences were found with post hoc tests in vowels [i] and [u]. For both groups, vowel [a] has a significantly longer duration due to the V-to-V influence from [i] ([paCi] and [piCa]) by 6% for the NH and 4% for the HI, and [u] ([paCu] and [puCa]) by 10% for the NH and 6% for the HI, in comparison with the corresponding [a] in the symmetrical disyllable [paCa]. The duration of vowel [i] significantly decreases by 6% across from [a] for the HI but not statistically significantly for the NH. Vowel [u] is significantly shortened in an [a] transconsonantal context for both groups; for the HI, [u] is shortened in an [i] context as well, but for the NH this duration decrease is not statistically significant.

In general, the differences between the two groups here are not as many and as significant as with consonantal context. This may be related to the fact that both groups are attempting to keep a rhythm which affects the relative duration of the two vowels in the disyllable. Hence, it is expected that [a] in a symmetrical disyllable ([paCa]) will be allocated a shorter duration than, for example, [a] in [paCi], as [i] is a shorter vowel in duration which allows [a] to lengthen. This sort of rules seems to be in effect for both groups. HI [i] and [u] duration seems a bit more sensitive to transconsonantal vowel effects which may have to do with their longer durations that allow for more shortening than the corresponding NH values which are shorter in comparison, to begin with.

Measured Vowel	Context	Duration & St Dev (ms)			
		NH		HI	
i	i	80	(46)	105	(46)
	a	74	(44)	99	(46)
	u	82	(48)	108	(45)
a	a	101	(46)	126	(44)
	i	107	(47)	131	(44)
	u	111	(46)	134	(44)
u	u	94	(47)	117	(46)
	i	90	(44)	113	(42)
	a	85	(49)	108	(46)

Table 4.13. Mean duration (in ms) of vowels [i], [a] and [u] produced in the vocalic context of [i], [a] and [u] by speakers with NH and HI.

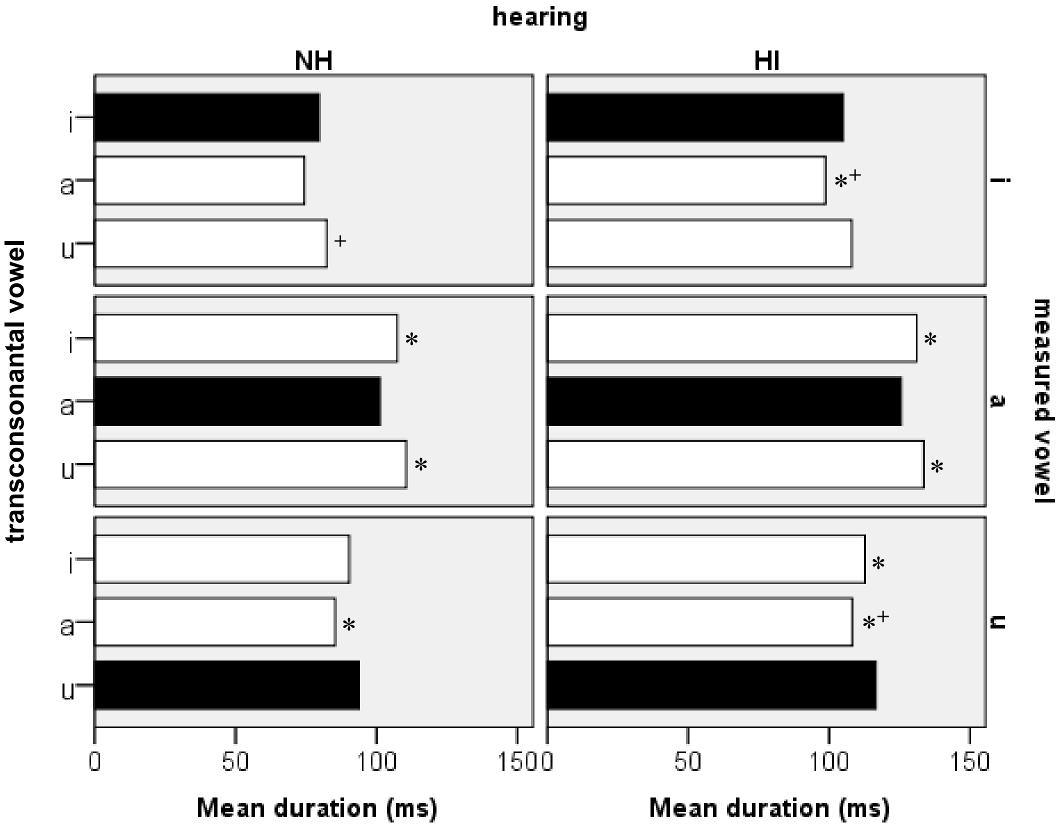


Fig. 4.23. Mean duration (in ms) of vowels [i], [a] and [u] produced in the context of [i], [a] and [u] by speakers with NH and HI. There is one panel for each measured vowel which contains three bars, one for each of the three vocalic contexts. Black bars represent vowels in symmetrical disyllables. Within hearing group statistically significant difference between the vowel in the symmetrical disyllable and its counterpart in an asymmetrical disyllable is denoted with the symbol [*], while between the vowel and its couterpart in the two asymmetrical disyllables with symbol [$^+$] (p<.05).

SYNOPSIS

This section summarizes the main findings regarding the influence of hearing, gender, intelligibility, stress, syllable position, consonantal and vocalic context on the duration of the three vowels [i], [a], [u].

- **hearing**
    - The vowel duration pattern is [a] > [u] > [i] for both hearing groups.
    - Vowels produced by speakers with HI are significantly longer than those produced by speakers with NH. HI [a] is about 23%, [u] 26% and [i] 32% longer than the corresponding NH vowels
- **gender**
    - Female HI vowels are the longest, followed by male HI vowels, female NH and lastly male NH vowels.
    - The duration difference between the two genders, i.e., longer female than male vowels, is more pronounced for the NH than the HI.
    - The duration difference between the NH and the HI vowels is slightly more pronounced in male speakers.
- **intelligibility**
    - All intelligibility groups follow the aforementioned pattern of vowel duration, which is [a] > [u] > [i].
    - The very high intelligibility group (consisting of two female speakers) has the highest duration values, while the high intelligibility group has the lowest and closest to the ones of the NH group.
- **stress**
    - All three HI vowels are significantly longer than the corresponding NH vowels in both stress conditions.

  - Unstressed vowels are significantly shorter than stressed vowels for both groups, although the difference is more pronounced for the NH.
  - The vowel duration sensitivity to stress follows the pattern [i] > [u] > [a] for both groups.
- **position**
  - HI vowels are always significantly longer than NH vowels in both syllable positions.
  - Vowels in second syllable position are always significantly longer for both groups.
  - The difference in vowel duration due to position is more pronounced for the NH than the HI, as with the stress factor.
- **stress & position**
  - Vowel duration for both the NH and the HI is significantly longer when the vowel is stressed and located in the second syllable rather than stressed and in the first syllable. The difference is a lot more prominent for the NH.
  - When a vowel is unstressed, it is significantly shorter when positioned in the second syllable for the NH, although the difference is not as pronounced as in their stressed vowels. For the HI, syllable position does not play a statistically significant role in their unstressed vowel duration.
- **stress, position & gender**
  - Duration values are significantly longer for the female speakers of both groups when vowels are stressed.

  - In the unstressed condition, the female NH vowels are still significantly longer than the male ones, but the female HI vowels are significantly shorter than the HI male vowels.
  - Female HI speakers lengthen their stressed vowels almost twice as much as male HI speakers, while this gender difference is negligible for the NH.
  - As with the NH genders, both HI genders lengthen their stressed second syllable position vowels. Female speakers do so more than male speakers, although this difference is more pronounced for the HI.
  - Contrary to the NH pattern, according to which, unstressed second position vowels are significantly shorter for both genders, female HI speakers significantly shorten their unstressed first syllable position vowels while male HI speakers do the opposite, following the aforementioned NH trend.
  - Thus, the NH pattern regarding gender differences in vowel duration changes due to stress and position is observed only to some extent by the HI group.
- **consonantal context**
  - HI vowels are significantly longer than HI vowels in all consonantal contexts.
  - For the NH group, the high vowels are significantly longer in the bilabial context, while for the HI group, this trend can be discerned but does not reach significance.

  - The low vowel [a] is longer for both groups in the alveolar and especially in the fricative context, but this pattern is statistically significant only for the HI group.
  - Thus, duration patterns according to vowel identity and consonantal context present comparable trends but do not reach statistical significance similarly in the two hearing groups.
- **consonantal context & syllable position**
  - Pre-consonantally the two hearing groups display different durational patterns.
  - For the NH, the open vowel [a] is significantly longer before the fricative than the bilabial stop. The close vowels [i] and [u] are longer before the bilabial stop than the two alveolars but not statistically significantly.
  - For the HI, all three vowels are significantly longer before the alveolars than the bilabial, and especially before the fricative.
  - Post-consonantally the two hearing groups demonstrate similar patterns of vowel duration. For both groups, vowels [i] and [u] are significantly longer after the bilabial than the alveolars, while the duration of vowel [a] is not influenced significantly by consonantal context.
  - All NH and HI vowels are longer post- than pre-consonantally in the bilabial and the alveolar stop context. However, the duration of HI vowels [i] and [a] in the context of the fricative does not follow this general pattern of word-final lengthening.

- **vocalic context**
    - The HI display significantly longer vowel durations than the NH in all transconsonantal vocalic contexts.
    - For both groups, the duration of [a] is lengthened significantly in the context of both [i] and [u], while HI [i] and [u] are shortened more than the corresponding NH vowels.
    - Overall, V-to-V durational effects are similar for the two groups regarding open vowel [a]. Concerning the two close vowels, the two groups show the same trends but more effects are located for the HI group.

4.4. Consonant-to-Vowel Coarticulation in HI vs. NH speech

Consonantal coarticulatory effects for the NH and the HI group were examined on the F1mid and F2mid of the three vowels in symmetrical disyllables [pVCV]. The bilabial context is taken as a neutral base so as to check statistical significance of the anticipatory and the carryover influence of the alveolar plosive [t] and the fricative [s] on the F1 and F2 of the steady state of [i], [a] and [u] within hearing group with Tukey post hoc tests. Figures 4.24. to 4.26. below present interval plots (a mean symbol with a 95% confidence interval bar) of (a) F1mid and (b) F2mid, so as to make *within group* comparisons between the bilabial context [p] and the alveolar contexts [t] or [s]. Consonant-to-vowel effects are indicated by the statistically significant aforementioned comparisons. A statistically significant difference ($p < .05$) between the bilabial context [p] and the alveolar contexts [t] or [s] is denoted with an asterisk [*]. Additionally, within group comparisons between the two alveolar contexts [t] and [s] are also made so as to examine if F1mid and F2mid are significantly different in the two alveolar environments, and that statistical significance ($p<.05$) is denoted with a cross [$^+$].

4.4.1. Consonantal context effects on [i]

Since [i] is a fairly constrained vowel we do not expect significant C-to-V effects. As we observe in Table 4.14. and Fig. 4.24. our expectations are confirmed; neither group shows statistically significant coarticulatory effects when comparing the bilabial with the alveolar contexts. Nevertheless, certain trends are discernible for the two groups.

Both NH and HI F1 show relatively minor influence from the alveolar environments. In the anticipatory direction, both groups display a slight F1 raising in the [t] context and F1 lowering in the [s] context in comparison with the bilabial context, although these effects are somewhat more pronounced for the HI which may mean that the HI need to anticipate an alveolar constriction more than the NH. In the carryover direction the two groups present opposing patterns; both alveolar consonants raise F1 for the NH, whereas F1 drops slightly for the HI.

Concerning F2, the NH display bidirectional C-to-V effects of relatively greater magnitude than the HI. Nevertheless, the patterns of change are similar for both groups. For the NH, both alveolars raise F2 in the anticipatory direction, whereas in the carryover direction, [t] causes F2 raising and [s] F2 lowering. For the HI, there is minimal change in the anticipatory direction, and a slight [s] F2 lowering in the carryover direction.

hearing	**direction**	**Context**	**F1mid (StDev) in Hz**	**F2mid (StDev) in Hz**
NH	anticipatory	p[i]pi	374 (74)	2254 (218)
		p[i]ti	379 (72)	2341 (223)
		p[i]si	363 (62)	2328 (211)
	carryover	pip[i]	364 (63)	2276 (204)
		pit[i]	367 (62)	2332 (235)
		pis[i]	375 (62)	2227 (235)
HI	anticipatory	p[i]pi	349 (54)	2058 (214)
		p[i]ti	359 (59)	2078 (205)
		p[i]si	335 (52)	2080 (255)
	carryover	pip[i]	365 (72)	2089 (273)
		pit[i]	363 (59)	2092 (252)
		pis[i]	353 (46)	2048 (304)

Table 4.14. Mean F1mid and F2mid values and StDev in Hz of vowel [i] of the NH and the HI group in first syllable position (anticipatory) and second syllable position (carryover) in the consonantal environments of [p], [t] and [s]. The formant and StDev values correspond to the interval bars in Fig. 4.24.

(a)

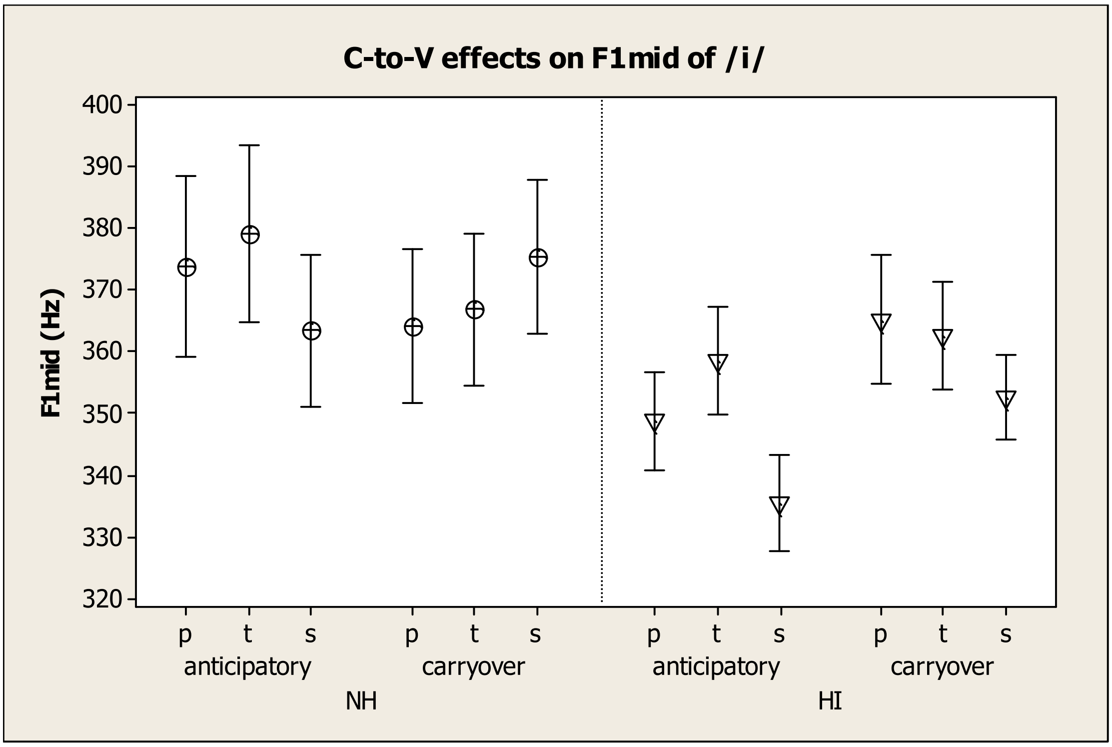
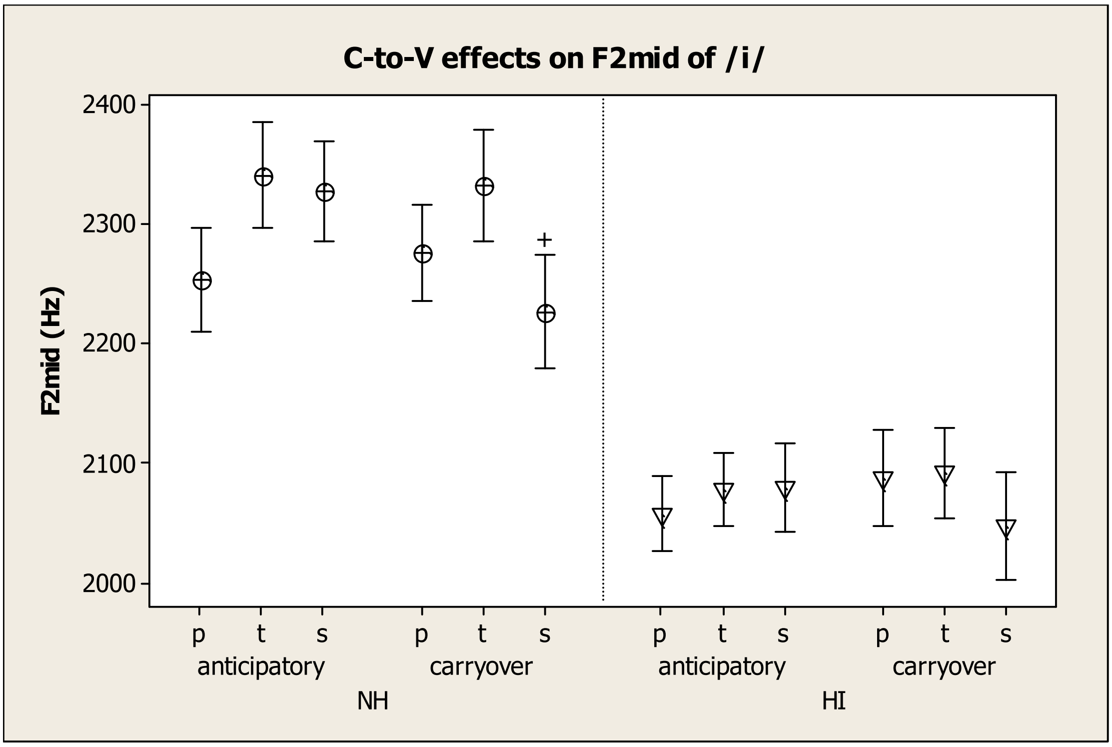


Fig. 4.24. Anticipatory and carryover effects on [i] (a) F1mid (above) and (b) F2mid (below) of the consonants [p], [t] and [s]. Symbol [$^+$] denotes statistically significant difference ($p< .05$) between the two alveolar contexts [t] and [s] within group. No stat. significance was found between bilabial and alveolar contexts.

(b)



4.4.2. Consonantal context effects on [a]

Our data is in accordance with the literature which generally reports this vowel to be more sensitive to coarticulatory effects than the high front vowel (Recasens et al., 1997). Hence we expect that the F2 of the low vowel [a] will rise in the alveolar context, as the tongue assumes a more forward position to form the alveolar constriction. The results show that, for the NH group, the effects reach statistical significance in the F2 but not the F1, while the HI manifest a strong coarticulatory influence from [s] on both formants (Table 4.15. and Fig. 4.25.).

More specifically, as far as the F1 axis is concerned, it is noteworthy that the fricative context triggers statistically significant lowering effects on the HI F1, both in the anticipatory and in the carryover direction, whereas the lowering effects on the NH F1 are not statistically significant in either direction. The [t] context does not bring about statistically significant effects for either group, although a slight F1 raising is discerned for the NH in both directions, while HI F1 remains at the same level when comparing the alveolar stop with the bilabial context. As regards the F2, both groups show significant effects from [t] and [s] in the anticipatory direction, but for the NH the effects are of an even greater magnitude in the carryover direction, while for the HI carryover effects are not statistically significant.

hearing	direction	Context	F1mid (StDev) in Hz	F2mid (StDev) in Hz
NH	anticipatory	p[a]pa	803 (124)	1283 (152)
		p[a]ta	814 (128)	1426 (167)
		p[a]sa	799 (128)	1433 (151)
	carryover	pap[a]	800 (133)	1267 (171)
		pat[a]	818 (126)	1447 (165)
		pas[a]	786 (132)	1433 (164)
HI	anticipatory	p[a]pa	749 (134)	1235 (179)
		p[a]ta	749 (127)	1366 (163)
		p[a]sa	723 (120)	1399 (186)
	carryover	pap[a]	770 (146)	1283 (156)
		pat[a]	763 (150)	1334 (142)
		pas[a]	737 (158)	1336 (182)

Table 4.15. Mean F1mid and F2mid values and StDev in Hz of vowel [a] of the NH and the HI group in first syllable position (anticipatory) and second syllable position (carryover) in the consonantal environments of [p], [t] and [s]. The formant and StDev values correspond to the interval bars in Fig. 4.25.

(a)

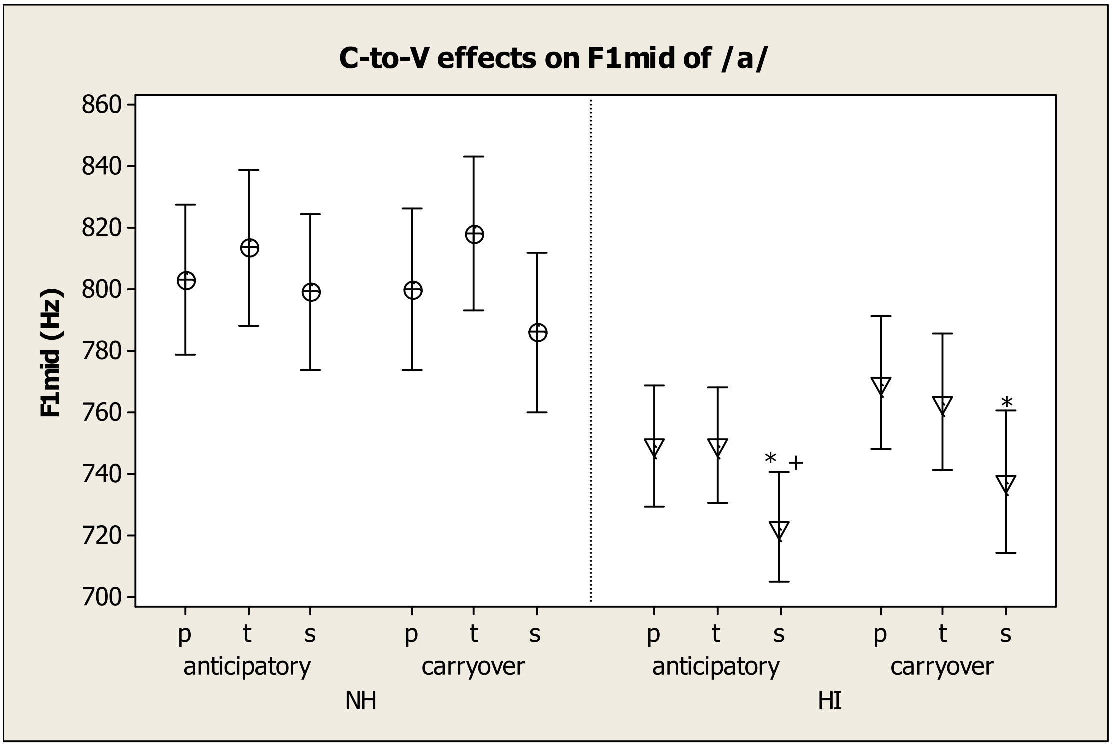
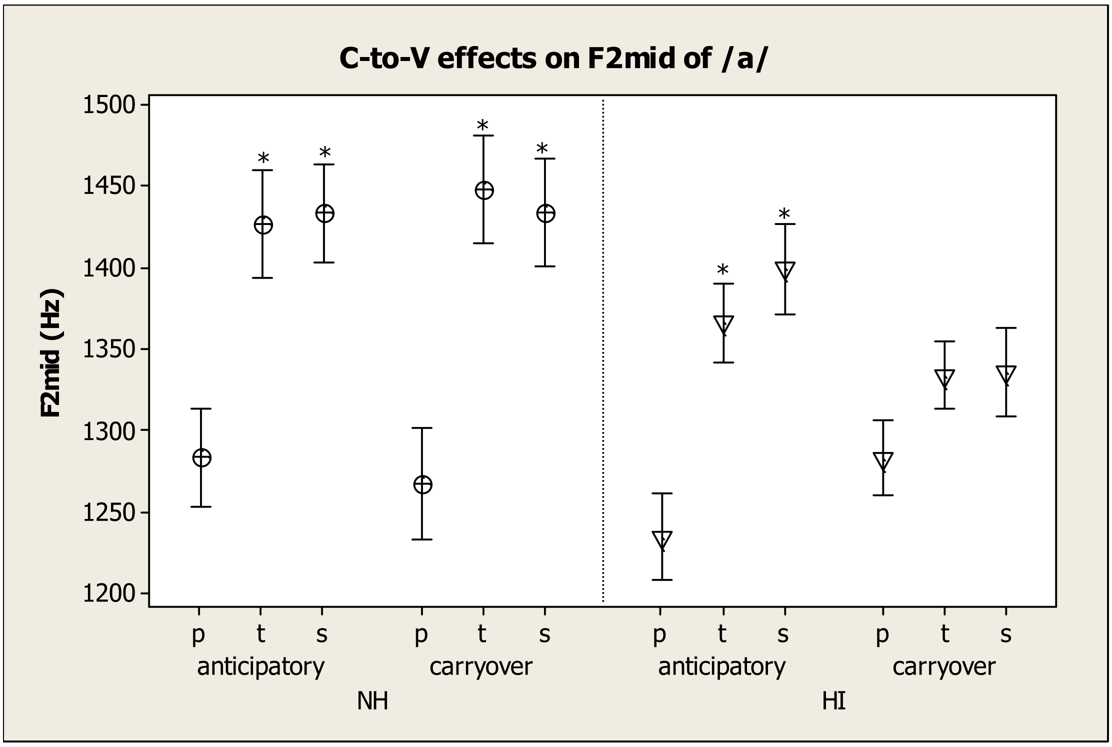


Fig. 4.25. Anticipatory and carryover effects on [a] (a) F1mid (above) and (b) F2mid (below) of the consonants [p], [t] and [s]. Symbol [*] denotes statistically significant difference (p< .05) between the bilabial ([p]) and the alveolar contexts ([t] or [s]), and symbol [$^+$] between the two alveolar contexts ([t] and [s]) within group.

(b)



4.4.3. Consonantal context effects on [u]

This vowel is also less constrained than [i], thus we may expect C-to-V effects especially in the F2 axis. Post hoc tests on the comparisons between the bilabial and the alveolar contexts demonstrate that effects are statistically significant on F2 as expected (Table 4.16. and Fig. 4.26.).

Concerning the F1, effects are statistically non significant for both groups, but looking at the pattern we note that the two groups follow the same trend, which is F1 raising from [t] in the anticipatory direction and F1 lowering from [s] in both directions, and effects of greater magnitude in the anticipatory direction. In addition, the HI display strong anticipatory effects from [s].

As mentioned above, for F2, effects are statistically significant for both groups, in both directions and from both alveolar contexts, except for the carryover influence from [t] for the HI. The HI generally demonstrate effects of lesser magnitude than the NH. For both groups effects from [s] are stronger than from [t], but for the HI this difference is also statistically significant. Moreover, we observe that F2mid values display increased variability for the HI group compared to the NH group (see standard deviation values in Table 4.16.).

hearing	direction	Context	F1mid (StDev) in Hz	F2mid (StDev) in Hz
NH	anticipatory	p[u]pu	418 (69)	734 (91)
		p[u]tu	420 (76)	945 (81)
		p[u]su	405 (60)	971 (92)
	carryover	pup[u]	408 (77)	705 (105)
		put[u]	402 (69)	880 (98)
		pus[u]	404 (67)	961 (129)
HI	anticipatory	p[u]pu	364 (60)	1058 (155)
		p[u]tu	375 (79)	1168 (196)
		p[u]su	345 (60)	1238 (241)
	carryover	pup[u]	379 (74)	1028 (155)
		put[u]	365 (52)	1080 (164)
		pus[u]	378 (61)	1159 (215)

Table 4.16. Mean F1mid and F2mid values and StDev in Hz of vowel [u] of the NH and the HI group in first syllable position (anticipatory) and second syllable position (carryover) in the consonantal environments of [p], [t] and [s]. The formant and StDev values correspond to the interval bars in Fig. 4.26.

(a)

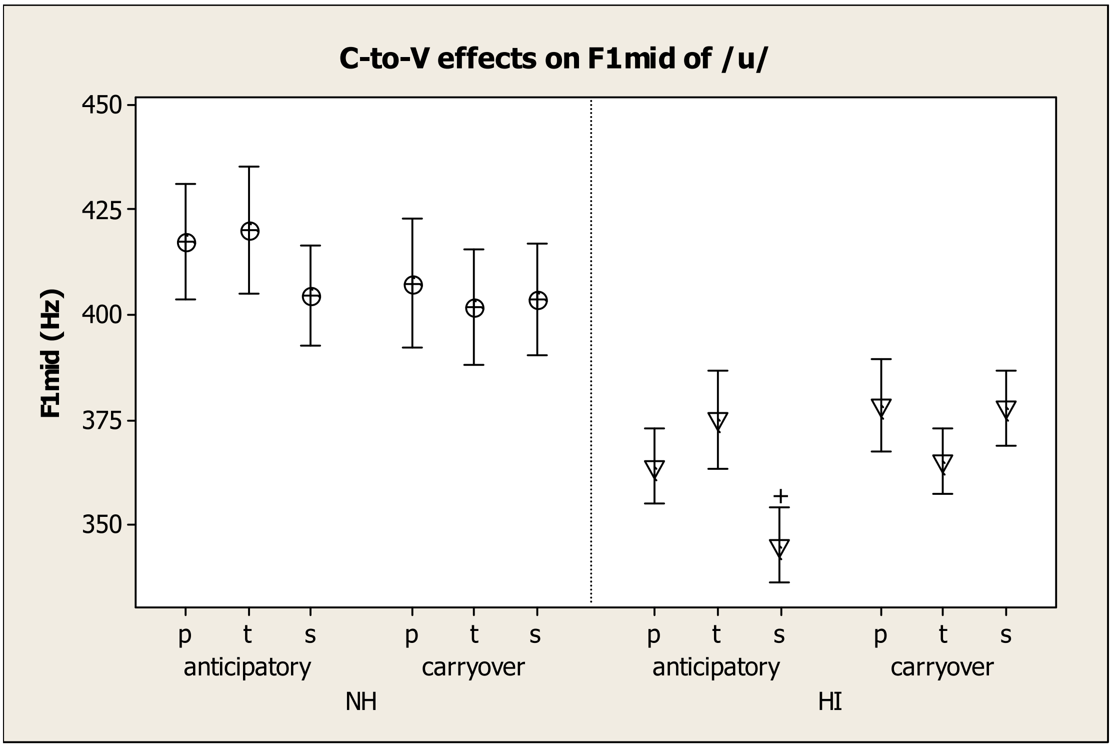
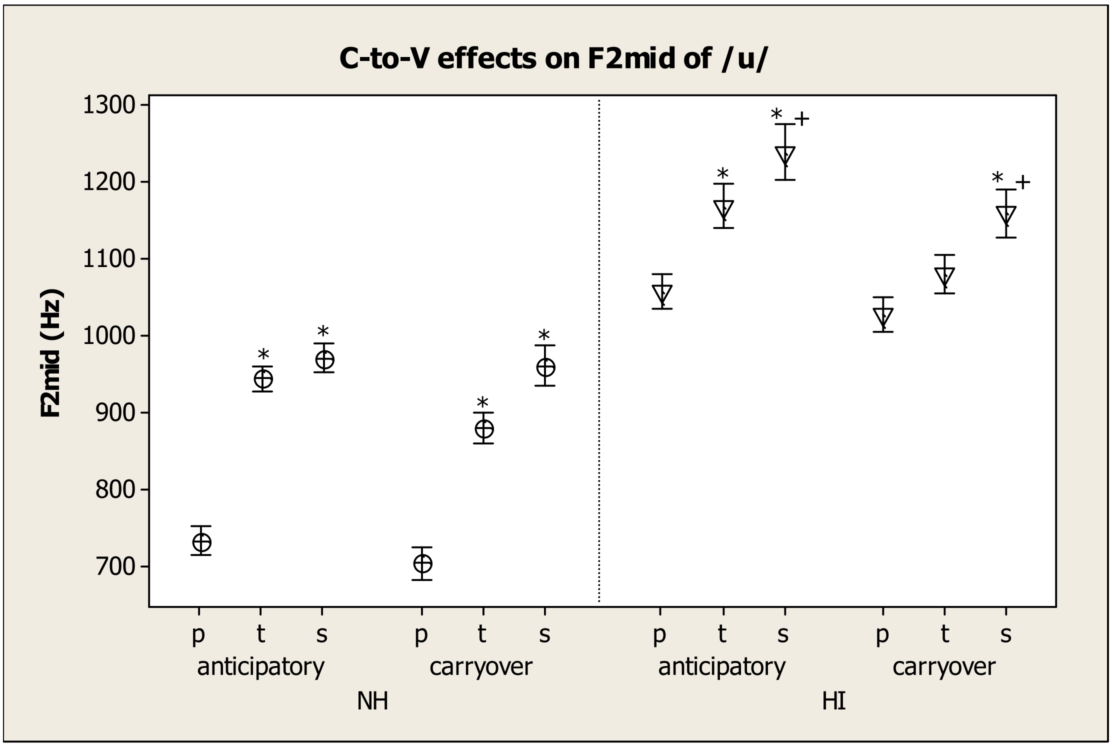


Fig. 4.26. Anticipatory and carryover effects on [u] (a) F1mid (above) and (b) F2mid (below) of the consonants [p], [t] and [s]. Symbol [*] denotes statistically significant difference ($p< .05$) between the bilabial ([p]) and the alveolar contexts ([t] or [s]), and symbol [$^+$] between the two alveolar contexts ([t] and [s]) within group.

(b)



Summary

On the basis of the F1mid and F2mid within group comparisons between the bilabial and the two alveolar contexts, [t] and [s], which were found statistically significant ($p<.05$), we summarize the effects of consonantal context on the steady state of the three point vowels [i], [a], [u] as produced by the NH and by the HI (see also Fig. 4.27. below).

- Overall, C-to-V effects along the F1 axis are minimal for both groups with few exceptions for the HI group, whereas along the F2 axis there are significant effects on vowels [a] and [u] for both groups.
- Vowel sensitivity to consonantal effects for both the NH and the HI group decreases as follows:
    - F2 axis: [u] > [a] > [i]
    - F1 axis: [a] > [u], [i]
- Vowel [i] appears to be the most constrained of the three point vowels; effects are not statistically significant for either group. Nevertheless, we observe that, for the NH, the alveolar stop causes some fronting, while, for the HI, this vowel seems more constrained, possibly indicating more tongue/palate contact in comparison with the NH [i]. We also note that, in both groups, the fricative causes opposite effects in the two directions, that is, it makes [i] fronter pre-consonantally and more back post-consonantally. This divergence due to position does not occur in the other two vowels. Both [t] and [s] cause fronting regardless of direction to [a] and [u] in both groups.
- For the NH, vowel [a] demonstrates statistically significant fronting from both alveolars in both directions. The HI show significant fronting from both alveolars but only in the anticipatory direction. Moreover, the fricative causes significant [a]

raising for the HI, whereas neither alveolar causes significant change for NH [a] in the F1 axis.

- Vowel [u] is significantly fronted in the alveolar context for both groups, although effects are of a greater magnitude for the NH. The HI [u] is already quite fronted in relation to the NH [u] in the bilabial context which may limit further fronting influences for the HI. Additionally, this vowel is much more variable for the HI vs. the NH group along the F2 axis. Fronting effects from [s] are yet again more pronounced at a statistically significant level in comparison to effects from [t] for the HI which may again suggest a more constrained and thus more demanding fricative in degree of tongue involvement for the HI. In addition, there is a raising effect on [u] from the fricative. This raising is nonsignificant for the NH group, but for the HI group it is significant when compared to the alveolar stop.
- Regarding the NH, the alveolar stop generally causes coarticulatory effects of greater magnitude to both the F1 and F2 of [i] and [a], whereas [u] receives more effects from the fricative. For the HI, the fricative instigates greater influence to all three vowels.

In general, the NH show more C-to-V effects in statistical significance and magnitude than the HI whose vowel space is smaller. There is a preference to the carryover direction by NH effects especially on F2 of [a] and [u] which is in contrast with HI effects mostly occurring in the anticipatory direction. It is noteworthy that the fricative triggers more effects for the HI in the majority of environments. That, in combination with the aforementioned favouring towards the anticipatory direction, may be related to the more constrained articulation of the HI [s].

(a)

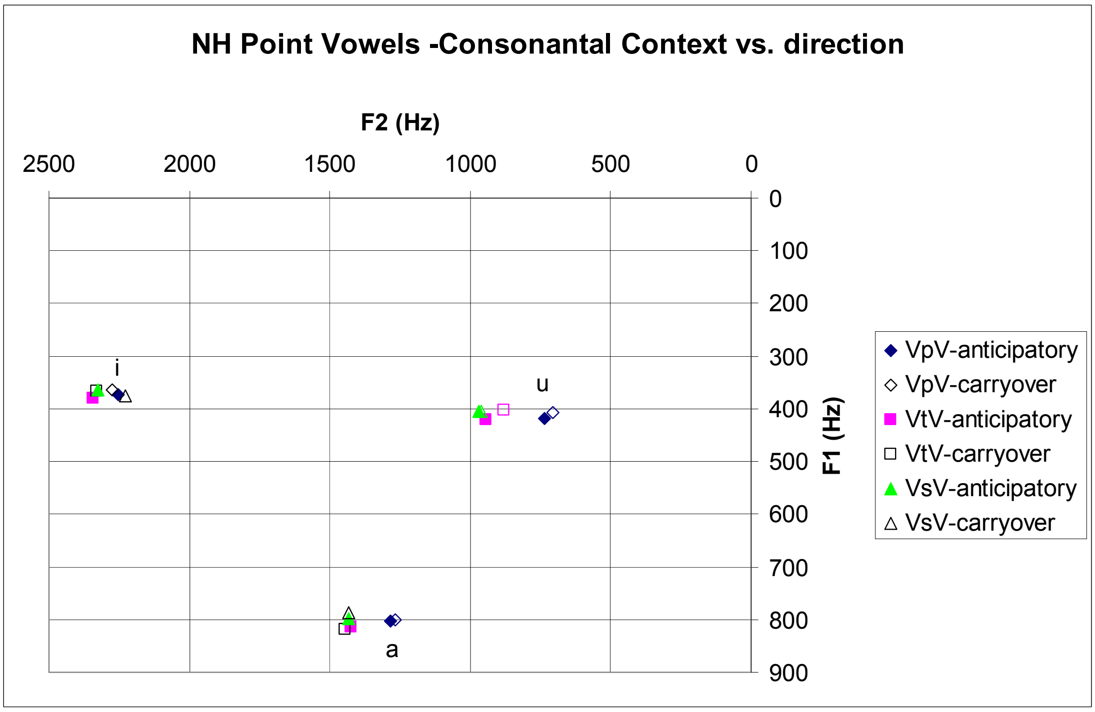
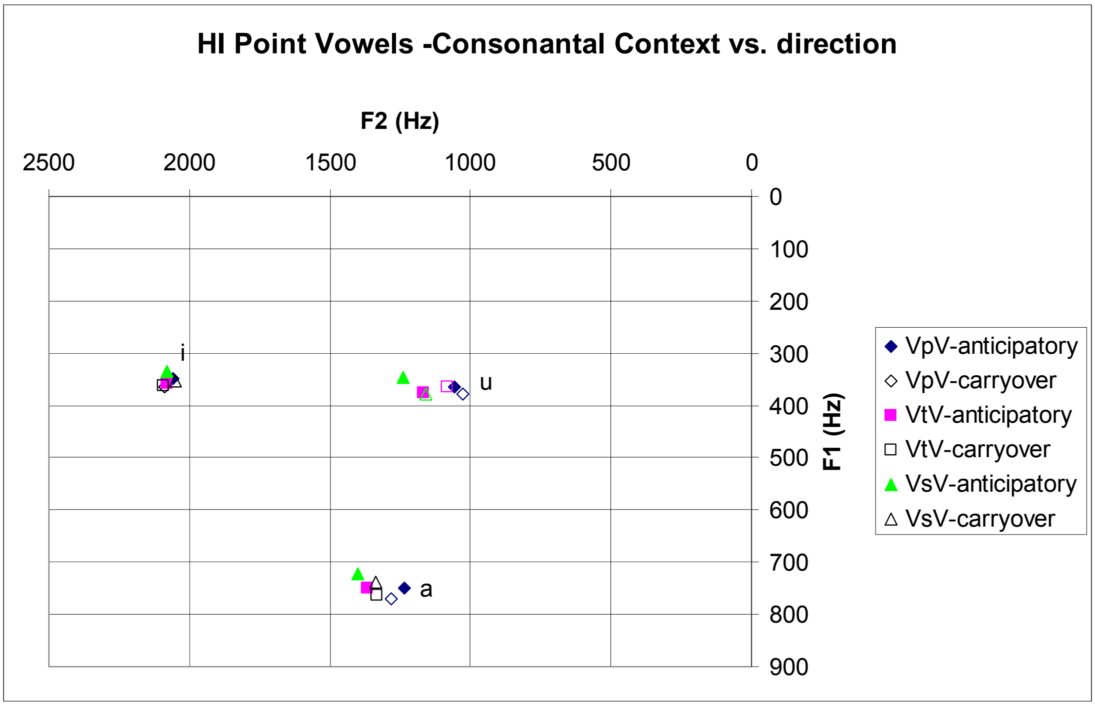


Fig. 4.27. Consonantal context effects on the three point vowels [i], [a], [u] of (a) the NH (above) and (b) the HI (below) in the anticipatory and the carryover direction. The vowel points were computed from mean F1mid and F2mid values.

(b)



4.5. Stress Effects on HI vs. NH C-to-V Coarticulation

F1mid and F2mid measurements of the three vowels ([i], [a], [u]) in the two stress conditions and in the three consonantal contexts ([p], [t] and [s]) were taken. Within group, vowel and stress condition pairwise comparisons were made on the F1mid and F2mid between the bilabial and each of the two alveolar contexts. Pairs that were found statistically significantly different indicated the alveolar and stress environment that produced significant effects on F1mid or/and F2mid, thus uncovering the role of stress in C-to-V coarticulation. Table 4.17. summarizes the mean F1 and F2 formant values and the pairwise comparisons carried out as well as their statistical significance. F1 comparisons were not statistically significant with the exception of that between the bilabial and fricative context of the unstressed HI [a]. The results concerning F2 are also presented in Fig. 4.28. below. The bars represent the difference between F2mid in the alveolar ([t] or [s]) minus F2mid in the bilabial ([p]) context (ΔF2), provided in the right section of Table 4.17. The data is pooled across the two coarticulatory directions.

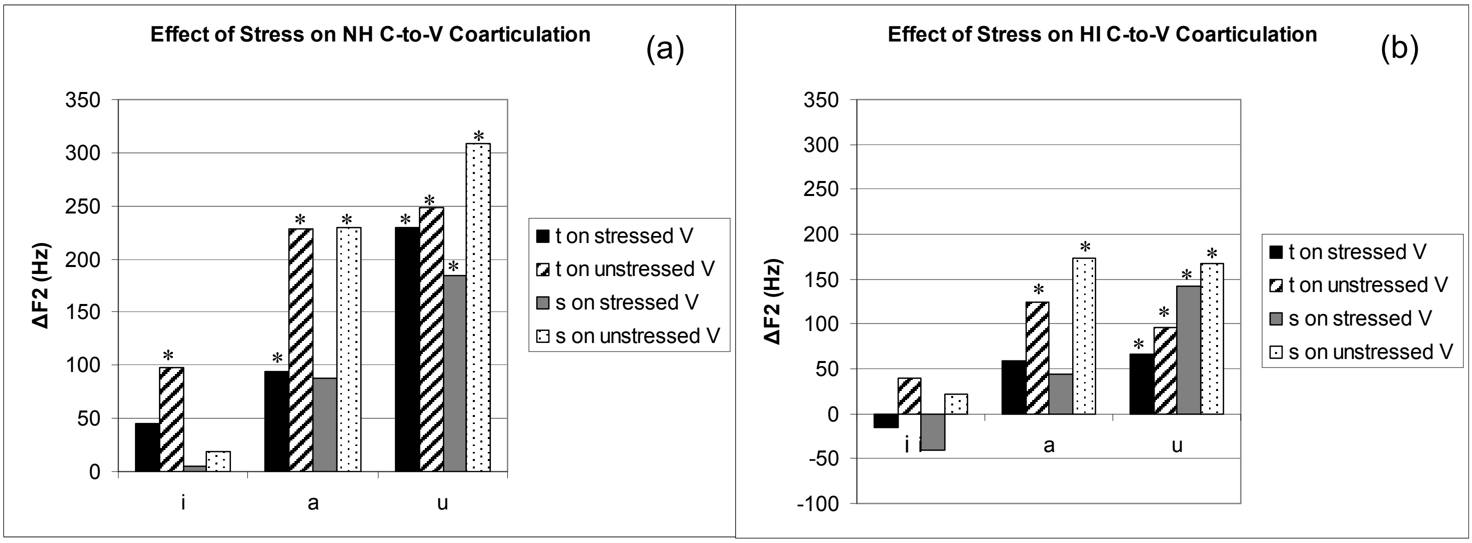


Fig. 4.28. Effect of stress on (a) NH (left) and (b) HI (right) C-to-V F2 Coarticulation. Symbol [*] denotes statistical significance of comparison between the bilabial and the alveolar contexts within group and stress condition (p<.05). Y axis values correspond to ΔF2mid column of Table 4.17.

NH		F2mid & StDev (Hz)		F1mid & StDev (Hz)				
Stress	Context							
stressed	ipi	2337	203	374	71		ΔF2mid (Hz)	ΔF1mid (Hz)
	iti	2382	226	381	71	1_iti-ipi	45	8
	isi	2342	220	380	66	1_isi-ipi	5	7
unstressed	ipi	2194	194	364	67			
	iti	2291	224	365	63	2_iti-ipi	*97	0
	isi	2212	219	358	56	2_isi-ipi	19	-6
stressed	apa	1343	166	842	134			
	ata	1438	163	853	131	1_ata-apa	*95	11
	asa	1430	152	835	126	1_asa-apa	87	-8
unstressed	apa	1208	125	762	108			
	ata	1436	169	779	110	2_ata-apa	*229	17
	asa	1437	163	751	120	2_asa-apa	*229	-11
stressed	upu	722	94	413	73			
	utu	859	84	416	71	1_utu-upu	*136	3
	usu	907	96	412	68	1_usu-upu	*185	-1
unstressed	upu	717	104	412	73			
	utu	966	73	406	74	2_utu-upu	*249	-6
	usu	1026	95	397	56	2_usu-upu	*309	-16
HI		F2mid & StDev (Hz)		F1mid & StDev (Hz)				
Stress	Context							
stressed	ipi	2139	220	363	68		ΔF2mid (Hz)	ΔF1mid (Hz)
	iti	2123	193	373	65	1_iti-ipi	-16	10
	isi	2099	247	351	54	1_isi-ipi	-41	-12
unstressed	ipi	2007	251	351	59			
	iti	2047	256	348	49	2_iti-ipi	40	-3
	isi	2029	306	337	45	2_isi-ipi	22	-14
stressed	apa	1293	174	802	151			
	ata	1351	153	800	142	1_ata-apa	59	-2
	asa	1336	188	782	148	1_asa-apa	44	-20
unstressed	apa	1225	158	717	113			
	ata	1348	155	713	122	2_ata-apa	*124	-4
	asa	1398	180	679	110	2_asa-apa	*174	*-38
stressed	upu	1028	143	381	69			
	utu	1095	176	377	72	1_utu-upu	*67	-4
	usu	1170	215	370	65	1_usu-upu	*142	-11
unstressed	upu	1058	166	362	65			
	utu	1154	191	363	61	2_utu-upu	*95	1
	usu	1226	244	353	59	2_usu-upu	*168	-8

Table 4.17. On the left, mean F1 and F2 values (Hz) and StDev (Hz) of stressed and unstressed point vowels in symmetrical disyllables of different consonantal contexts ([pVpV], [pVtV], [pVsV]) produced by the NH (above) and the HI (below). On the right, ΔF1 and ΔF2 within group and within stress condition difference of [t] and [s] context from the bilabial context. Symbol [*] denotes statistically significant difference (p<.05).

For both groups, the unstressed vowels generally receive more coarticulatory effects than their stressed counterparts. Nevertheless, based on the number of the statistically significant comparisons, stress seems to be a more influential factor in the C-to-V coarticulation of the NH than that of the HI. For the NH, the difference between C-to-V effects on unstressed vs. stressed vowels is very pronounced in magnitude and it is true for all three vowels and in both alveolar contexts, while for the HI, it is not always the case; firstly, the HI unstressed [i] does not receive significant effects as it occurs with the NH unstressed [i], and secondly, although the NH [u] receives more effects when unstressed from both alveolars, for the HI, the unstressed [u] receives less effects from [t] when compared with the effects of [s] on the stressed [u] (compare the two middle bars of [u] in Fig. 4.28.(b)). This difference has an impact on the vowel spaces in Fig. 4.29., where it is evident that NH unstressed [u] is more fronted due to the alveolar context, whereas the absence of stress is not of the same importance for the HI [u]. This additional observation further supports the general claim that stress influences C-to-V NH coarticulation more than HI coarticulation.

With the help of Fig. 4.29. below, we can observe the aforementioned differences regarding the influence of consonantal context on stressed vs. unstressed NH and HI vowels in their vowel chart locations. It seems that HI stressed [i] becomes more back in the alveolar context and unstressed [i] more front, although not statistically significantly, whereas the NH [i] becomes more front in both stress conditions, although the fronting effect is more evident (and as shown in Fig. 4.28. also statistically significant) in the unstressed condition. Moreover, the more robust C-to-V effect on the NH unstressed [u] in comparison with that on the HI counterpart is also manifested in the fronter position occupied by the NH unstressed [u] in both alveolar contexts vs. the more back position of the stressed [u] in these contexts, as opposed to the lack of such a clear effect for the HI unstressed [u]. An additional interesting difference between the NH and the HI concerning the effects of the fricative vs. the alveolar stop on unstressed [a], is that the fricative causes more raising (see NH vs. HI ΔF1mid values in right section of Table 4.17.) and fronting effects in comparison with the alveolar stop on the unstressed [a] of the HI, whereas both alveolars cause the same amount of fronting to the unstressed [a] of the NH.

(a)

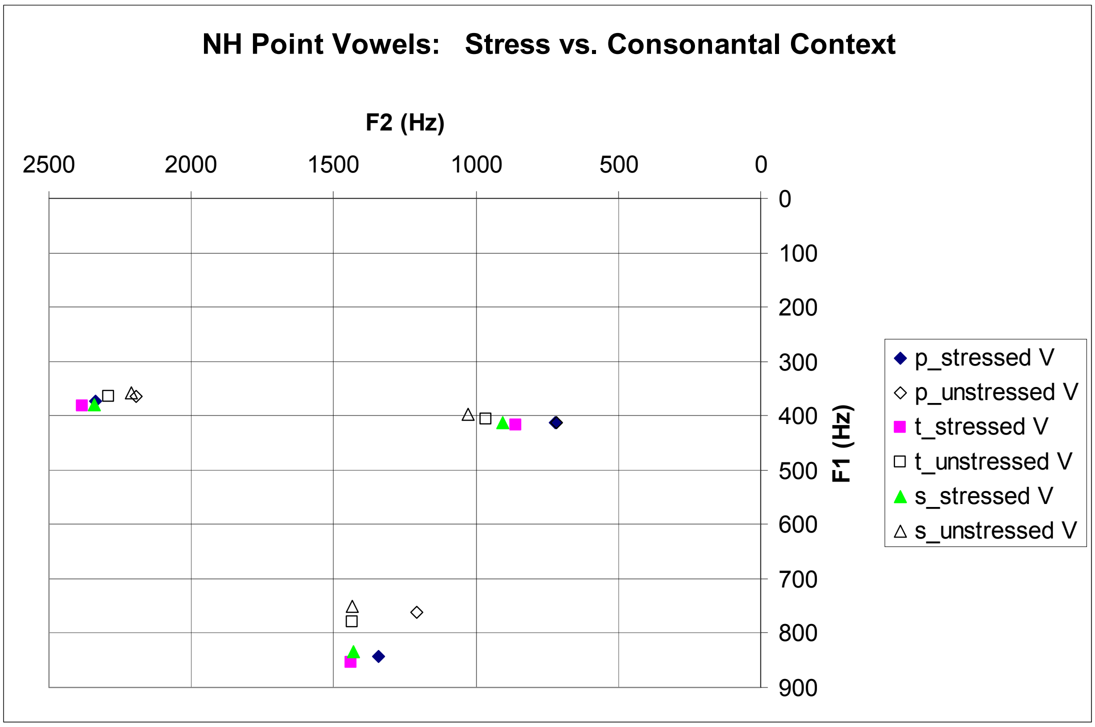
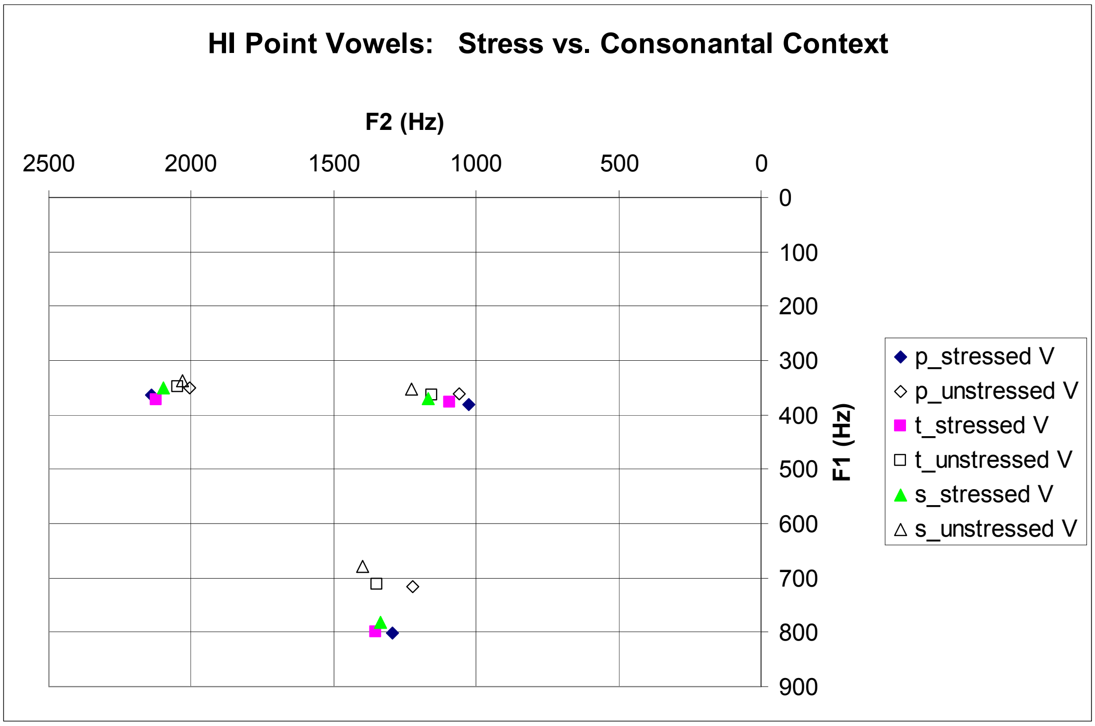


Fig. 4.29. Vowel space computed from mean F1mid and F2mid values of stressed (filled) and unstressed (unfilled) point vowels in symmetrical disyllables of bilabial, alveolar stop and alveolar fricative context produced by (a) the NH (above) and (b) the HI (below).

(b)



SYNOPSIS

This section summarizes the main findings regarding the influence of hearing, stress and syllable position on consonant-to-vowel coarticulation from an examination of F1 and F2 formant values at the midpoint of the three vowels [i], [a], [u] in symmetrical disyllables.

- **C-to-V Coarticulation**
  - For both groups, C-to-V effects along the F1 are minimal, whereas significant effects along the F2 are noted.
  - The NH group shows more C-to-V effects along the F2 in statistical significance and magnitude than the HI.
  - The HI group shows more effects from the fricative [s] on vowel height than the NH group.
  - The vowel sensitivity pattern to consonantal effects for both groups decreases in the order [u] > [a] > [i] in the F2 axis and [a] > [u], [i] in the F1 axis.
  - Vowel [i] appears to be the most constrained of the three point vowels along the front/back dimension for both groups and especially the HI.
  - Among the three HI vowels, vowel [u] displays increased F2 variability in all consonantal contexts relative to the norm.
  - There is a preference to the carryover direction by NH effects especially on F2 of [a] and [u] which is in contrast with HI effects mostly occurring in the anticipatory direction.
  - Regarding the NH, the alveolar stop generally causes coarticulatory effects of greater magnitude to both the F1 and F2 of [i] and [a], whereas [u] receives more effects from the fricative. For the HI, the fricative instigates greater influence to all three vowels.

  - The fricative triggers overall more effects for the HI than the NH. That, in combination with the aforementioned tendency for more effects in the anticipatory direction, may be related to a more constrained articulation of the HI [s] than normal.

- **stress & C-to-V Coarticulation**
  - For both groups, the unstressed vowels generally receive more coarticulatory effects than their stressed counterparts.
  - For the NH, this difference is very pronounced in magnitude and it is true for all three vowels and in both alveolar contexts, while for the HI, it occurs in the majority of cases, but there are exceptions. Therefore, stress influences C-to-V NH coarticulation more than HI coarticulation.
  - Main differences between the NH and the HI stress effects on C-to-V coarticulation:
    - NH [u] is more fronted when unstressed regardless of context, whereas HI [u] is more fronted in the fricative context; thus, stress interacts with consonantal context for the HI [u].
    - NH unstressed [i] is significantly fronted by the alveolar stop, while its stressed counterpart is not. The HI [i] does not receive significant F2 effects in either stress condition.
    - The fricative causes more raising and fronting effects on the HI unstressed [a] in comparison with the alveolar stop, while effects on NH unstressed [a] from both alveolars are of an equal magnitude.

Chapter 5

Results –Part 2

Vowel-to-Vowel Coarticulation

5.1. Effects of Hearing & Context on V-to-V Coarticulation

In this section we will be looking at context effects in terms of magnitude and temporal extent, that is, V-to-V (i.e. [i]-to-[a], [u]-to-[a], [a]-to-[i], [u]-to-[i], [a]-to-[u] and [i]-to-[u]) anticipatory and carryover effects over the bilabial stop [p], the alveolar stop [t] and the fricative [s], within the two hearing groups, i.e., normal hearing (NH) and hearing impaired (HI), as well as between the two groups.

5.1.1. F1

Univariate ANOVAs carried out for F1 formant variables versus **hearing** (NH or HI), **gender** (male or female), **measured vowel** ([i], [a] or [u]), **transconsonantal vowel** ([i], [a] or [u]), **consonant** ([p], [t] or [s]), **stress** (measured vowel stressed or unstressed) and **position** (measured vowel in the first syllable for anticipatory CA or measured vowel in the second syllable for carryover CA) showed that all factors are statistically significant at the start, mid and end point (Appendix 2.1., F1). The interaction referring to context influence hearing* measured V* transcons V* C* position was found significant for F1end (F(8, 15035)=3.322, p<.01).

Tukey pairwise comparisons were conducted on F1 values of the same measurement point of the fixed vowel in pairs, e.g., the F1start of the second [i] in [ipi] was compared with the F1start of [i] in [api] to examine whether carryover effects from [a] to [i] are statistically significant at vowel start. These post hoc tests revealed statistically significant differences between combinations of context factors within each group. The general level of statistical significance was set at p<.05 and is denoted in Figures 4.2.1 - 4.2.6 with one asterisk [*], while two additional levels at p<.01 [**] and p<.0001 [***] are also reported where located.

Regarding between groups differences, ANOVAs for ΔF1 variables, that is variables based on the subtraction of F1 of the fixed vowel of the symmetrical disyllable minus F1 of the corresponding vowel in the disyllable containing a different vowel whose influence we wish to examine (section 3.5.2.), versus the factors **hearing** (NH or HI), **gender** (male or female), **V-to-V** (six different combinations of measured vowel & transconsonantal vowel), **consonant** ([p], [t] or [s]), **direction** (anticipatory or carryover) and **stress** (measured vowel stressed or unstressed) were run, and all factors were found statistically significant at all measurement points, except for stress at start and end (Appendix 2.1., ΔF1). The interaction of factors hearing* V-to-V* C* direction was found statistically significant at all three vowel points (start: F(10, 9969)=3.067, p<.01, mid: F(10, 9971)=2.469, p<.01, end: F(10, 9969)=5.026, p<.0001).

Further post hoc tests were run for between group effects at the same measurement point that reached statistical significance, and are denoted in Figures 4.2.1. - 4.2.6. with crosses in the manner described above (i.e., [$^{+}$] for p<.05, [$^{++}$] for p<.01 and [$^{+++}$] for p<.0001). F1 trajectories displayed in Figures 5.1. - 5.6. correspond to the three measurement points of the measured vowel (onset, middle and offset); they do not depict the whole disyllable, as we wish to present only the parts of the pairs that are comparable. For example, for the pair [papa]-[papi] we will present and compare the trajectories of the first [a] in [papa] and of [a] in [papi]. The second [a] in [papa] and the [i] in [papi] are not compared and therefore not presented in the figures.

5.1.1.1. Fixed [i]

- **Influence of [a] on [i] (iCi-iCa and aCi-iCi)** (Table 5.1. & Fig. 5.1.)

Prediction: Raising of F1

- Anticipatory direction (iCi-iCa)

There are no significant effects at the start, mid or end of [i] for either group. The NH show a small raising of F1 at the end of [i] in anticipation of [a] over [p] and [t], but no effects over [s] (see Fig. 5.1.a). In fact, although not statistically significant, the effects over [s] are increasing from the end to the start of the vowel in the opposite direction (negative effects). The HI trajectories do not deviate significantly from the aforementioned trend. In general, the HI demonstrate even less effects than the NH over the more constricted [t] and [s], and show small effects in the expected direction over [p], which increase slightly at the mid point and are very small at the start and end of the vowel.

- Carryover direction (aCi-iCi)

For the NH, there are significant effects over [p] at the start of [i] ($p<.0001$) which decrease gradually towards the end of the vowel (see Fig. 5.1.b). The same pattern repeats over [t] and [s], but no statistical significance was found at any measurement point. Moreover, the effects are in the expected direction over all three consonants. For the HI, the effects are almost nonexistent at the start of the vowel regardless of consonant type and continue to be very small up to the end of the vowel. Comparing NH and HI effects over the alveolar [t], moving towards the end of the vowel, NH effects seem to decrease, whereas the opposite occurs with the HI. In addition, although at a low degree, the effects for the HI are negative at the mid and end measurement points over [p].

- **Influence of [u] on [i] (iCi-iCu and uCi-iCi)** (Table 5.2. & Fig. 5.2.)

Prediction: No significant shift of F1

- Anticipatory direction (iCi-iCu)

There are no significant effects for either group regardless of consonant type. F1 movement pattern is almost identical for both groups (see Fig. 5.2.a).

- Carryover direction (uCi-iCi)

As above, no significant effects were detected for either group. For both the NH and the HI, F1 trajectories of [iCi] and [uCi] coincide at all measurement points, with the exception of NH [ipi-upi] at the vowel onset, where however effects are still not significant (see Fig. 5.2.b).

- **Summary**

Overall, on F1, [i] seems to be a fairly constrained vowel for both groups, as it does not allow significant coarticulatory effects from [a] regardless of the nature of the intervening consonant. Some carryover coarticulatory effects are evident for the NH group at vowel onset over [p], which is explicable considering the lingual freedom it allows adjacent vowels as opposed to alveolar consonants (Recasens, 1985). In addition, greater carryover vs. anticipatory effects across the bilabial [p] have been documented before for Greek (Nicolaidis, 1997; Koenig & Okalidou, 2003, Asteriadou, 2008). The HI group seems to follow a similar coarticulation pattern, although they fail to demonstrate any effects over [p] in any direction and their F1 receives less overall context influence. The lack of effects from [u] on [i] was expected, as they are both high vowels, hence no significant shift is demanded of the tongue dorsum in terms of height. The HI coarticulation pattern is in agreement with the NH pattern across all consonants.

direction	[a] on fixed [i]	NH						HI					
		ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev	ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev
anticipatory	pipa-pipi	-4	46	2	43	13	41	9	43	15	42	10	51
	pita-piti	7	51	6	38	17	48	2	47	0	43	-5	49
	pisa-pisi	-10	42	-5	32	-3	37	5	48	3	31	-1	38
carryover	papi-pipi	***56***	43	25	40	9	36	7	50	-5	49	-6	59
	pati-piti	25	43	11	38	-1	38	6	48	5	39	17	66
	pasi-pisi	36	94	10	46	8	52	8	39	14	41	3	55

Table 5.1. Mean F1 difference and StDev (in Hz) of the disyllable pairs [iCi]-[iCa] (anticipatory direction) and [aCi]-[iCi] (carryover direction), where C=p, t, s, at the three measurement points of [i]. HI values are highlighted. Statistically significant differences within group are in bold rectangles (p<.05 and p<.0001 for values in *bold italics*).

direction	[u] on fixed [i]	NH						HI					
		ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev	ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev
anticipatory	pipu-pipi	6	33	0	33	8	40	1	38	8	42	3	48
	pitu-piti	-6	43	1	36	5	44	-3	41	0	40	-6	45
	pisu-pisi	6	46	5	36	-3	45	-3	47	-3	33	-7	41
carryover	pupi-pipi	25	35	7	38	-7	43	6	41	-4	46	0	62
	puti-piti	0	42	1	34	-3	52	3	42	-1	37	9	60
	pusi-pisi	-5	36	8	36	3	53	0	37	3	40	-7	58

Table 5.2. Mean F1 difference and StDev (in Hz) of the disyllable pairs [iCi]-[iCu] (anticipatory direction) and [uCi]-[iCi] (carryover direction), where C=p, t, s, at the three measurement points of [i]. HI values are highlighted. No statistically significant differences were found.

(a)

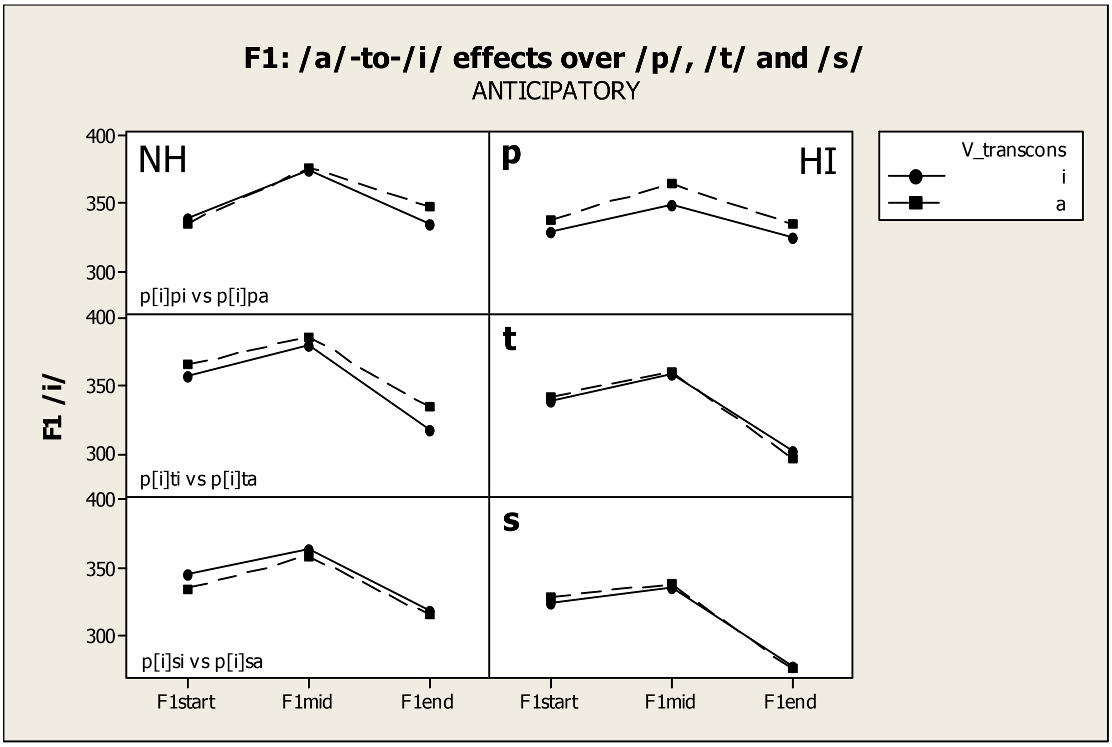
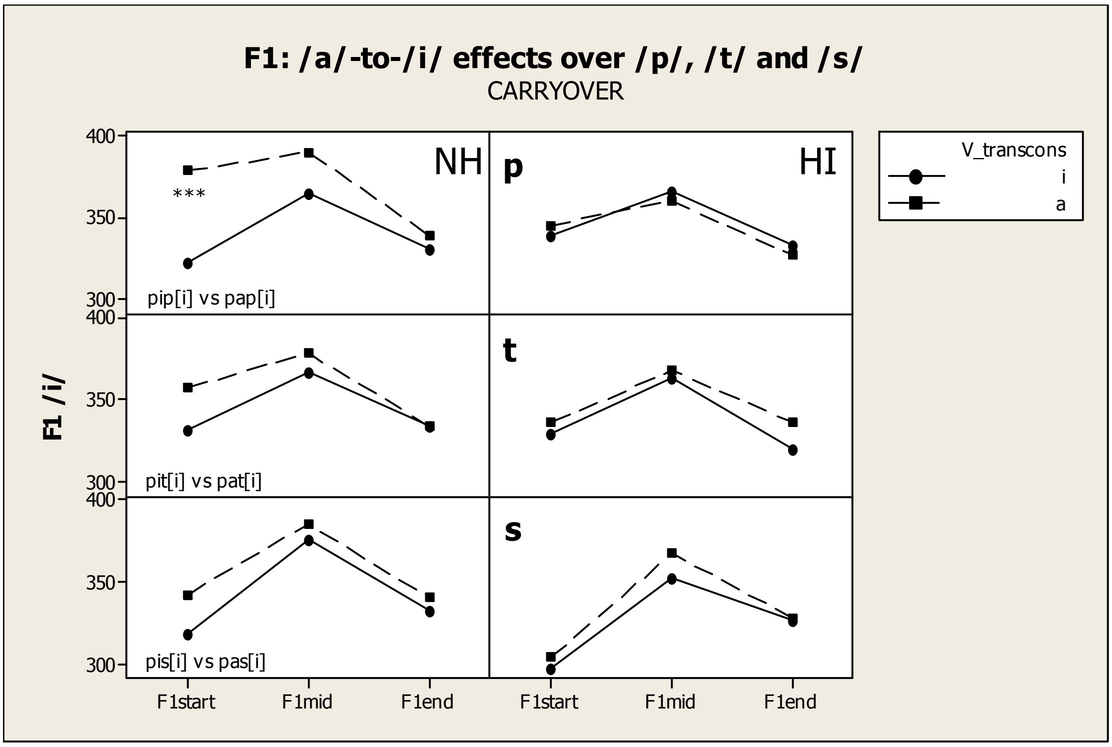


Fig. 5.1. F1 [a]-to-[i] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. Significant statistical difference is displayed within group with [*]: p < .05, [**]: p < .01 or [***]: p < .0000. No stat. significant difference was found between groups.

(b)



(a)

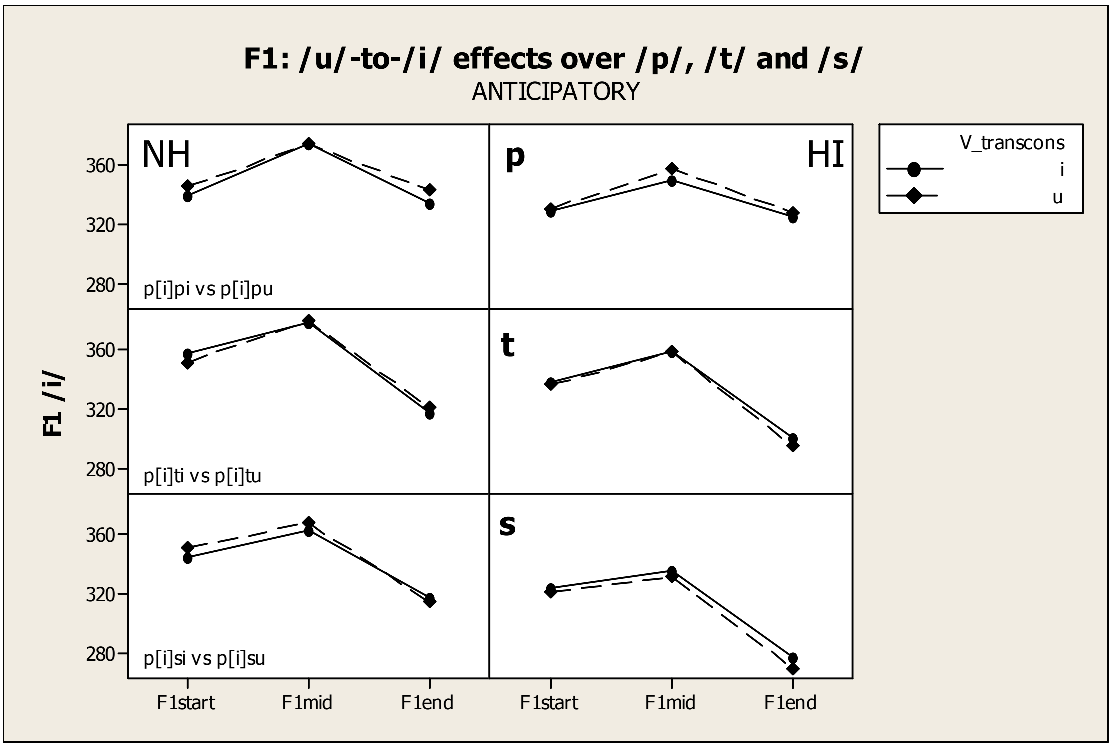
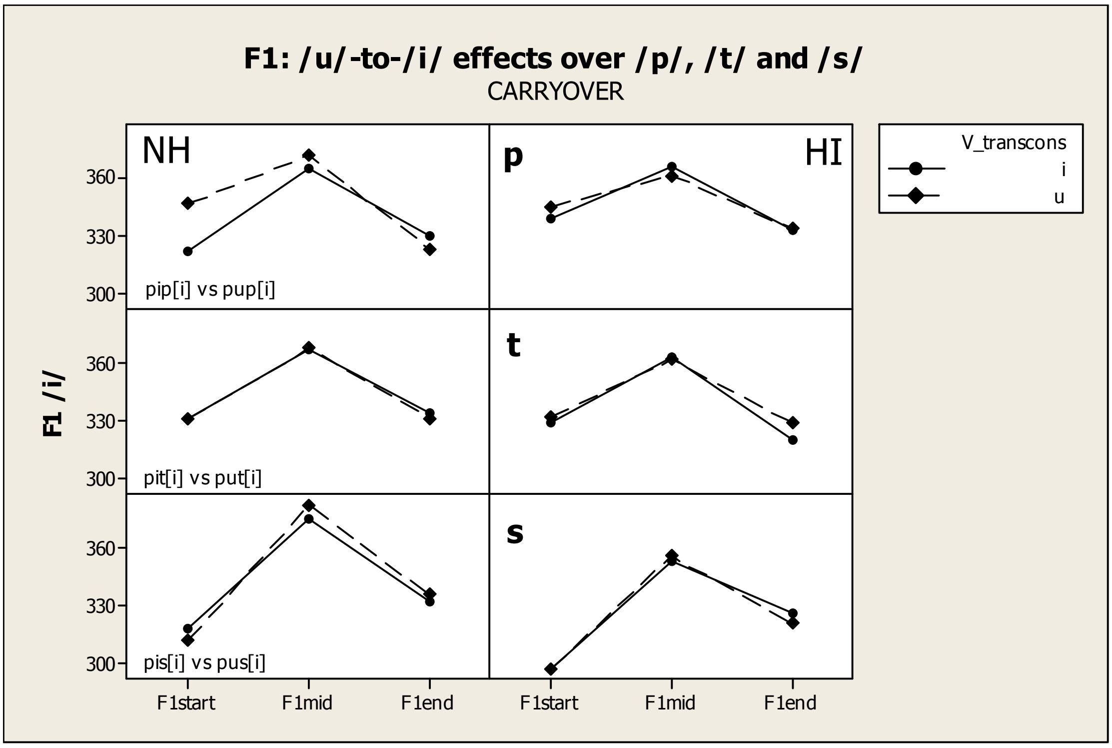


Fig. 5.2. F1 [u]-to-[i] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. No stat. significant difference was found within or between groups.

(b)



5.1.1.2. Fixed [ɑ]

- **Influence of [i] on [a] (aCa-aCi and aCa-iCa)** (see Table 5.3. & Fig. 5.3.)

Prediction: Lowering of F1

  - Anticipatory direction (aCa-aCi)

For the NH there are no significant effects across any of the consonants. The HI pattern is similar over the bilabial [p] and the fricative [s], but effects are significant ($p<.0001$) at vowel offset over the alveolar [t], which may be due to a lessened degree of tongue dorsum contact or jaw elevation for some of the HI subjects (see Fig. 5.3.a).

  - Carryover direction (aCa-iCa)

There are significant effects ($p<.0001$) over all three consonants for the NH at vowel onset. The HI seem to follow this pattern over the bilabial and the fricative ($p<.01$ and $p<.0001$ correspondingly). Although the effects over these two consonants are smaller for the HI, no statistically significant differences were found between the two groups (see Fig. 5.3.b). Conversely, a significant difference between the two groups is the absence of carryover effects over the alveolar stop of the HI. Moreover, negative coarticulatory effects over [s] at the offset of the vowel are evident ($p<.0001$). There is a trend for negative effects for both groups at vowel offset, although not statistically significant.

- **Influence of [u] on [a] (aCa-aCu and aCa-uCa)** (see Table 5.4. & Fig. 5.4.)

Prediction: Lowering of F1

  - Anticipatory direction (aCa-aCu)

As regards the NH, there are effects at the offset of the vowel across [t] ($p<.05$) and [s] ($p<.0001$), while for [p], effects are evident but not statistically significant. The HI manifest a similar pattern, showing effects across all consonants ($p<.0001$) in the expected direction. Neither for the NH nor the HI do coarticulatory effects continue towards the onset of the vowel.

- Carryover direction (aCa-uCa)

Along the same lines with the anticipatory effects, carryover effects are significant at vowel onset over all consonant types (p<.0001) for both groups. Nevertheless, NH effects in comparison with HI effects are significantly larger over [p] (p<.0001) and [t] (p<.05). No evidence of coarticulatory effects was found at the mid and end points for either group.

➢ Summary

Regarding normal articulation, high vowels [i] and, especially, [u] significantly lower the first formant of the low mid vowel [a] at V1 offset and V2 onset. Carryover effects are larger than anticipatory effects, especially regarding [i] (see Table 5.3.). The more constricted consonants [t] and [s] do not seem to block V-to-V coarticulatory effects in selected cases. This is in keeping with Recasens (1989) who documents anticipatory V-to-V effects over [t] in Catalan VC[ə]CV utterances and Butcher (1989) supporting that V-to-V coarticulation is very similar over [p] and [t] tokens in an EPG study of English VCV sequences. Although the English [s] has been documented to hinder coarticulation (Öhman, 1966; Carney & Moll, 1971), there has been evidence of coarticulatory effects across the Greek [s] (Nicolaidis, 1997). For both groups, [u] exerts more influence than [i] both in degree and in direction, that is, [u] effects are both anticipatory and carryover, whereas [i] effects are mostly carryover. In an F1 investigation of VCV sequences, Recasens et al. (2000) also report a tendency towards the carryover component in the fixed [a] context. In general, the HI demonstrate somewhat more anticipatory effects over [p] and [t] on fixed [a] than the NH, especially with [u] as the transconsonantal vowel. While HI [i]-to-[a] anticipatory effects occur only across the alveolar plosive, [u]-to-[a] coarticulatory phenomena are evident across all consonants.

direction	[i] on fixed [a]	NH						HI					
		ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev	ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev
anticipatory	papa-papi	7	68	1	46	4	58	5	63	1	57	16	85
	pata-pati	-1	56	-3	43	34	58	10	67	1	65	***46***	80
	pasa-pasi	4	55	11	54	42	117	11	62	5	57	23	83
carryover	papa-pipa	***52***	57	0	41	-32	97	33	66	2	62	26	120
	pata-pita	***48***	55	9	42	-13	92	22	60	-9	67	-2	103
	pasa-pisa	***50***	64	2	43	-15	111	***39***	69	-5	73	***-48***	162

Table 5.3. Mean F1 difference and StDev (in Hz) of the disyllable pairs [aCa]-[aCi] (anticipatory direction) and [iCa]-[aCa] (carryover direction), where C=p, t, s, at the three measurement points of [a]. HI values are highlighted. Statistically significant differences within group are in bold rectangles (p<.01 and for values in *bold italics* p<.0001).

direction	[u] on fixed [a]	NH						HI					
		ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev	ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev
anticipatory	papa-papu	8	58	7	45	49	73	5	64	9	58	***55***	92
	pata-patu	9	72	18	43	54	64	17	64	25	57	***71***	93
	pasa-pasu	11	58	25	44	***78***	113	4	64	13	66	***18***	168
carryover	papa-pupa	***92***	61	9	43	-12	94	$^{+++}$***49***	72	15	69	30	118
	pata-puta	***62***	58	23	40	17	99	$^{+}$***32***	59	14	64	21	101
	pasa-pusa	***70***	69	14	37	-8	116	***53***	68	-6	64	-3	126

Table 5.4. Mean F1 difference and StDev (in Hz) of the disyllable pairs [aCa]-[aCu] (anticipatory direction) and [uCa]-[aCa] (carryover direction), where C=p, t, s, at the three measurement points of [a]. HI values are highlighted. Statistically significant differences within group are in bold rectangles (p<.05 and for values in *bold italics* p<.0001) and differences between groups are denoted with a cross in front of HI values ($^{+}$: p<.05,$^{++}$: p<.01, $^{+++}$: p<.0001).

(a)

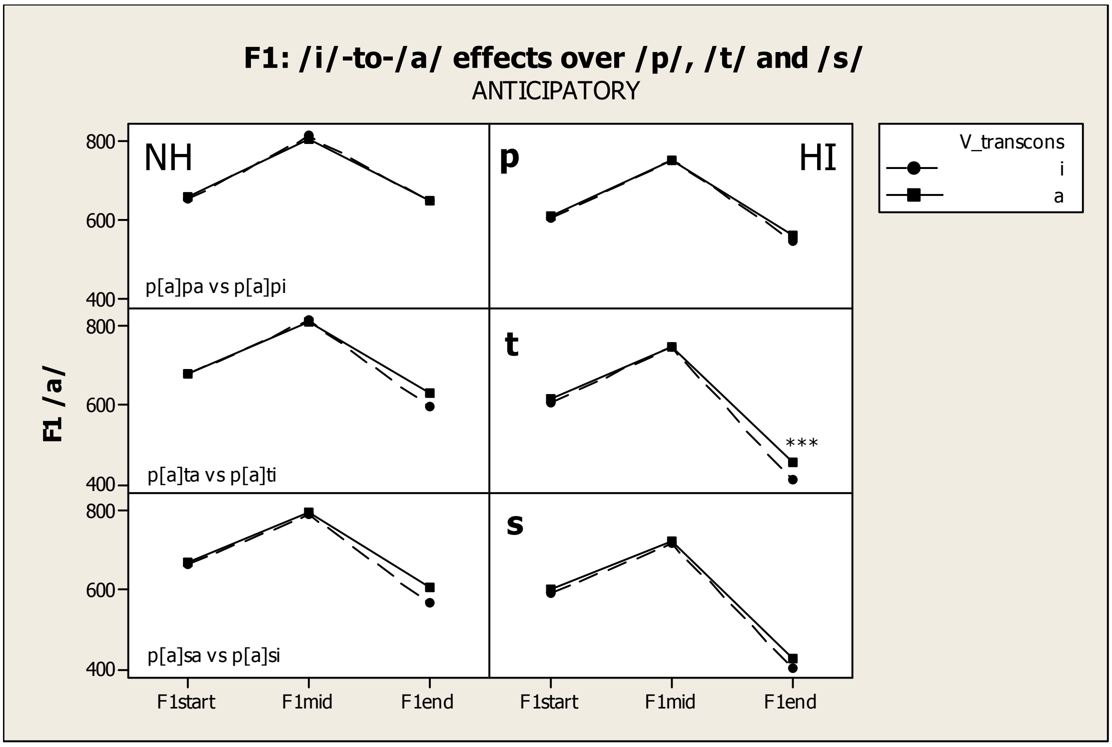
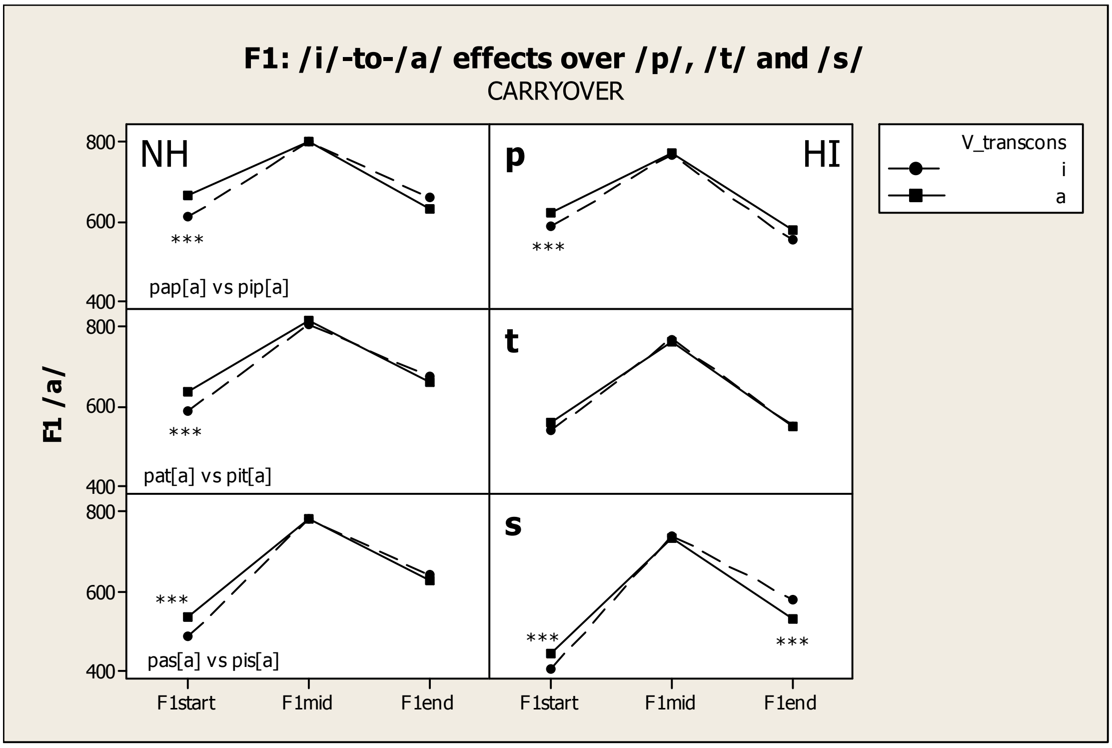


Fig. 5.3. F1 [i]-to-[a] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. Significant statistical difference is displayed within group with [*]: p < .05, [**]: p < .01 or [***]: p < .0000. No stat. significant difference was found between groups.

(b)



(a)

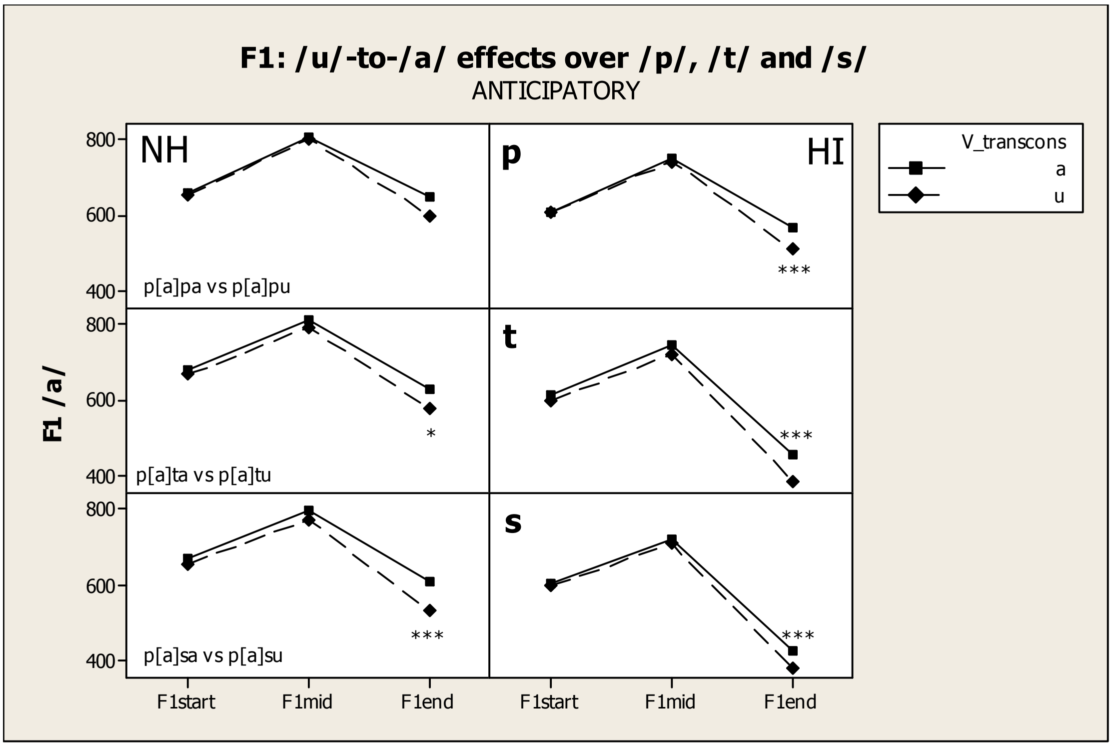
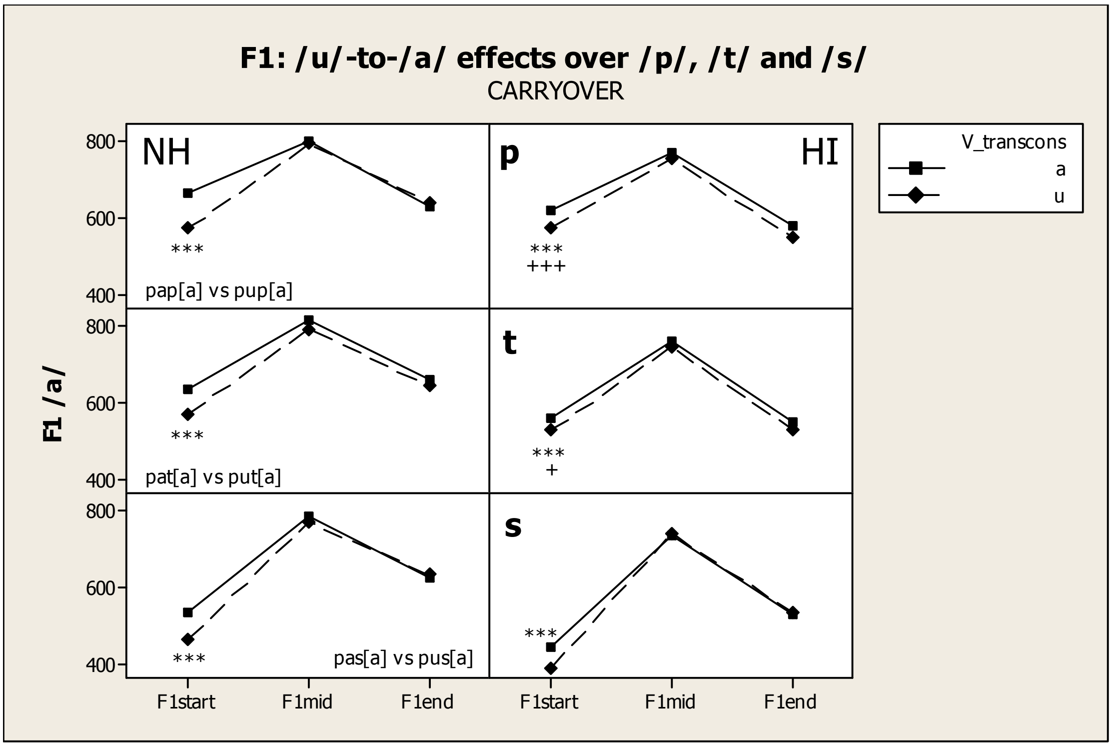


Fig. 5.4. F1 [u]-to-[a] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. Significant statistical difference is displayed within group with [*]: p < .05, [**]: p < .01 or [***]: p < .0000 and between groups with [$^{+}$]: p<.05, [$^{++}$]: p<.01 or [$^{+++}$]: p<.0001.

(b)



5.1.1.3. Fixed [u]

- **Influence of [a] on [u] (uCu-uCa and aCu-uCu)** (see Table 5.5. & Fig. 5.5.)

Prediction: F1 raising

- Anticipatory direction (uCu-uCa)

The NH show significant F1 raising over [p] at vowel offset (p<.0001) and although effects seem to move up to vowel onset, they are not significant at any other measurement point. The plosive [t] seems to completely block coarticulation, while some effects of a lesser degree were found at the vowel onset only, over the fricative [s] (p<.05). The HI do not display any significant effects, although some small effects over [p] at vowel mid and end are shown (see Fig. 5.5.a).

- Carryover direction (aCu-uCu)

The NH show significant effects at vowel onset only over the bilabial, which extend to the end of the vowel (p<.0001). The HI do not display significant effects apart from an unexpected F1 raising at the vowel offset over the fricative [s] (p<.05) (see Fig. 5.5.b).

- **Influence of [i] on [u] (uCu-uCi and iCu-uCu)** (see Table 5.6. & Fig. 5.6.)

Prediction: No significant shift of F1

- Anticipatory direction (uCu-uCi)

There is no significant shift in F1 in either group with the exception of a significant F1 raising in the [p] context for the NH (p<.0001). The effect is significant at the vowel offset and onset. For the HI there are no significant effects regardless of consonant context (see Fig. 5.6.a).

- Carryover direction (iCu-uCu)

Again effects are nonsignificant for either group, except for the NH over [p] (see Fig. 5.6.b). The F1 raising is evident at the vowel onset ($p<.0001$) and vowel offset ($p<.01$).

➢ Summary

For the NH speakers, the F1 of the high-back rounded vowel [u] seems to be more sensitive to coarticulatory effects than the high-front [i] and less sensitive than the low-mid [a]. The low vowel [a] raises the F1 of [u] as expected, but these bidirectional effects only occur over the bilabial [p], which is generally assumed to favour V-to-V coarticulation. These effects are large and can be present at the other end of the vowel. The high vowel [i] also causes a significant F1 raise to [u], contrary to expectations. These dissimilatory effects may relate to differences in jaw position or serve perceptual distinctiveness (section 6.4.1.). The HI group does not display any significant coarticulatory effects regardless of consonant type.

Both groups show some effects over the fricative [s] but in different directions; for the NH, significant effects are in the anticipatory direction at vowel onset ([pusu]-[pusa]) and for the HI, in the carryover direction at vowel offset ([pusu]-[pasu]). It seems that, in the fixed [u] context, no effects are permitted close to the constriction for the fricative which may explain why they appear the other end of the vowel. Similar restrictions due to the articulatory demands of frication have been documented in the literature (Recasens, 1984b; Fowler & Brancazio, 2000).

(a)

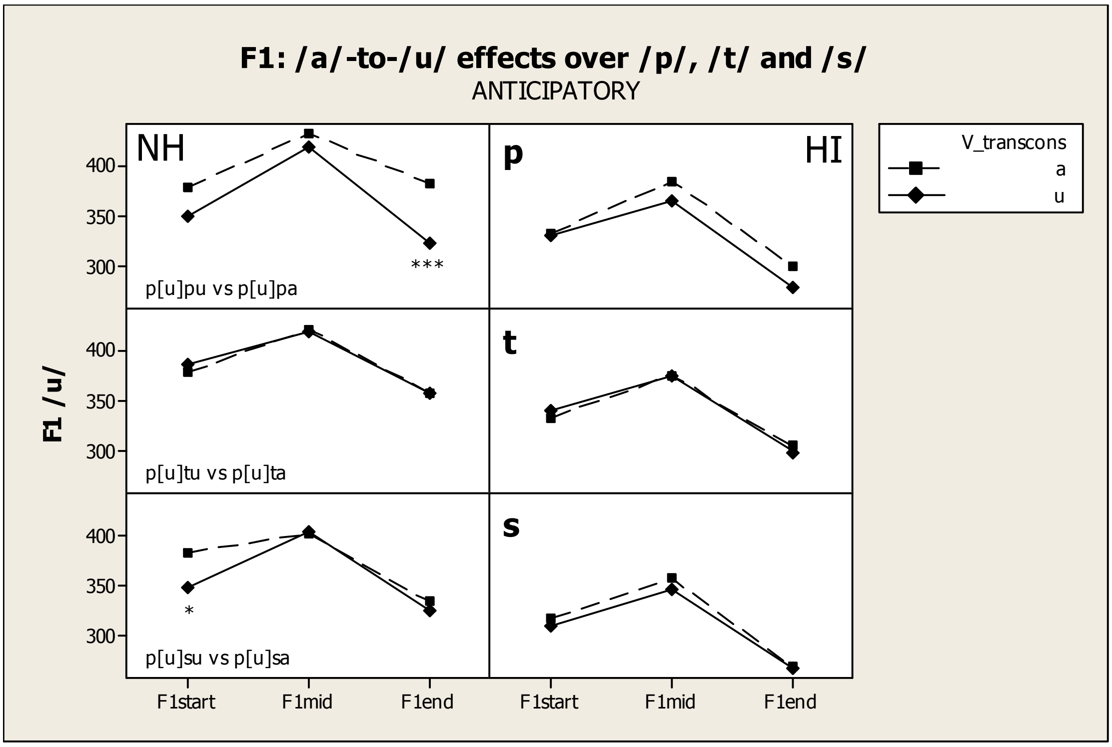
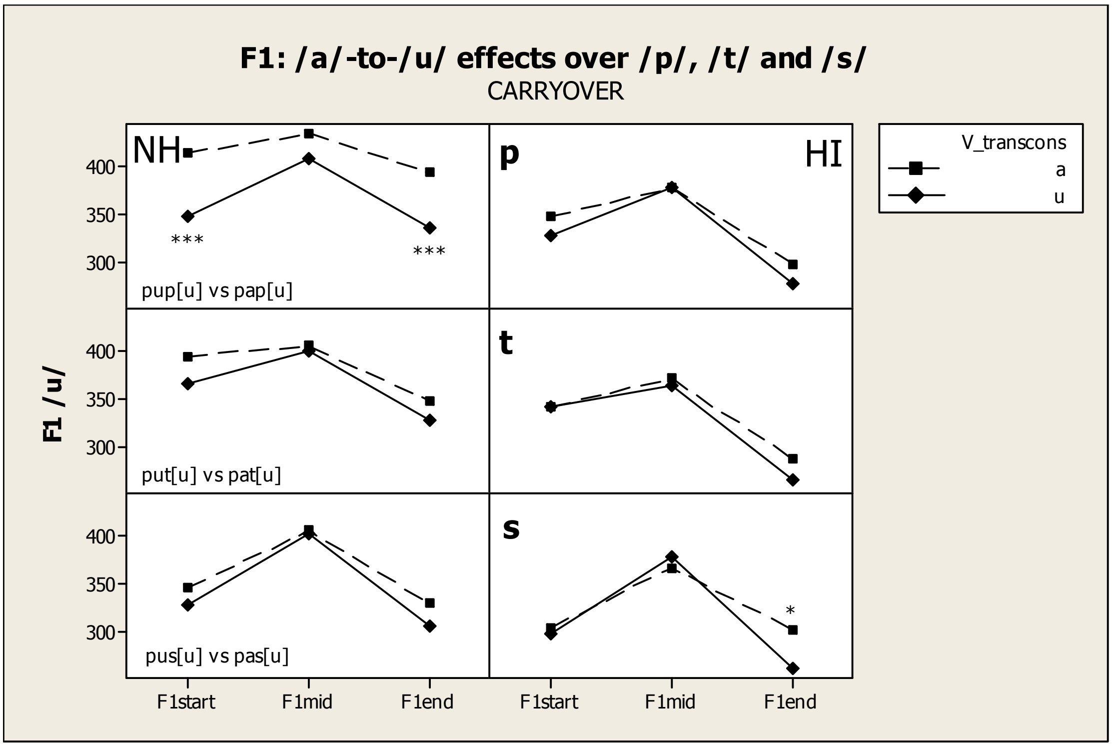


Fig. 5.5. F1 [a]-to-[u] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. Significant statistical difference is displayed within group with [*]: p < .05, [**]: p < .01 or [***]: p < .0000. No stat. significant difference was found between groups.

(b)



(a)

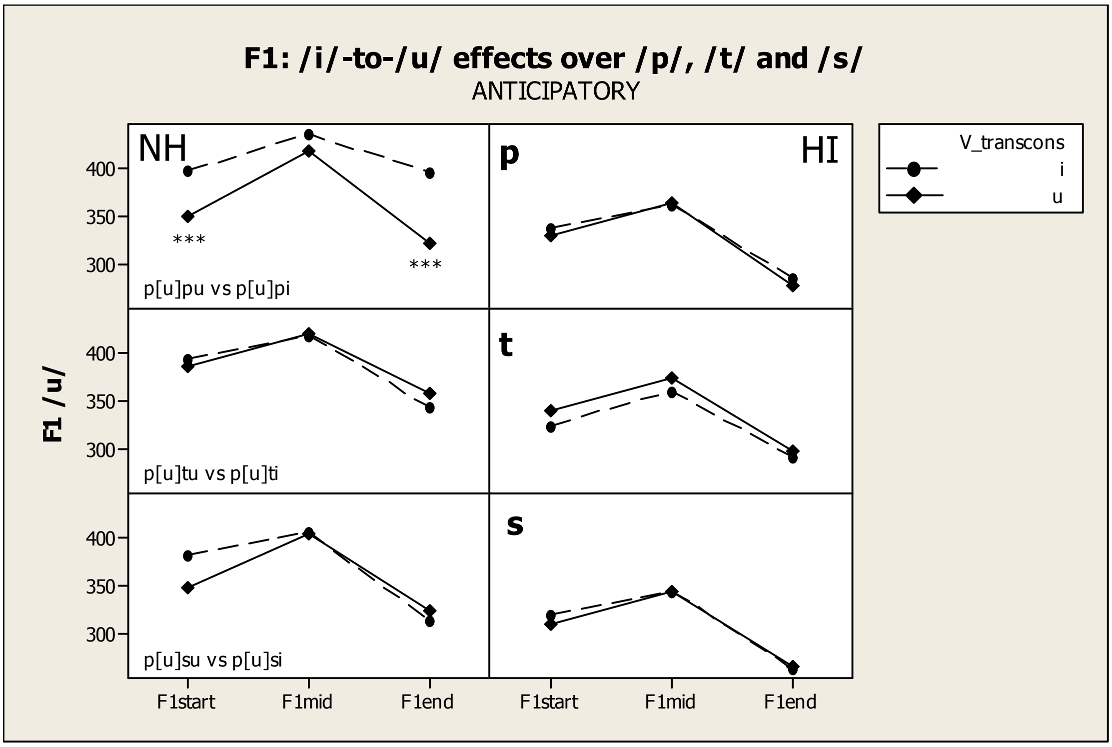
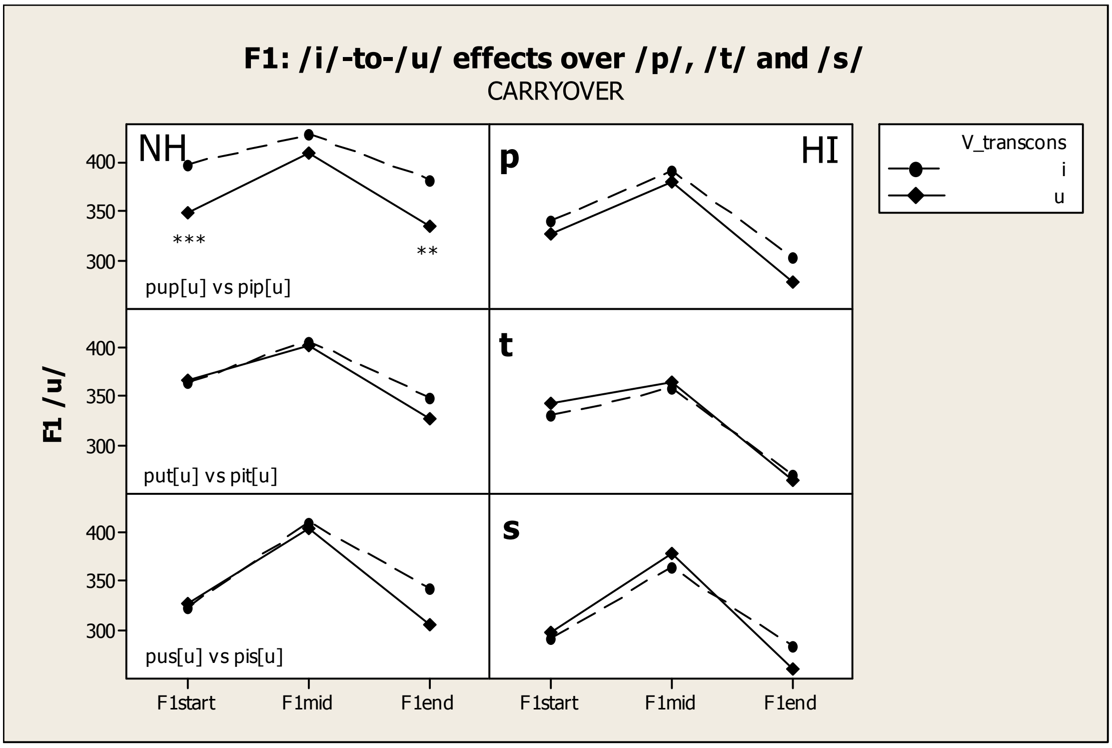


Fig. 5.6. F1 [i]-to-[u] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. Significant statistical difference is displayed within group with [*]: p < .05, [**]: p < .01 or [***]: p < .0000. No stat. significant difference was found between groups.

(b)



direction	[a] on fixed [u]	NH						HI					
		ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev	ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev
anticipatory	pupa-pupu	28	61	13	46	***60***	88	2	54	18	57	21	76
	puta-putu	-7	65	2	34	0	60	-7	63	2	48	6	60
	pusa-pusu	35	67	-2	52	9	50	7	56	13	41	1	44
carryover	papu-pupu	***65***	71	20	39	***44***	75	22	64	-1	65	21	75
	patu-putu	33	50	10	43	34	80	-1	41	5	62	24	80
	pasu-pusu	19	49	2	43	26	57	7	43	-11	52	40	82

Table 5.5. Mean F1 difference and StDev (in Hz) of the disyllable pairs [uCu]-[uCa] (anticipatory direction) and [aCu]-[uCu] (carryover direction), where C=p, t, s, at the three measurement points of [u]. HI values are highlighted. Statistically significant differences within group are in bold rectangles (p<.05 and for values in *bold italics* p<.0001).

direction	[i] on fixed [u]	NH						HI					
		ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev	ΔF1start	StDev	ΔF1mid	StDev	ΔF1end	StDev
anticipatory	pupi-pupu	***47***	63	17	35	***73***	98	8	62	-2	49	8	54
	puti-putu	9	67	-2	34	-13	48	-16	56	-15	50	-3	62
	pusi-pusu	35	67	1	44	-10	46	10	58	2	41	-3	41
carryover	pipu-pupu	***50***	65	21	42	47	86	14	58	11	57	25	76
	pitu-putu	-2	51	5	31	22	64	-12	39	-8	48	6	60
	pisu-pusu	-3	49	7	35	38	55	-4	41	-14	46	21	61

Table 5.6. Mean F1 difference and StDev (in Hz) of the disyllable pairs [uCu]-[uCi] (anticipatory direction) and [iCu]-[uCu] (carryover direction), where C=p, t, s, at the three measurement points of [u]. HI values are highlighted. Statistically significant differences within group are in bold rectangles (p<.01 and for values in *bold italics* p<.0001).

5.1.2. F2

ANOVAs were carried out for variables F2start, F2mid and F2end as with F1 above. All factors, except stress at the start point, were found statistically significant (Appendix 2.1., F2). The interaction showing context influence hearing* measured V* transcons V* C* position was found significant for F2start (F(8, 15039)=2.936, p<.01). Tukey post hoc tests on the interaction revealed significant within group differences in some contexts, indicating significant coarticulatory effects. These effects are denoted in Figures 5.7 - 5.12 with [*] for p<.05, [**] for p<.01 and [***] for p<.0001.

Additional ANOVAs were run for ΔF2 variables, to find between group differences at the points where significant coarticulatory effects were present (see Appendix 2.1., ΔF2) and are denoted with crosses (i.e., [$^{+}$] for p<.05, [$^{++}$] for p<.01 and [$^{+++}$] for p<.0001). The factor V-to-V (section 3.5.2.1., Table 3.9.) is statistically significant at all three points. Hearing is statistically significant at the end, gender at the midpoint and stress is not significant at any point. Consonant and direction are significant at the start and the end, but not at the midpoint. Tukey post hoc tests were conducted using the interaction hearing* V-to-V* C* direction, so as to locate significant between group differences in the aforementioned contexts. As with F1 trajectories above (section 5.1.1.), F2 trajectories displayed in Figures 5.7 - 5.12 correspond to the three measurement points of the measured vowel (onset, middle and offset).

5.1.2.1. Fixed [i]

- **Influence of [a] on [i] (iCi-iCa and iCi-aCi)** (see Table 5.7. & Fig. 5.7.)

Prediction: Lowering of F2

  - Anticipatory direction (iCi-iCa)

No significant effects are manifested at any measurement point during the production of [i] by the NH. A lowering effect (91 Hz) appears near the constriction of the bilabial, but it does not reach statistical significance. Concerning the HI, significant coarticulatory effects, which extend back to the vowel onset, occur over the bilabial, reaching their maximum near consonant closure. In contrast to the bilabial context, significant effects over the alveolar plosive occur only at vowel midpoint, while over the fricative they are evident only at vowel onset (see Fig. 5.7.a). Overall, the HI show the presence of more anticipatory effects in all consonant contexts compared to the NH.

  - Carryover direction (iCi-aCi)

The NH group demonstrates effects at the vowel onset which reach significance only over the bilabial. In the more constrained contexts effects are of a lesser degree (89 Hz over [t] and 69 Hz over [s]). Effects at vowel onset for the HI group are of an even smaller magnitude and they do not reach significance over any of the consonantal contexts. Hence, for both groups the same trend is detected; the less constrained the consonant the larger the coarticulation magnitude (see Fig. 5.7.b). The only exception is an unexpected increase of carryover effects towards vowel offset in the context of the fricative for the HI (184 Hz, $p<.0001$).

- **Influence of [u] on [i] (iCi-iCu and iCi-uCi)** (see Table 5.8. & Fig. 5.8.)

Prediction: Lowering of F2

- Anticipatory direction (iCi-iCu)

There are significant effects at vowel offset over the bilabial for the NH (199 Hz, p<.0001). These effects diminish gradually towards vowel onset. The two alveolar consonants do not allow significant effects from [u], although lowering of F2 does occur at vowel offset and increases to some degree towards the start of the vowel, although without reaching significance. For the HI, significant effects over the bilabial are evident at vowel offset similarly to the NH. However, these effects are of a significantly smaller magnitude in relation to those by the NH group (between group difference: 101 Hz, p<.05). Nevertheless, they continue to be significant at the vowel center, as opposed to the NH effects which do not reach significance at the midpoint. Regarding the two alveolars, in contrast to the NH pattern, significant F2 lowering occurs at vowel offset of a similar degree for both consonants (93 Hz over [t] and 95 Hz over [s]). The effects do not reach statistical significance at the middle of the vowel, although [t] seems to allow somewhat larger effects than [s] (contrary to the NH pattern), and at vowel onset effects become negative over both consonants (see Table 5.8.).

- Carryover direction (iCi-uCi)

NH effects over the bilabial are of a great magnitude (292 Hz, p<.0001) at vowel onset but do not reach significance at the middle and end of the vowel. Although to a lesser degree, the alveolar plosive allows significant effects at vowel onset only as well. Across the fricative, effects are even smaller and do not reach significance, although they remain relatively stable over the three measurement points. The HI also display significant effects over the bilabial at vowel onset, although of a smaller magnitude than the NH. The difference between the two groups is 183 Hz, but it is not found statistically significant, probably because of the high standard deviation levels generated by great variability in both groups. Over the alveolar plosive, effects are quite small at vowel onset and increase towards the end where they reach significance, in contrast with the NH (see Fig. 5.8.b). The HI fricative, on the other hand, allows significant lowering of the F2 at vowel onset (91 Hz, $p<.0001$), but effects become even larger at vowel offset (123 Hz, $p<.0001$). Thus, in this context, NH and HI speakers show similar patterns, but for the HI effects are larger and statistically significant at onset and offset.

➢ Summary

Regarding the [a] context, effects are limited for the NH group, as their high front vowel [i] seems to be quite constrained. The context that allows most effects across is the bilabial, whereas the alveolar plosive and the fricative seem to impede the influence exerted by the transconsonantal vowel (see Fig. 5.7.). The NH favour the carryover component, in contrast to the HI who display more effects in the anticipatory direction, with evidence of effects also at the midpoint and the onset of the vowel. Carryover effects for the HI were minimal in all contexts, except at the vowel offset over the fricative.

Comparing Fig. 5.7. with Fig. 5.8., we note that F2 effects on [i] are larger in the [u] context for the NH, as this vowel has an even lower F2 than [a]. The bilabial context allows significant effects that gain greater magnitude in the carryover direction. The two alveolars seem to hinder the appearance of significant effects around them. Although the HI present slightly more effects than the NH in the [a] context, their [i] is still more influenced by [u] than [a] similarly to the NH. The HI show more effects in the anticipatory direction, and compared to the NH, for whom carryover influence appears to reduce from vowel onset towards the end, the HI tend to demonstrate relatively discontinuous effects, e.g. in [pisi]-[pusi] where carryover effects reduce from onset to midpoint, where there is very little or no influence from the transconsonantal vowel, and increase again at the end point. In comparison to the NH coarticulation, a significant amount of effects is allowed over the more constrained consonantal contexts, also found in the literature (Okalidou & Harris, 1999).

(a)

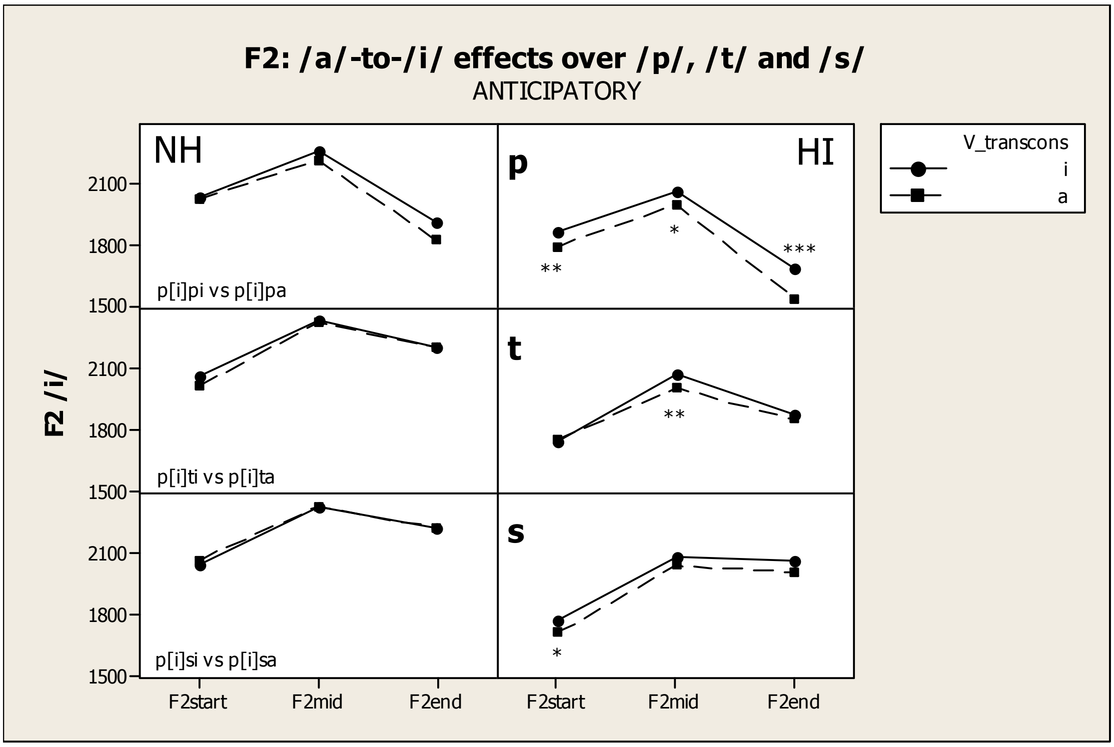
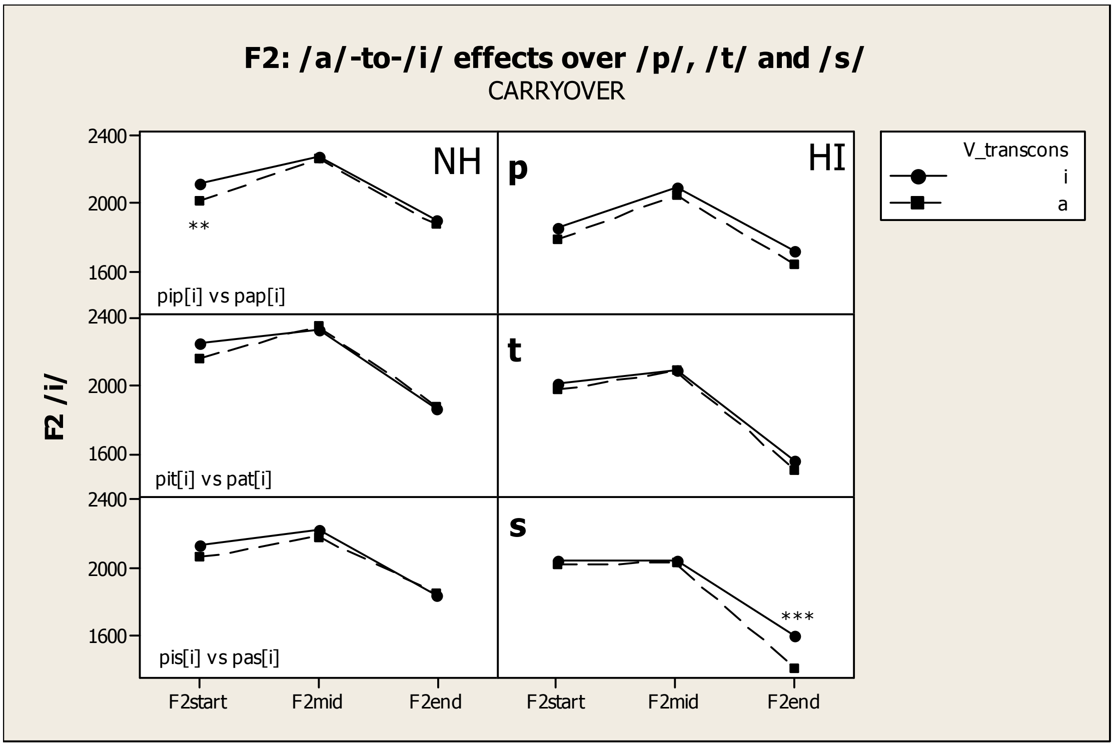


Fig. 5.7. F2 [a]-to-[i] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. Significant statistical difference is displayed within group with [*]: p < .05, [**]: p < .01 or [***]: p < .0000. No stat. significant difference was found between groups.

(b)



(a)

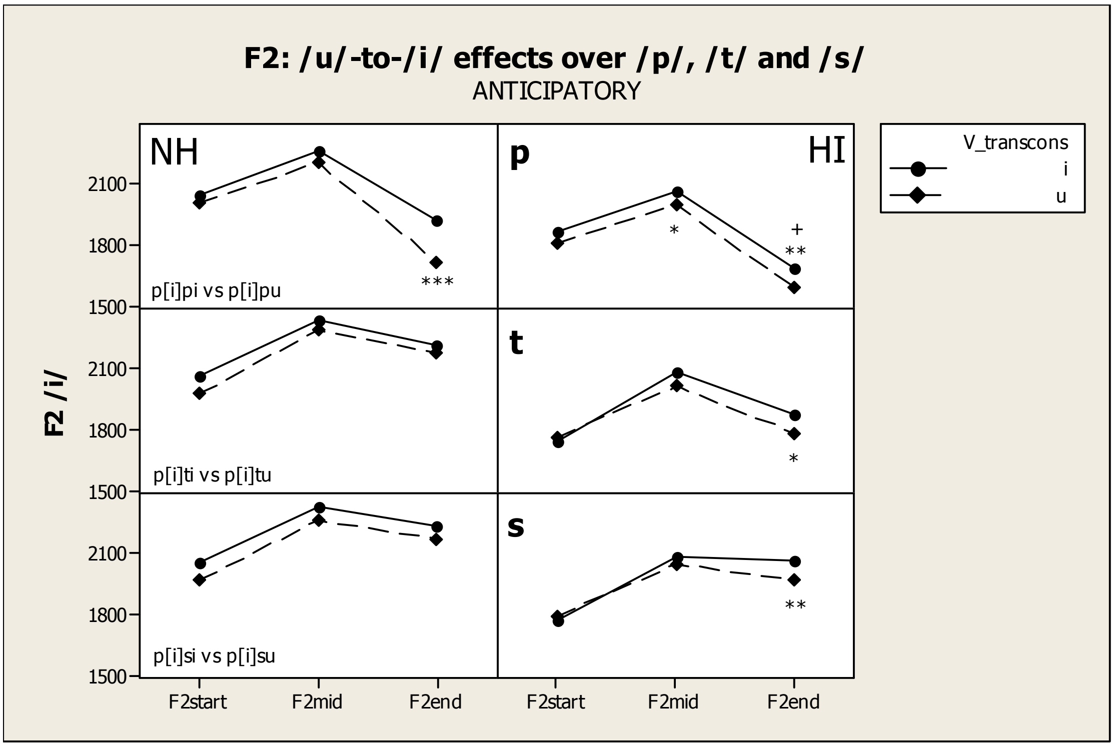
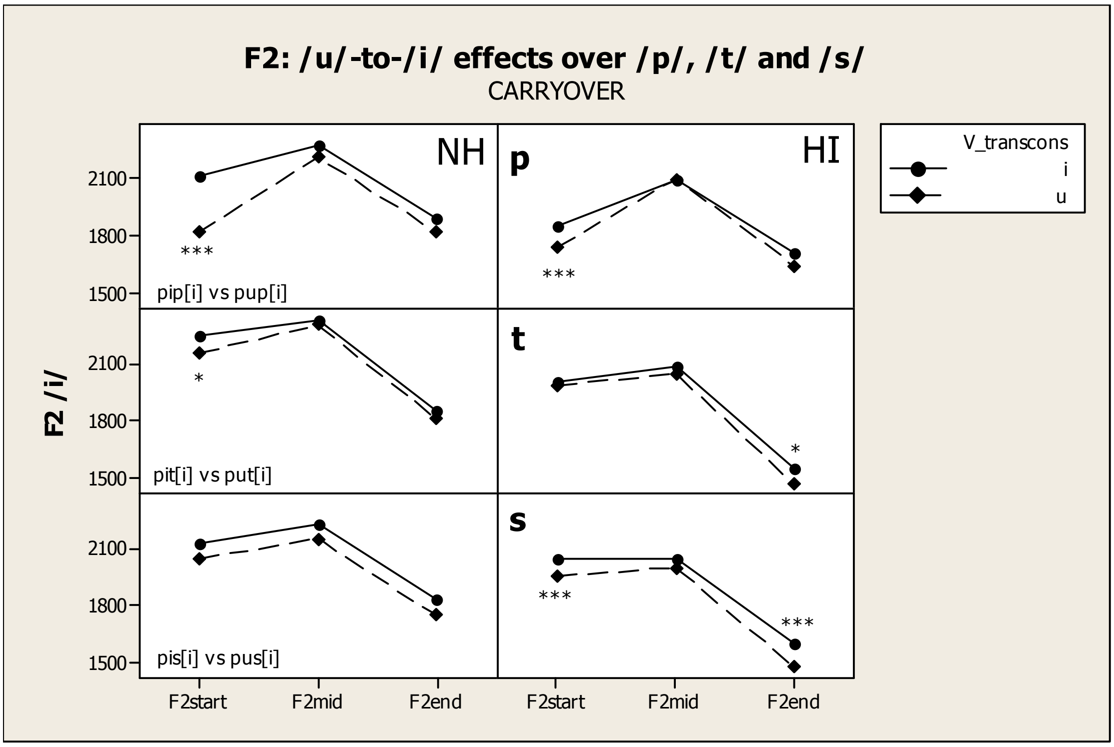


Fig. 5.8. F2 [u]-to-[i] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. Significant statistical difference is displayed within group with [*]: $p < .05$, [**]: $p < .01$ or [***]: $p < .0000$ and between groups with [$^{+}$]: $p<.05$, [$^{++}$]: $p<.01$ or [$^{+++}$]: $p<.0001$.

(b)



direction	[a] on fixed [i]	NH						HI					
		ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev	ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev
anticipatory	pipi-pipa	18	109	45	110	91	164	73	158	65	216	***151***	230
	piti-pita	36	187	11	71	4	120	-3	157	73	166	23	150
	pisi-pisa	-20	116	-5	75	2	124	62	190	39	126	57	143
carryover	pipi-papi	102	141	19	133	27	207	68	244	45	227	75	328
	piti-pati	89	89	-4	103	-17	316	39	113	8	161	49	250
	pisi-pasi	69	114	41	112	-6	267	25	113	23	175	***184***	399

Table 5.7. Mean F2 difference and StDev (in Hz) of the disyllable pairs [iCi]-[iCa] (anticipatory direction) and [aCi]-[iCi] (carryover direction), where C=p, t, s, at the three measurement points of [i]. HI values are highlighted. Statistically significant differences within group are in bold rectangles (p<.05 and for values in *bold italics* p<.0001).

direction	[u] on fixed [i]	NH						HI					
		ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev	ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev
anticipatory	pipi-pipu	37	103	57	122	***199***	157	59	174	68	190	$^{+}$98	240
	piti-pitu	79	170	49	66	33	113	-17	158	67	165	93	193
	pisi-pisu	85	121	64	80	60	112	-12	221	36	161	95	179
carryover	pipi-pupi	***292***	161	63	116	77	258	***109***	182	-4	180	73	235
	piti-puti	89	98	27	109	43	272	25	97	43	151	80	275
	pisi-pusi	82	92	66	129	91	239	***91***	155	48	160	***123***	319

Table 5.8. Mean F2 difference and StDev (in Hz) of the disyllable pairs [iCi]-[iCu] (anticipatory direction) and [uCi]-[iCi] (carryover direction), where C=p, t, s, at the three measurement points of [i]. HI values are highlighted. Statistically significant differences within group are in bold rectangles (p<.05 and for values in *bold italics* p<.0001). Differences between groups are denoted with crosses in front of HI values (+: p<.05,++: p<.01, +++: p<.0001).

5.1.2.2. Fixed [ɑ]

- **Influence of [i] on [a] (aCa-aCi and aCa-iCa)** (see Table 5.9. & Fig. 5.9.)

Prediction: Raising of F2

- Anticipatory direction (aCa-aCi)

It is evident that raising of F2 takes place for both groups, despite the fact that this difference does not reach statistical significance due to increased within group variability. For both groups the effects are maximum near the consonant and gradually decrease towards vowel onset. The HI [a] shows a slightly increased influence in the bilabial context rather than in the alveolar context, whereas the opposite is true for the NH [a], but these within and across group differences are not statistically significant (see Fig. 5.9.a).

- Carryover direction (aCa-iCa)

Coarticulatory effects are more sizeable in this direction for both groups. Regarding the NH, effects are found statistically significant at vowel onset in all consonantal contexts, while the difference between bilabial vs. alveolar context, with larger effects over the latter, is even more obvious in this direction; effects are greatest at vowel onset over the fricative. It is noteworthy that, although statistically significant only at vowel onset, effects appear to be present throughout the vowel, declining from vowel onset towards the endpoint. For the HI, on the other hand, influence is in the expected direction, but effects are of a lower magnitude at vowel onset and minimized at the other two measurement points (see Fig. 5.9.b). As mentioned above for the HI in the anticipatory direction, the largest carryover effects at vowel onset are observed over the bilabial, while effects over the alveolar context are significantly smaller in comparison to the respective NH effects.

- **Influence of [u] on [a] (aCa-aCu and aCa-uCa)** (see Table 5.10. & Fig. 5.10.)

Prediction: Lowering of F2

  - Anticipatory direction (aCa-aCu)

Overall, coarticulatory effects for both groups are nonsignificant which is related to the fact that the F2 distance between vowels [u] and [a] is less, hence the minor influence exerted from one to the other in the F2 dimension. Nevertheless, a trend is discernible for the NH, according to which, the fricative context allows relatively more effects to cross over (see Fig. 5.10.a). This also occurs for the HI, although for them it is both alveolar contexts that display a slight tolerance to V-to-V coarticulation with effects evident over [t] and [s] at vowel end only. However, the effects do not reach statistical significance.

  - Carryover direction (aCa-uCa)

Concerning the NH group, the bilabial seems the most permissive context towards coarticulatory effects at vowel onset only, whereas the alveolar plosive seems to be quite intolerant to effects throughout the vowel as in the anticipatory direction. Interestingly, negative effects are present in the fricative context, which convert to positive at vowel midpoint (see Fig. 5.10.b). Such discontinuities have been reported in the literature especially in velar and alveolar contexts (Recasens, 2002:2840). For the HI effects, regardless of consonantal context, are negligible, probably due to the fronted position of their [u].

- **Summary**

As expected, [i] exerts far more influence than [u] on the F2 of low-mid [a] for both groups. Regarding [i]-to-[a] coarticulation, favouring the carryover component is a characteristic shared by the two groups, but their behaviour diverges regarding consonantal context; for the NH, alveolar context is more tolerant to coarticulatory effects, while the HI illustrate more influence over the bilabial plosive (see Table 5.9.).

Effects from [u] are nonsignificant for both groups. Concerning the NH, effects are present across the bilabial in the carryover direction, whereas in the anticipatory direction, some effects are evident over the fricative (see Fig. 5.10.a). In comparison with the NH, slightly more effects are manifested over both alveolars in the anticipatory direction for the HI (see Table 5.10.), but V-to-V HI coarticulation seems blocked over all consonantal contexts in the carryover direction.

(a)

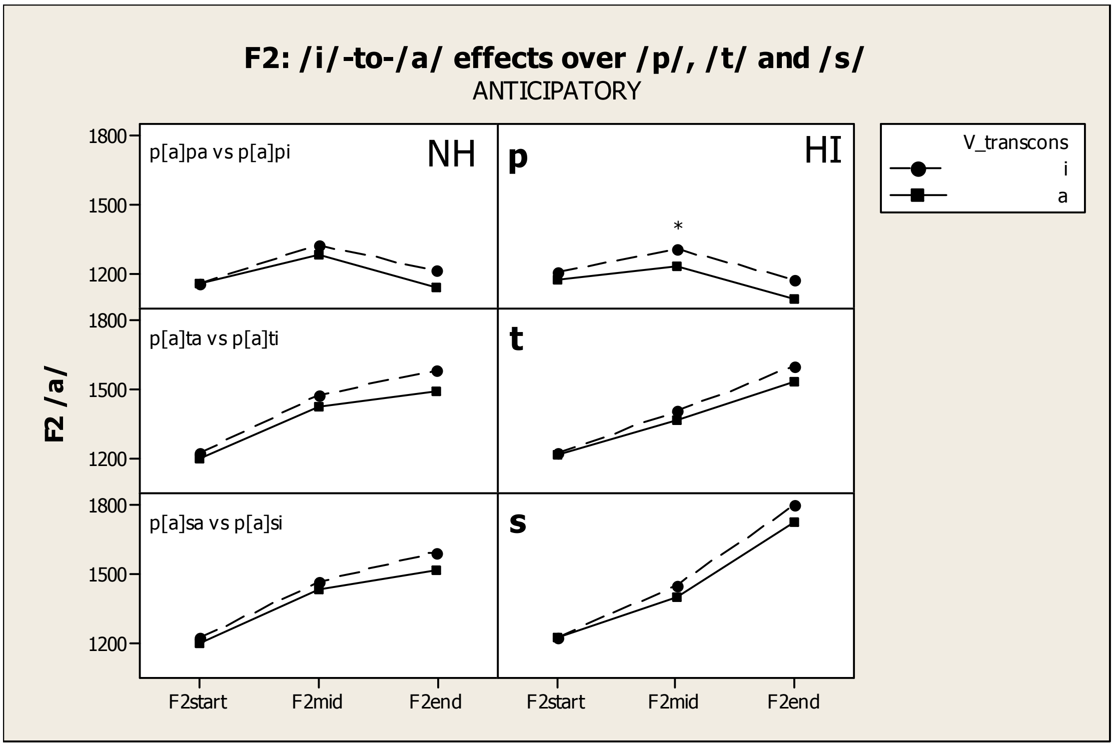
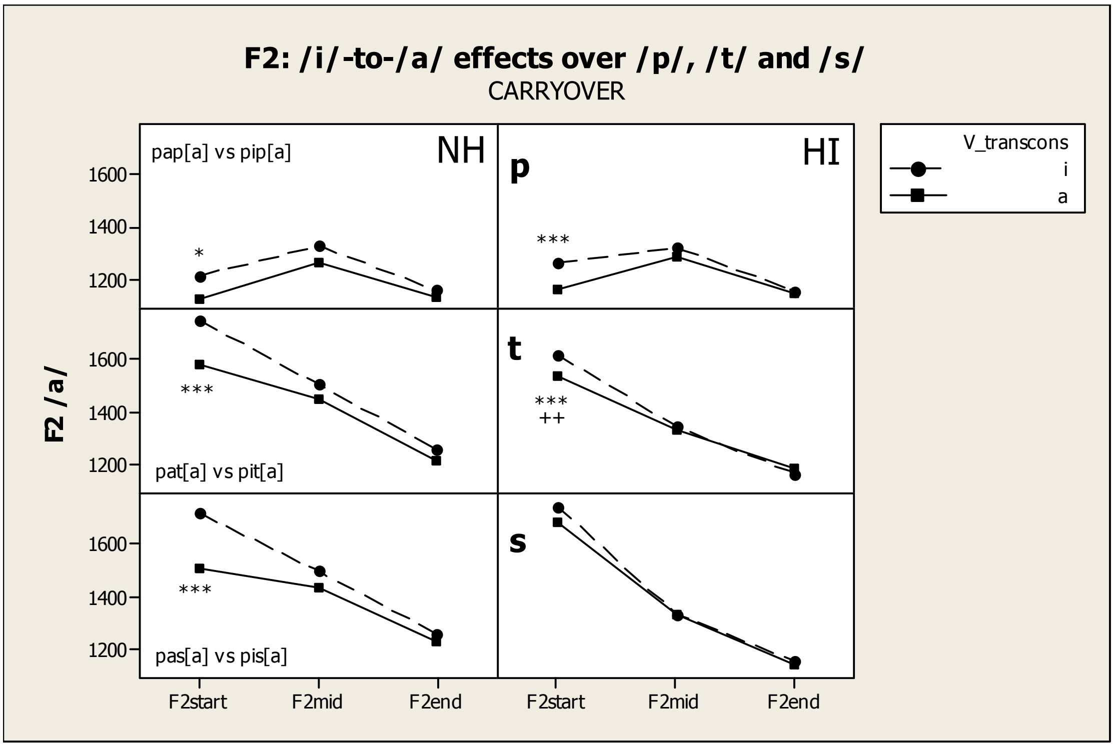


Fig. 5.9. F2 [i]-to-[a] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. Significant statistical difference is displayed within group with [*]: p < .05, [**]: p < .01 or [***]: p < .0000 and between groups with [$^{+}$]: p<.05, [$^{++}$]: p<.01 or [$^{+++}$]: p<.000.

(b)



(a)

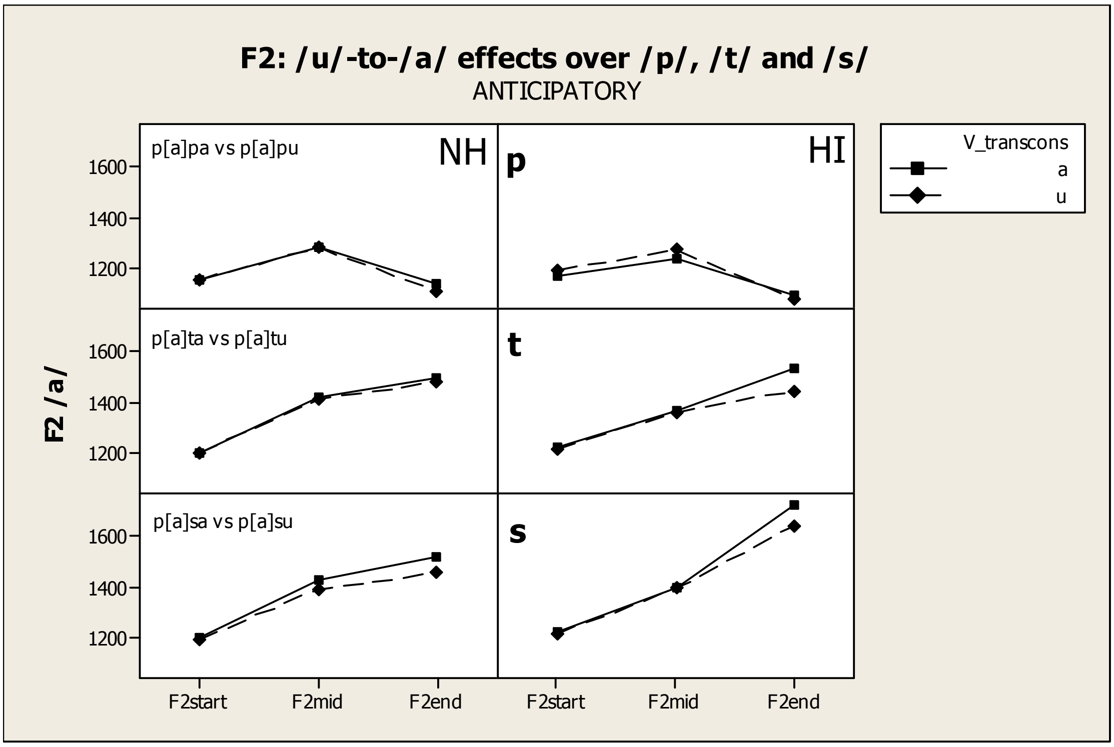
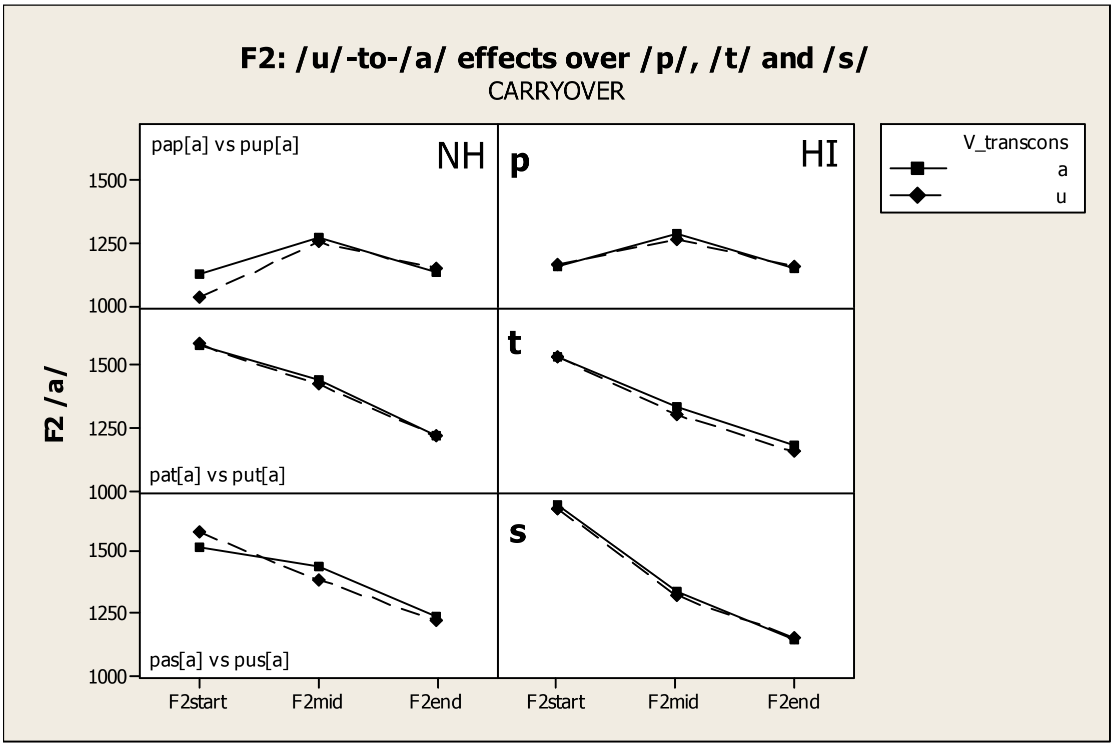


Fig. 5.10. F2 [u]-to-[a] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. Significant statistical difference is displayed within group with [*]: p < .05, [**]: p < .01 or [***]: p < .0000 and between groups with [$^{+}$]: p<.05, [$^{++}$]: p<.01 or [$^{+++}$]: p<.000.

(b)



direction	[i] on fixed [a]	NH						HI					
		ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev	ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev
anticipatory	papi-papa	-4	78	34	72	64	94	35	98	71	105	83	126
	pati-pata	22	85	50	58	91	79	5	95	42	94	69	107
	pasi-pasa	19	75	34	61	81	103	6	91	53	100	76	132
carryover	pipa-papa	87	105	61	81	25	99	***103***	146	37	123	9	145
	pita-pata	***171***	81	59	69	44	117	$^{++}$***83***	104	13	89	-17	131
	pisa-pasa	***208***	101	65	70	30	112	61	108	-1	123	15	123

Table 5.9. Mean F2 difference and StDev (in Hz) of the disyllable pairs [aCa]-[aCi] (anticipatory direction) and [iCa]-[aCa] (carryover direction), where C=p, t, s, at the three measurement points of [a]. HI values are highlighted. Statistically significant differences within group are in bold rectangles (p<.05 and for values in *bold italics* p<.0001). Differences between groups are denoted with crosses in front of HI values ($^{+}$: p<.05,$^{++}$: p<.01, $^{+++}$: p<.0001).

direction	[u] on fixed [a]	NH						HI					
		ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev	ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev
anticipatory	papa-papu	1	84	3	70	28	94	-20	100	-38	102	14	95
	pata-patu	1	76	14	62	16	71	0	97	3	103	90	149
	pasa-pasu	9	80	42	62	61	102	8	85	4	91	83	175
carryover	papa-pupa	96	102	14	78	-11	105	-2	111	19	114	-5	121
	pata-puta	-8	88	20	61	2	111	1	105	30	94	29	107
	pasa-pusa	-61	117	51	82	10	119	19	127	17	109	-9	123

Table 5.10. Mean F2 difference and StDev (in Hz) of the disyllable pairs [aCa]-[aCu] (anticipatory direction) and [uCa]-[aCa] (carryover direction), where C=p, t, s, at the three measurement points of [a]. HI values are highlighted. No stat. significance was found within group.

5.1.2.3. Fixed [u]

- **Influence of [a] on [u] (uCu-uCa and uCu-aCu)** (see Table 5.11. & Fig. 5.11.)

Prediction: F2 raising

- Anticipatory direction (uCu-uCa)

Due to the short distance between these two vowels along the F2 axis, the NH group does not exhibit significant effects in any consonantal context. Among the three contexts, the fricative allows some effects from the upcoming [a], while the alveolar plosive seems to block V-to-V effects (see Fig. 5.11.a). As far as the HI are concerned, statistically significant effects appear across both [t] and [s] at vowel offset. Thus, for both groups, relatively more effects are observed over the fricative, but more effects are present for the HI than the NH in the alveolar context (see Table 5.11.).

- Carryover direction (uCu-aCu)

Here neither group displays significant coarticulatory effects in any context. Regarding the NH, there are some small positive effects across the bilabial. Effects are even smaller across the alveolar plosive, while near the fricative effects are negative. For the HI, effects are essentially blocked across all consonants (see Fig. 5.11.b).

- **Influence of [i] on [u] (uCu-uCi and uCu-iCu)** (see Table 5.12. & Fig. 5.12.)

Prediction: F2 raising

  - Anticipatory direction (uCu-uCi)

Concerning the NH, although effects did not reach statistical significance[30], they are evident at vowel offset regardless of consonantal context. The least favourable environment is that of the alveolar plosive, whereas the bilabial and especially the fricative context seem to allow coarticulatory effects. Effects over the two alveolars are of a greater magnitude and were found statistically significant at vowel offset for the HI (see Fig. 5.12.a). The HI alveolar plosive seems to allow the most effects from [i] in comparison to the fricative, while no significant effects are evident over the bilabial. Some effects at vowel midpoint are observed in the fricative context for both groups, although not statistically significant (see Table 5.12.).

  - Carryover direction (uCu-iCu)

Statistically significant effects at vowel onset are manifested for the NH group across all consonantal contexts, while no effects are observed for the HI (see. Fig. 5.12.b). For the NH, in agreement with Recasens et al. (1997), it is the two plosives that allow the most sizeable effects, although they are still significant across the fricative as well. Conversely, coarticulatory effects are not significant over any consonant and at any measurement point for the HI group.

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[30] Sizeable effects (52 to 112 Hz) were not found statistically significant because of within group variability and the high number of missing values which relates to the fact that unstressed high vowels are subject to extreme shortening, devoicing or elision in certain environments (Dauer, 1981:17 –see also section 2.4.1).

➢ Summary

Between the front [i] and the more central [a], we anticipate more coarticulatory influence on the back [u] from the former. This premise is confirmed by the NH but not by the HI in any direction. Firstly, the HI favour the anticipatory component in both cases, whereas the NH display more substantial effects in the carryover direction, especially in [i]-to-[u] coarticulation (see Table 5.11. Table 5.12.). Secondly, regardless of direction, the HI [u] seems to either block or receive effects of similar magnitude from both transconsonantal vowels, presenting an almost identical picture for the two notably different vocalic contexts. In opposition, the NH favour effects from [i] especially in the carryover direction.

As far as consonantal context is concerned, a different pattern can be discerned according to direction for each group. In both [a] and [i] vocalic contexts, more anticipatory effects occur across the NH fricative than the other two consonants, whereas in the carryover direction, the bilabial and the alveolar stop seem more tolerant towards carryover effects than the fricative. The trend is different for the HI; firstly the alveolar plosive and secondly the fricative seem to allow most of the anticipatory effects, while the bilabial constitutes the least favourable context for V-to-V coarticulation. In the carryover direction, HI coarticulation is essentially blocked.

(a)

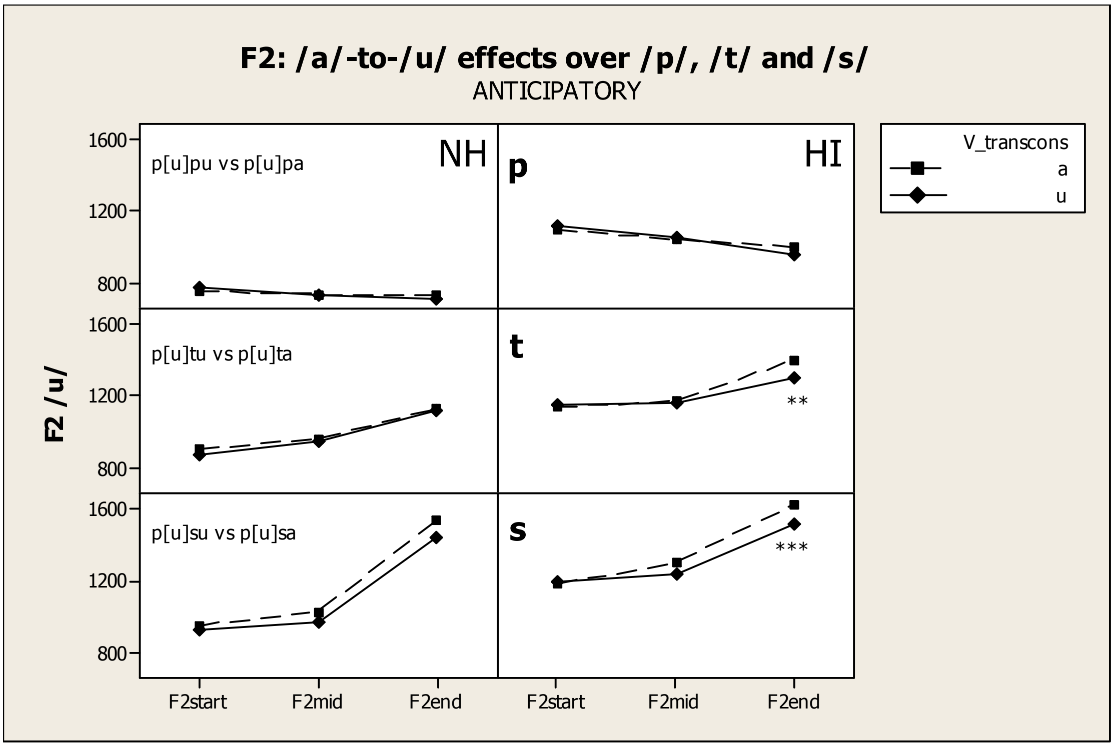
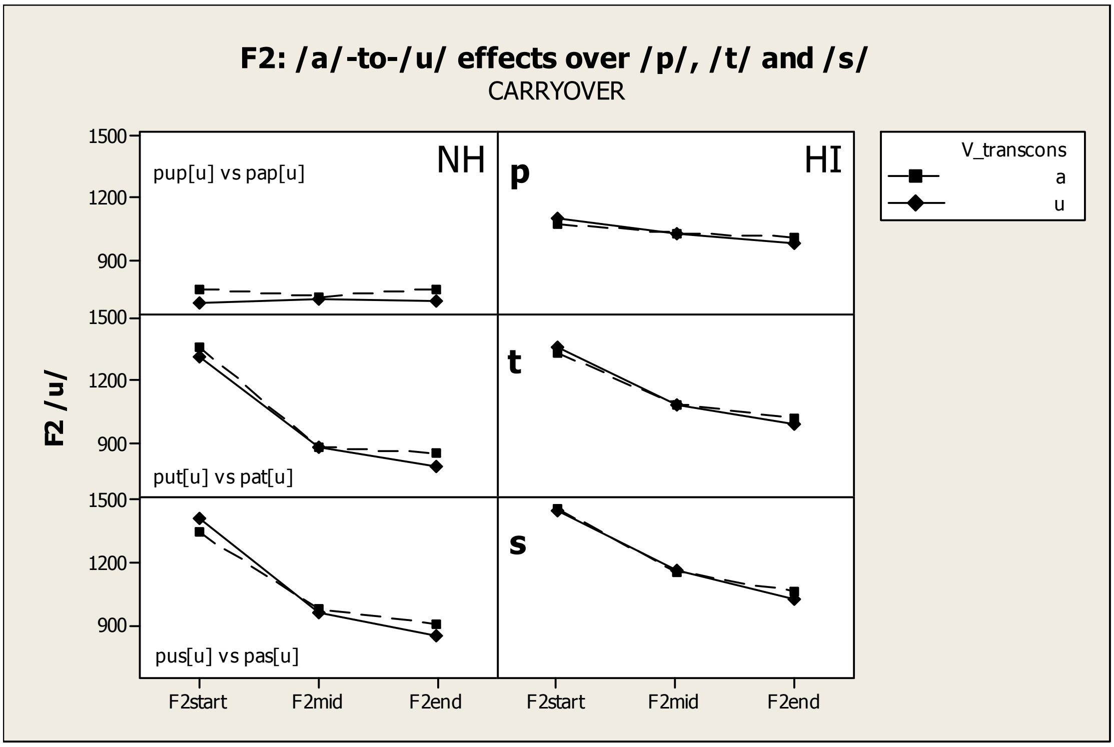


Fig. 5.11. F2 [a]-to-[u] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. Significant statistical difference is displayed within group with [*]: p < .05, [**]: p < .01 or [***]: p < .0000 and between groups with [$^{+}$]: p<.05, [$^{++}$]: p<.01 or [$^{+++}$]: p<.000.

(b)



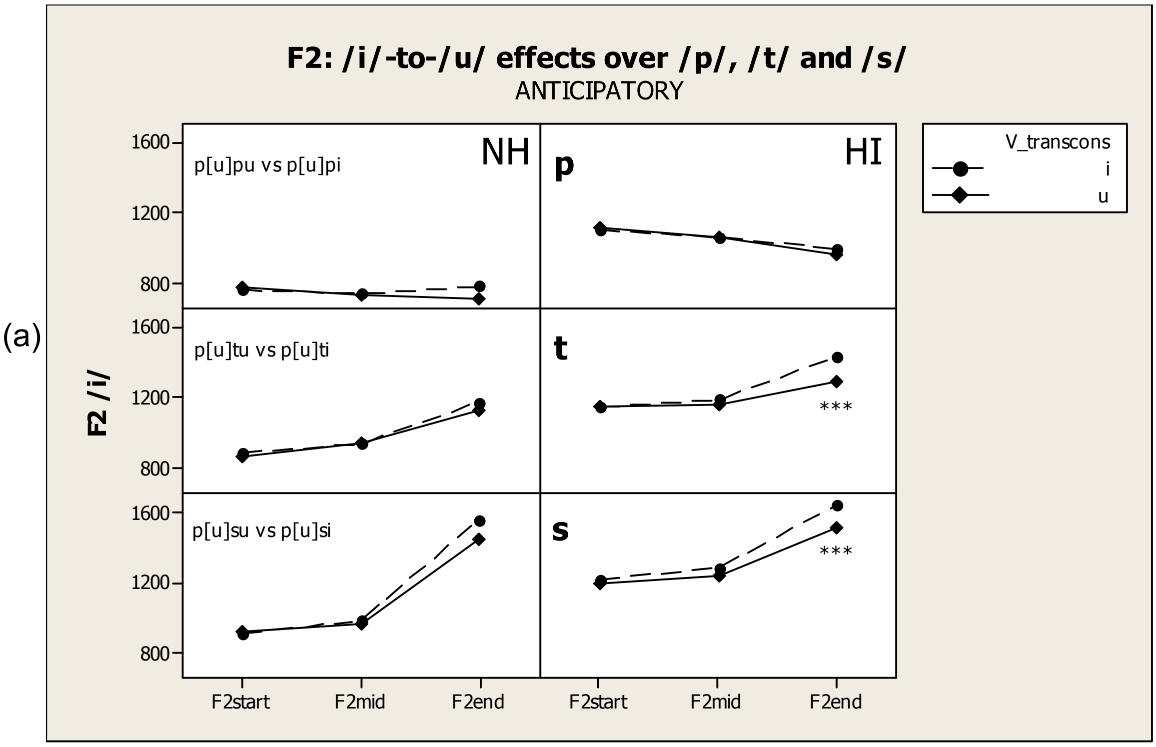
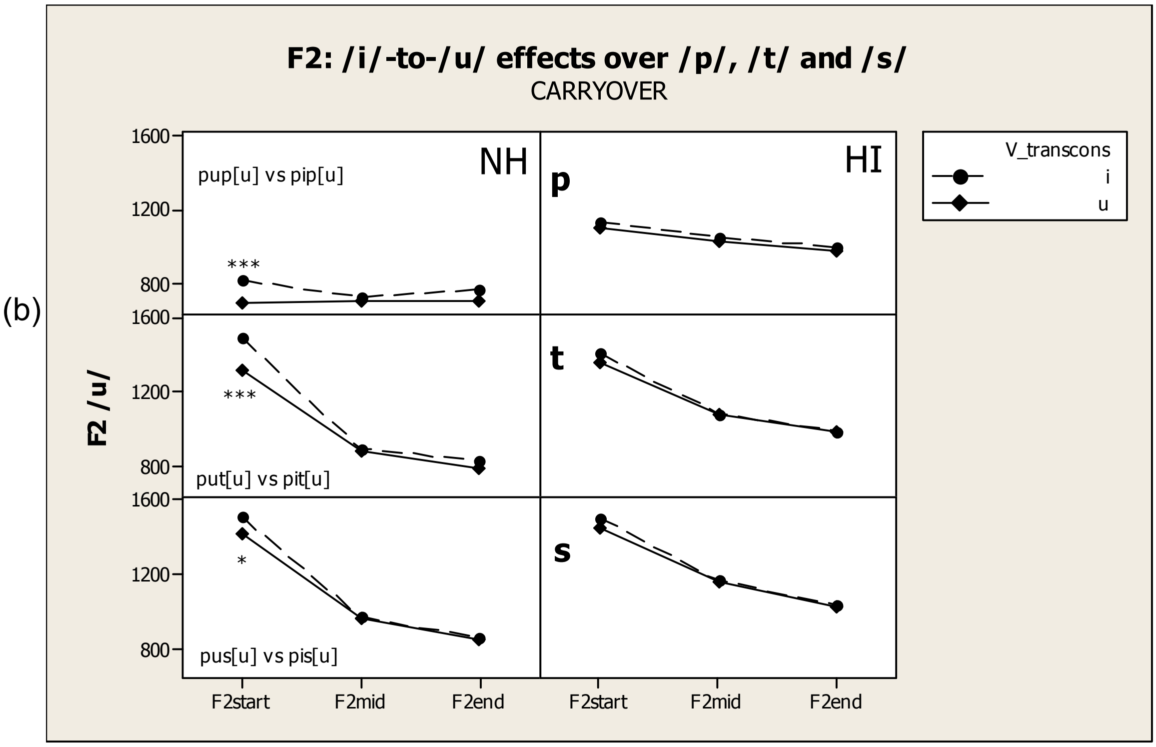


Fig. 5.12. F2 [i]-to-[u] (a) anticipatory (above) and (b) carryover (beneath) effects in the consonant context of [p], [t] and [s]. Significant statistical difference is displayed within group with [*]: p < .05, [**]: p < .01 or [***]: p < .0000 and between groups with [$^{+}$]: p<.05, [$^{++}$]: p<.01 or [$^{+++}$]: p<.000.



direction	[a] on fixed [u]	NH						HI					
		ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev	ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev
anticipatory	pupa-pupu	-23	104	5	87	23	138	-19	124	-13	121	39	134
	puta-putu	34	147	20	91	6	135	-5	135	8	135	104	169
	pusa-pusu	29	136	58	93	91	259	-18	132	51	186	***94***	239
carryover	papu-pupu	69	101	10	79	102	263	-27	136	-2	124	45	213
	patu-putu	49	115	4	74	54	138	-16	156	8	124	27	141
	pasu-pusu	-76	164	17	109	59	164	14	205	0	185	39	165

Table 5.11. Mean F2 difference and StDev (in Hz) of the disyllable pairs [aCa]-[aCu] (anticipatory direction) and [uCa]-[aCa] (carryover direction), where C=p, t, s, at the three measurement points of [u]. HI values are highlighted. Statistically significant differences within group are in bold rectangles (p<.01 and for values in *bold italics* p<.0001).

direction	[i] on fixed [u]	NH						HI					
		ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev	ΔF2start	StDev	ΔF2mid	StDev	ΔF2end	StDev
anticipatory	pupi-pupu	-14	124	8	79	69	128	-16	121	6	107	34	138
	puti-putu	19	131	-4	82	52	138	-1	115	24	172	***137***	232
	pusi-pusu	-16	151	16	91	112	238	43	184	65	177	***93***	249
carryover	pipu-pupu	***127***	138	22	81	67	122	31	145	21	144	22	125
	pitu-putu	***181***	143	13	83	44	124	53	148	2	115	1	129
	pisu-pusu	99	184	9	95	14	118	63	206	9	188	10	143

Table 5.12. Mean F2 difference and StDev (in Hz) of the disyllable pairs [uCu]-[uCi] (anticipatory direction) and [iCu]-[uCu] (carryover direction), where C=p, t, s, at the three measurement points of [u]. HI values are highlighted. Statistically significant differences within group are in bold rectangles (p<.05 and for values in *bold italics* p<.0001).

5.1.3. SYNOPSIS

5.1.3.1. The Context Factor in NH vs. HI F1 & F2 Coarticulation at V1offset and V2onset

Both groups follow similar F1 and F2 coarticulation patterns overall. Nevertheless, there are differences between the two groups in the degree of coarticulatory effects depending on consonantal context and coarticulatory direction which are discussed below. Figures 5.13 - 5.15 demonstrate the degree and statistical significance of F1 coarticulatory influence (ΔF1) and Figures 5.16 - 5.18 those of F2 (ΔF2) on each one of the three vowels from the other two vocalic contexts, separately for the NH and the HI group, at V_1 offset (anticipatory) and V_2 onset (carryover), as these measurement points are located closest to the transconsonantal vowel and were found in many cases to exhibit sizable and statistically significant V-to-V effects.

F1

F1 coarticulation patterns are similar for both groups overall, i.e. they both show significant F1 lowering of [a] from both [i] and [u], while effects on the F1 of the high vowels [i] and [u] are not as affected, especially for the HI. As far as consonantal context is concerned, for the NH, the bilabial allows significantly larger effects than the alveolar contexts on both the high vowels, while effects on [a] are evident over all three consonants with the alveolar context being more permissive in the anticipatory direction. For the HI, consonantal context is immaterial for [i] and [u] as effects are very small on the high vowels, while they demonstrate coarticulation on [a] over all three consonants as the NH; however we note that, in the anticipatory direction, HI effects over [s] are less than the corresponding NH effects. Overall, more effects are present in the carryover direction for the NH, except for [i]-to-[u] coarticulation, whereas neither direction is clearly favoured regarding HI [i]-to-[a] coarticulation which is the only one of the three fixed vowel contexts presenting significant effects.

Fixed [i]

- Overall, NH [i] is slightly more coarticulated than HI [i].
- Effects by low [a] are more prominent than those by high [u] for the NH, while this difference is not as highlighted for the HI.
- Greater coarticulatory effects occur over the bilabial compared to the alveolar context for the NH. This is also true for the HI, although effects are very small.

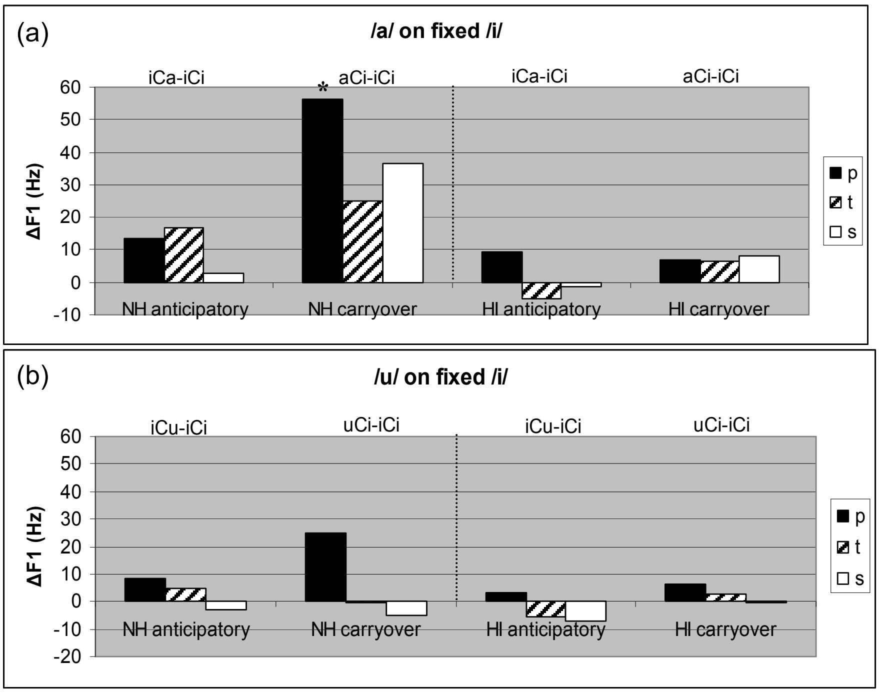


Fig. 5.13. Context induced coarticulation on F1 of [i] (a) from [a] (above) and (b) from [u] (below), at vowel offset for anticipatory and at vowel onset for carryover effects ([*]: within group difference, p<.05).

- Greater carryover than anticipatory effects are generally present for the NH. Coarticulatory directionality cannot be as easily identified for the HI, as effects are very small.

Fixed [a]

- The low [a] is the vowel receiving the most coarticulatory effects, especially from [u], for both groups.
- Effects are evident across all consonantal contexts for both groups.
- For the NH, greater effects over the bilabial occur in the carryover direction, while larger effects over the two alveolars, and especially the fricative, are evident in the anticipatory direction. For the HI, the bilabial and the fricative allow more effects than the alveolar plosive in the carryover direction, whereas effects over [t] are greater compared to the other two contexts in the anticipatory direction.

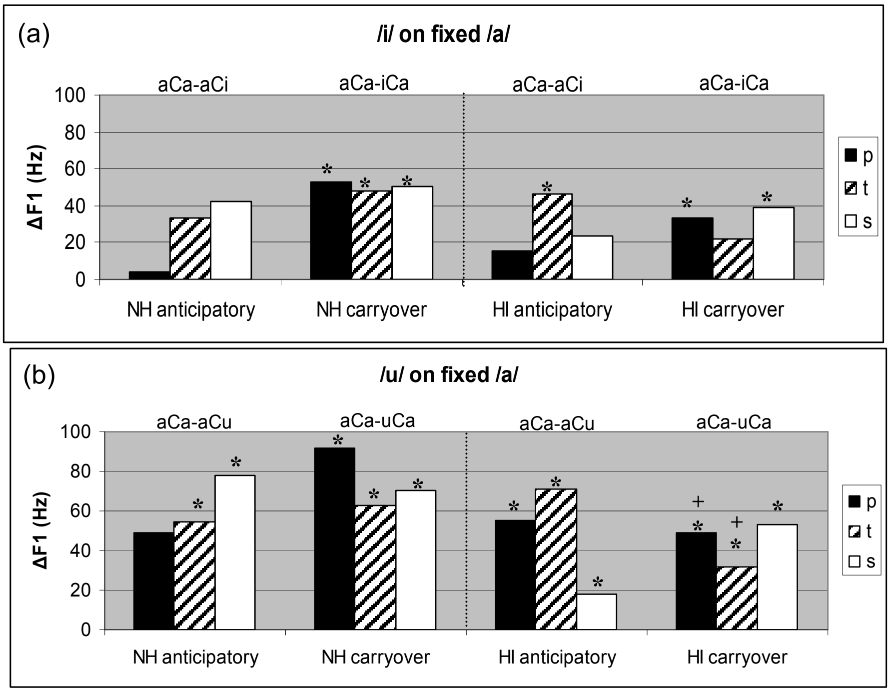


Fig. 5.14. Context induced coarticulation on F1 of [a] (a) from [i] (above) and (b) from [u] (below), at vowel offset for anticipatory and at vowel onset for carryover effects ([*]: within group and [$^+$]: between group difference, p<.05).

- Comparing effects across the two alveolar contexts, for the NH, smaller effects are allowed over [t] than [s] in both directions and in both vocalic contexts. For the HI, this occurs in the carryover direction, while in the anticipatory direction more effects are evident across [t] than [s].
- Generally, carryover effects are more prominent for the NH, while directional preference is more variable for the HI.

Fixed [u]

- Effects on [u] are greater for the NH than the HI.
- The vast majority of effects occur in the bilabial context for both groups, but they are negative.
- Effects in the alveolar contexts are minimal for both groups.
- Overall, no strong preference for coarticulatory direction can be discerned for either group.

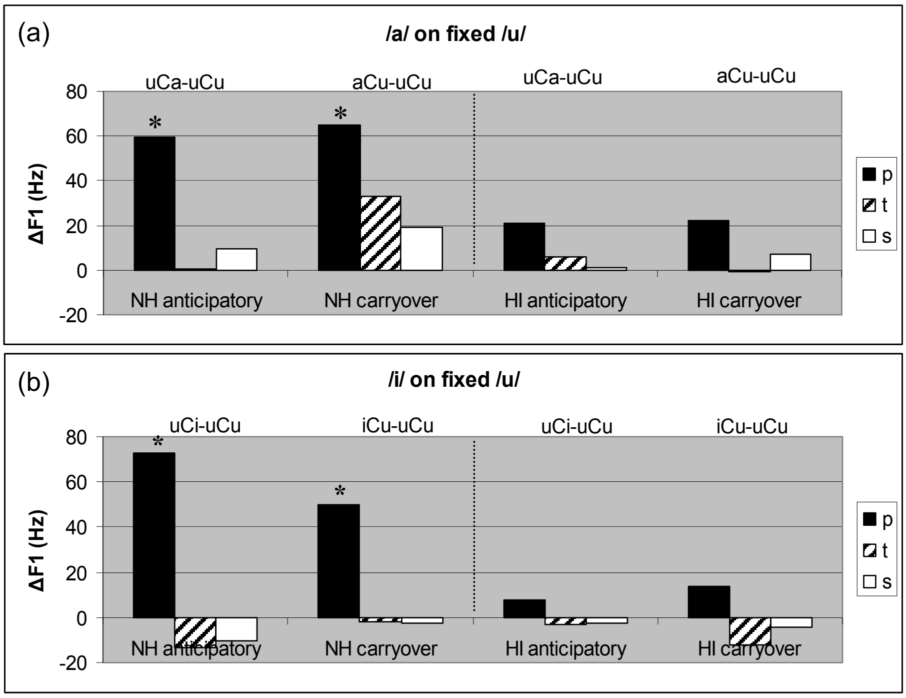


Fig. 5.15. Context induced coarticulation on F1 of [u] (a) from [a] (above) and (b) from [i] (below), at vowel offset for anticipatory and at vowel onset for carryover effects ([*]: within group difference, p<.05).

F2

F2 coarticulation effects are present for both groups with overall greater effects in absolute magnitude for the NH, but comparable in number of contexts and statistical significance for the two groups. For both groups [u]-to-[i] and [i]-to-[u] coarticulation is more prominent than [a]-to-[i] or [u], due to the longer distance between the F2 of the two high vowels, while [i]-to-[a] effects are larger than [u]-to-[a] effects. Regarding consonantal context, for the NH, the bilabial allows more coarticulation when the fixed vowel is [i], while larger effects are present over the alveolars on [a] and [u], especially in the cases of [i]-to-[a] and [i]-to-[u] coarticulation. The HI follow the normal pattern in fixed [a] and [u] contexts, that is, they show more effects on [a] and [u] over the alveolars, while coarticulation on [i] over the bilabial compared with the alveolars is not as salient as for the NH. Concerning direction, carryover effects are larger than anticipatory effects for the NH, while for the HI the opposite holds, except for [i]-to-[a] coarticulation.

Fixed [i]

- In general, both groups show significant coarticulation, although in most cases effects are more sizeable in absolute terms for the NH.
- The high front vowel [i] receives more overall influence from [u] rather than [a] for both groups.

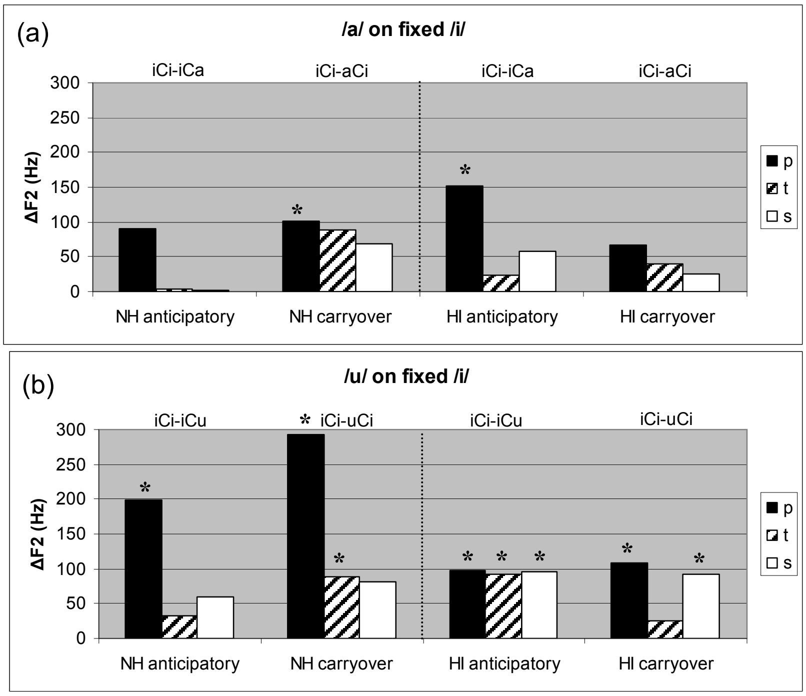


Fig. 5.16. Context induced coarticulation on F2 of [i] (a) from [a] (above) and (b) from [u] (below), at vowel offset for anticipatory and at vowel onset for carryover effects ([*]: within group and [$^{+}$]: between group difference, p<.05).

- Greater effects are present in the carryover direction for the NH, while generally the opposite holds for the HI; i.e., they show more effects in the anticipatory direction.
- Larger effects are evident over the bilabial in both directions for the NH. This is also true for the HI, although in selected cases, i.e. in [iti]-[itu], [isi]-[isu] and [isi]-[usi], significant effects over the alveolars are also present.

Fixed [a]

- The NH show overall more coarticulation than the HI.
- For both groups [a] displays a lot more coarticulatory effects from [i] than from [u], although this does not occur to such a degree with the HI.
- Again, the NH effects occur mostly in the carryover direction, whereas for the HI there is variability and the degree of directional effects depends largely on vocalic context, i.e., [i] induces bidirectional effects with prominence of the carryover component, whereas effects from [u] are mostly anticipatory.

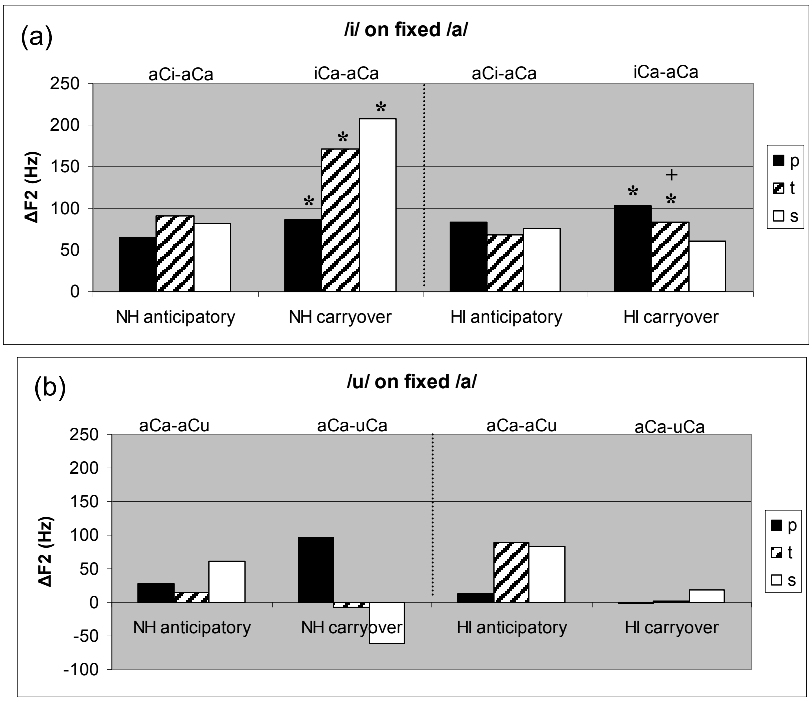


Fig. 5.17. Context induced coarticulation on F2 of [a] (a) from [i] (above) and (b) from [u] (below), at vowel offset for anticipatory and at vowel onset for carryover effects ([*]: within group and [$^+$]: between group difference, p<.05).

- Regarding consonantal context, two opposing patterns emerge for the two groups. For the HI, greater effects are evident over the bilabial from [i] and over the alveolars from [u], whereas for the NH, effects are larger over the alveolars from [i] and over the bilabial from [u].

Fixed [u]

- For both groups [i] exerts a greater amount of influence than [a] on [u].
- Generally, greater carryover effects are present for the NH, while the HI show more effects in the anticipatory direction.
- Both groups display significant coarticulatory effects over [t] and [s], especially from [i].
- In the majority of cases, greater coarticulatory effects are present over one or both alveolars compared with the bilabial for both groups.

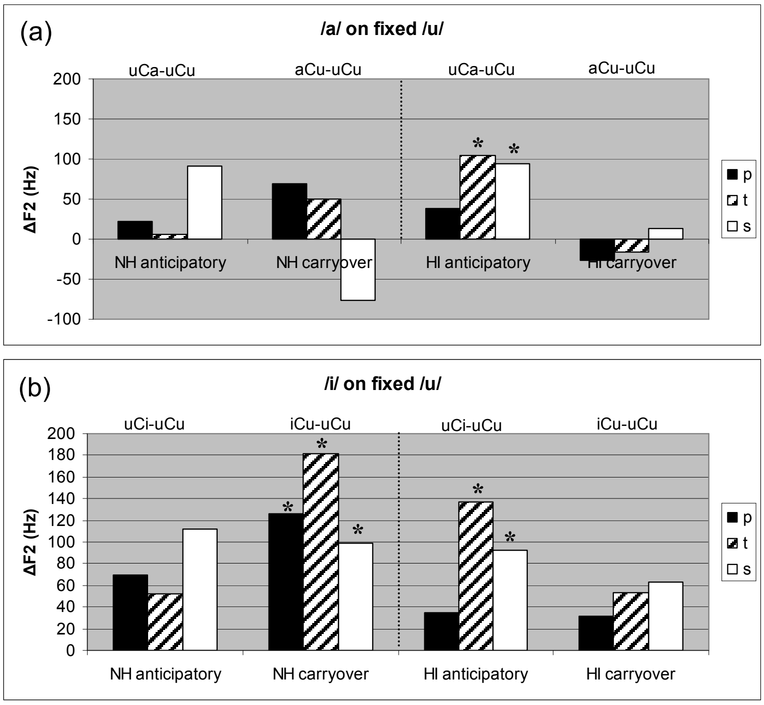


Fig. 5.18. Context induced coarticulation on F2 of [u] (a) from [a] (above) and (b) from [i] (below), at vowel offset for anticipatory and at vowel onset for carryover effects (*: p<.05).

5.1.3.2. Temporal Extent of NH vs. HI F1 & F2 V-to-V Coarticulation

The above summarized description and Figures 5.13-5.18 refer to V-to-V coarticulatory phenomena observed at the measurement point closest to the transconsonantal vowel, i.e., V_1 offset for anticipatory and V_2 onset for carryover effects. Looking at the other two measurement points along the vowel, a general tendency for reduced coarticulation at the vowel midpoint was detected throughout the data, for the normal hearing and the hearing impaired group. In many cases, effects were maximum at one end, minimal at vowel midpoint and slightly increased again at the other end. The low rate of coarticulation phenomena at vowel midpoint found in our data may indicate that in Greek the vowel steady state remains relatively invariable from transconsonantal influences, so that perceptual clarity can be achieved. See section 6.4.2. for a discussion.

Regarding the temporal extent of the effects present in the productions of the two groups, some principal observations are summarized below.

F1

- For the NH group, effects that extend to the other end of the vowel reached statistical significance in the [apu]-[upu], [ipu]-[upu] (carryover) and [upi]-[upu] (anticipatory) pairs, denoting coarticulatory flexibility in the bilabial context on the high back vowel.
- Coarticulatory effects for the HI group, as a rule, did not reach the other end. The pair [asa]-[isa] constitutes an atypical exception, where carryover effects began as positive and statistically significant at vowel onset and reached significance again, but as negative, at vowel offset.

F2

As with F1, there is not a great number of significant effects at other measurement points. Nevertheless, effects that extend along the vowel are evident in certain contexts, sometimes common for both groups and in other instances different.

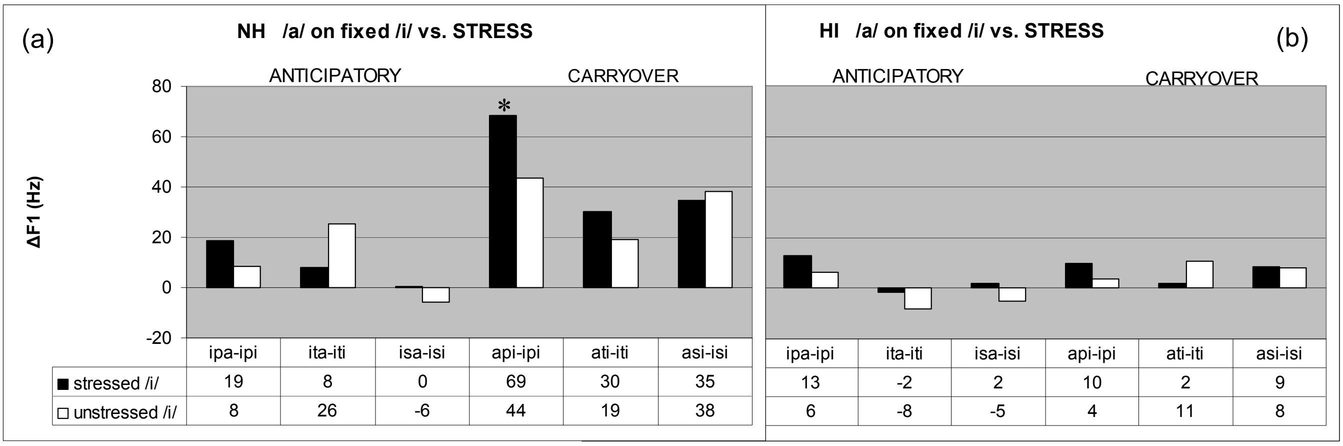
- The HI group shows extensive effects in [iCi]-[iCa] pairs, while the NH does not (see Fig. 5.7.a and 5.8.a). This may have to do with the preference of HI coarticulation to the anticipatory direction, but it could also be associated with differences in the degree of articulatory constraint in the production of high vowel [i] between the two groups. Absence of effects on [i] for the NH group suggests greater degree of articulatory constraint during the production of NH [i].
- Both groups display extensive coarticulatory effects on [i] from vowel [u]; effects from [u] are greater in comparison to those from [a]. It is also noteworthy that, in [iti]-[uti] and [isi]-[usi] pairs, effects reach their maximum at the other end of the vowel for the HI group, signifying blocking of effects near the alveolars.

5.2. V-to-V Coarticulation and Stress

5.2.1. F1

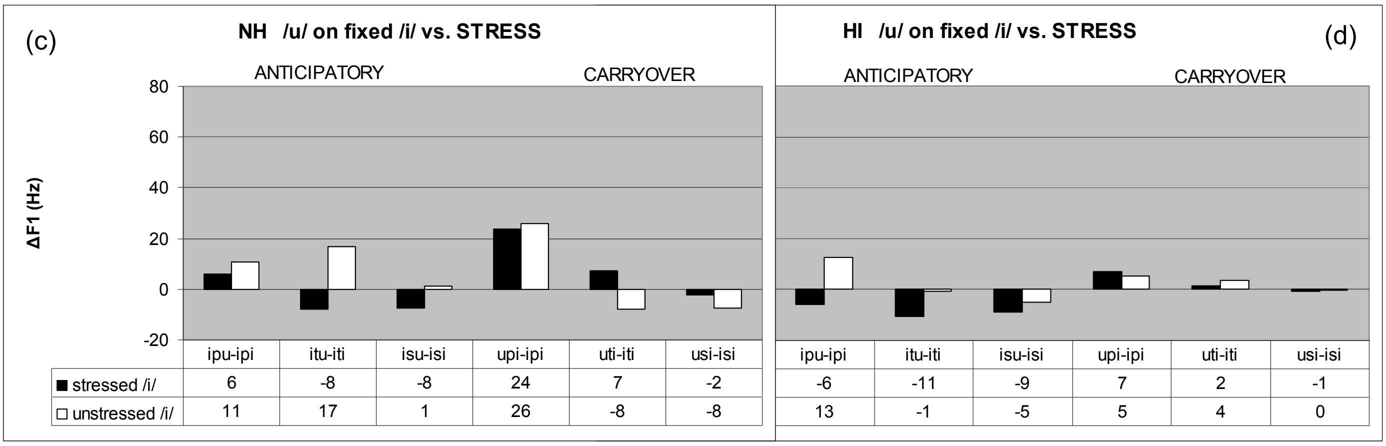
Stress was a statistically significant factor for all three F1 measurement points (start: F(1, 15035)=308.298, p<.0001, mid: F(1, 15036)=1608.664, p<.0001, end: F(1, 15035)= 654.720, p<.0001) and for the middle of the vowel regarding ΔF1 (F(1, 9971)=6.644, p<.05). Looking into the interaction hearing* measured V* transconsonantal V* C* stress, post hoc tests revealed significant coarticulatory effects in stressed and unstressed fixed vowel contexts for the NH and the HI group.

In Figures 5.19-5.21., the asterisk [*] located above the stressed or/and unstressed condition presents statistically significant effects. In the cases where significant effects were found in both conditions, we observe the degree of effects (bar size). Anticipatory effects are displayed at vowel offset (first syllable) and carryover effects at vowel onset (second syllable). Table 5.13. below summarizes the results (see also Appendix 2.3.: V-to-V Coarticulation Tables, Stress & Context –F1)

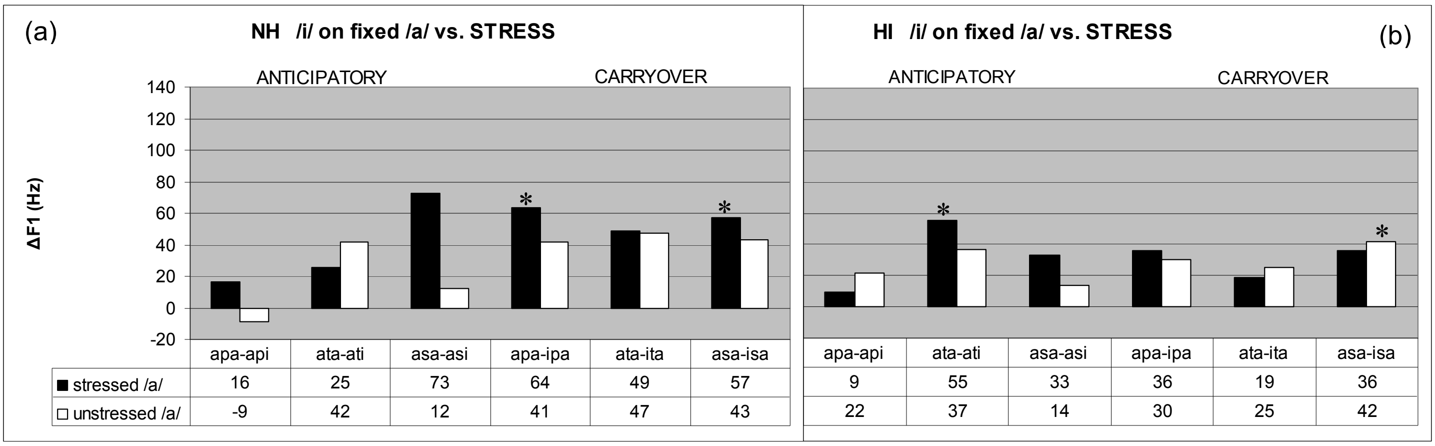


	ipa-ipi	ita-iti	isa-isi	api-ipi	ati-iti	asi-isi	ipa-ipi	ita-iti	isa-isi	api-ipi	ati-iti	asi-isi
■ stressed /i/	19	8	0	69	30	35	13	-2	2	10	2	9
□ unstressed /i/	8	26	-6	44	19	38	6	-8	-5	4	11	8

Fig. 5.19. F1 coarticulatory effects (ΔF1) in Hz on fixed vowel [i] in the stressed vs. the unstressed condition, from [a] (above) produced by (a) the NH and (b) the HI and from [u] (below) produced by (c) the NH and (d) the HI. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk (p<.05).



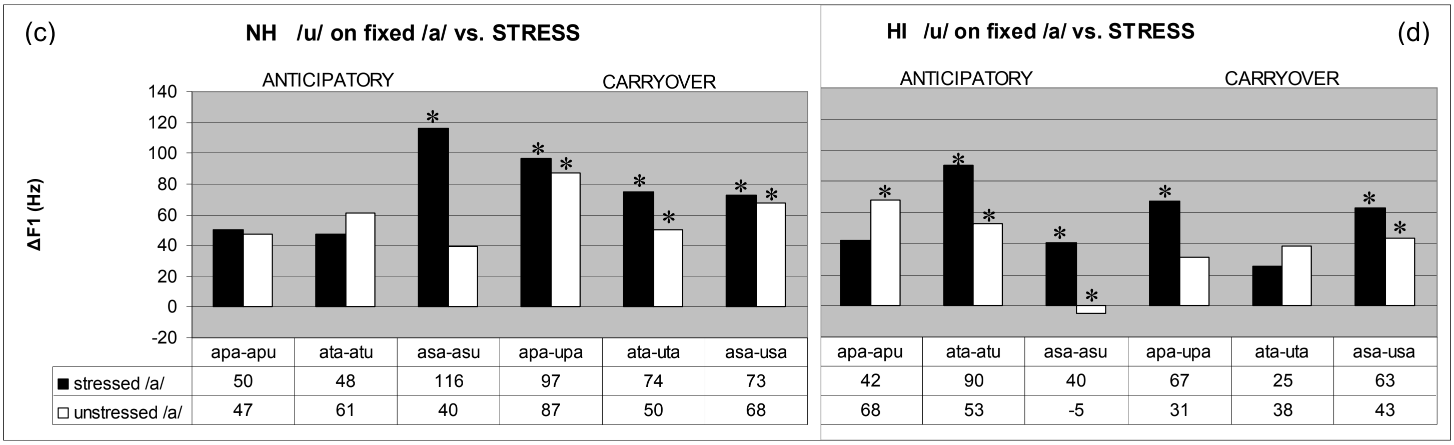
	ipu-ipi	itu-iti	isu-isi	upi-ipi	uti-iti	usi-isi	ipu-ipi	itu-iti	isu-isi	upi-ipi	uti-iti	usi-isi
■ stressed /i/	6	-8	-8	24	7	-2	-6	-11	-9	7	2	-1
□ unstressed /i/	11	17	1	26	-8	-8	13	-1	-5	5	4	0



	apa-api	ata-ati	asa-asi	apa-ipa	ata-ita	asa-isa
■ stressed /a/	16	25	73	64	49	57
□ unstressed /a/	-9	42	12	41	47	43

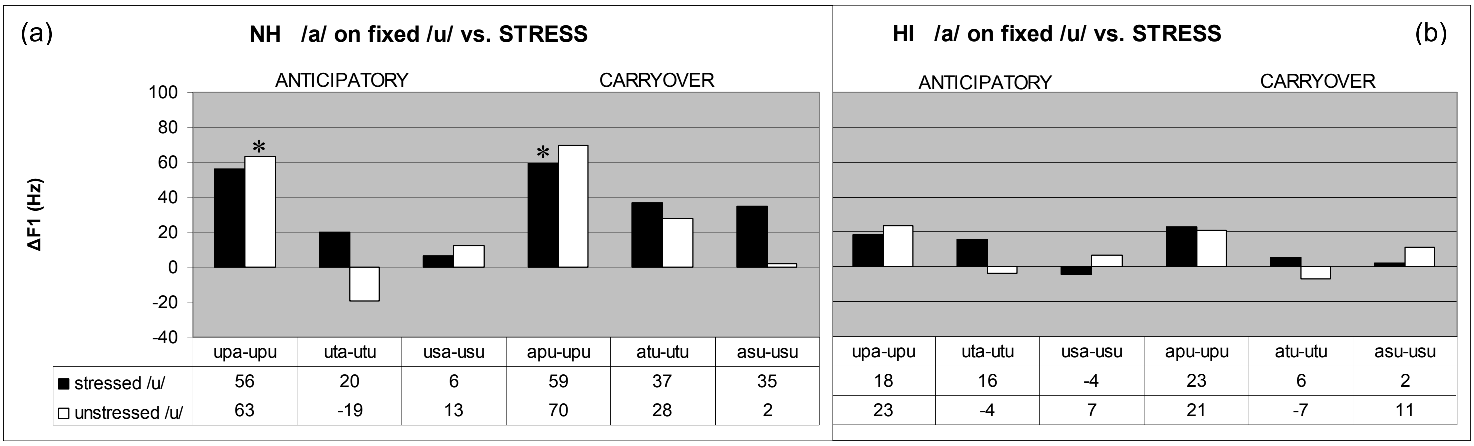
	apa-api	ata-ati	asa-asi	apa-ipa	ata-ita	asa-isa
■ stressed /a/	9	55	33	36	19	36
□ unstressed /a/	22	37	14	30	25	42

Fig. 5.20. F1 coarticulatory effects (ΔF1) in Hz on fixed vowel [a] in the stressed vs. the unstressed condition, from [i] (above) produced by (a) the NH and (b) the HI and from [u] (below) produced by (c) the NH and (d) the HI. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk (p<.05).



	apa-apu	ata-atu	asa-asu	apa-upa	ata-uta	asa-usa
■ stressed /a/	50	48	116	97	74	73
□ unstressed /a/	47	61	40	87	50	68

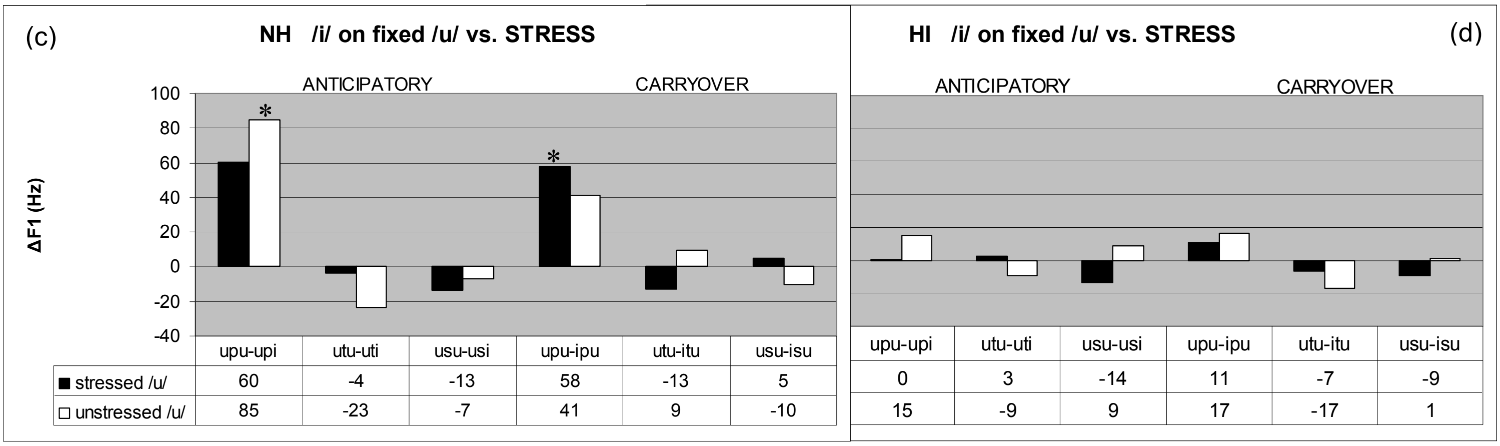
	apa-apu	ata-atu	asa-asu	apa-upa	ata-uta	asa-usa
■ stressed /a/	42	90	40	67	25	63
□ unstressed /a/	68	53	-5	31	38	43



	upa-upu	uta-utu	usa-usu	apu-upu	atu-utu	asu-usu
■ stressed /u/	56	20	6	59	37	35
□ unstressed /u/	63	-19	13	70	28	2

	upa-upu	uta-utu	usa-usu	apu-upu	atu-utu	asu-usu
■ stressed /u/	18	16	-4	23	6	2
□ unstressed /u/	23	-4	7	21	-7	11

Fig. 5.21. F1 coarticulatory effects (ΔF1) in Hz on fixed vowel [u] in the stressed vs. the unstressed condition, from [a] (above) produced by (a) the NH and (b) the HI and from [i] (below) produced by (c) the NH and (d) the HI. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk (p<.05).



	upu-upi	utu-uti	usu-usi	upu-ipu	utu-itu	usu-isu
■ stressed /u/	60	-4	-13	58	-13	5
□ unstressed /u/	85	-23	-7	41	9	-10

	upu-upi	utu-uti	usu-usi	upu-ipu	utu-itu	usu-isu
■ stressed /u/	0	3	-14	11	-7	-9
□ unstressed /u/	15	-9	9	17	-17	1

F1 Coarticulation	ANTICIPATORY (1st syllable)		CARRYOVER (2nd syllable)	
	NH	HI	NH	HI
[a] on fixed [i]			[p] stressed	
[u] on fixed [i]				
[i] on fixed [a]			[p] stressed	
		[t] stressed		
			[s] stressed	[s] unstressed
[u] on fixed [a]		[p] unstressed	[p] stressed	[p] stressed
		[t] stressed	[t] stressed	
	[s] stressed	[s] stressed	[s] stressed	[s] stressed
[a] on fixed [u]	[p] unstressed		[p] stressed	
[i] on fixed [u]	[p] unstressed		[p] stressed	

Table 5.13. Vocalic and consonantal contexts where statistically significant F1 coarticulatory effects were located for the fixed vowel in the stressed vs. the unstressed condition or both (p<.05). Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Contexts where significant effects were found in *both* the stressed and the unstressed condition have been highlighted and the condition with the higher degree of effects is stated.

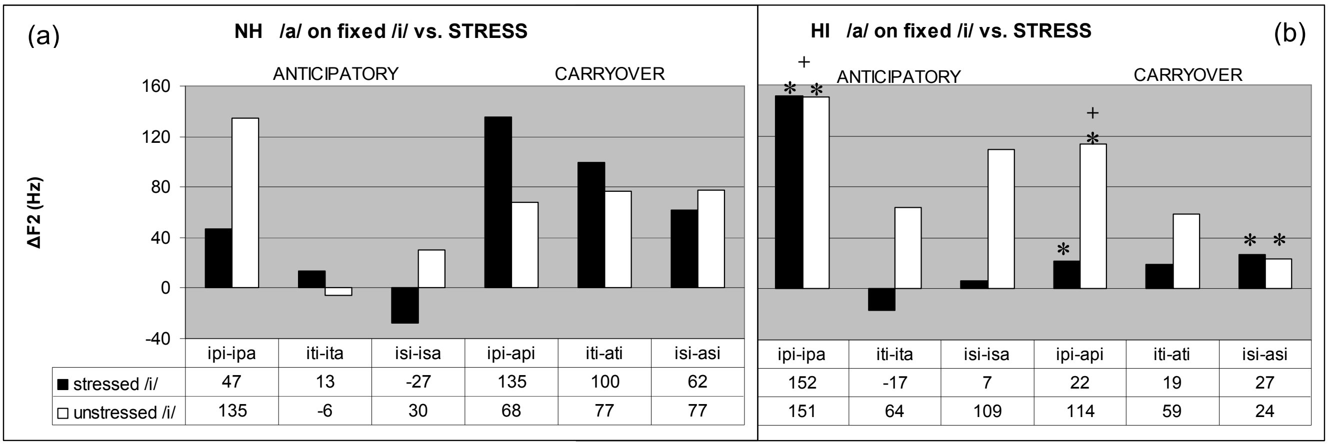
It is noteworthy that, for both groups, the majority of stress related effects occur on fixed [a] (see Fig. 5.20.), an observation also made earlier when examining the shift of vowel space vs. stress (section 4.2). We had observed that both NH and HI high vowels do not undergo any significant F1 shift, whereas [a] does. Hence, it became apparent that a shift along the F1 axis was more prominent for [a] than for the high vowels. As we see in Fig. 5.20. and Table 5.13., for both groups, the stressed [a] generally receives more effects than its unstressed counterpart in almost all consonantal contexts. Because of the aforementioned significant F1 shift due to the absence of stress, the unstressed [a] is already too central to be submitted to further significant F1 lowering from [i] or [u].

Concerning the fixed [i] context, effects are generally blocked, especially for the HI (see Fig. 5.19.b and d), thus significant stress effects are only present for the NH in one case, i.e. the stressed second-syllable [i] in [aˈpi]-[iˈpi] sequences receives significantly more effects than the unstressed [i] in [ˈapi]-[ˈipi] from [a] which is again more centralized (see Fig. 5.19.a).

F1 coarticulation is also very small for the HI in the fixed [u] context, thus significant stress effects are not detected (see Fig. 5.21.b and d). For the NH, effects are allowed mainly over [p] and as we observe in Table 5.13., the first-syllable [u] is more influenced by both [a] and [i] when unstressed, whereas the second-syllable [u] receives more effects when stressed. The larger influence on first-syllable unstressed [u] can be explained since the other two vowels are more peripheral when stressed and in the second syllable, thus exerting more influence (section 4.2., Table 4.5). In the second syllable position, more effects show on stressed [u] in [aˈpu] than the unstressed [u] in [ˈapu], as the unstressed word-final [u] is already too central to receive significant influence from the other vowels.

5.2.2. F2

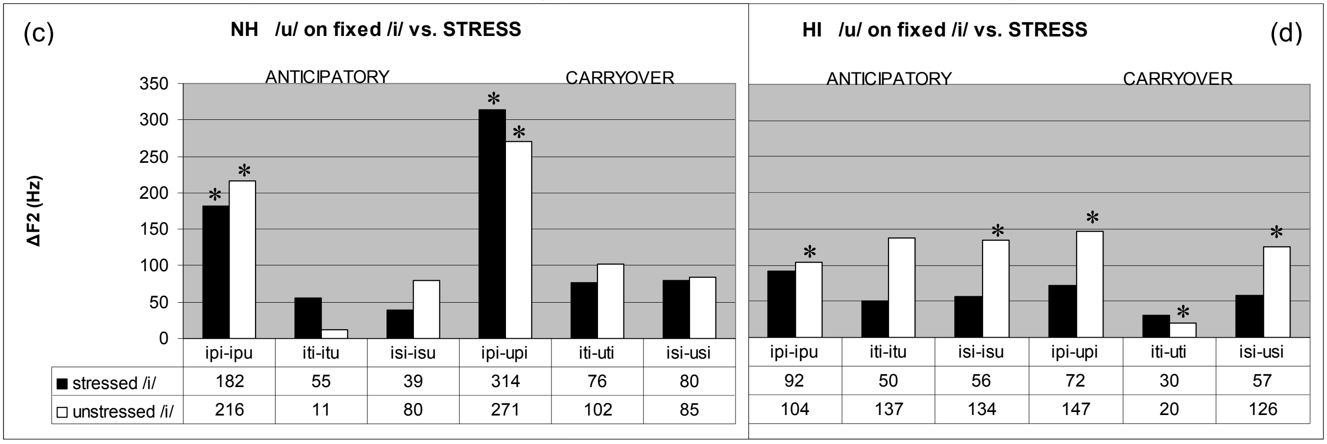
Univariate ANOVAs for F2 and ΔF2 variables showed that stress is a statistically significant factor for F2mid and F2end (mid: F(1, 15045)=50.672, p<.0001, end: F(1, 15038)=87.891, p<.0001), but not for ΔF at any measurement point. Post hoc tests in the interaction hearing* measured V* transconsonantal V* C* stress revealed which stressed and unstressed contexts show significant coarticulatory effects. As above, statistically significant effects (ΔF2) on contexts in the stressed vs. the unstressed condition at vowel offset (anticipatory) and onset (carryover) have been marked with an asterisk [*] above the corresponding bars in Figures 5.22.-5.25 below. A summary of the statistically significant results is given in Table 5.14. For a more comprehensive report, see Appendices: Results, Appendix 2.3.: V-to-V Coarticulation Tables, Stress & Context –F2.



	ipi-ipa	iti-ita	isi-isa	ipi-api	iti-ati	isi-asi
■ stressed /i/	47	13	-27	135	100	62
□ unstressed /i/	135	-6	30	68	77	77

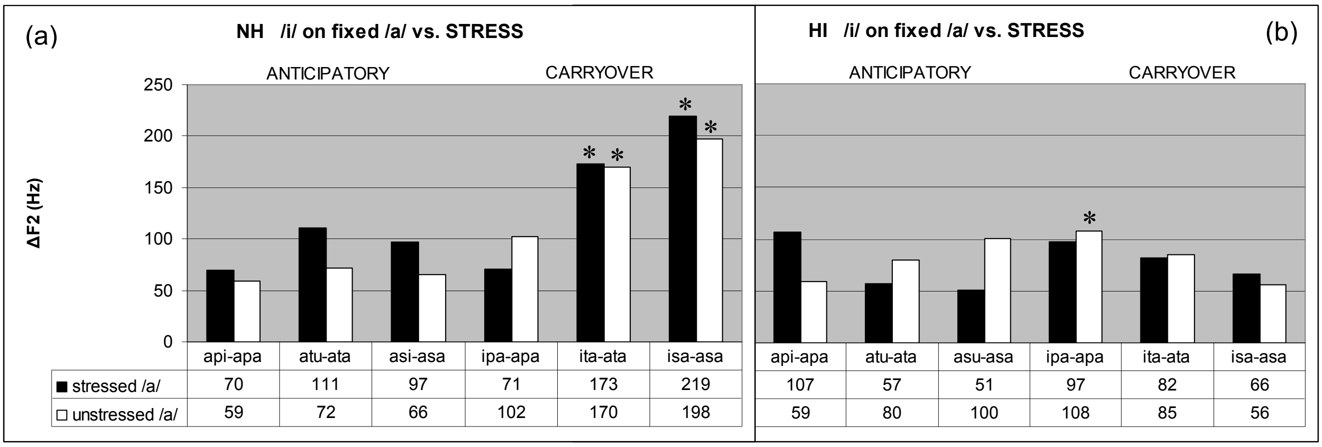
	ipi-ipa	iti-ita	isi-isa	ipi-api	iti-ati	isi-asi
■ stressed /i/	152	-17	7	22	19	27
□ unstressed /i/	151	64	109	114	59	24

Fig. 5.22. F2 coarticulatory effects (ΔF2) in Hz on fixed vowel [i] in the stressed vs. the unstressed condition, from [a] (above) produced by (a) the NH and (b) the HI and from [u] (below) produced by (c) the NH and (d) the HI. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk. The symbol [$^+$] indicates stat. sig. difference between the two conditions (p<.05).



	ipi-ipu	iti-itu	isi-isu	ipi-upi	iti-uti	isi-usi
■ stressed /i/	182	55	39	314	76	80
□ unstressed /i/	216	11	80	271	102	85

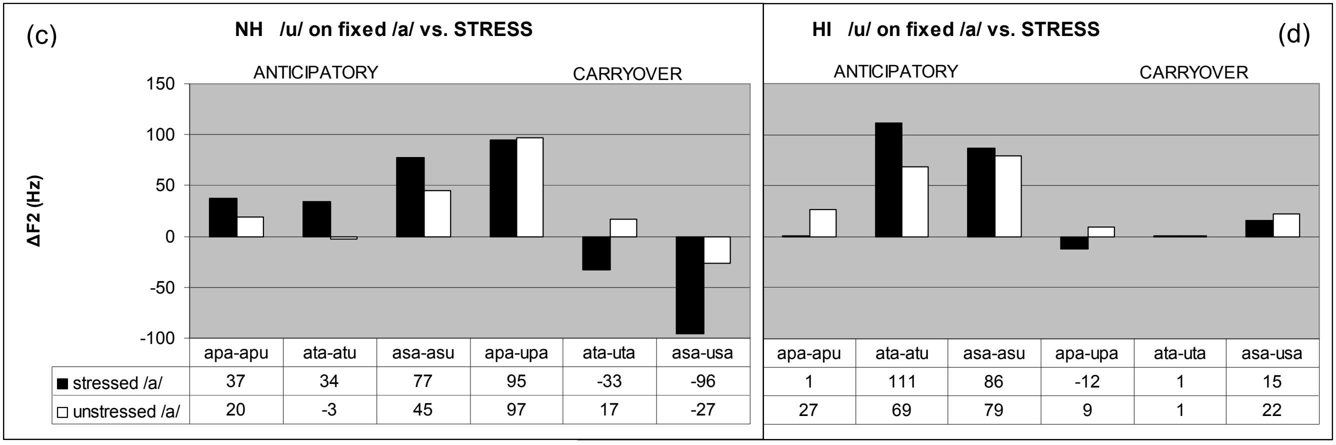
	ipi-ipu	iti-itu	isi-isu	ipi-upi	iti-uti	isi-usi
■ stressed /i/	92	50	56	72	30	57
□ unstressed /i/	104	137	134	147	20	126



	api-apa	atu-ata	asi-asa	ipa-apa	ita-ata	isa-asa
■ stressed /a/	70	111	97	71	173	219
□ unstressed /a/	59	72	66	102	170	198

	api-apa	atu-ata	asu-asa	ipa-apa	ita-ata	isa-asa
■ stressed /a/	107	57	51	97	82	66
□ unstressed /a/	59	80	100	108	85	56

Fig. 5.23. F2 coarticulatory effects (ΔF2) in Hz on fixed vowel [a] in the stressed vs. the unstressed condition, from [i] (above) produced by (a) the NH and (b) the HI and from [u] (below) produced by (c) the NH and (d) the HI. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk (p<.05).



	apa-apu	ata-atu	asa-asu	apa-upa	ata-uta	asa-usa
■ stressed /a/	37	34	77	95	-33	-96
□ unstressed /a/	20	-3	45	97	17	-27

	apa-apu	ata-atu	asa-asu	apa-upa	ata-uta	asa-usa
■ stressed /a/	1	111	86	-12	1	15
□ unstressed /a/	27	69	79	9	1	22

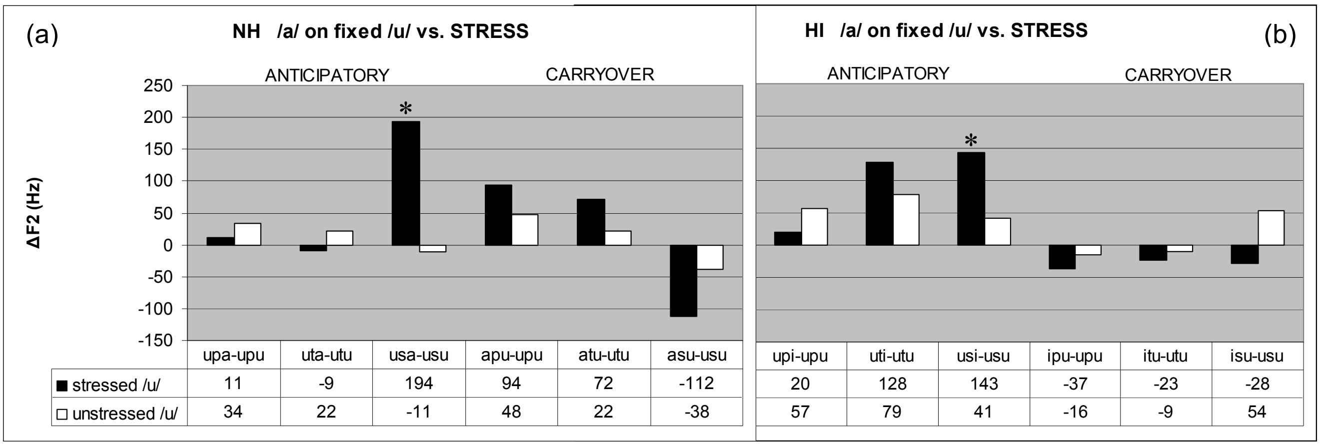
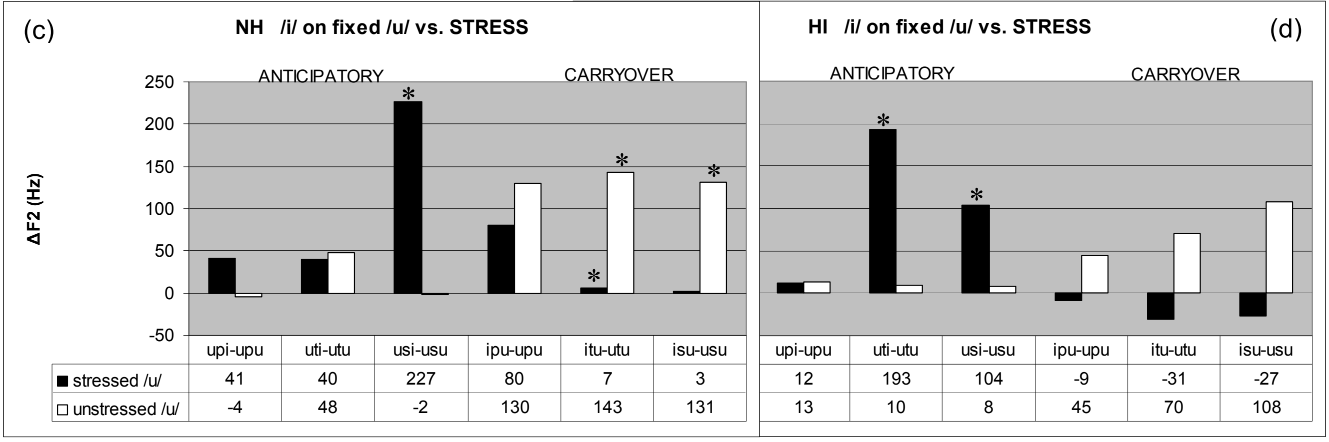


Fig. 5.24. F2 coarticulatory effects (ΔF2) in Hz on fixed vowel [u] in the stressed vs. the unstressed condition, from [a] (above) produced by (a) the NH and (b) the HI and from [i] (below) produced by (c) the NH and (d) the HI. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk ($p<.05$).



F2 Coarticulation	ANTICIPATORY (1st syllable)		CARRYOVER (2nd syllable)	
	NH	HI	NH	HI
[a] on fixed [i]		[p] stressed		[p] unstressed
				[s] stressed
[u] on fixed [i]	[p] unstressed	[p] unstressed	[p] stressed	[p] unstressed
				[t] unstressed
		[s] unstressed		[s] unstressed
[i] on fixed [a]				[p] unstressed
			[t] stressed	
			[s] stressed	
[u] on fixed [a]				
[a] on fixed [u]	[s] stressed	[s] stressed		
[i] on fixed [u]				
		[t] stressed	[t] unstressed	
	[s] stressed	[s] stressed	[s] unstressed	

Table 5.14. Vocalic and consonantal contexts where statistically significant F2 coarticulatory effects were located for the fixed vowel in the stressed vs. the unstressed condition or both ($p<.05$). Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Contexts where significant effects were found in *both* the stressed and the unstressed condition have been highlighted and the condition with the higher degree of effects is stated.

Regarding the fixed [i] context, the HI generally present more coarticulatory effects than the NH and we note that these effects are mostly on the unstressed [i] in the [p] and [s] context (see Fig. 5.22.b and d and Table 5.14.). As a highly constrained vowel, it is not surprising that the unstressed [i] will receive more effects than its stressed counterpart. The NH present significant effects only in the bilabial context and these effects seem to occur in both stress conditions (see Fig. 5.22.c).

In the fixed [a] context, significant effects for both groups are evident only on second-syllable [a] (see Fig. 5.23.a and b). For the NH these effects appear in both stress conditions, although the stressed [a] displays slightly more coarticulation than its unstressed counterpart. As mentioned in Chapter IV (section 4.2., Fig. 4.13.a), the second-syllable stressed [a] is more peripheral and its position possibly allows more space for movement. It is noteworthy that [i]-to-[a] effects appear in an alveolar rather than in a bilabial context which may be related to the articulatory proximity of [i] with an alveolar rather than a bilabial consonant; the tongue remains in a more front position in an [ita] or [isa] than in an [ipa] production, hence causing a more substantial raising to the F2 of [a].

We make a similar observation regarding [i]-to-[u] effects which also occur in the alveolar rather than the bilabial consonantal context for both groups which can be explained along the same lines (see Fig. 5.24.). Concerning the stress factor, although the HI do not display significant carryover effects, the two groups present a similar pattern regarding anticipatory effects (see Fig. 5.24.a vs. b and c vs. d). We note that coarticulatory effects are evident on the stressed [u] when it is located in the first syllable and on the unstressed [u] when it is located in the second syllable. The latter is expected as an unstressed second-syllable [u] is quite weak and susceptible to influence. The former, that is, significant effects on a stressed first-syllable vowel, may not be expected, but strong anticipatory influence during V_1 from a second-syllable [i] which is associated with preprogramming issues has been documented in the literature (Recasens, 1984b:1634).

➢ Summary

F1 coarticulation of both hearing groups is influenced by stress in the fixed [a] context, whereas effects in fixed [i] and [u] contexts show stress influence for the NH group only, as HI [i] and [u] coarticulation is essentially blocked. For both groups, the stressed [a] is more coarticulated than its unstressed counterpart in the majority of consonantal contexts and in both syllable positions, as, in the unstressed condition, it assumes a central position which does not permit a lot of movement. Regarding NH high vowels [i] and [u], they both display more effects when stressed in the second syllable position, where, as argued above, they assume a more peripheral position and are allowed more movement. Significant effects were also located on the unstressed first-syllable [u] which may be related to a strong anticipatory influence exerted by a transconsonantal second-syllable stressed [i] or [a].

Concerning F2 coarticulation on fixed [i], the HI display significant effects on the unstressed counterpart and in more consonantal contexts than the NH, who show effects mostly over the bilabial and in both stress conditions. Regarding fixed [a], the NH and HI display different patterns of [i]-to-[a] coarticulation; the NH show effects on stressed second-syllable [a] over the two alveolars, and the HI on unstressed second-syllable [a] over the bilabial. The unexpected NH pattern may be associated with fronter tongue placement during the preceding [i] + [t]/[s] which extends into the second-syllable [a]. A similar pattern is also observed in NH [i]-to-[u] coarticulation, where effects are significant again over the two alveolars on the unstressed second-syllable [u], while the HI do not show effects over any consonant on the second-syllable [u], but they do show effects on the first-syllable stressed [u] over both alveolars. It is expected that the unstressed second-syllable [u] is weak enough to receive substantial influence, while the stressed first-syllable [u] shows effects probably due to the strong anticipatory influence of [i] or [a] + [t] and especially [s] (see Table 5.14.).

5.3. V-to-V Coarticulation and Gender

5.3.1. F1

Gender was found statistically significant at all F1 measurement points (start: F(1, 15035)=7216.933, p<.0001, mid: F(1, 15036)=12347.468, p<.0001, end: F(1, 15035)= 3953.509, p<.0001) and all ΔF1 measurement points (start: F(1, 9969)=8.365, p<.01, mid: F(1, 9971)=43.110, p<.0001, end: F(1, 9969)=63.270, p<.0001). Tukey pairwise comparisons within the interaction hearing* measured vowel* transconsonantal vowel* consonant* position* gender were conducted so as to detect where significant coarticulatory effects appeared for each gender.

Figures 5.25.-5.27. display F1 coarticulatory effects on the three fixed vowels at V1offset (anticipatory effects) and V2onset (carryover effects) for male and female NH and HI groups. Statistically significant effects are indicated with an asterisk [*] above the corresponding bar. In contexts where both genders present statistically significant effects, the degree of coarticulation (bar size) is taken into account and stated in Table 5.15. Hence, Table 5.15. summarizes statistically significant effects on the three fixed vowels for each gender for the NH and the HI groups. For a more comprehensive report, see Appendices: Results, Appendix 2.3.: V-to-V Coarticulation Tables, Gender & Context –F1.

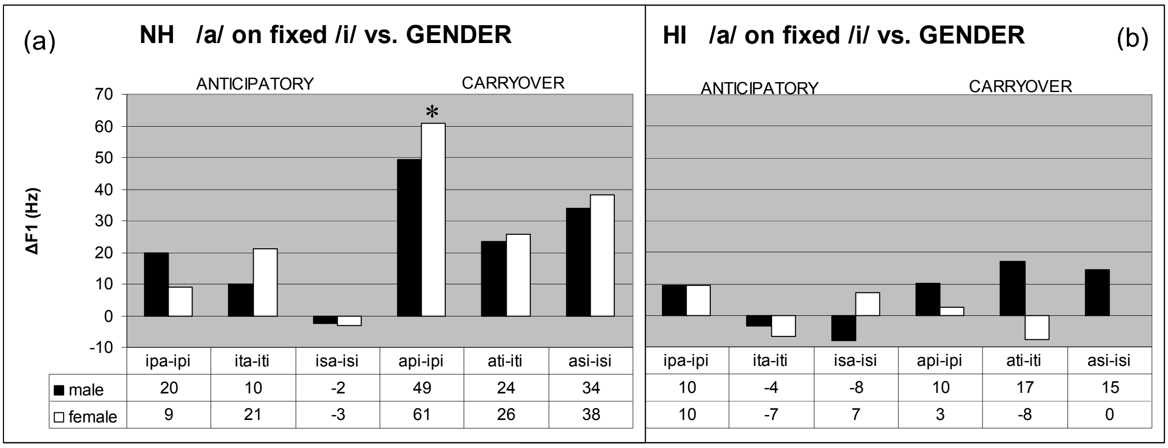
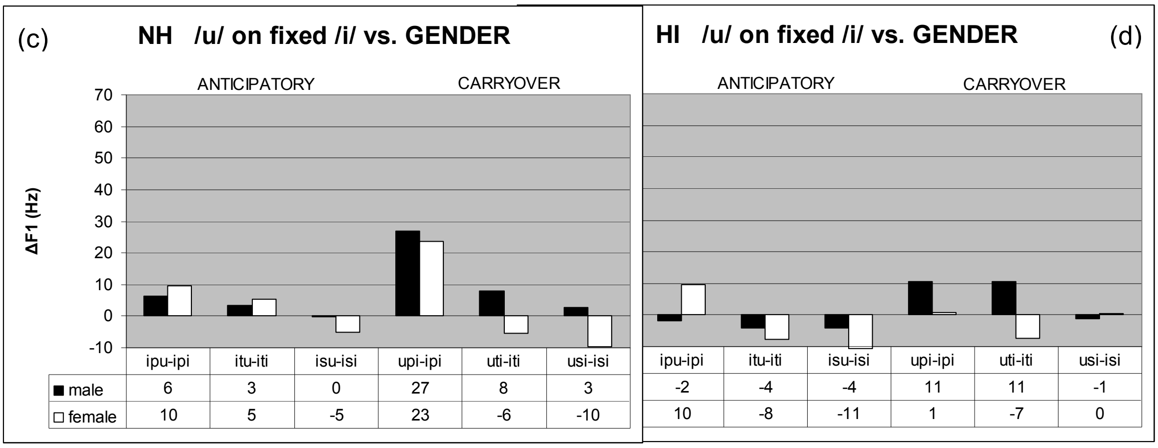


Fig. 5.25. F1 coarticulatory effects (ΔF1) in Hz on fixed vowel [i] from [a] (above) and from [u] (below), produced by NH (a and c) and HI (b and d) male vs. female subjects. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk (p<.05).



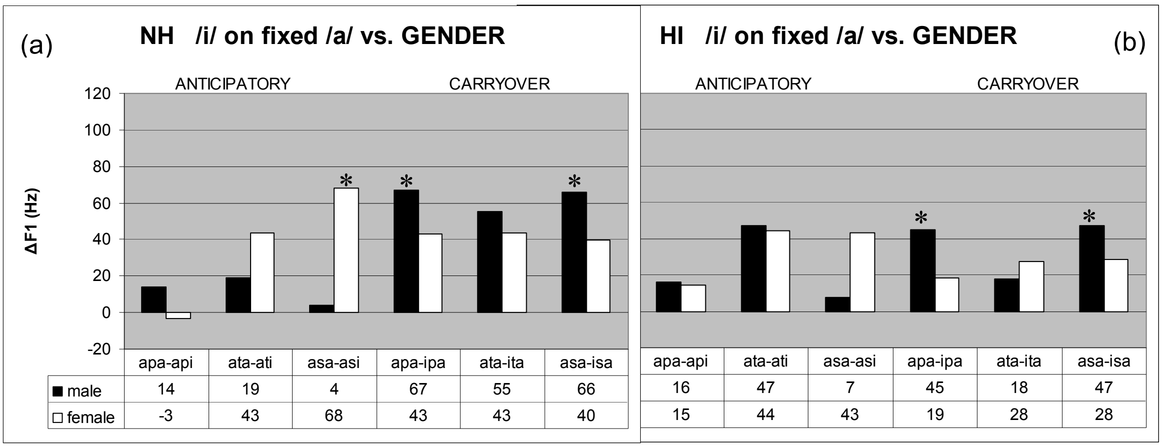
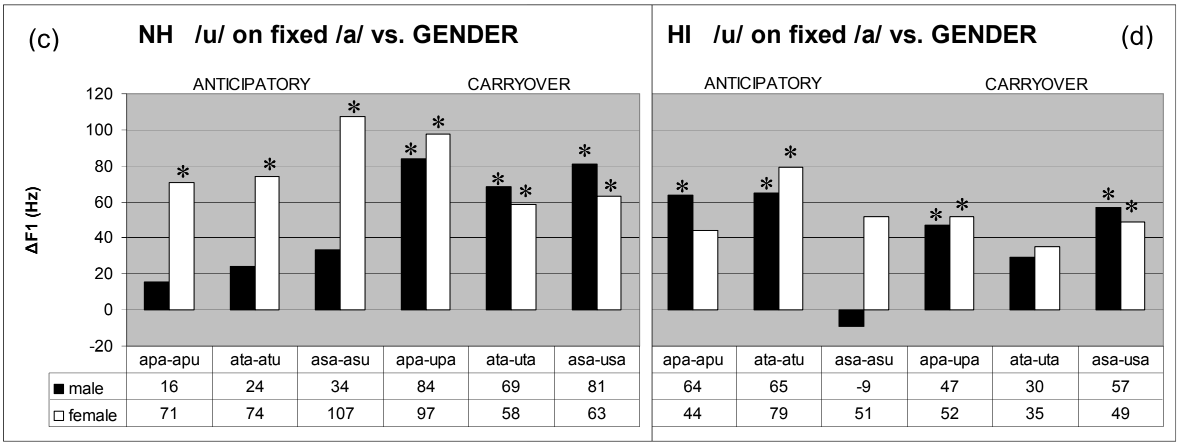


Fig. 5.26. F1 coarticulatory effects (ΔF1) in Hz on fixed vowel [a] from [i] (above) and from [u] (below), produced by NH (a and c) and HI (b and d) male vs. female subjects. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk (p<.05).



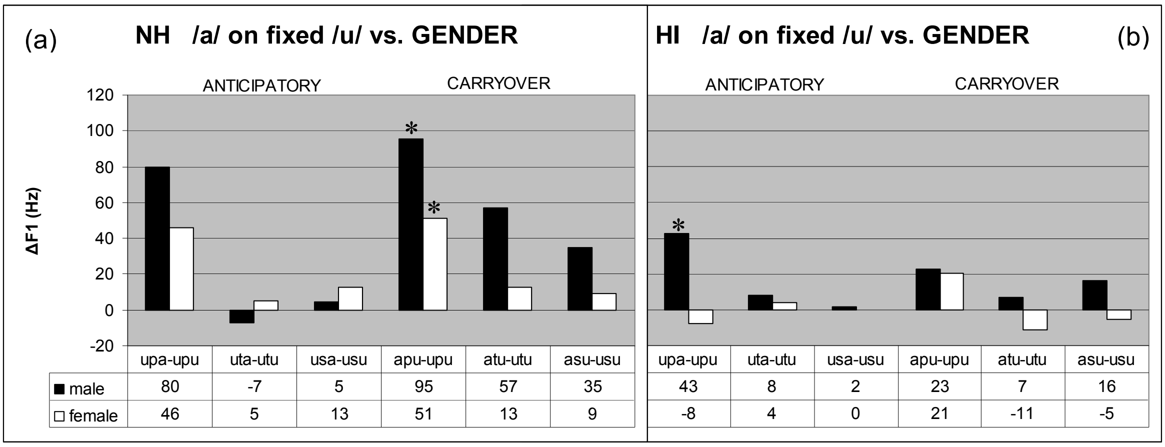
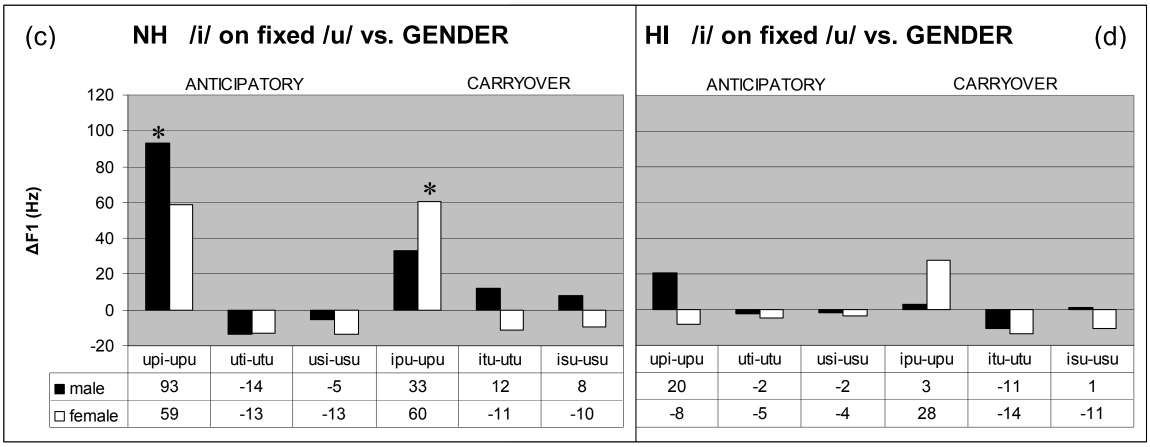


Fig. 5.27. F1 coarticulatory effects (ΔF1) in Hz on fixed vowel [u] from [a] (above) and from [i] (below), produced by NH (a and c) and HI (b and d) male vs. female subjects. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk ($p<.05$).



F1 Coarticulation	ANTICIPATORY		CARRYOVER	
	NH	HI	NH	HI
[a] on fixed [i]			[p] female	
[u] on fixed [i]				
[i] on fixed [a]			[p] male	[p] male
	[s] female		[s] male	[s] male
[u] on fixed [a]	[p] female	[p] male	[p] female	[p] female
	[t] female	[t] female	[t] male	
	[s] female		[s] male	[s] male
[a] on fixed [u]		[p] male	[p] male	
[i] on fixed [u]	[p] male		[p] female	

Table 5.15. Vocalic and consonantal contexts where statistically significant F1 coarticulatory effects were located for each gender or both ($p<.05$). Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Contexts where significant effects were found for *both* genders have been highlighted and the condition with the higher degree of effects is stated.

As reported earlier (section 5.1.3.1.), both groups demonstrate F1 coarticulatory effects mostly in the fixed [a] context, and especially when [u] is the transconsonantal vowel. The NH female group seems to coarticulate more in the anticipatory direction, whereas the male in the carryover direction (see Table 5.15.). Concerning [aCa]-[uCa] pairs, both genders seem to coarticulate significantly, although slightly greater effects for the male were found post-alveolarly (see Fig. 5.26.c). The HI generally display less effects and their coarticulatory patterns are more variable as far as gender is concerned.

Concerning the other two fixed contexts, the fixed [i] receives significant effects only for the female NH group in [ipi-api] pairs (see Fig. 5.25.a). As regards the fixed [u] context, effects are significant mostly for the NH male group over the bilabial, while for the HI male only in [upu-upa] pairs.

Overall, regarding F1 coarticulation on [a] which appears to be the most robust among the three fixed vowel contexts, the majority of effects, especially in the anticipatory direction, lie in the female NH group (see Table 5.15.). This result may be associated with the enlarged female vowel space which allows for larger movement. As reported earlier (section 4.1.2., Table 4.3. and Fig. 4.6.), the NH female vowel space is larger than the NH male by 133292 Hz^2, giving the female vowels a bigger area in which to move. This enhanced possibility for female vowel movement is expected to manifest itself along the F1 primarily in the low vowel [a], since this vowel is mainly accountable for the female vowel space enlargement along this axis. The distance between the high vowels [i] or [u] and [a] is longer for the female than the male group; [a-i] distance is longer for the female than the male group by a mean of 119 Hz and [a-u] by a mean of 119 Hz (based on values in Table 4.3).

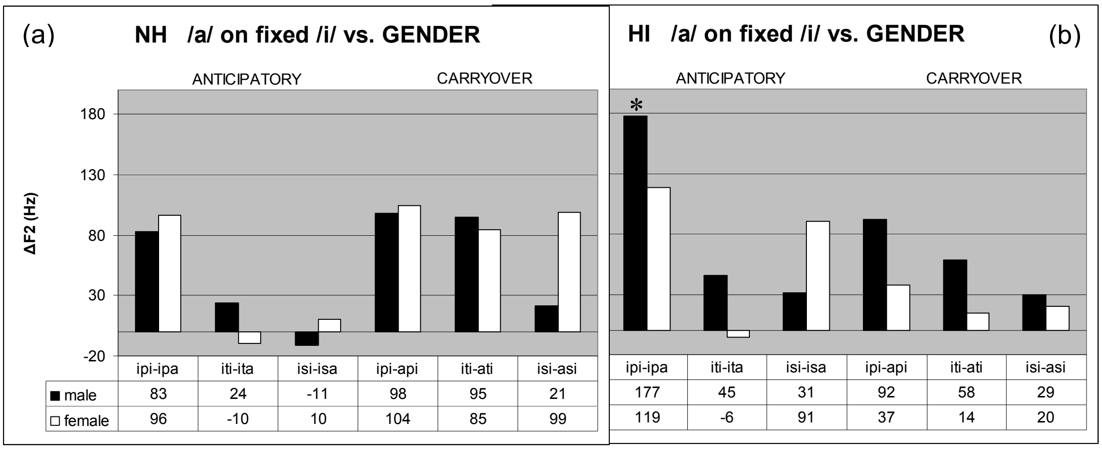
However, a similar observation can be made for the HI, that is, the distance between the two high vowels and [a] is greater for the female than the male HI group, and actually more so than between the NH gender groups; [a-i] distance is longer for the female than the male HI group by a mean of 172 Hz and [a-u] by a mean of 159 Hz. Nevertheless, there is no preference towards the female vs. the male gender as far as HI coarticulation is concerned. After normalization, the vowel ellipses demonstrate that the variability in F1 displayed by the two genders is much higher for the female vs. the male speakers in the NH group than in the HI group (see Fig. 4.8.a and b). This difference may partly account for the absence of strong gender preference in F1 coarticulation in HI speech.

Therefore, besides vowel space size, individual articulatory practices, not necessarily related to gender, may also influence coarticulation (see below, section 5.4.).

5.3.2. F2

Regarding F2 coarticulation, gender was found statistically significant for all F2 measurement points (start: F(1, 15039)=6966.822, p<.0001, mid: F(1, 15045)=9549.159, p<.0001, end: F(1, 15038)= 4546.601, p<.0001), while for ΔF2 it was significant at the midpoint (F(1, 9973)=43.110, p<.0001). As with F1 above, Tukey post hoc tests in the interaction hearing* measured vowel* transconsonantal vowel* consonant* position* gender were executed to find context coarticulatory effects for the NH and HI gender groups.

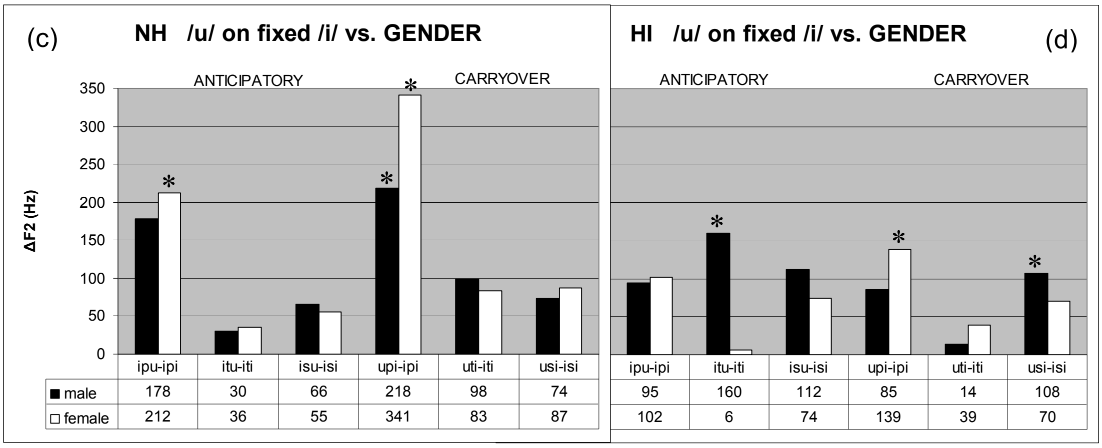
As with F1 above, figures 5.28.-5.30. display F2 coarticulatory effects on the three fixed vowels at V1offset (anticipatory effects) and V2onset (carryover effects) for male and female NH and HI groups. An asterisk [*] above a bar indicates that statistically significant effects were found for that gender. Table 5.16. presents a summary of the statistically significant effects only; if both genders display significant effects, the slot is highlighted and the gender with the higher degree of effects is reported. For a more comprehensive presentation, see Appendices: Results, Appendix 2.3.: V-to-V Coarticulation Tables, Gender & Context –F2.



NH	ipi-ipa	iti-ita	isi-isa	ipi-api	iti-ati	isi-asi
■ male	83	24	-11	98	95	21
□ female	96	-10	10	104	85	99

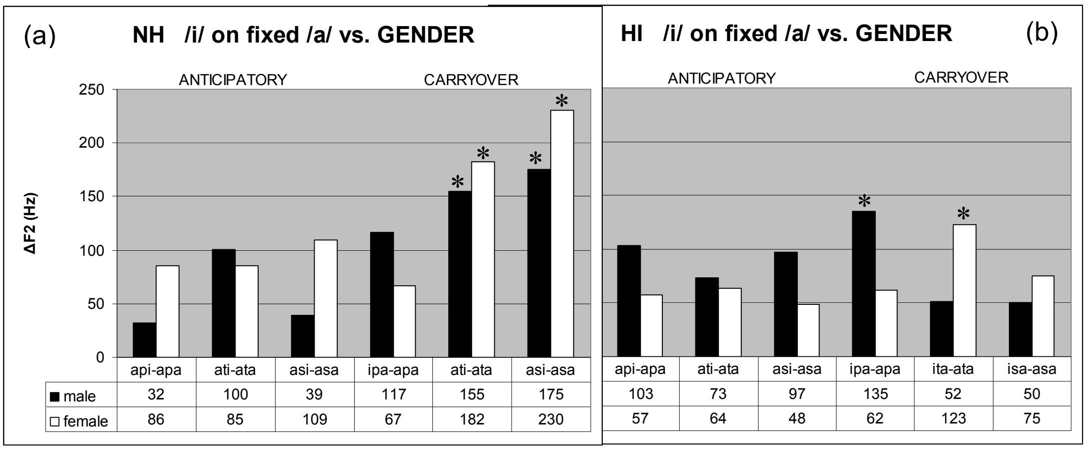
HI	ipi-ipa	iti-ita	isi-isa	ipi-api	iti-ati	isi-asi
■ male	177	45	31	92	58	29
□ female	119	-6	91	37	14	20

Fig. 5.28. F2 coarticulatory effects (ΔF2) in Hz on fixed vowel [i] from [a] (above) and from [u] (below), produced by NH (a and c) and HI (b and d) male vs. female subjects. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk (p<.05).



NH	ipu-ipi	itu-iti	isu-isi	upi-ipi	uti-iti	usi-isi
■ male	178	30	66	218	98	74
□ female	212	36	55	341	83	87

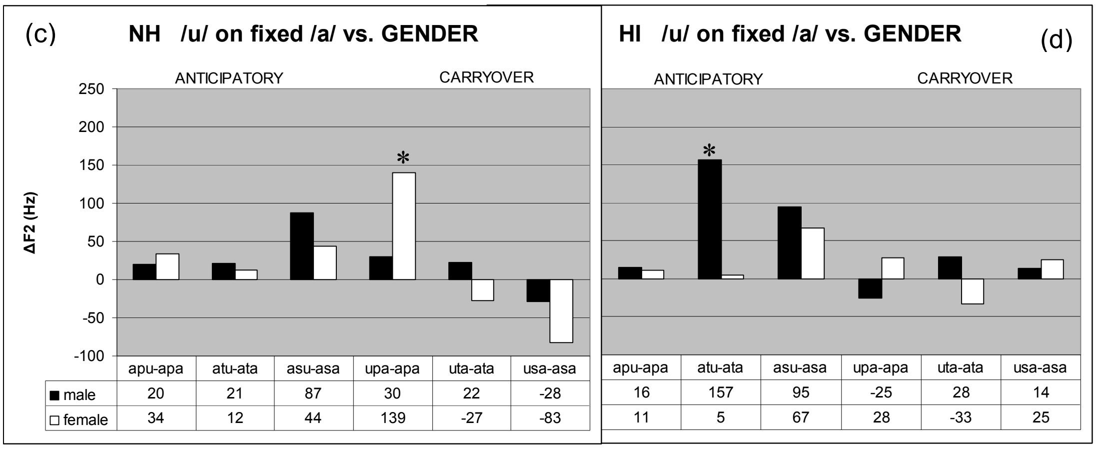
HI	ipu-ipi	itu-iti	isu-isi	upi-ipi	uti-iti	usi-isi
■ male	95	160	112	85	14	108
□ female	102	6	74	139	39	70



NH	api-apa	ati-ata	asi-asa	ipa-apa	ati-ata	asi-asa
■ male	32	100	39	117	155	175
□ female	86	85	109	67	182	230

HI	api-apa	ati-ata	asi-asa	ipa-apa	ita-ata	isa-asa
■ male	103	73	97	135	52	50
□ female	57	64	48	62	123	75

Fig. 5.29. F2 coarticulatory effects (ΔF2) in Hz on fixed vowel [a] from [i] (above) and from [u] (below), produced by NH (a and c) and HI (b and d) male vs. female subjects. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk (p<.05).



NH	apu-apa	atu-ata	asu-asa	upa-apa	uta-ata	usa-asa
■ male	20	21	87	30	22	-28
□ female	34	12	44	139	-27	-83

HI	apu-apa	atu-ata	asu-asa	upa-apa	uta-ata	usa-asa
■ male	16	157	95	-25	28	14
□ female	11	5	67	28	-33	25

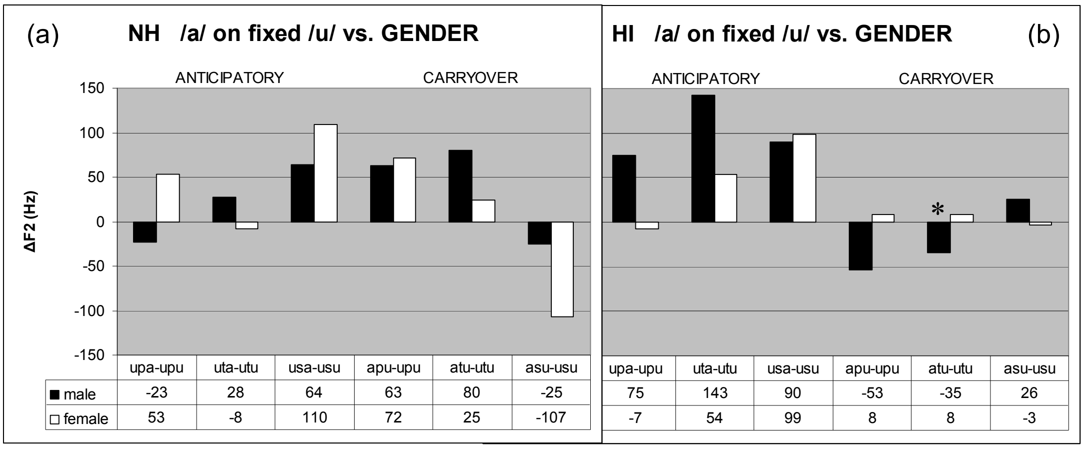
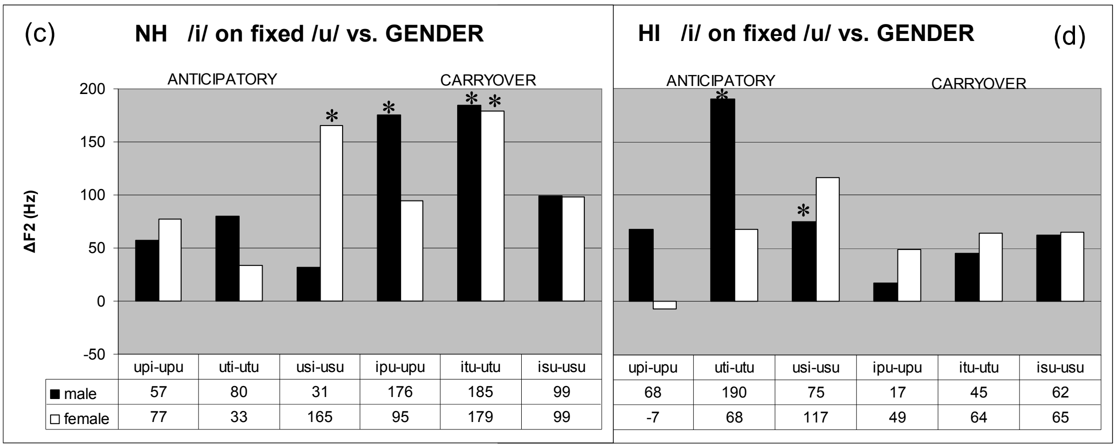


Fig. 5.30. F2 coarticulatory effects (ΔF2) in Hz on fixed vowel [u] from [a] (above) and from [i] (below), produced by NH (a and c) and HI (b and d) male vs. female subjects. Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Significant effects are denoted with an asterisk (p<.05).



F2 Coarticulation	ANTICIPATORY		CARRYOVER	
	NH	HI	NH	HI
[a] on fixed [i]		[p] male		
[u] on fixed [i]	[p] female		[p] female	[p] female
		[t] male		
				[s] male
[i] on fixed [a]				[p] male
			[t] female	[t] female
			[s] female	
[u] on fixed [a]		[t] male	[p] female	
[a] on fixed [u]				[t] male
[i] on fixed [u]			[p] male	
		[t] male	[t] male	
	[s] female	[s] male		

Table 5.16. Vocalic and consonantal contexts where statistically significant F2 coarticulatory effects were located for each gender or both (p<.05). Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Contexts where significant effects were found for *both* genders have been highlighted and the condition with the higher degree of effects is stated.

For both groups, the contexts accumulating the majority of statistically significant F2 effects are [i]-to-[u] and [u]-to-[i], as well as [i]-to-[a] in the carryover direction (see Table 5.16.). Concerning the NH, the female group tends to present more coarticulation than the male group. In the anticipatory direction, the effects of the male group do not reach significance in any context, while significant [i]-to-[u] and [u]-to-[i] effects do occur for the female group (see Fig. 5.28.c and Fig. 5.30.c). In the carryover direction, significant effects are evident in both gender groups, although the female group demonstrates slightly larger effects in most contexts except for the fixed [u] context, where the male group shows more effects.

Regarding the HI, we do not observe the aforementioned NH female trend. In contrast, in the anticipatory direction, all contexts with significant effects were produced by the male group (see Table 5.16.), while in the carryover direction, effects are present in both gender groups. The different coarticulation vs. gender trends between the two hearing groups may be related to their within-group male/female F2 range difference.

As with F1 above, the F2 distance between the front vowel [i] and the back [u] or mid [a], is much longer for the female than the male NH group. The [u-i] distance for the female NH group is 254 Hz longer than that of the male and the [i-a] distance 100 Hz longer (based on values in Table 4.3). This offers the female more room for movement along the F2 axis. On the other hand, the corresponding distance between front and back vowels of the HI group is considerably shorter, due to [u] fronting and [i] backing (section 4.1.1., Fig. 4.3). Hence, the gender difference is also shorter compared with that between the NH male and female groups; the [i-u] distance is 197 Hz longer and the [i-a] distance just 5 Hz longer for the HI female than that of the HI male group. Therefore, the female HI vowels do not have the advantage of much additional room for movement along the F2 axis in comparison with the female NH vowels vs. the male NH vowels. Nevertheless, the male HI group displays significant F2 coarticulatory effects in the anticipatory direction, in spite of their compressed vowel space. After normalization, based on the vowel ellipses (see Fig. 4.8.a and b), we observe that the male speakers of the HI group show higher variability than the female speakers which could be related to the preference of HI articulation towards the male gender.

V-to-V coarticulation is also associated with other parameters besides vowel location in the vowel chart (section 6.4.4).

➢ Summary

Regarding the NH, most F1 and F2 coarticulatory effects occur for the female group, especially in the anticipatory direction. In the carryover direction, both gender groups display significant F1 and F2 coarticulatory effects, although the female group again presents slightly more effects. For the HI, on the other hand, we do not discern a pattern for increased anticipatory or carryover effects in either F1 or F2 coarticulation for the female group (see Tables 5.15. and 5.16.). Significant F1 bidirectional effects as well as F2 carryover effects seem evenly distributed between the two genders, whereas significant F2 anticipatory effects are only evident in the male HI group, in contrast with the NH whose corresponding effects appear in the female group.

The NH pattern for increased anticipatory coarticulation in the female group may be related to the wider F1 and F2 distance among female vowels in comparison with that of male vowels. This difference between the two genders in F1 and F2 vowel distance is not as pronounced for the HI, whose vowel space is relatively compressed. Moreover, after normalization, the male speakers of the HI group display higher vowel variability when compared with the female speakers of the same group, whereas the opposite occurs with speakers in the NH group. Thus, increased articulatory variability of male speakers with HI may partly account for their greater V-to-V coarticulation. In addition to vowel space differences and group articulatory variability, gender group coarticulatory patterns may differ due to individual articulatory strategies not necessarily associated with gender (section 6.4.4.).

5.4. V-to-V Coarticulation and Intelligibility

The nine HI subjects were divided into three groups (intel 1: very high, intel 2: high and intel 3: medium) according to their speech intelligibility as rated by 54 naïve listeners. The composition of the groups is two female subjects of very high intelligibility, two female and three male subjects of high intelligibility and two male subjects of medium intelligibility (section 3.4).

Separate GLM ANOVAs were run for F1start, F1mid, F1end and F2start, F2mid, F2end variables vs. intelligibility, gender, measured vowel, transconsonantal vowel, stress and position (for a report on the influence of intelligibility on vowel midpoint, see section 4.1.3). Intelligibility was a significant factor for all variables (F1start: F(3, 15035)=323.740, p<.0001, F1mid: F(3, 15036)=512.168, p<.0001, F1end: F(3, 15035)= 699.003, p<.000, F2start: F(3, 15039)=353.269, p<.0001, F2mid: F(3, 15045)=145.940, F2end: F(3, 15038)=60.764, p<.000). Next, we ran separate GLM ANOVAs for ΔF1start, ΔF1mid, ΔF1end and ΔF2start, ΔF2mid, ΔF2end variables vs. intelligibility, gender, V-to-V, consonant, stress and direction. Intelligibility was a significant factor for all variables (ΔF1start: F(3, 9969)=16.989, p<.0001, ΔF1mid: F(3, 9971)=9.986, p<.0001, ΔF1end: F(3, 9969)= 17.773, p<.0001, ΔF2start: F(3, 9974)=3.782, p<.05, ΔF2mid: F(3, 9973)=8.446, p<.0001, ΔF2end: F(3, 9973)=10.144, p<.0001).

In order to locate the contexts in which each intelligibility group demonstrated statistically significant coarticulatory effects, we executed Tukey post hoc tests using the interaction intelligibility* measured vowel* transconsonantal vowel* consonant* position. Wherever effects were present we performed additional post hoc tests using the interaction intelligibility* V-to-V* consonant* direction, so as to detect statistical differences in coarticulation among the intelligibility groups and between the groups and the NH group.

5.4.1. F1

Figures 5.31.-5.33. below present F1 coarticulatory effects on vowels [i], [a] and [u] at V1offset (anticipatory effects) and V2onset (carryover effects) for the NH group and the three hearing impaired groups with very high (intel 1), high (intel 2) and medium (intel 3) intelligibility. The asterisk [*] above a bar indicates that statistically significant effects were found for that group, while the cross [$^+$] denotes statistically significant difference between that group in comparison with the NH group. Table 5.18. summarizes statistically significant effects only at V1offset and V2offset for the aforementioned groups. For a more comprehensive report, see Appendices: Results, Appendix 2.3.: V-to-V Coarticulation Tables, Intelligibility & Context –F1.

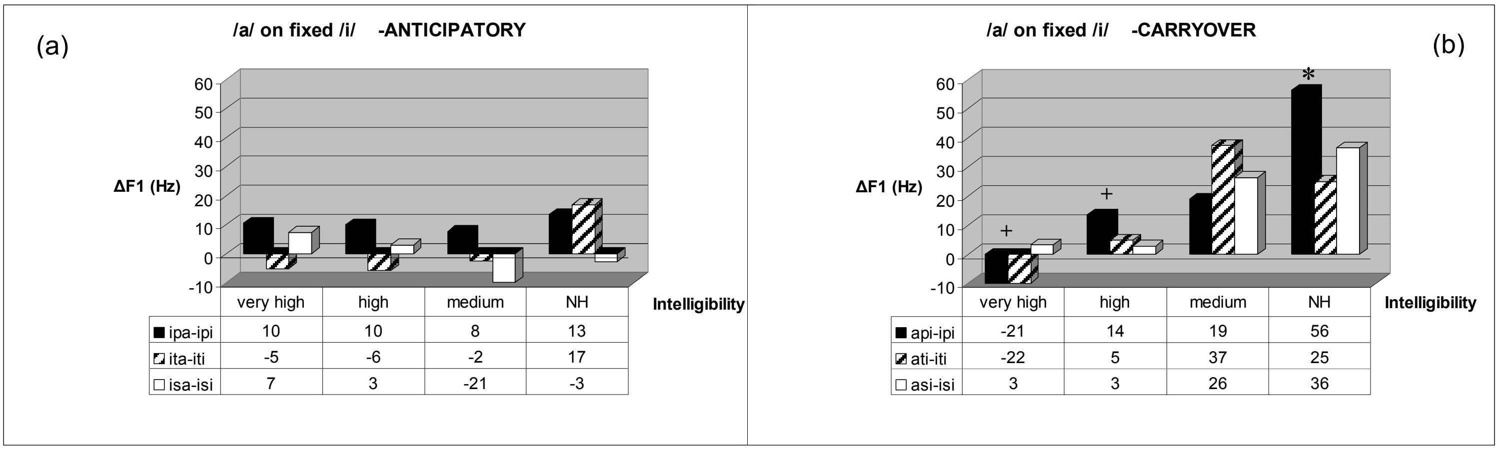
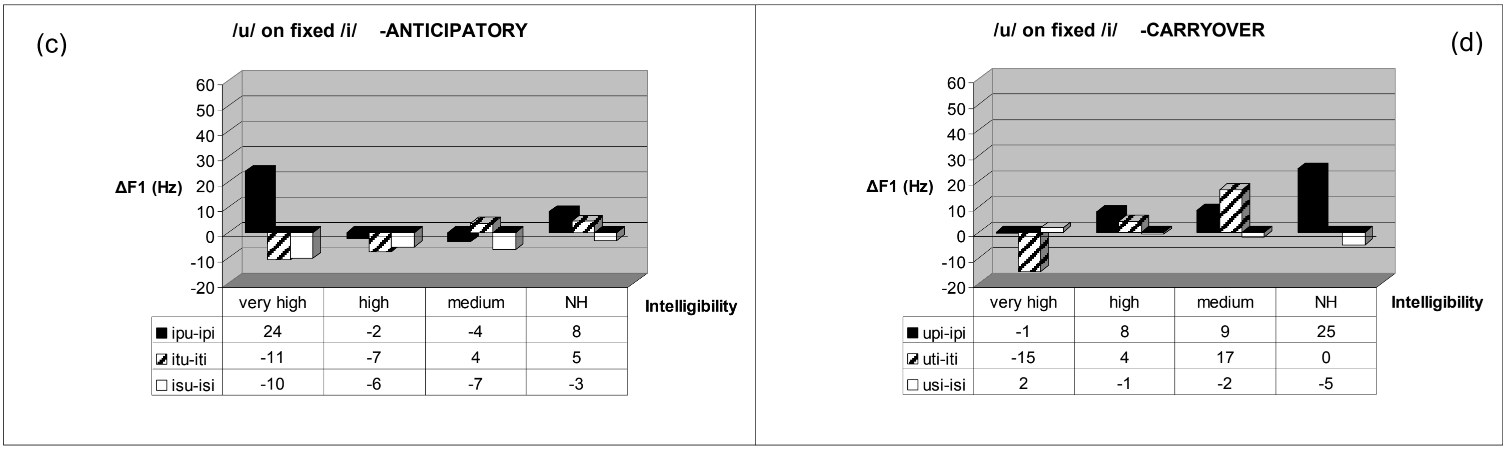


Fig. 5.31. F1 coarticulatory effects (ΔF1) in Hz on fixed [i] from [a] (above) and [u] (below) in disyllables produced by the three HI groups (very high, high and medium intelligibility) and the NH group. Anticipatory effects (a and c) are reported at vowel offset and carryover effects (b and d) at vowel onset. Symbol [*] denotes statistically significant coarticulatory effects within group and [$^+$] statistically significant difference in comparison to the NH group (p<.05).



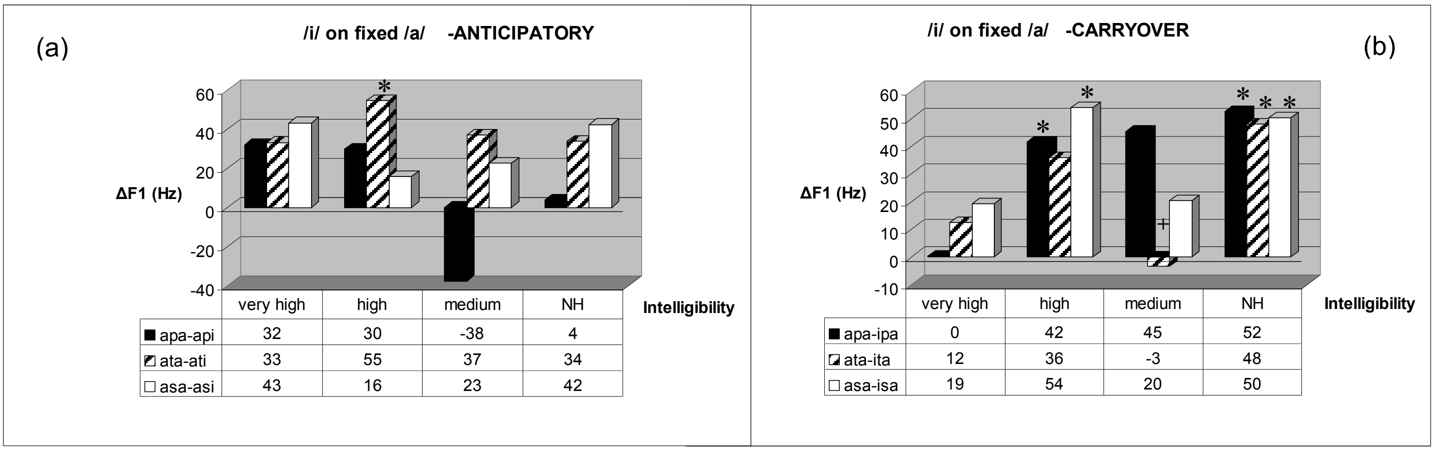
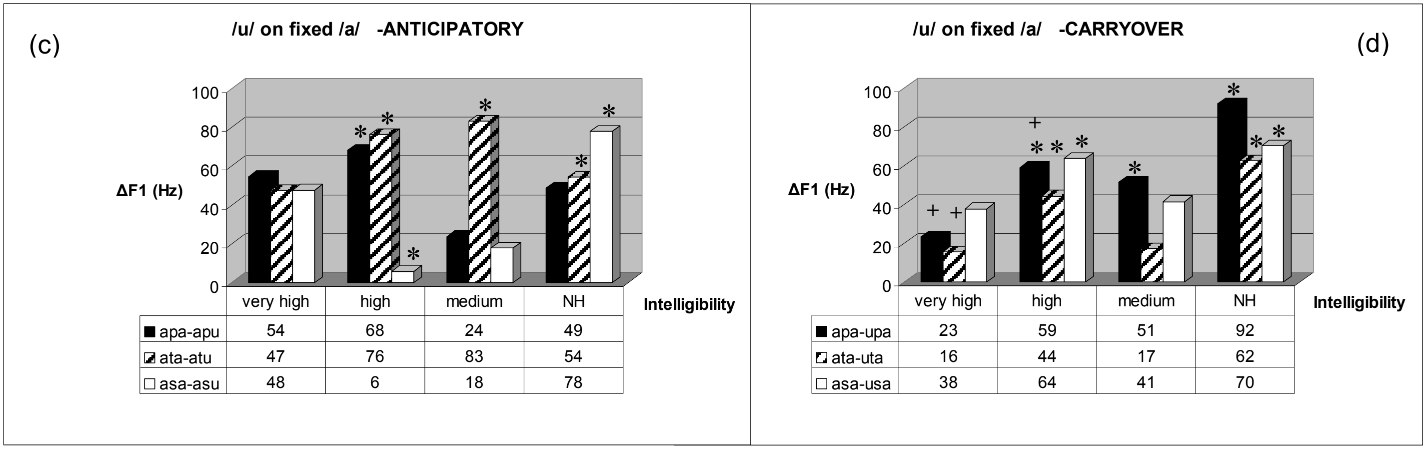


Fig. 5.32. F1 coarticulatory effects (ΔF1) in Hz on fixed [a] from [i] (above) and [u] (below) in disyllables produced by the three HI groups (very high, high and medium intelligibility) and the NH group. Anticipatory effects (a and c) are reported at vowel offset and carryover effects (b and d) at vowel onset. Symbol [*] denotes statistically significant coarticulatory effects within group and [$^+$] statistically significant difference in comparison to the NH group (p<.05).



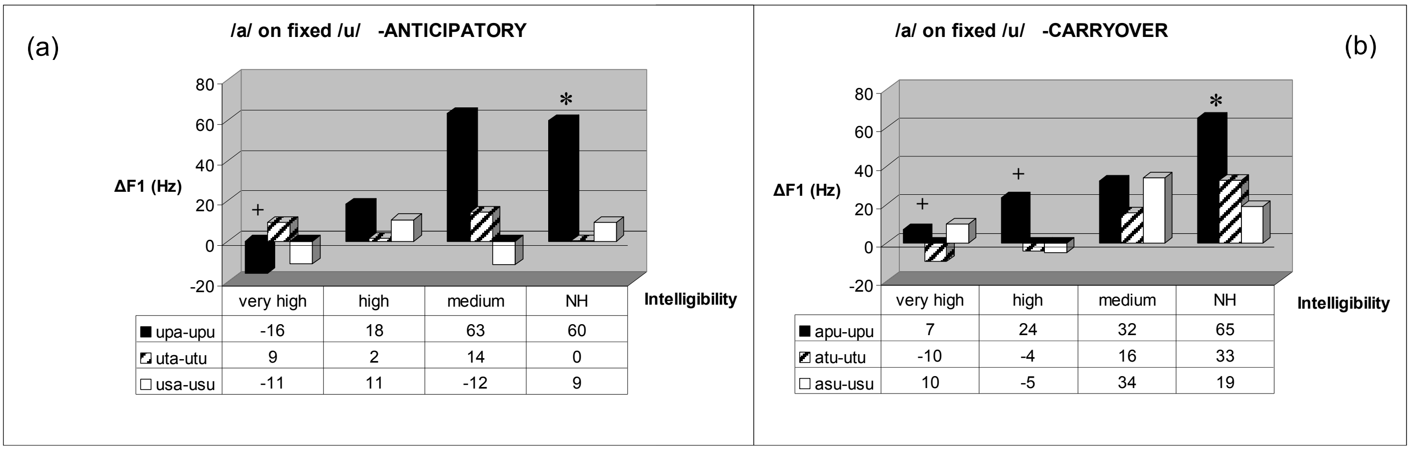
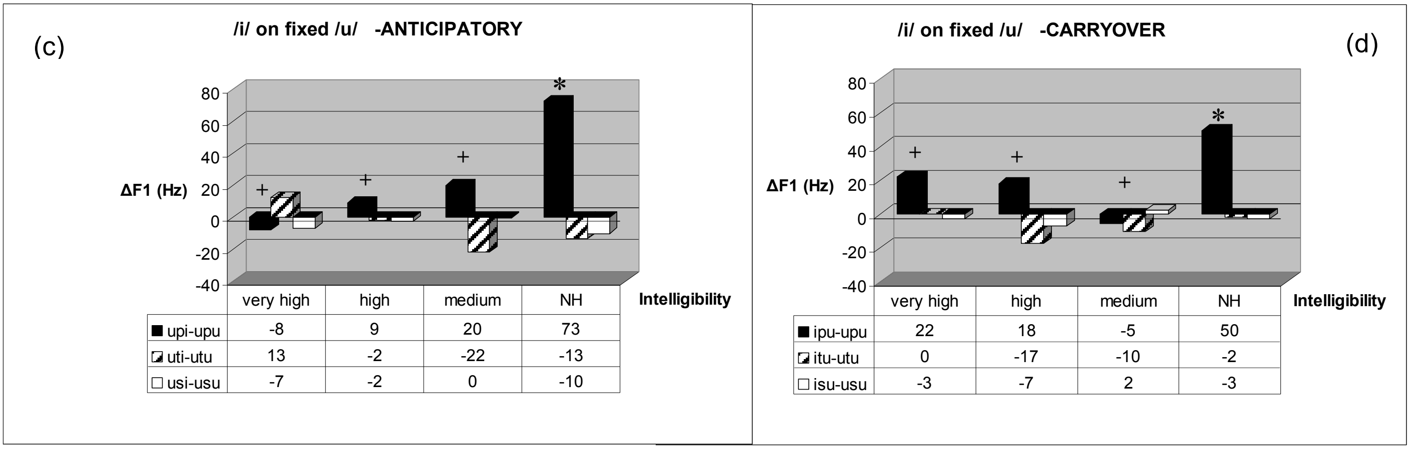


Fig. 5.33. F1 coarticulatory effects (ΔF1) in Hz on fixed [u] from [a] (above) and [i] (below) in disyllables produced by the three HI groups (very high, high and medium intelligibility) and the NH group. Anticipatory effects (a and c) are reported at vowel offset and carryover effects (b and d) at vowel onset. Symbol [*] denotes statistically significant coarticulatory effects within group and [$^+$] statistically significant difference in comparison to the NH group (p<.05).



F1 Coarticulation	ANTICIPATORY				CARRYOVER			
	INTEL 1 (very high)	INTEL 2 (high)	INTEL 3 (medium)	NH	INTEL 1 (very high)	INTEL 2 (high)	INTEL 3 (medium)	NH
[a] on fixed [i]								[p] *** ≠1,2
[u] on fixed [i]								
[i] on fixed [a]						[p] **		[p] ***
		[t] **						[t] *** ≠3
						[s] ***		[s] ***
[u] on fixed [a]		[p] ***				[p] *** ≠1,NH	[p] *	[p] *** ≠1,2
		[t] ***	[t] *** ≠1	[t] *		[t] **		[t] *** ≠1
		[s] *** ≠1,3,NH		[s] *** ≠2		[s] ***		[s] ***
[a] on fixed [u]				[p] *** ≠1				[p] *** ≠1,2
[i] on fixed [u]				[p] *** ≠1,2,3				[p] *** ≠1,2,3

Table 5.17. F1 anticipatory and carryover effects in the productions of the three intelligibility groups (intel 1=very high, intel 2=high & intel 3=medium) and the NH group. Statistical significance is denoted by asterisks ([*]: p < .05, [**]: p < .01 or [***]: p < .0000). Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Between group differences are signified with [≠] followed by the number or name of the group(s) whose effects were found statistically different (p<.05).

The fixed [a] was the context where most of the NH and all HI significant coarticulatory effects were located (see Table 5.17. and Fig. 5.32.). The NH show significant anticipatory effects over the alveolars (see Fig. 5.32.a and Fig. 5.32.c) and significant carryover effects over all consonants with the highest degree over the bilabial (see Fig. 5.32.b and Fig. 5.32.d).

Regarding the HI groups, the group of high intelligibility (intel 2) displays the most effects of all groups; the highest degree of coarticulation is over [t] in the anticipatory and over [s] in the carryover direction, while in many contexts it surpasses the NH size of coarticulation (see Fig. 5.32.). The group of medium intelligibility (intel 3) also manifests coarticulatory influence but their significant effects are a lot less than those of the NH and the intel group 2. These effects are induced by [u] only and occur over [t] in the anticipatory and over [p] in the carryover direction. Finally, the group of very high intelligibility (intel 1) shows coarticulatory effects which do not reach significance in any context (see Table 5.17.). This unexpected occurrence may be related to the fact that the speech of one of the two members of this group (HI_01) was very slow and deliberate. Hence her productions, although highly intelligible, may not allow as much V-to-V effects as those of other HI speakers.

Concerning the fixed [i] and fixed [u] contexts, no significant effects were located for any of the HI groups (see Table 5.17.). In the fixed [i] context, the NH display significant effects only in [ipi]-[api] pairs (see Fig. 5.31.b), suggesting a constrained [i] production (section 5.1.1.1. Fixed [i], Summary), and in the fixed [u] context they show significant bidirectional effects again only over the bilabial in [upu]-[upa], [upu]-[apu], [upu]-[upi] and [upu]-[ipu] pairs (see Fig. 5.33.a, b, c, d). Tukey pairwise comparisons between the NH and the three intelligibility groups, conducted on the above four pairs as well as the [ipi]-[api] pair, where NH effects are significant, showed that the intel 1 group is significantly different in all five contexts from the NH, the intel group 2 in all but one context and the intel group 3 in two contexts (note the symbol [$^+$] in Fig. 5.31.b and Fig. 5.33.a, b, c, d). This may indicate a difficulty of the HI to resemble the NH coarticulatory pattern in fixed high vowel contexts over the bilabial, and that this difficulty is not directly related to intelligibility, since the group with the highest intelligibility (intel 1) was the one deviating from the NH pattern in all contexts and the group with the lowest intelligibility (intel 2) the one resembling the NH the most.

5.4.2. F2

As with F1 above, F2 coarticulatory effects on the three vowels at V1offset (anticipatory effects) and V2onset (carryover effects) are demonstrated for the NH group and the three hearing impaired groups with very high (intel 1), high (intel 2) and medium (intel 3) intelligibility in figures 5.34-5.36. The asterisk [*] above a bar indicates that statistically significant effects were found for that group, while the cross [$^+$] denotes statistically significant difference between that group in comparison with the NH group. Table 5.18. summarizes statistically significant effects only at V1offset and V2offset for the aforementioned groups. For a more comprehensive report, see Appendices: Results, Appendix 2.3.: Coarticulation Tables, Intelligibility & Context – F2.

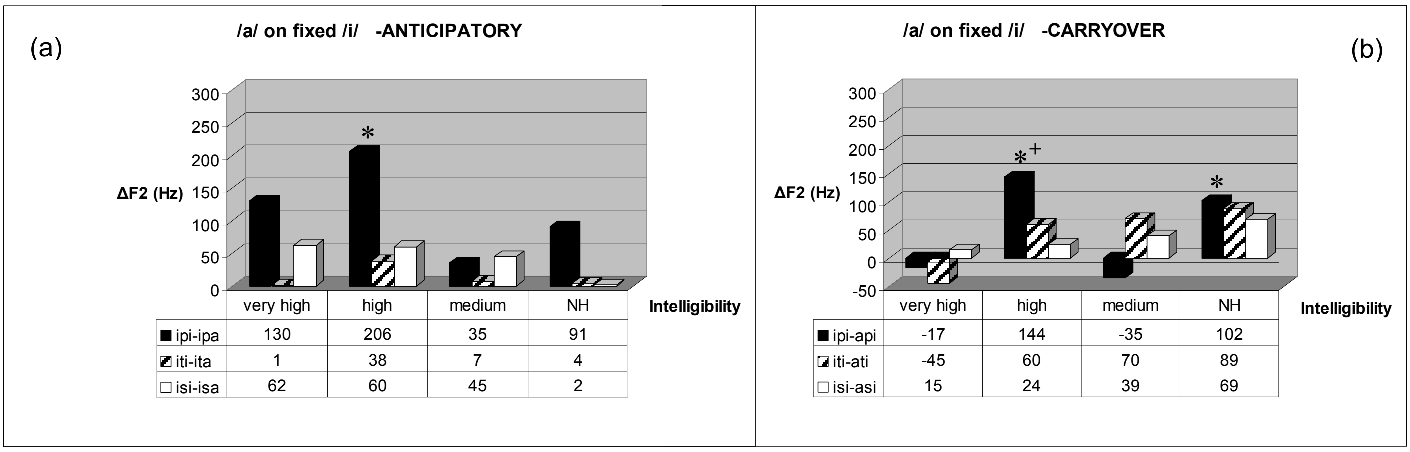
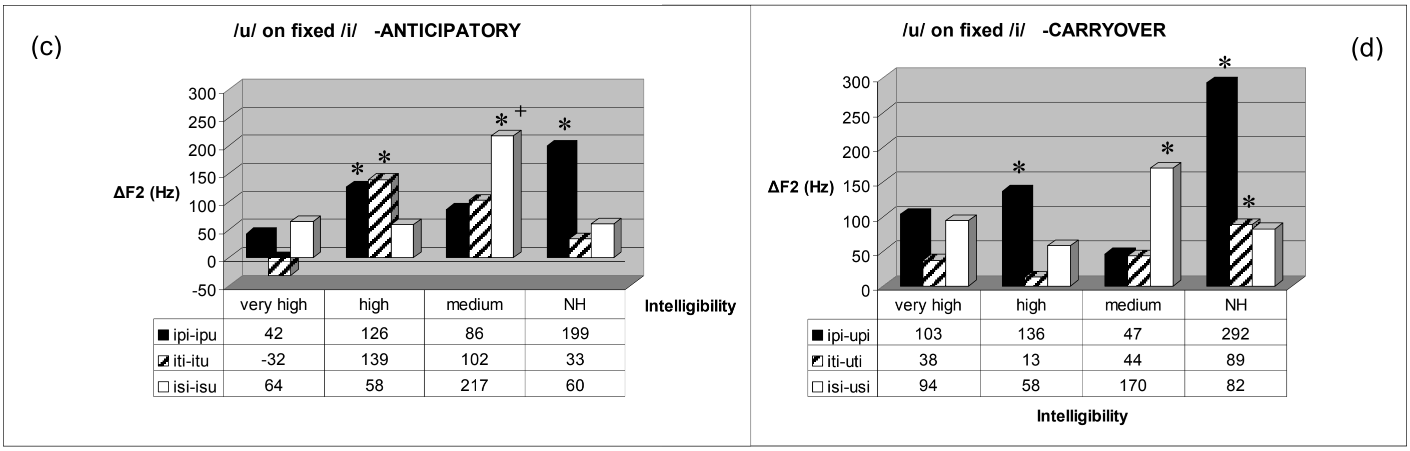


Fig. 5.34. F2 coarticulatory effects (ΔF2) in Hz on fixed [i] from [a] (above) and [u] (below) in disyllables produced by the three HI groups (very high, high and medium intelligibility) and the NH group. Anticipatory effects (a and c) are reported at vowel offset and carryover effects (b and d) at vowel onset. Symbol [*] denotes statistically significant coarticulatory effects within group and [$^+$] statistically significant difference in comparison to the NH group (p<.05).



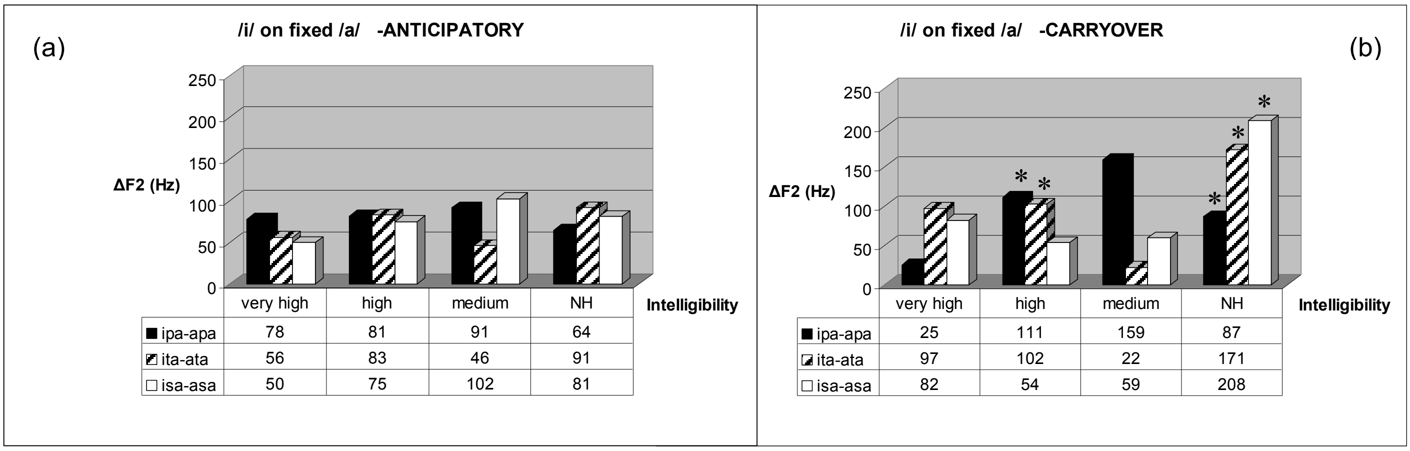
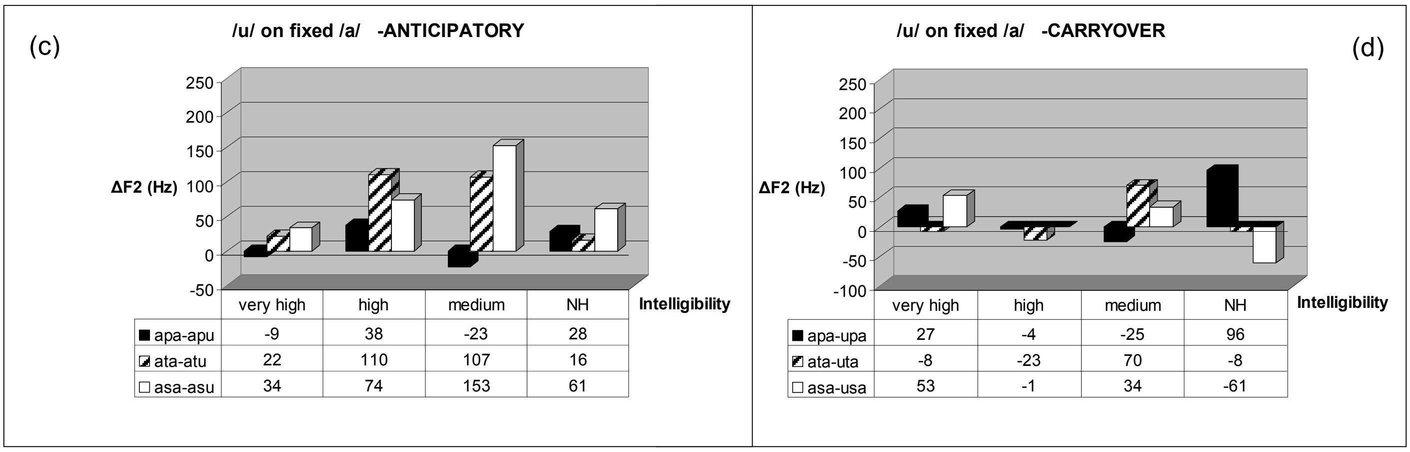


Fig. 5.35. F2 coarticulatory effects (ΔF2) in Hz on fixed [a] from [i] (above) and [u] (below) in disyllables produced by the three HI groups (very high, high and medium intelligibility) and the NH group. Anticipatory effects (a and c) are reported at vowel offset and carryover effects (b and d) at vowel onset. Symbol [*] denotes statistically significant coarticulatory effects within group and [$^+$] statistically significant difference in comparison to the NH group (p<.05).



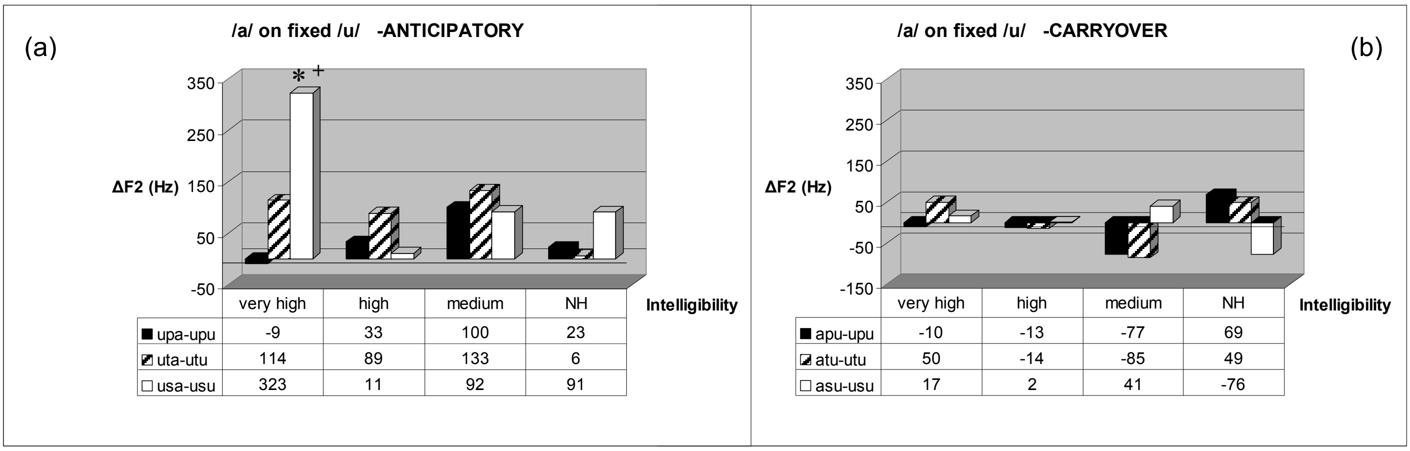
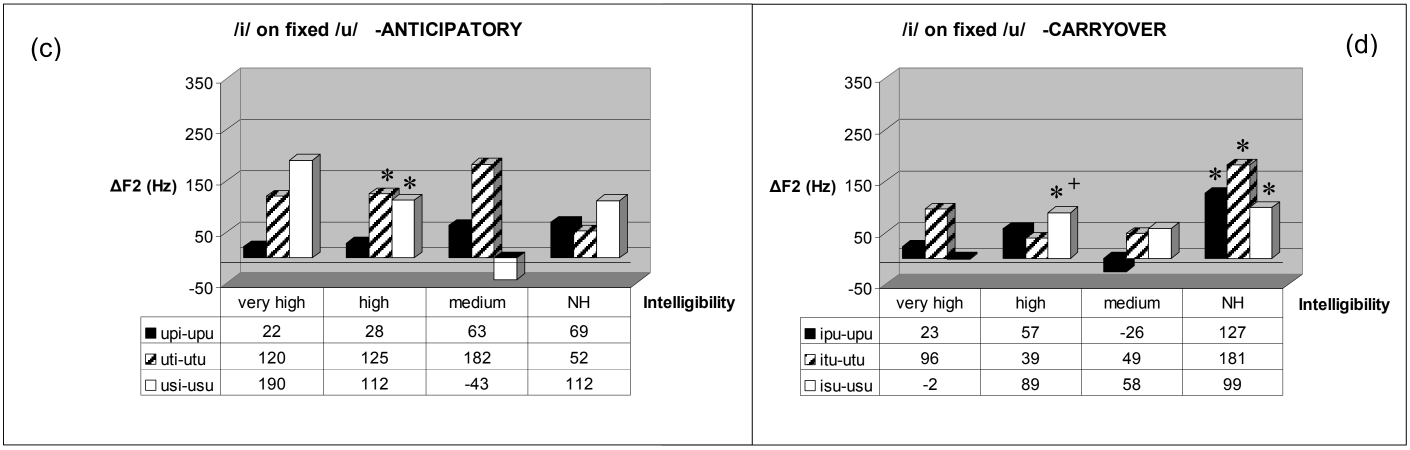


Fig. 5.36. F2 coarticulatory effects (ΔF2) in Hz on fixed [u] from [a] (above) and [i] (below) in disyllables produced by the three HI groups (very high, high and medium intelligibility) and the NH group. Anticipatory effects (a and c) are reported at vowel offset and carryover effects (b and d) at vowel onset. Symbol [*] denotes statistically significant coarticulatory effects within group and [$^+$] statistically significant difference in comparison to the NH group (p<.05).



F2 Coarticulation	ANTICIPATORY				CARRYOVER			
	INTEL 1 (very high)	INTEL 2 (high)	INTEL 3 (medium)	NH	INTEL 1 (very high)	INTEL 2 (high)	INTEL 3 (medium)	NH
[a] on fixed [i]		[p] *** ≠3				[p] *** ≠1,3,NH		[p] ** ≠2
[u] on fixed [i]		[p] **		[p] ***		[p] ** ≠1		[p] ***
		[t] **						[t] *
			[s] ** ≠2,NH	≠3			[s] *	
[i] on fixed [a]						[p] **		[p] *
						[t] **		[t] ***
								[s] ***
[u] on fixed [a]								
[a] on fixed [u]								
	[s] *** ≠2,3,NH			≠1				
[i] on fixed [u]								[p] ***
		[t] *						[t] ***
		[s] *				[s] * ≠NH		[s] * ≠2

Table 5.18. F2 anticipatory and carryover effects in the productions of the three intelligibility groups (intel 1=very high, intel 2=high & intel 3=medium) and the NH group. Statistical significance is denoted by asterisks ([*]: p < .05, [**]: p < .01 or [***]: p < .0000). Anticipatory effects are reported at vowel offset and carryover effects at vowel onset. Between group differences are signified with [≠] followed by the number or name of the group(s) whose effects were found statistically different (p<.05).

For the NH, significant carryover F2 V-to-V coarticulation was found in the majority of fixed vowel contexts except for the [u]-to-[a] and [a]-to-[u] contexts (see Table 5.18.) which is expected as the F2 distance between these two vowels is not as great as that between [i] and [u] or even [i] and [a] (section 4.1.1. Hearing, Fig. 4.1.3). In the anticipatory direction, statistically significant effects were found only in [ipi]-[ipu] pairs (see Table 5.18. and Fig. 5.34.c).

Among the HI groups, the highly intelligible group (intel 2) is, as with F1, the one showing the significant F2 effects in the most contexts; in fact, this group displays increased coarticulation in comparison to the NH group, especially in the anticipatory direction (see Table 5.18.). As mentioned above, the NH group shows statistically significant anticipatory effects only in [ipi]-[ipu] pairs, whereas the highly intelligible group displays anticipatory effects in [ipa]-[ipi], [ipu]-[ipi] [itu]-[iti] (see Fig. 5.34.a and c), [uti]-[utu] and [usi]-[usu] pairs (see Fig. 5.36.c). In the carryover direction though, the intel group 2 seems to display significant effects in less contexts than the NH and in the contexts where both groups show effects, the intel group 2 either coarticulates more ([ipi]-[api], [ipa]-[apa]) or less ([ipi]-[upi], [ita]-[ata], [isu]-[usu]) than the NH.

The very highly intelligible group (intel 1) shows statistically significant effects only in one context, namely in [usa]-[usu] pairs (anticipatory direction) (see Fig. 5.36.a). In this context neither the NH nor any other HI group show any significant effects over the fricative or any other consonant. In addition, we observed that the intel group 1 presents statistically significant carryover effects in the fixed [i] context in the pairs [asi]-[isi], [uti]-[iti] and [usi]-[isi], but not at V2onset as expected, rather at V2offset which may indicate that in alveolar contexts no significant effects are allowed near the consonantal constriction (see Appendix 2.3., V-to-V Coarticulation Tables, Intelligibility –F2).

Finally, the medium intelligibility group displays less coarticulatory effects than the NH and the intel group 2. The only contexts with significant effects are [isu]-[isi] and [usi]-[isi] (see Fig. 5.34.c and d). Although the NH and the highly intelligible group do present effects in these contexts, they do not reach significance. Hence the intel 3 group shows increased [u]-to-[i] coarticulation over the fricative, while effects in other contexts are statistically nonsignificant.

➢ Summary

A comparison between the NH and the HI groups showed that the NH display significant bidirectional F1 effects and significant carryover F2 effects in more contexts than any HI group, while the highly intelligible group (intel 2) surpasses the NH in the number of contexts with significant F2 anticipatory effects. In addition, in contexts where F1 and F2 effects are sizeable for both the NH and the intel group 2 (i.e., the fixed [a] context for F1, and the [u]-to-[i], [i]-to-[a] and [i]-to-[u] contexts for F2), there are cases where the intel group 2 presents a higher degree of effects than the NH. The medium intelligibility group (intel 3) shows less F1 and F2 coarticulatory effects than both the NH and the intel group 2, and their significant effects occur mostly over alveolars. Opposite to what we expected, the very high intelligibility group (intel 1) is the one that showed the least F1 & F2 coarticulation of all groups.

Chapter 6

Discussion

In this Chapter we provide a concise presentation and critical discussion of the research findings reported in Chapter V, Part 1 and Part 2. The results will be discussed in light of speech production theories and models with particular reference to the DAC model of coarticulation (Recasens et al., 1997).

6.1. Point Vowels: Vowel Distribution & Vowel Space in HI and NH Speech

One of the aims of the present study is to provide a comparison between the acoustic characteristics of point vowels [i, a, u] as produced by speakers with hearing impairment (HI) vs. normally hearing (NH) speakers. For this purpose, the vowels were produced in symmetrical disyllables of bilabial context which serves as a neutral environment in terms of tongue involvement during the production of the consonant (Strange et al., 2007).

6.1.1. Hearing

The acoustic analysis of the first two formants revealed that, among the three point vowels, the HI high back rounded vowel [u] deviates the most from its NH counterpart, in that it displays a significantly higher second formant. A higher F2 indicates a more anterior oral constriction during the production of [u]. The high front vowel [i], on the other hand, shows a lower F2 than normal, suggesting a more posterior constriction, although the difference ceases to be significant after normalization. A more problematic identification of Greek [u] vs. [i] is indicated in Vakalos' (2009) study, as listener ratings by 79 Greek speakers with mild-to-moderate

HI were significantly lower for [u] vs. front [i] and [e]. Thus, the more deviant production of [u] vs. [i] in our study may be associated with increased problems in [u] identification by Greek speakers with HI.

Contradictory results are reported in the literature regarding the frequency of erroneous production in relation to vowel backness in HI speech (section 2.3.2.1). According to Boone's theory (1966) speakers with HI "…tend to keep their tongues too far back and too low in their mouths, thus interfering with correct production of front and high vowels but achieving better production of back and low ones" (Gold, 1980:403). Our results do not lend full support to this theory, since, as inferred by F1 values, the tongue seems to adjust correctly to height, and the high F2 values for [u] do not suggest that the tongue lingers at a back position, at least not during the production of [u] or [a] in the bilabial context. Hence, backing of the front [i] and especially fronting of the back [u] indicate that the tongue cannot assume the correct position along the front/back dimension. Front vowels are reported as produced more correctly than back vowels in various studies (e.g., Hudgins & Numbers, 1942; Rubin, 1985) and fronting of back vowels has also been documented in Stein's (1980) cineradiographic study. Subtelny et al. (1992) also report a higher F2 frequency than normal for back vowel [u] produced by four deaf women.

Moreover, physiological measurements revealed that a uniform level of genioglossus activity for HI [i, ɪ, u] was responsible for failure to vary tongue position along the front/back dimension in an acoustic and EMG study conducted by McGarr & Gelfer (1983). In their investigation electromyographic records of the orbicularis oris activity showed that the differentiation between vowels [i] and [u] was primarily achieved through lip-rounding, as also suggested by our data. As described earlier (section 3.2.5.2.), productions of [u] are recurrently realized as [y] by the speakers with HI in our study, in their attempt to differentiate between [i] and [u] on the basis of lip-rounding mainly rather than both lip-rounding and a posterior tongue constriction appropriate for a high back vowel.

Both our findings concerning [u] fronting and [i] backing are indications of a more constricted formant range along the front/back dimension, in line with the literature (Monsen, 1976c, 1983b; Rothman, 1976; Van Tassel, 1980; Metz et al., 1985; Zimmermann & Rettaliata, 1981; Shukla, 1989; McCaffrey & Sussman, 1994; Ryalls et al., 2003). In our data, any differences existing between NH and HI vowels along the F1 dimension seem to be eliminated after normalization. The greater audibility of the first in relation to the second formant has been documented as an important factor in better performance at lower frequencies by speakers with HI. Hence the "shrinking" of the HI vowel space by 28% after normalization is largely attributed to the restricted front/back movement of the tongue as inferred from F2 formant values, a common finding in HI speech across many languages (Monsen, 1976a, 1976c; Rothman, 1976; McGarr & Gelfer, 1983; Okalidou, 1996; Ryalls et al., 2003, for French; Shukla, 1989, for Kannada; Ozbič & Kogovšek, 2010 for Slovene; Tseng, 2011 for Mandarin).

In our data, the production of the low central vowel [a] does not differ significantly in either axis from the NH counterpart. Better production of low vs. high vowels is reported in many studies (e.g, Nober, 1967; Smith, 1975; Geffner; 1975; Gold, 1980). Open vowels, e.g., [a], have greater inherent intensity, all else being equal, than less sonorous high vowels which might contribute to their better perception and production by speakers with HI, although this suggestion needs further investigation. In the present study, after normalization, the position of HI [i] coincides with that of NH [i] in the vowel space, whereas HI [a] seems more fronted in relation to NH [a], an observation that might be taken to suggest a better production of [i] vs. [a] by speakers with HI. However, a comparison in acoustic variability of HI vs. NH vowels reveals that the NH [i] displays much tighter within-category clustering than HI [i]. Similarly we observe that HI [u] is much more variable than NH [u]. This leads to some degree of overlap between some [i] and [u] tokens along the F2 axis for the HI speakers. Conversely, the variability of [a], albeit higher for the HI group, is relatively similar in NH and HI speech and does not seem to create overlap between [a] and [u] after normalization. Overall, HI vowels display a lot more variability than NH vowels as produced by the subjects in our study. Greater acoustic variability and articulatory instability in HI vs. NH productions has been noted extensively in the literature (e.g., McGarr & Harris, 1980; Osberger & McGarr, 1982; Dagenais & Critz-Crosby, 1992; Okalidou, 2002; Nicolaidis, 2004).

6.1.2. Hearing and gender

Cross-linguistically female vowel spaces are larger than male vowel spaces due to anatomical (Fant, 1966, 1975; Nordström, 1977; Goldstein, 1980) as well as sociophonetic reasons (Henton, 1995; Pierrehumbert et al., 2004; Johnson, 2006). This gender difference in vowel space has been reported in earlier studies on Greek NH speech (Sfakianaki, 1999; Vakalos, Iliadou, Eleytheriades, Iliades & Fourakis, 2003) and is also displayed in the present study in both the NH and the HI group. In addition, both before and after normalization, NH vowel spaces of both genders were found larger than the corresponding HI vowel spaces. The HI male group displays more extensive reduction (by about 10%) than the HI female group relative to the respective NH gender groups.

A within-hearing-group between-gender comparison after normalization showed that female vowels are more variable than male vowels in NH speech. This variability is especially evident along the F1 axis which may be indicative of more variable jaw displacement or tongue movement in height during vowel production by NH female speakers. A greater dispersion of female vs. male vowels in the vowel space has been reported in NH speech (Bradlow et al., 1996; Henton, 1995; Yang, 1996; Pierrehumbert et al., 2004; Heffernan, 2007; Vakalos, 2009) (section 2.2.3). Conversely, this gender-related within-vowel dispersion was not observed in the HI group. HI male [i] is more dispersed along the F1 axis and male [u] shows more dispersion along both axes than HI female corresponding vowels. HI female [i] demonstrates more scattering along the F2 and [a] along the F1 axis. Thus no consistent gender pattern regarding vowel variability can be discerned unlike with NH speakers. This finding may be related to the overall greater speaker-specific variability observed in HI speech. Gender seems to play a less important role in vowel acoustic characteristics as each speaker with HI may display different vowel production performance depending on other factors, such as degree of hearing loss, residual hearing, training, etc.

A between-hearing-group within-gender comparison after normalization revealed that both HI genders show considerable [u] fronting in comparison with the NH counterparts. Additionally all HI male vowels display much greater variability than NH male vowels, whereas the difference in variability between HI and NH female vowels is not as pronounced. Moreover, vowel sub-areas seem closer for HI speakers and especially male, although they remain distinct for all subgroups after normalization. Less tight within-category clustering for HI male vs. female speakers may also be associated with intelligibility level, as the speakers of the HI female group have a higher average level of intelligibility than the speakers of the HI male group (section 6.1.3. below).

6.1.3. Intelligibility

Subsequent to an intelligibility experiment, comprising words and sentences, judged by naïve listeners (section 3.4.), the speech of the 9 subjects with HI was found overall very intelligible (mean group score 88%). Hence, as a group, the speakers with HI participating in our study are quite intelligible. This score is higher than that reported in some studies rating HI speech (Brannon, 1964; Markides, 1983; Rubin, 1985; Abraham, 1989), but, overall, a lot of variability in average intelligibility scores is documented in the literature (section 2.3.3). This variability probably reflects differences in materials as well as subject variables such as age of amplification, hearing aid use, intervention type and duration, schooling, etc. Although profoundly HI, the speakers of our study made an early and consistent use of hearing aids, used almost exclusively oral communication, were in mainstream education and had had (some of them still having) substantive speech training over the years. It should be noted that 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).

The 9 speakers with HI were further divided into three groups on the basis of their intelligibility level: intel group 1 (very high intelligibility, > 90%) consisting of two female speakers, intel group 2 (high intelligibility, > 80%) including 2 female and 3 male speakers, and intel group 3 (medium intelligibility, > 60%) comprising two male speakers. Degree of hearing loss did not correlate with intelligibility, as also underlined by many researchers, especially for speakers with a hearing loss above 90 dB at 1000 Hz (Smith, 1975; Monsen, 1978; Osberger & McGarr, 1982; Metz et al., 1985). Thus, for example, speakers with the same average PTA belonged to different intelligibility groups or, in some cases, highly intelligible speakers had a higher degree of hearing loss than less intelligible speakers (section 3.4.6).

An interesting finding is that, in the speech of our subjects, intelligibility level seems to vary as a function of [u] fronting. More specifically, the lower the intelligibility level, the more anteriorly [u] is realized and the larger its distance from the NH [u] along the F2 axis. A more anterior [u] production certainly decreases the contrast with the high front vowel [i] and may impoverish vowel identification, hence speech intelligibility. As mentioned above, poorer listener identification of vowel [u] produced by Greek speakers with mild to moderate hearing loss is also reported in Vakalos' (2009) large-scale study. Moreover, McGarr & Gelfer (1983) observe 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).

The aforementioned [u] fronting that increases as the intelligibility level decreases leads to an overall vowel space reduction that also increases with the decline of intelligibility. A high correlation between vowel space and speech intelligibility has also been found for individuals with amyotropic lateral sclerosis (Turner, Tiaden & Weismer, 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. In our study, both before and after normalization, the order from largest to smallest vowel area is NH > very high > high > medium intelligibility vowel space. The other two vowels, [i] and [a], do not contribute to a considerable reduction of the vowel spaces of the intelligibility groups in comparison with the NH vowel space. Moreover, the overlap of tokens of the three vowel categories seems to increase as intelligibility level decreases.

Concerning vowel variability in intelligibility groups, we do not observe a directly inverse relationship as with [u] fronting and vowel space shrinkage. The high intelligibility group demonstrates the highest variance for [u] although, at least for vowels [i] and [a], it resembles the NH variance pattern. These two groups, NH group and high intelligibility group, consist of the same number of subjects, i.e., five subjects in each group. The very high intelligibility group displays the lowest degree of variability and the variability demonstrated by the medium intelligibility group is in-between that of the other two intelligibility groups. Thus, the relationship between vowel variability and intelligibility level does not seem to be directly inverse, although the differences in the composition of the groups, e.g., in subject number and gender, may interfere with the result even after normalization. The very high intelligibility group is composed of two female speakers who also have an almost identical mean PTA level and very similar hearing loss slopes, while the high intelligibility group consists of 2 female and 3 male speakers with mean hearing loss ranging from 91.7 to 103.3 dB HL. The medium intelligibility group, like the very high intelligibility group, consists of two speakers of the same gender, i.e., male, with very similar mean PTA levels and hearing loss slopes. Thus the very high and the medium intelligibility groups are more homogeneous than the high intelligibility group in terms of speaker characteristics.

6.1.4. Stress and syllable position

Stress was found to cause significant and similar effects to the quality of the point vowels [a] and [i] of both groups. Therefore, our data does not seem to confirm earlier reports concerning only minimal changes to vowel formant frequencies due to stress in NH speech (Dauer, 1980a). More specifically, stressed [a] is significantly more open and more anterior than its unstressed counterpart for both groups. A lower jaw position for stressed low vowels is well documented in the literature on NH speech in other languages (Stone, 1981; Kelso et al., 1985; Summers, 1987; Beckman et al., 1992; Erickson, 1998; Harrington et al., 2000) and in Greek (Nicolaidis, 1997; Botinis et al., 1995; Fourakis et al., 1999; Koenig & Okalidou, 2003; Nicolaidis & Sfakianaki, 2007), and [a] fronting is also reported (Nicolaidis, 1997; in fast tempo: Botinis et al., 1995, Fourakis et al., 1999; Nicolaidis & Sfakianaki, 2007, for NH male speakers).

Regarding the effect of stress on vowel [i], significant fronting is evident in both groups. A fronted tongue dorsum position for the stressed high vowel [i] has been reported for NH speech in American English (Erickson et al., 1999; Erickson, 2002) and Australian (Harrington et al., 2000) as well as Greek (Fourakis et al., 1999; Koenig & Okalidou, 2003; Nicolaidis & Sfakianaki, 2007). Nicolaidis (1997) also reports a more anterior lingual placement for [i] but only post-consonantally. As far as the vowel [u] is concerned, it does not seem significantly affected by stress condition for either group in our data. However, a slight lowering and backing of [u] under stress is interestingly observed for the HI group although it does not reach significance. Moreover, we note that stressed vowels in both groups have a higher mean F1 value, and are thus more sonorous than unstressed vowels, except for NH [u] that remains unchanged. Hence our results are in line with Nicolaidis & Rispoli (2005) who report lower F1 values for all unstressed Greek vowels except the high ones. Botinis et al. (1995) also observe an acoustic raising of all unstressed NH Greek vowels except for vowel [u] at normal tempo. Changes in formant frequency are generally more ‘subtle’ for the high back vowel [u] (Vakalos et al., 2003; Vakalos, 2009).

In both stressed and unstressed condition the NH vowel space is larger than the corresponding HI vowel space. Hence the overall vowel surface decreases in the order NH stressed > NH unstressed > HI stressed > HI unstressed. The aforementioned fronting of both [a] and [i] and the lowering of [a] in the stressed condition result in a substantial vowel space expansion for both groups. In particular, lack of stress causes a 24.8% shrinkage of the vowel space for the NH group and a slightly greater reduction of 28.4% for the HI group. Vowel space reduction due to absence of stress in NH speech is reported across languages (Tiffany, 1959; Miller, 1981; Fourakis, 1991, for American English; Chiang & Chiang, 2005, for Truku; Mooshammer & Geng, 2008, for German; Beňuš & Mády, 2010, for Slovak) and in Greek (Fourakis et al., 1999; Koenig & Okalidou, 2003; Nicolaidis & Rispoli, 2005; Baltazani, 2007; Nicolaidis & Sfakianaki, 2007; Lengeris, 2011) (sections 2.2.2. and 2.4.1).

Thus, according to our data, the effect of stress on the vowel space is slightly greater for speakers with HI. This difference is attributed to a more pronounced shift along the F1 for the HI group compared with the NH group. We observe that, although not statistically significant for all vowels, the difference in F1 of stressed vs. unstressed vowels is greater for the HI vowels, while the F2 shift is smaller. Hence the greater vowel space reduction percentage for the HI group is attributed to a more prominent shift in the F1 dimension. Similar results have been reported by Nicolaidis & Sfakianaki (2007) for Greek HI speech and Barzaghi & Mendes (2008) for Brazilian Portuguese HI speech (section 2.3.2.2). Stress effects on vowel quality are manifested through greater changes along the F1 axis for the speakers with HI, as this dimension is auditorily more accessible and can be easily manipulated via visible jaw movement. Barzaghi & Mendes (2008) report that the severely HI speaker in their study demonstrated greater jaw opening than the moderately HI speaker in an attempt to cue stress. Nicolaidis & Sfakianaki (2007) report a trend for similar to normal, if not greater, shift along the F1 and smaller than normal shift along the F2 due to stress for speakers with HI. Overall, the influence of stress on the point vowels is similar between the HI group and the NH group, but a trend towards increased sonority in combination with a restricted tongue front/back movement in the stressed vs. the unstressed condition when compared with the normative pattern is evident.

The data with regard to the effect of stress on the point vowels can be accounted by both the expansion model as well as the localized hyperarticulation property expounded in Chapter II (section 2.2.2). The lowering of [a] supports the claims of the *sonority expansion model* for higher F1 values during stressed vowel production (Beckman et al., 1992), while both the lowering and fronting of [a] as well as the fronting of [i] provide evidence for the *localized hyperarticulation approach* (de Jong, 1995) as they become more peripheral and hence more distinct. As discussed earlier, this model accounts for the emphasis of nonsonority features by stress resulting in improved vowel distinctiveness, i.e., a fronter constriction for the production of [i] would enhance its contrast with the high back [u] (see also section 6.2.2. below).

As regards stress and syllable position, the stressed vowel in the second position (post-consonantal) is more peripheral for both groups. This is more evident for vowels [a] and [i]. However, in the absence of stress, vowels are less peripheral in the second position for the NH group, whereas for the HI group more vowel reduction is observed in the first syllable position. However, as commented by Browman & Goldstein (1995), reduction is generally observed in the final syllable position, as this position is ‘weaker’ in the languages of the world. Conversely, the first syllable position is usually stronger as it carries important lexical information. Initial syllable strengthening has been hypothesized to benefit the listener by providing more cues for word identification, thus aiding lexical access (Fougeron & Keating, 1997). Unstressed vowels have been found less reduced in the first syllable of CVCVCV words (Farnetani & Vayra, 1996). Moreover, in their investigation of Creek[31] vowels, Johnson & Martin (2001) found that final-syllable vowels are centralized relative to vowels in initial syllables despite the fact that final syllables are longer. Consequently, we expect more extensive reduction caused by lack of stress in the second- rather than in the more stable first-syllable vowel in our data. NH speakers in the present study follow the expected pattern. We observe that stress is a significant factor only in second syllable position, i.e., absence of stress significantly lowers the F2 of [i] and both the F1 and F2 of [a]. The speakers with HI do not seem to follow the NH pattern. For them, stress significantly influences vowels [i] and [a] in both syllable positions. Thus, absence of stress causes a lowering of the F2 of [i] and of the F1 of [a] in both syllable positions for the HI group. Note also that when examined in conjunction with syllable position, stress does not cause significant fronting to HI [a]. Hence, stress interacts with syllable position for the HI vowels as well, but differently than for the NH vowels. A less stable first syllable than normal may indicate different gestural organization for the HI speakers (see also sections 6.2.2. and 6.4.3 below).

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[31] Creek is a Muskogean language spoken by several thousand individuals in eastern Oklahoma and central Florida.

6.2. Point Vowel Duration

6.2.1. Hearing, gender and intelligibility

The point vowel duration decreases in the order [a] > [u] > [i] for both the NH and the HI group. 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, 1980a; Fourakis et al., 1999; Arvaniti 1991, 2000). This pattern is also observed in the vowel durations of the speakers with HI of our study. We also note that all durational differences among the three vowels are statistically significant within each group. However, in accordance with the literature (section 2.3.2.2.), HI vowels are consistently longer than NH vowels; i.e., about 23% for HI [a], 26% for [u] and 32% for [i]. Even greater durational differences between HI and NH vowels have been reported in the literature (e.g., for English: Calvert, 1962; Reilly, 1979; for Portuguese: Coimbra et al., 2011).

Looking into gender, we observe that within each hearing group female vowels are significantly longer than male vowels. NH female speakers have been documented to produce longer vowel durations across languages (Hillenbrand et al., 1995, for American English; Simpson, 1998, for German; Ericsdotter & Ericsson, 2001, for Swedish; Simpson, 2001, for American English diphthongs and Simpson, 2002, for American English vowel sequences). This characteristic has been interpreted to relate to the greater distinctiveness of female speech (section 2.2.3). The difference in vowel duration between the two genders is more pronounced in the NH group of our study. Nevertheless, the HI group follows the NH trend for greater female vowel duration, albeit to a lesser extent. In Nicolaidis & Sfakianaki (2007), Greek female speakers with HI were also found to produce the longest vowels compared with male HI speakers as well as with NH speakers of both genders. An additional finding of the present study is that the difference between the NH and the HI vowel duration is more prominent in the male HI group, although female speakers with HI generally produce longer vowels than normal. As we discuss below, this finding could also be related to the lower average intelligibility level of the male HI group or to speaker-specific characteristics not associated with gender.

An examination of vowel duration in the intelligibility groups revealed that the durational pattern, i.e., [a] > [u] > [i], is observed regardless of intelligibility level. As mentioned above, the between-vowel type durational differences are also statistically significant for the NH and the HI group. Looking into the separate intelligibility groups, however, we found that for the very high intelligibility group vowel [i] is not significantly shorter than vowel [u], although they are both significantly shorter than [a]. Hence, the durational difference between [i] and [u] is not significant for this group, whereas it is for the NH and the other two intelligibility groups. However, these two vowels are not that different in terms of height. In the HI literature, less effect of intrinsic vowel duration in deaf speech has been noted by McGarr & Harris (1980) in a case study. However, the deaf speaker did not differentiate between [i] and [a] durations which could be considered a more deviant pattern compared with the universal intrinsic vowel duration pattern (Lehiste, 1970). That speaker was judged as fairly intelligible and was thus less intelligible than our very high intelligibility group.

Furthermore, the very high intelligibility group of our study displays the longest vowel durations of all groups. As a result, this group demonstrates the greatest differences in terms of vocalic duration in relation to the NH group. The group with the shortest durations, most resembling those of the NH vowels, is the high intelligibility group. The medium intelligibility group shows vowel duration values in-between those of the other two intelligibility groups. These results suggest that the relationship between speech intelligibility and segmental duration is not necessarily 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., Monsen, 1974; McGarr & Löfqvist, 1982; Stathopoulos et al., 1986; Samar et al., 1989; but see Robb & Pang-Ching, 1992).

6.2.2. Stress and syllable position

One timing abnormality referred to frequently in the literature is associated with the difficulty displayed by speakers with HI to cue stress via vowel duration variation. Some studies report restricted durational shortening in unstressed vs. stressed syllables (Stevens, Nickerson & Rollins, 1978; Osberger & Levitt, 1979; McGarr & Harris, 1980). Conversely, excessive duration differences due to stress have also been found in HI speech (Reilly, 1979, for American English; Barzaghi & Mendes, 2008, for Brazilian Portuguese). According to our data, statistically significant durational shortening is evident for both the NH and the HI group, although the difference is slightly more pronounced (by about 10% overall) for the NH group. Similar results have been reported for vowel duration vs. stress in Greek by Nicolaidis & Sfakianaki (2007). Unstressed vowel shortening is well documented in Greek NH speech (section 2.4.1). Hence speakers with HI participating in this study follow the normative pattern of stress-induced durational shortening. In addition, the pattern of durational shortening in the absence of stress progresses in the form of [i] > [u] > [a] for both groups (see section 4.3.3. for percentages). This pattern is associated with high vowel reduction in the unstressed condition, a common phenomenon in NH speech reported for Greek and for other languages (Dauer, 1980b; Nicolaidis & Rispoli, 2005; Baltazani 2007). The vowels in our experiment were located between voiceless consonants, an environment especially favourable for high vowel reduction. Hence the increased shortening of [i] and [u] relative to [a] in the unstressed condition is expected in NH speech and our data shows that the pattern is demonstrated in both NH and HI speech.

Regarding vowel duration and position in the syllable, we found that, for both the NH and the HI group, vowels in the second syllable are always significantly longer than their counterparts in the first syllable, but the duration difference due to position is almost twice as prominent in the NH group. More specifically, [i] is longer when located in the second syllable by 41% for the NH and by 24% for the HI, [a] is longer by 32% for the NH and by 15% for the HI, and [u] is longer by 41% for the NH and 23% for the HI. When examining stress in combination with syllable position, we observe that stressed vowels are consistently longer in the second syllable for both the NH and the HI group, although again the difference is twice as large for the NH. In particular, we found that [i] is longer when located in the second syllable by 41% for the NH and by 24% for the HI, [a] is longer by 32% for the NH and by 15% for the HI, and [u] is longer by 41% for the NH and 23% for the HI. Unstressed vowels, on the other hand, are significantly shorter in the second syllable position for the NH group, although half as much in comparison with the position effect on their stressed vowels, i.e., NH unstressed [i], [a] and [u] are 18%, 14% and 13% shorter correspondingly when located in the second than in the first syllable. HI unstressed vowels are not significantly affected by syllable position.

We must note here that there was stress clash (adjacent stresses) in cases where stress was placed on the second syllable of the test-word. E.g., in the utterance ‘ˈleʝe paˈpa ˈpali’, there is stress clash between the underlined syllables, i.e., the second syllable of the test-word and the first syllable of the last word of the carrier phrase. Experiments on Greek stress conducted by Arvaniti (2000) also showed stressed vowel lengthening word-finally which the researcher attributes to stress clash (see also Malikouti-Drachman & Drachman, 1980; Nespor & Vogel, 1989). An important finding is that, speakers with HI demonstrate this kind of lengthening, albeit to half the extent observed in NH speech. Arvaniti (1994) maintains that such strategies for resolving stress clash are essential for the preservation of rhythm in Greek.

In contrast, shortening of the unstressed vowels in the second syllable position was found significant only for the NH group. Greek unstressed vowels have been reported as longer when immediately preceding than following a stressed syllable (Dauer, 1980a; Arvaniti, 1994; Baltazani, 2007). A tendency for increased reduction of unstressed vowels in second vs. first syllable position is also noted by Nicolaidis (1997) for the vowels [i] and [a], and by Arvaniti (2000) but only for the vowel [u] among all Greek vowels in her stress clash experiment, and for the tested vowel [a] when stress clash was avoided. Both researchers used disyllables similar to ours, the former researcher in isolation and connected speech, and the latter in carrier phrases. Arvaniti’s observation about limited position vs. stress-induced effects on duration is confirmed by our NH data on unstressed vowel shortening in the second syllable position; as commented above, position effects were found less robust than stress-induced effects in NH speech. For the HI group this effect is even smaller and does not reach significance.

A possible interpretation for the decreased effects on vowel duration due to syllable position in HI speech is the minor perceptibility of position vs. stress-induced lengthening in NH speech (Arvaniti, 2000). Stressed vowel lengthening regardless of syllable position and stressed vowel lengthening due to stress clash are characterised by greater temporal magnitude in NH speech and are thus more audible features that speakers with HI may be able to discern and attempt to reproduce in their speech. Other features, such as word-final unstressed vowel reduction, that may not be as audibly prominent, may not be as easily perceived and are thus not located in their speech. However, further research is required to arrive at safer conclusions.

We subsequently wished to investigate whether stress and position effects influence vowel duration differently for the two genders within each hearing group. More pronounced durational differences between stressed and unstressed vowels have been reported in NH female speech for Swedish (Ericsdotter & Ericsson, 2001). In agreement with these reports, our results showed that, female speakers in both groups differentiate between their stressed and unstressed vowels more extensively than male speakers, but this difference was found twice more pronounced in the HI group. Specifically, stressed second position vowels are longer than stressed first position vowels by 30% for NH male and 79% for NH female speakers, while just by 4% for HI male and 54% for HI female speakers. The reason for this exaggerated difference between HI gender groups is that male speakers with HI lengthen their stressed vowels by half the NH percentage, while female speakers do so at a rate comparable to the normal one. Additionally, female speakers with HI shorten their unstressed vowels more than normal. In particular, HI female vowels are shorter on average when unstressed than HI male vowels, whereas NH female vowels are consistently longer than NH male vowels regardless of stress condition. Hence the NH gender-specific pattern related to stress vs. duration is only partly observed in the HI group.

Regarding the interaction between stress and position effects on duration in the two gender groups, as we mentioned above, the general NH trend is for stressed vowels to be lengthened and unstressed vowels shortened word-finally, although the latter occurs to a lesser degree. This trend is followed by both NH genders with the NH female speakers demonstrating greater stressed vowel lengthening word-finally. As far as the HI group is concerned, this trend is not observed consistently in both genders. More specifically, female speakers with HI demonstrate stressed vowel lengthening word-finally, although to a smaller degree than the corresponding lengthening displayed by NH female speakers, and their unstressed vowels are reduced in the first rather than in the second syllable position contrary to the NH pattern. The male speakers with HI, display very small stressed vowel word-final lengthening (4%) and regarding unstressed vowels they follow the NH pattern. Overall, it seems that NH gender-related trends are to some extent observed in HI speech, e.g., increased stressed vowel lengthening in female vs. male speech. The male speakers with HI of our study seem to face more difficulty following well-established NH patterns, e.g., stressed vowel word-final lengthening, while the female speakers with HI seem to display more normal-like duration patterns, at least those that are more prominent in NH speech. This may be related to their higher average intelligibility level of the female speakers with HI.

6.2.3. Consonantal Context

An examination of the effect of consonantal context on vowel duration in the two hearing groups regardless of vowel position revealed that, for the NH group, close vowels [i] and [u] are significantly longer in the bilabial context, while open vowel [a] is longer in the fricative context but not significantly. For the HI group, vowel [a] was found significantly longer in the fricative context, while the two close vowels were longer in the bilabial context, although the difference did not reach significance.

Looking at consonantal context in combination with syllable position we observe that the differences in consonantal influence on vowel duration between the two groups originate essentially from the pre-consonantal position. Regarding the effect of consonant on the preceding vowel, longer vowel durations before fricatives than plosives have been reported for English NH speech (e.g., Peterson & Lehiste, 1960; Sharf, 1964; Naeser, 1970), while conflicting evidence has been provided concerning vowel duration according to consonantal place of articulation, with some researchers claiming that vowels are longer before alveolar and velar than labial consonants (Crystal & House, 1988; Lehiste, 1976) and others maintaining the opposite (Luce & Charles-Luce, 1985). According to our NH data, the open vowel [a] is significantly longer when located before the fricative, confirming the studies above, while the close vowels [i] and [u] are longer before the bilabial stop rather than the fricative, albeit not significantly. Similar findings to ours are reported by Nicolaidis (1997) for the NH Greek vowels [a] and [i]. The researcher observes that the Greek vowel [a] is longer when followed by the fricative [s] than by plosives [p] and [t], but consonantal effects on the duration of [i] are very small and variable. The author concludes that the quality of the influenced vowel plays an important role in the degree of consonant effect on its duration, a postulation also supported by the present data.

Regarding the HI group, we observe a different pattern of consonant induced duration variation on the preceding vowel. The duration of all three HI first-position vowels increases according to consonantal context as follows: fricative > alveolar stop

> bilabial stop. This differential duration pattern is very prominent in the HI group. On the other hand, post-consonantally the two groups follow essentially the same pattern. All NH and HI vowels are longer after the bilabial stop, although this difference is significant only for the close vowels [i] and [u]. These results are in agreement with studies that document longer vowel durations after stops than fricatives in some languages (e.g., Chung et al., 1999, for Korean), although the influence of the initial consonant has been reported as inconsistent or negligible compared to that of the final consonant on vowel duration in English CVC sequences (Peterson & Lehiste, 1960; Crystal & House, 1988; Naeser, 1970; Port, 1981). For Greek, Nicolaidis (1997) reports that, in connected speech, the longest vowel duration occurs after [p], similarly to current findings.

The HI trend for significantly longer vowel durations before alveolars, and before the fricative in particular, contrasts the NH pattern especially concerning the close vowels. This dissimilarity may be related to the difficulty that speakers with HI encounter during alveolar production or to their differential consonant articulation compared to the norm. Various timing distortions have been reported in connection with the formation of alveolar voiceless plosives by speakers with HI (McGarr & Campbell, 1995; McGarr & Löfqvist, 1982; Metz et al., 1982; Lane & Perkell, 2005). Fricatives, in particular, have been found the least correctly produced consonants in HI speech (Dagenais & Critz-Crosby, 1991). Nicolaidis (2004) observes that the Greek fricative [s] is among the consonants that deviate from normal across all speakers with HI in her study. These production difficulties or aberrations may have an effect on vowel duration as well. Cinefluorographic data from Stein (1980) indicates that the voice offset of vowels is frequently timed inappropriately relative to the production of voiceless final consonants by speakers with HI. This may result in a deviant pattern of vowel duration as a function of the type of the postvocalic consonant (McGarr & Campbell, 1995), a claim supported by our data as well. The difference from the NH pattern is especially evident in close vowels [i] and [u]. Overall, speakers with HI may elongate pre-consonantal vowels in alveolar contexts either because more time is required in anticipation of the production of the alveolars.

Conversely, the closer resemblance of the HI post-consonantal vowel duration pattern to the NH pattern could be associated with the role of mechanical or other physiological constraints related to the carryover influence of the consonant on the duration of the following vowel. These constraints could be accountable for the regularity observed in duration variation in both hearing groups. On the other hand, pre-consonantal vowel duration has been argued to be either entirely learned or to have both a physiological and a learned behaviour basis (Raphael et al., 1977). Moreover, the CV syllable has been claimed to be a fundamental form with stable phase relations among the articulators (Kelso et al., 1986) and to predominate in infant babbling (Locke, 1983). The more normal-like post-consonantal vowel duration pattern observed in speakers with HI of our study could, therefore, be associated with the tighter phasing relationship of the two segments. However, this account is only tentative; a parallel examination of relative timing would be required to shed light on this issue.

One last observation concerns pre- vs. post-consonantal vowel duration in the two hearing groups. As we discussed above (section 6.2.2.), both NH and HI vowels are longer in the second than the first syllable. However, when examining the consonant factor as well, we note that the aforementioned statement refers to all three NH vowels in all consonantal contexts, but not to HI vowels [i] and [a] in the fricative context. HI first- and second-position [i] and [a] vowels are equally long in the context of [s]. According to our data, HI vowels in the fricative context are already quite long pre-consonantally and that effectively may limit substantial lengthening post-consonantally so as to maintain an appropriate rhythm. Additionally, extended constriction durations for fricatives in HI speech have been documented in English (Calvert, 1961) and in Greek (Nicolaidis, 2007). If the fricative is longer than normal and the following vowel is still lengthened due to syllable position, the second syllable could reach a much longer duration relative to the first syllable. Hence a possible reason for avoiding final-position vowel lengthening in the fricative context is attempting to maintain proportionate first- and second-syllable durations in order to achieve an acceptable rhythm (Farnetani & Recasens, 1993).

6.2.4. Vocalic Context

Effects from the transconsonantal vowel were located in both groups. The durational pattern is similar for the two groups as far as the open [a] is concerned, but there are some differences in V-to-V durational effects on the close vowels.

The open vowel [a] lengthens significantly in the context of the two close vowels [i] and [u] for both groups, although the degree of the effect is relatively smaller for the HI group. Significant lengthening effects on [a] from the transconsonantal [i] are also reported by Nicolaidis (1997). Regarding the close vowels, the NH speakers demonstrate significant shortening effects on [u] from [a]. The speakers with HI show relatively more effects than the NH; both HI [i] and [u] are shortened by the open [a], and [u] is also shorter in the context of [i].

As mentioned above, HI vowels are longer than NH vowels in all contexts and positions. HI [a] was found about 23%, [u] 26% and [i] 32% longer than the corresponding NH vowels. The open vowel [a] generally seems to follow the NH pattern more closely, i.e., it shows less prolongation and it displays similar acoustic variability with the NH [a]. McGarr & Campbell (1995) note that speakers with HI may prolong articulator contacts, approximations, constrictions and transitions in order to maximize vibrotactile feedback. However, there is evidence that segment lengthening is not as extensive when visible cues are also available, e.g., during the production of [a]. Open vowel posture durations and opening and closing durations of the jaw and the lower lip comparable to NH durations have been documented in a number of studies (McGarr & Campbell, 1995). Thus, it is possible that the involvement of the visible lip and jaw in the articulation of open vowel [a] may play a role in its more normal-like V-to-V durational pattern. Additionally, we have found that the normal intrinsic vowel duration pattern is followed by the HI group of the present study (see above, subsection 6.2.1). V-to-V lengthening effects on [a] from the close vowels is indicative of a compensatory strategy displayed in the speech of both the NH and the HI group of this study. This strategy has been associated with the maintenance of relatively stable disyllable duration and of normal speech rhythm in NH speech (Lehiste, 1970). Concerning the close vowels, the overall V-to-V pattern is similar for the two groups, but more effects reach significance for the HI group probably due to the fact that HI close vowels are longer, therefore allowing for more extensive shortening than the already quite short NH close vowels.

6.3. Consonant-to-Vowel Coarticulation

As expounded in earlier sections (section 2.2.1.3.), according to the DAC model of coarticulation, the degree of articulatory constraint of the intervocalic consonant plays an important role in the magnitude, temporal extent and direction of C-to-V effects (Recasens et al., 1997). A highly constrained consonant, i.e., a consonant with high demands upon the tongue dorsum, is coarticulation resistant and hence coarticulation aggressive (high DAC value), inflicting large C-to-V effects on adjacent vowels. However, the size and extent of the effects also depends on the nature of the vowel, with highly constrained vowels, such as the high front [i], being less susceptible to consonantal influence compared with low or back vowels (section 2.5.2). The foregoing mostly applies to consonantal effects along the F2 dimension; F1 coarticulatory patterns have been found to reflect trends in both lingual and jaw articulation (section 2.2.1.5). In the section below we discuss the results regarding C-to-V coarticulation in light of the DAC model. We, thus, investigate if predictions based on the DAC model account satisfactorily for C-to-V effects in NH Greek speech, and more specifically, for effects from the alveolars [t] and [s] on vowels [i], [a], [u] at the temporal midpoint, but also, and more importantly, examine the extent to which HI speech follows these NH coarticulatory patterns.

6.3.1. C-to-V Coarticulation in HI vs. NH Speech

Regarding the F1 dimension, C-to-V effects from the two alveolars are not significant for the NH group. These results are in line with Keating et al. (1994) who report no significant vowel variation in height due to consonantal context in English as well as with Farnetani & Faber (1992) who do not locate significant effects on jaw height from the intervocalic consonant in Italian. They also agree with ultrasound measurements that show small variability in vowel lingual height due to consonantal context (Zharkova, 2007). Although effects did not reach significance for the NH, a trend for vocalic raising, i.e., higher jaw/tongue position, in the environment of the fricative is observed, especially anticipatorily. A raising effect from the fricative is in accordance with Mooshammer et al. (2007) who report low tongue tip position but relatively high jaw position for /s/ as opposed to low tongue tip position accompanied by a low jaw position during the production of other alveolar consonants in /aCa/ sequences. In a recent EMA study including all three Catalan point vowels, Recasens & Espinosa (2009) document slightly larger effects on [a] relative to [u]; these sounds involve raising of the tongue tip and blade in the [s] environment. In addition, Recasens & Pallarès (2000) found small C-to-V effects, similar across consonants, on [i], but large raising effects on [a] in Catalan[32]. Overall, our finding regarding the small consonantal effect on vowel height seems to be in agreement with Lindblom's (1983) proposal that consonants vary their jaw height according to that of adjacent vowels but vowels do so to a much lesser extent (section 2.2.1.5).

For the HI group, C-to-V effects along the F1 axis are also small and the overall pattern shares a lot of similarities with the NH one. However, the aforementioned trend observed in NH speech for vocalic raising in the fricative context is statistically significant in HI speech. HI low vowel [a] was found significantly more raised both pre- and post-consonantally in the fricative compared with the bilabial context. In addition, vowels [a] and [u] were found more raised by the fricative than by the alveolar stop pre-consonantally. The vowel [i], although displaying a similar trend, was not significantly raised by any alveolar consonant, since it already has a high position.

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[32] Although both the present study and that of Recasens & Pallarès (2000) are acoustic, methodology differs. We locate statistical significance of C-to-V effects induced by alveolars in comparison with the bilabial context at the temporal midpoint of the two sequences, whereas Recasens & Pallarès compare effects within the same sequence, that is, F1 values near V1 offset and V2 onset with the steady-state value of that sequence corresponding to averages across repetitions for each speaker (p. 504).

Consonantal effects on NH vowels along the F2 dimension were found significant on vowels [a] and [u], whereas the high front vowel [i] does not show appreciable effects. Additionally, effects are of greater magnitude for [u] than [a]. Minimal consonantal effects on [i] in the environment of [t] and [s] are attributable to the compatibility of tongue body placement between the close vowel and the two coronals as also noted in Nicolaidis' (1997) EPG study that renders similar findings. Our results are also consistent with Recasens & Espinosa's (2009) findings of considerable fronting for back vowels [a] and [u], but not [i] in Catalan. The researchers also report more effects along the horizontal dimension for [u] compared to [a]. As for [i], there is no significant fronting from the alveolars as indicated by our data, but a significantly more back realization of post-consonantal [i] is observed in the fricative as opposed in the alveolar stop context. A similar tongue retraction during [i] as a function of [s] is also noted by Recasens & Espinosa (2009)[33].

According to our NH data, both alveolars cause substantial fronting to the central vowel [a] and the back vowel [u]. A comparison between the relative coarticulatory aggression of the two alveolars did not reveal statistically significant differences, although a trend for slightly more prominent fronting from the alveolar stop [t] can be discerned post-consonantally for [a], whereas [u] is more anterior in the fricative context in both syllable positions. Nicolaidis (1997) makes a similar observation based on EPG data of Greek NH speech about the increased coarticulatory influence of [t] vs. [s] on [a], although in that study the difference is located pre-consonantally. Recasens (1990), correlating EPG and acoustic data of Catalan NH speech, reports large effects of tongue dorsum fronting in symmetrical CVC utterances from dentals and alveolars on vowels [a] and [u] in the progression

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[33] No comparison can be carried out between relative effects of [t] and [s] in Catalan based on that study, as it did not include [t].

[s] > [ʃ] > [t]. He attributes the relatively larger effects in front dorsum activity from [s] and [ʃ] compared with [t] to the high requirements on the shaping of the tongue body in fricative production. EPG studies in Greek (Nicolaidis, 1994, 1997) have shown that the Greek fricative is realized less anteriorly ranging from a retracted alveolar to postalveolar, while the constriction for [t] can be further forward in the dental region (section 2.2.4). Thus, slightly more fronting on [a] from the dentoalveolar [t] relative to an alveolar to postalveolar [s] can be expected. Moreover, the aforementioned tongue retraction during the production of [i] occurs due to the fricative, while the alveolar stop causes a slight fronting relative to the bilabial, providing more evidence towards a more posterior constriction during [s] than [t].

NH consonantal effects seem to be slightly more prominent in the carryover direction especially for vowels [i] and [a]. Post-consonantally, vowel [a] assumes a more anterior position in the context of both [t] and [s], while vowel [u] does so in the context of [s]. Vowel [i], when disyllable-final, displays retraction in the context of [s]. Based on the foregoing, and since no significant movement was located in terms of height as discussed above, there appears to be some degree of centralization post-consonantally. Nicolaidis (1997) also located greater anterior displacement and raising during post-consonantal [a] especially at the midpoint and end of the vowel and less anteriority and raising for [i] in her EPG study of NH Greek speech. The author comments that articulatory distance between [i] and [a] is greater in the pre-consonantal position in terms of lingual anteriority, while their distance in terms of height remains stable. Our acoustic data seem to reflect these EPG findings. The DAC model does not make clear predictions regarding the directionality of coarticulatory effects of the alveolars on [i] (Recasens, et al., 1997). However, a prominence of carryover effects of [s] and [n] is observed, in line with our results, attributed to inertial requirements associated with the raising of the tongue dorsum during the high vowel [i]. Regarding the vowel [a], the DAC model predicts favouring of the anticipatory component by fricatives [s] and [ʃ] due to the tightly controlled apical activity during their formation. However, as mentioned above, the Greek fricative has been found more variable and thus its production seems to be governed by differential demands. Consequently, mechanico-inertial constraints related to tongue dorsum activity during the production of the /sa/ sequence could take precedence and result in a slight prominence of carryover effects on [a].

The HI F2 C-to-V coarticulatory pattern presents a lot of basic similarities with the one described above for the NH group. The general observation about the manifestation of significant effects on [a] and [u] but not on [i] from the alveolars is also true for the HI vowels. Nevertheless there are some essential differences in the effects on each vowel between the two groups. Firstly, the size of C-to-V effects is overall smaller for the HI than the NH group. Less pronounced C-to-V effects in HI have been reported by various researchers, i.e., less robust influences between consonant and vowel reflected in restricted vowel F2 transitions (Monsen, 1976c; Rothman, 1976), less distinction between vowel environments in terms of centroid values and F2 differences (Waldstein & Baum, 1991; Baum & Waldstein, 1991; Ryalls et al., 1993), less C-to-V coarticulation on both the schwa and stressed vowels [i], [u] and [a] (Okalidou, 1996; Okalidou & Harris, 1999) and smaller vocalic effects on Greek consonants (Nicolaidis, 2007) (section 2.3.4).

The decreased coarticulatory magnitude in HI speech has been attributed to lesser differentiation of HI vowels (Waldstein & Baum, 1991; Okalidou & Harris, 1999). Consequently, a direct comparison between the absolute size of NH vs. HI coarticulation effects is not valid, as the F2 range of HI vowels is already restricted

(Okalidou, 2002). Nevertheless, a comparison between the number of contexts displaying significant coarticulation effects in HI vs. NH speech reveals that, overall, the HI group demonstrates C-to-V coarticulation in fewer contexts than the NH group. In addition, the difference between effects induced by the fricative vs. the alveolar plosive on vowels [a] and [u] is greater for the HI than the NH group. More specifically, fronting effects from the two alveolars on the central low HI [a] (the vowel among the three that most resembles its NH counterpart -see above 6.1.1.), are not significant in both directions, similarly to the NH [a], but only in the anticipatory direction. Additionally, the HI high back [u] that was found already significantly fronted in the bilabial context, still displays significant fronting effects from the fricative in both directions, but the alveolar stop causes significant fronting only anticipatorily. Moreover, the fricative induces a significantly more anterior production of [u] than the alveolar stop for the HI, whereas for the NH group this trend, although discernible, was not statistically significant. Finally, C-to-V effects on HI [i], a vowel located more posteriorly in the bilabial context than the NH counterpart, are not substantial, similarly with effects on the NH [i]. However, the post-consonantal NH [i] displays a significant retraction in the fricative environment that is not significant for the HI [i]. All the above suggest fronter placement and differential coarticulatory aggression of the fricative relative to the alveolar stop in HI speech.

Concerning coarticulatory directionality in HI speech, an opposite pattern to the NH one emerges, in that the anticipatory component is clearly predominant in C-to-V effects from both alveolars. As mentioned above, no significant carryover effects were located on [a], while only the fricative induces carryover effects on [u]. Effects on [i] are nonsignificant in either direction. Consequently, HI [a] and [u] are more fronted in the pre-consonantal position contrary to NH [a] and [u] that generally receive more fronting effects in the post-consonantal position. Direct comparison of our results with HI directionality patterns reported in other studies is not possible, as, to our knowledge, studies that have examined coarticulation in relation to direction of influence differ from ours in terms of type of effects and nature of vowels. For example, Waldstein & Baum (1991) and Baum & Waldstein (1991) have looked at coarticulatory directionality in V-to-C effects, and more specifically, anticipatory and carryover lip-rounding effects of [u] on consonants [ʃ], [t] and [k]. They found that anticipatory effects are of a lesser magnitude and shorter temporal extent than normal, whereas carryover effects are of a comparable size and extent to normal. This finding was attributed to the different nature of anticipatory vs. carryover effects, i.e., the former reflecting planning and the latter being indicative of mechanical constraints. The present study does not look into V-to-C effects of lip rounding, but rather C-to-V fronting and raising effects which are different in nature. Moreover, Okalidou & Harris (1999) investigate C-to-V effects on schwa and the three point vowels [i], [a], [u], but effects on schwa are examined only anticipatorily, while effects on the point vowels are examined only in the carryover direction. Hence a directionality pattern comparison is not possible.

The prevalence of the anticipatory component in HI C-to-V coarticulation as well as the extensive fronting and raising in the fricative context may be in part attributable to the differential articulation of alveolar consonants, and especially the fricative, by the HI speakers. As expounded in an earlier section (section 3.2.5.2), the alveolars present various distortions in the speech of the participants with HI. The fricative [s] is very frequently realized (a) more anteriorly, (b) as the palatal [ʃ] or [ç] or (c) as a sound between [s] and [ç], and the alveolar stop is often affricated or produced with a retracted constriction. Nicolaidis (2004), with the use of EPG, provides a detailed description of deviant consonantal articulation, especially of the fricative [s], in the speech of four Greek speakers with HI, two of them also participating in the present study[34]. An extended anterior constriction of [s] and/or a retracted constriction of [t] by the speakers with HI could result in a more pronounced difference in fronting than normal between the two alveolars. At the same time, a more "extensive involvement of the tongue dorsum in the articulation [of the fricative] resulting in […] a constriction distributed along the whole of the palatal surface" (Nicolaidis, 2004: 425) could require a higher mandible position and contribute to increased raising (lower F1) in the HI fricative environment, as mentioned above.

The foregoing could also provide a possible interpretation for the preference of the anticipatory component in HI C-to-V effects in the contexts under examination. According to Recasens et al. (1997), fricatives [s] and [ʃ] as well as other consonants with high manner requirements exert strong gestural anticipation in the [a] context[35]. Mechanico-inertial constraints associated with the apical activity demanded of the tongue dorsum during fricative production in the [a] context take precedence, hence the emphasis to the anticipatory component. Therefore, the more constrained HI fricative, in terms of palatal contact, may favour the opposite direction than that preferred by a more variable NH fricative like the Greek [s]. Moreover, the salience of anticipatory effects is also reflected in the durational pattern discussed earlier (section 6.2.3). We observe that the HI post-consonantal [a] and [i] are not longer than their pre-consonantal counterparts in the fricative context as it occurs in NH sequences. This occurrence may be related to additional time needed in order to prepare for a

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[34] Subjects HI_01, HI_02 and HI_04 also take part in Nicolaidis' EPG studies (2004, 2007).

[35] The [u] context is not examined in that study.

more demanding fricative constriction and it is observable in both high and low vowels.

Overall, the vowel sensitivity pattern to consonantal effects follows the same order for both the NH and the HI group. In the F1 axis, vowel raising decreases in the order [a] > [u], [i], and in the F2 axis vowel fronting decreases in the order [u] > [a] > [i]. Therefore, the high front vowel [i] displays a higher degree of constraint compared with the back vowels[36] and receives the least effects among the three point vowels in both dimensions due to its articulatory proximity to the alveolars. This finding is in line with the DAC model that predicts negligible or small effects on vowels from synergistic consonants of a similar DAC value (Recasens et al., 1997). Concerning the relative size of the effects on [a] vs. [u], [a] receives larger raising effects and [u] larger fronting effects as expected based on their articulatory distance from the alveolars. Back vowels show more coarticulatory susceptibility at tongue regions not directly involved in their constriction formation. According to Recasens & Espinosa (2009:2290), "variability at tongue dorsum surface occurs mostly vertically for /a/ presumably since this pharyngeal vowel allows for little room for backward tongue body movement, and antero-posteriorily for /u/, which has been attributed to contraction of the posterior genioglossus muscle (Perkell, 1990)". The authors mention that dentoalveolars and alveolopalatals cause tongue front raising and stretching to [a] and [u]. These coarticulatory trends are observed in both hearing groups, albeit to different degrees. Based on the foregoing evidence, although the HI [s] generally presents a lot of articulatory variability across speakers (Nicolaidis, 2004), it seems that its various realizations are more constrained than normal.

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[36] As mentioned earlier, Greek [ɐ] is central. The term "back vowels" is used here so as to group the two vowels [ɐ] and [u] as "non-front" as opposed to the front vowel [i].

6.3.2. Stress effects on HI vs. NH C-to-V Coarticulation

Regarding the F1 dimension, stress does not significantly influence NH C-to-V coarticulation in any vowel context. In contrast, the unstressed HI [a] receives significant C-to-V effects from the fricative, while its stressed counterpart does not. Thus, lack of stress allows more raising of the tongue and/or jaw in the environment of the fricative for the HI speakers. Increased changes along the F1 than the F2 due to stress across consonantal contexts have been reported for speakers with HI (Nicolaidis & Sfakianaki, 2007; Barzaghi & Mendes, 2008); moreover, as already mentioned, the more constrained realization of the HI fricative, could induce additional raising effects on the unstressed HI [a]. Conversely, lack of stress does not seem to favour increased raising effects on NH vowels from the alveolars. The degree of raising effects as a function of stress and consonantal context on Greek NH [a] and [i] were also found small and variable respectively by Nicolaidis (1997).

In the F2 dimension, stress was found to significantly influence both NH and HI coarticulation, but to a different degree. Concerning the NH group, all three vowels, when unstressed, receive larger C-to-V effects from [t] and [s]. This finding is in accordance with postulations about greater contextual assimilation in the unstressed condition (Fourakis, 1991; Lindblom, 1963; Moon & Lindblom, 1994) and in line with Koenig and Okalidou (2003) who report greater consonantal effects on unstressed Greek vowels. More specifically, according to our data, lack of stress allows for more C-to-V coarticulation in all contexts, except for [s]-to-[i] effects which are not significant in either stress condition. Increased lingual anteriority of [a] and [i] in the context of [t] and [s] due to lack of stress is also documented by Nicolaidis (1997), although the effect of stress on C-to-V coarticulation on [i] was found variable. Similarly, stress effects on [i] F2 coarticulation were not as robust in both alveolar contexts as those on [a] and [u] in our data as well.

For the HI group, stress plays a less important role in C-to-V coarticulation. Our conclusion is based on within-group comparisons and not by directly comparing absolute NH vs. HI coarticulation magnitudes. This finding is in line with our expectations based on the literature mentioned above, reporting less stress effects on the F2 axis in various consonantal contexts. Firstly, C-to-V effects on HI [i] are not significantly larger in the unstressed condition. Secondly, the HI [u] is not consistently more fronted in the alveolar context when unstressed, as opposed to the NH [u]. Thirdly, HI [a], similarly to the NH [a], is significantly more fronted when unstressed. However, lack of stress seems to cause C-to-V effects of a similar magnitude from both alveolars on the NH [a], whereas C-to-V effects on the HI [a] are larger in the fricative context. This finding, in combination with the increased raising effects on unstressed HI [a] from the fricative, suggests that absence of stress plays a more important role in the fricative vs. the alveolar stop for the HI [a], while no such differential stress influence as a function of consonantal context is discerned for the NH [a].

As discussed earlier (section 6.2.2.), the differentiation between stressed and unstressed HI vowels in the bilabial context is somewhat smaller than that found for the NH. This could contribute to a less pronounced impact of stress on alveolar contextual effects since C-to-V effects are measured using the bilabial context as a base. Additionally, the increased temporal distance between HI consonant and unstressed vowel could play a role in weakening the coarticulatory influence of consonantal context at vowel midpoint compared with C-to-V effects on the shorter NH unstressed vowels. Moreover, it is evident that the fricative induces relatively more C-to-V effects than the alveolar stop on HI vs. NH unstressed vowels. This finding could be related to the aforementioned more constrained production of the HI vs. the NH fricative. In line with the DAC model, more constrained consonants induce larger C-to-V effects and thus the HI fricative causes relatively more extensive fronting compared with the alveolar stop on unstressed HI vowels, while this differential influence is not as pronounced on unstressed NH vowels.

6.4. Vowel-to-Vowel Coarticulation

As expounded earlier (section 2.2.1.4.), according to the DAC model, "the relationship between coarticulatory sensitivity and DAC becomes more complex when V-to-V effects are accounted for [compared with C-to-V effects]" (Recasens et al., 1997:546). The reason is that the magnitude and size of V-to-V effects in VCV sequences is associated with tongue body requirements for the production of both the adjacent consonant *and* the opposite vowel (Recasens, 1999). Hence, less V-to-V effects are expected to manifest in the fixed [i] context than in the context of the back vowels [a] and [u]. Additionally, the identity of the intervocalic consonant is expected to promote or block V-to-V effects; the higher the degree of tongue-dorsum contact required for the production of the consonant the less the magnitude and extent of V-to-V coarticulation (Recasens, 1984b). Thus, we expect more transconsonantal effects over the unconstrained bilabial [p] than the alveolars [t] and [s] (section 2.5.2). In section 6.4.1. below we discuss V-to-V effects at V_1 offset (anticipatory) and V_2 onset (carryover) in the three fixed vowel contexts [i, a, u] over the three consonants [p, t, s] in HI vs. NH speech, while the temporal extent of V-to-V effects in HI vs. NH speech, measured at three points in each vowel, namely, onset, midpoint and offset of both V_1 and V_2, is commented on in section 6.4.2. Subsequently, the influence of stress, gender and intelligibility on NH and HI coarticulation is discussed in three separate sections.

6.4.1. V-to-V Coarticulation in HI vs. NH Speech

In the F1 axis, articulatory distance is greater between the close vowels [i, u] and the open vowel [a]. We, therefore, expect V-to-V effects to be more substantial in pairs consisting of one close and one open vowel, e.g., /aCi/-/iCi/ but not /uCi/-/iCi/.

In the fixed [i] context, we observe significant [i] lowering only from [a] across the bilabial in the carryover direction for the NH group. Our results are in agreement with Recasens & Pallarès (2000), who report small V-to-V size effects along the fixed [i] vowel overall, but larger carryover than anticipatory effects from [a] through the bilabial [p]. Hence, according to our data, V-to-V effects reach significance only in the pair /api/-/ipi/ for the NH, while effects are minimal in all cases for the HI group. In the fixed [u] context, we find the expected lowering of [u] from the open [a] over the bilabial in both the anticipatory and the carryover direction for the NH group only, while the HI group again shows no significant effects. Hence, significant V-to-V effects occur in pairs /upa/-/upu/ and /apu/-/upu/ for the NH. We also detect significant bidirectional dissimilatory effects from [i] on [u] over the bilabial for the NH group, i.e., [i] causes significant lowering to [u] across [p] in NH speech.

This occurrence could be partly attributed to differences in jaw opening between [i] and [u]. According to Gay (1974:262), [i] is realized with a more open jaw than [u] "probably to make room for the bunching of the tongue". This difference in jaw position between the two vowels may be more pronounced in the bilabial context because the tongue is least involved and the jaw has a lower position than during alveolar stop and fricative production (Keating et al., 1994). Moreover, [u] has been found higher than [i] due to lip rounding (Perkell, 1969). In addition, this dissimilatory effect may also be related to an attempt for perceptual differentiation, e.g., in /ipu/ sequences [u] is significantly fronted, hence maintaining a lower position could be considered an effort to ensure perceptual clarity.

A third possible explanation for this dissimilatory phenomenon has to do with the trough effect, a momentary deactivation of the tongue musculature responsible for the surrounding vowel production (Bell-Berti & Harris 1974, Gay 1975). Troughs have also been found for lip movements in /uCu/-sequences (Bell-Berti & Harris 1974; Perkell 1986). The trough appears during the oral closure of the bilabial. Fuchs, Hoole, Brunner & Inoue (2004) claim that mostly /VpV/-sequences exhibit tongue lowering during bilabial closure. In our data, this interpretation could entail the appearance of a trough in /upu/ sequences. In this case, the deactivation of the tongue and lip musculature described above might influence the production of [u] in /upu/ near the consonant (onset and offset). Tongue lowering during bilabial closure may cause [u] to be more raised than usual. Thus, the [u]-lowering effect found in /upi/ or /ipu/ vs. /upu/ sequences may be the result not of a dissimilatory lowering influence from [i], but of the higher production of [u] in /upu/ due to the trough effect. An interesting observation is that although this effect is quite strong in NH speech -it reaches the other end of both V_1 and V_2 and it only appears in the bilabial context-, it is not observed in the corresponding HI sequences. Absence of similar evidence in HI speech may suggest differences in the motor organization of gestures, as the trough effect has been associated with the aerodynamic constraints for the consonant and the coarticulatory influence of lip rounding (Fuchs et al., 2004). This issue holds great interest and merits further investigation.

In the fixed [a] context, the expected raising of low [a] from high vowels [i] and [u] is evident for both the NH and the HI group across not only the bilabial but also the two alveolars. For both groups, the high back vowel [u] seems to cause significant raising to [a] in more consonantal contexts and of somewhat greater magnitude than does the high front [i]. This occurrence could be related to perceptual clarity purposes. Prominent transconsonantal fronting effects are induced by [i] as opposed to minimal effects along the F2 caused by [u]. Thus, for both groups, [u] vs.

[i] may have a relatively larger influence on [a] along the F1, but [i] causes significant effects on [a] along both the F1 and F2 axes. An additional factor contributing to slightly less raising effects from [i] than expected may be associated with the acoustic variability displayed by this Greek vowel. Similar results have been reported for the Greek [i] by EPG (Nicolaidis, 1997) and acoustic (Asteriadou, 2008) studies (section 2.2.1.1).

It is noteworthy that the HI group displays significant V-to-V effects in as many or even more contexts than the NH group, e.g., /ata/-/ati/, /apa/-/apu/. A comparison between the effects of the two groups revealed that the HI group presents statistically smaller effects only in /apa/-/upa/ and /ata/-/uta/ pairs, while in other contexts where both groups show significant effects, there is no statistical difference between the two groups. Hence, the HI group displays equally strong coarticulatory influences as the NH group in most contexts.

As far as consonantal environment and coarticulatory direction in the [a] context is concerned, for the NH group effects from both high vowels are larger over the bilabial in the carryover direction, while anticipatory V-to-V effects seem to be favoured across the alveolars, with the fricative being more permissive than the alveolar stop. For the HI group, anticipatory effects from both high vowels seem to be favoured across [t], while carryover effects are larger across [p] and [s]. Overall, the carryover component is more prominent than the anticipatory component in NH coarticulation, whereas this preference is less obvious in HI coarticulation.

Regarding NH speech, larger F1 V-to-V effects in the fixed [a] than the fixed [i] context with relative prominence of the carryover component for both fixed vowel contexts are also reported by Recasens & Pallarès (2000). Moreover, Mok (2011) finds that, in Thai, vowel [a] is more susceptible to V-to-V coarticulation in F1 than high vowels [i] and [u]. F1 formant frequency reflects both vertical jaw and tongue position. The high position assumed by the mandible and tongue during close vowel production does not seem to allow significant influence in height from the opposite vowel; an intervening consonant also formed with a high jaw, such as the alveolar [t] or [s], would diminish V-to-V influence even further. The bilabial [p] does not maintain a jaw height as consistent as that of alveolars (Tuller et al., 1981) and demands less jaw (Lee, 1994) and tongue involvement in its production, thus allowing more vowel-dependent height influence across. However, in the fixed [a] context we do observe significant bidirectional V-to-V effects across the two alveolars; more specifically, in the anticipatory direction the two alveolars seem to allow for more effects than the bilabial. In these contexts, i.e., /ati/-/ata/, /asi/-/asa/ and /atu/-/ata/, /asu/-/asa/, the low vowel [a] undergoes more raising *anticipatorily* due to the high vowels [i] and [u] when the intervening consonant is alveolar rather than bilabial. A possible interpretation is that when the second syllable (CV_2) is composed of an alveolar + high vowel (e.g., /a*ti*/, /a*si*/) the jaw and tongue are both at a higher position than when the second syllable consists of a bilabial + high vowel (e.g., /a*pi*/). Hence, in the first case, the low [a] receives an increased raising influence originating from a whole syllable that needs to be formed with a higher jaw/tongue body position, whereas, in the second case, the raising effect mainly comes from the high vowel and is not as pronounced.

The fact that such an observation is not made in the carryover direction, i.e., effects in /ipa/-/apa/ are larger than in /*it*a/-/ata/ or /*is*a/-/asa/, may be related to the greater cohesiveness of the consonant with the following rather than with the preceding vowel, i.e., CV_2 vs. V_1C (Kozhevnikov & Chistovich, 1965; Tuller & Kelso, 1990; Lindblom et al., 2002; Zharkova & Hewlett, 2009). In keeping with this notion, the sequence alveolar + high vowel (CV_2) is bound to cause more raising to the preceding [a] than high vowel + alveolar (V_1C) to the following [a]. More cohesional binding of the CV unit is maintained by Sussman, Bessell, Dalston & Majors (1997) who showed that, in VCVs, CV locus equation slopes remain unchanged across different initial vowel contexts, suggesting a less pronounced carryover influence on the CV syllable. Similar findings of stronger impact on the trans-syllabic V_1 by V_2 than vice versa are reported by Mondarresi et al. (2004) who claim that their results suggest that CV cohesion plays a role in determining bidirectional coarticulatory effects in open syllables.

An explanation for the relative prominence of the carryover raising effects in /ipa/-/apa/ and /upa/-/apa/ sequences vs. the nonsignificant anticipatory raising effects in /api/-/apa/ and /apu/-/apa/ sequences can be provided considering the interarticulator programming data of Löfqvist & Gracco (1999). Their data show that the tongue movement trajectory is larger in /ipa/ than in /api/ sequences[37]. Moreover, Šimko, Cummins & Beňus (2011) argue that, in a sequence such as /ipa/, at the beginning of the transit from /i/ to /a/ the already high position of the tongue and jaw means that the lip aperture is smaller, allowing the consonantal gesture to start later or be effected with less force. A less forceful consonantal gesture in /ipa/ may allow more V-to-V effects than a more forceful closure in /api/. This account seems to fit to our data concerning sequences with both high vowels.

Our results regarding less V-to-V effects on the high vowels [i] and [u] than the low vowel [a] as well as greater carryover V-to-V effects over the bilabial than the two alveolars are in accordance with the DAC model, that assigns small DAC values to low vowels and bilabials as they are segments produced with less tongue dorsum

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[37] The same is true for /upa/ vs. /apu/ sequences for three out of four speakers (Löfqvist & Gracco, 1999:1871, Fig. 5).

involvement (Recasens et al., 1997). However, F1 V-to-V effects were found larger across the fricative than the alveolar plosive for the NH group in both directions and the HI group in the carryover direction. This is contrary to the DAC model that predicts greater coarticulatory resistance from [s] than [t] due to frication demands. However, as noted earlier, Greek /s/ displays more variability and thus less constraint in its production than the English /s/ (Nicolaidis, 1997). Tongue positioning and groove width are less critical for Greek /s/ due to the absence of contrastive fricatives in the alveolar region, in line with the linguistic constraint hypothesis put forth by Manuel & Krakow (1984). Nicolaidis (1997) argues that the Greek alveolar /t/, on the other hand, may be more constrained due to the existence of the Greek affricate /t^{s}/ as well as more lingual bracing against the palate. This pattern of consonantal constraint, namely [t] > [s] > [p], emerging from our F1 V-to-V data in the fixed [a] context (since this is the only vocalic fixed context among the three where effects are present across all consonants for both groups) is observed bidirectionally for the NH group, but only in the carryover direction for the HI group.

The speakers with HI demonstrate prominent anticipatory V-to-V effects across [t] along the F1 which may suggest more variable vertical jaw/tongue position during the production of the alveolar stop as compared with the normal one. As commented previously (section 6.3.1.), the fricative induces more C-to-V raising effects than the other two consonants to the [a] for speakers with HI; consequently, an already raised [a] is bound to receive less raising effects from the high vowels [i] and [u]. Moreover, according to Recasens et al. (1997), V-to-V effects diminish as the coarticulatory aggression of the intervocalic consonant increases. A less constrained [t] than [s] along the F1 as produced by speakers with HI may allow more V-to-V effects across the former than the latter, at least anticipatorily as shown in our data.

Therefore, regarding coarticulatory directionality along the F1, V-to-V effects are more prominent in the carryover direction for the NH group, while the HI group does not display an equally strong directional preference; anticipatory effects are significant in more contexts for the HI than the NH group regarding fixed [a]. The tendency for large carryover V-to-V effects, especially across labials, in NH speech reported in the literature (Sussman, MacNeilage & Hanson, 1973; Magen, 1997) has been associated with the slow articulation of the massive jaw. Recasens & Pallarès (2000:503) state that "the finding that F1 vocalic effects generally consistently favour the carryover component is in accordance with the V-to-V component being ruled by the jaw rather than by the tongue". The speakers with HI seem to follow the general F1 normal pattern, but also exhibit differences probably related to differential jaw and tongue height placement during vowel and consonant production. Different topological features, i.e., tongue and lip configurations, found in HI speech may also relate to dissimilarities between NH and HI coarticulatory patterns. Jaw opening is a visible feature, frequently reported as normal-like in HI speech. Many studies have shown that deaf and hearing speakers use similar magnitudes of jaw displacement in vowel production; however, ratios of tongue-to-jaw displacement may differ (McGarr & Campbell, 1995). In addition, tongue configuration has been found less accurate in HI vowels (Crouter, 1963; Subtelny et al., 1987). F1 reflects both jaw and tongue displacement, hence differences in F1 coarticulatory patterns are associated with both articulators as well as differential dynamics and timing in HI speech. There is evidence of similar opening and closing durations of the jaw and the lower lip, and comparable jaw and lip velocities in speakers with NH and HI (Tye-Murray & Folkins, 1990), but also reports of greater displacements and faster tongue tip, jaw and lower lip velocities for speakers with HI (Stein, 1980; Zimmermann & Rettaliata, 1981). These results suggest a dependency on visual articulators, i.e., jaw and lip, in order to perform acceptable articulatory movements due to lack of auditory feedback. According to the EMA study of jaw V-to-V effects in NH speech carried out by Recasens (2002b), V-to-V effects in jaw vertical displacement are not always pronounced in the carryover direction as V-to-V effects in F1 (Recasens & Pallarès, 2000); mandibular V-to-V effects across fricatives [s, ʃ] as well as across the bilabial [p] and the alveolar [n] in /aCa/-/aCu/ pairs favour the anticipatory component[38]. The researcher mentions the possibility that the disagreement observed in directionality between vertical jaw displacement data and F1 data (in NH speech) is associated with articulatory factors other than jaw displacement influencing F1 coarticulation (p. 91). Thus, if jaw vertical displacement is reflected to a greater extent in F1 coarticulatory effects in HI than in NH speech, then a more prominent anticipatory component in the aforementioned contexts can be explained.

In the F2 axis, a general observation holding for both the NH and the HI group is that V-to-V effects are more pronounced in terms of statistical significance and magnitude between the front [i] and the back [u] than between the mid [a] and [i] or [u]. This result is expected as the articulatory distance between the two high vowels is maximum along the F2. The DAC model predicts more coarticulatory resistance and aggression for the palatal vowel [i] than the back vowels, due to the entire tongue body being highly constrained during the production of the former (Recasens & Espinosa, 2009). A relatively higher coarticulatory aggression from [i] on the two back vowels than vice versa is observed in our V-to-V NH data. In agreement with our findings, greater coarticulatory aggressiveness for [i] is also documented in the literature (American English: Gay, 1977b; Butcher & Weir, 1976; Catalan and

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[38] See Recasens (2002:90), Fig. 2.

Spanish: Recasens, 1985, 1987; Recasens et al., 1997; Recasens & Espinosa, 2009; Italian: Farnettani, Vagges & Magno-Caldognetto, 1985; Scottish English: Zharkova, 2007; Thai: Mok, 2011).

Although inducing significant V-to-V effects on the other two vowels, as far as its resistance is concerned, NH [i] undergoes quite substantial backing, especially from [u] in the bilabial context. Large V-to-V effects from [a] [39] on [i] in lingual anteriority have been found with EPG by Nicolaidis (1997) and in F2 lowering by Asteriadou (2008). Both studies report prominence of effects over the bilabial [p], while the acoustic study also documents sizeable effects over the alveolar plosive [t] which is also supported by our results, although effects in the bilabial context are much greater, in agreement with Nicolaidis (1997). Based on the above, the increased variability displayed by [i] in Greek compared with other languages that have more vowels has been attributed to differences in vowel inventory size. According to Manuel & Krakow's (1984) postulation, the Greek [i] is allowed a larger degree of variability as it can occupy a larger part of the relatively sparse Greek vowel space.

A comparison between [u]-to-[i] and [i]-to-[u] coarticulation for the NH group shows that [i] backing occurs mainly over the bilabial and is quite extensive, while [u] fronting takes place across all three consonants, at least in the carryover direction, but is of lesser magnitude over the bilabial. We note that [u] fronting in /*it*u/ sequences is especially prominent probably due to the cumulative effect of both the [i] and [t] fronting as opposed to /*i*pu/ sequences where the consonantal context does not cause further fronting. According to Recasens (1999), facilitation of the lip protrusion gesture is an additional reason for tongue fronting to occur during the production of labial vowels, e.g., [u] and [o], in the vicinity of dentoalveolars, e.g., [t].

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[39] A comparison of results concerning [u] coarticulation is not possible as it was not examined in previous studies in Greek. In general, many past studies have concentrated on [i] vs. [a] coarticulation due to their distance in both height and backness.

The HI group follows the NH trend described above regarding [i] aggression, i.e., HI [i] induces significant effects to both [a] and [u]. Additionally, the HI group resembles the NH group in that, HI [i] displays susceptibility to V-to-V effects from the other two vowels. In fact, this susceptibility is increased compared with the NH in number of consonantal contexts, especially concerning [u]-to-[i] anticipatory coarticulation. We observe that speakers with HI show significant [u]-to-[i] effects across all three consonants anticipatorily while such effects only occur over the bilabial for speakers with NH. More specifically, HI effects over the bilabial were found statistically less in size in comparison with NH effects, while effects over the alveolars are significant only for the HI group. Similar results have been reported by Okalidou (1996) and Okalidou & Harris (1999) for anticipatory V-to-V coarticulation effects in American deaf speech. They found that deaf speakers tend to show greater /i-u/ and /i-a/ F2 differences anticipatorily during the schwa in the alveolar /d/ context than hearing speakers, but not in the bilabial /b/ context. Although a direct comparison is not feasible as we examine full quality vowels and not the schwa, our results similarly show that the HI group presents more V-to-V anticipatory effects in fixed high vowel contexts across alveolars, i.e., fixed [i] and [u] contexts, than the NH group.

Concerning the fixed mid vowel [a] context, both groups show significant V-to-[a] effects only from [i] and not from [u] which is expected in terms of articulatory distance. Moreover, effects for both groups are significant only in the carryover direction. [i]-to-[a] effects for the NH group occur across all consonantal contexts in the order [s] > [t] > [p], i.e., the fricative allows the most effects. These results do not seem to be in line with the DAC model, according to which more V-to-V coarticulation is bound to occur across the unconstrained bilabial than alveolars. We observe more carryover fronting of the mid [a] in /isa/ and /ita/ than in /ipa/ sequences. This result can be explained if we consider that in /*is*a/ and /*it*a/ the tongue assumes and remains at a front position for both [i] and the intervening consonant inducing large carryover fronting effects due to articulatory overshoot, while in /*i*pa/ the fronting effect is not accentuated by the consonantal environment. Recasens et al. (1997) report larger carryover [i]-to-[a] effects across the alveolar [n] than the bilabial [p] along the F2, while effects over [s] are slightly less than those over [p] [40]. As mentioned above, the Greek [s] allows for more articulatory variability which could account for the sizeable V-to-V effects across the Greek fricative. Nicolaidis (1997) also documents V-to-V effects over the Greek fricative [s] in her NH EPG data.

The opposite trend is followed by the HI group, in that [i]-to-[a] effects are larger across the bilabial than the alveolar stop, while they do not reach significance across the fricative. This pattern runs counter to the one described above for fixed high vowel contexts, i.e., more coarticulation across alveolars. Hence, regarding the fixed [a] context, the HI pattern falls within the predictions of the DAC model. A possible reason for the difference in [i]-to-[a] coarticulation across alveolars between the NH and the HI group is that the alveolar stop and the fricative have been found more constrained overall in HI articulation (see also section 6.3.1. above). EPG data on Greek HI speech provided by Nicolaidis (2004) show that Greek speakers with HI may produce simultaneous postalveolar and medio/postpalatal constriction for [s], thus producing a more constrained fricative than normal. In the fixed high vowel contexts, however, V-to-V effects are more sizeable across the two alveolars mainly anticipatorily. Therefore, anticipatory effects are significant in /usi-usu/ and /isu-isi/, but not in /asi-asa/ sequences, for the HI group.

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[40] Carryover F2 [i]-to-[a] effects are 112.56 Hz over [n], 81.40 Hz over [p] and 67.20 Hz over [s] in size (Recasens et al., 1997:552, Table II).

According to the aforementioned rationale, the HI constrained fricative should not allow V-to-V effects to occur in the fixed high vowel contexts either. However, the significant effects found in /uCi-uCu/ and /iCu-iCi/ sequences, where the intervening consonant is mainly alveolar, are anticipatory, while in /iCa-aCa/ sequences they are carryover. The syllables of the former type (e.g., /Ci/, /Cu/, where C = [t, s]) are more constrained, as both the consonant and the vowel have high DAC values. According to Recasens (1987:311), “no carryover V-to-V effects are expected to occur for a highly constrained CV_2 sequence”.

In addition to the above, an interpretation put forth in the literature is that certain types of CV syllable are more overlapped for the speakers with HI, thus inducing stronger anticipatory effects. Okalidou and Harris (1999) report larger anticipatory V-to-V effects across the alveolar [d] in HI than NH speech. Based on their findings, the researchers claim that deaf speech is reminiscent of developing speech in certain aspects of gestural patterning. Increased anticipatory coarticulation was also located in the fricative context in the speech of NH 3-6-year-old children in English (Boucher, 2007). Evidence provided by Nittrouer (1993) and Goodell and Studdert-Kennedy (1993) indicates that CV syllables are largely overlapped in early child speech, especially when both the consonant and the vowel gestures engage the same articulatory subsystem, i.e., the tongue. Drawing from the above, Okalidou and Harris (1999:408) claim that “their [deaf speakers’] tongue gestures are less sharply differentiated into the functional subsystems (e.g., tongue tip, tongue dorsum) that are marshaled for production of consonant-vowel gesture sequences”. Our results regarding HI anticipatory V-to-V effects provide supporting evidence for this claim.

Hence, coarticulatory directionality along the F2 seems to differ between the NH and the HI group, in that V-to-V effects mostly prefer the carryover component for the former and the anticipatory component for the latter. Prominence of carryover effects for the NH group lies within the DAC model expectations, for the majority of vocalic and consonantal contexts examined in this study. According to the EMA study of VCV coarticulatory direction carried out by Recasens (2002a), vocalic carryover prevails upon vocalic anticipation in the environment of front lingual consonants (e.g., [t] in our data), because apical anticipation is not particularly salient. Tongue tip and tongue dorsum horizontal movement are presumed to be associated during apical consonant production, while the vertical movement is relatively independent. Additionally, tongue tip and dorsum display more carryover influence than anticipation during [p] and lingual fricative production mostly in sequences without [i] (Recasens, 2002a). In our data, NH V-to-V effects across the three consonants are indeed prominent in the carryover direction in fixed [a] and [u] contexts. In addition to the carryover, salient anticipatory effects appear in the fixed [i] context over the bilabial for the NH, in line with Recasens (2002a). As far as the fricative [s] in particular is concerned, we observe that V-to-V effects are prominent only in fixed non-front vowel contexts, which is in accordance with the DAC model (Recasens, 2002a). The salience of carryover effects in /VsV/ sequences without [i] is explained assuming that, after an unconstrained vowel, anticipation of the lingual gesture for the fricative is not as strong as after the palatal [i]. In addition, it is argued that anticipatory lip protrusion for [u] seems to be blocked by the fricative (Recasens, 2002a). This is confirmed in our NH data, as all anticipatory [u]-to-[V] effects across the fricative in the F2 were found nonsignificant.

Regarding the HI group, coarticulatory directionality differs from the NH pattern especially in the fixed high vowel contexts, where the anticipatory component is much more prominent for the HI than the NH group. As mentioned earlier, HI [t] and [s] are overall more constrained than normal. Most speakers with HI display increased tongue dorsum contact during [t] and [s] production (section 6.3.1. above) (cf. Nicolaidis, 2004). When followed by a high vowel the whole CV_2 syllable tends to become more heavily palatalized in HI speech, rendering strong anticipatory influence on the preceding V_1. Thus, in /u*ti*/-/utu/ and /u*si*/-/usu/ sequences, we observe strong anticipatory effects for the HI group whereas, for the NH group, effects are strong in the carryover direction. Similarly, in the fixed [i] context, the HI group presents anticipatory [u]-to-[i] effects over the two alveolars while the NH group does not. However, salient anticipatory effects over the alveolars occur in /uta/-/utu/ and /usa/-/usu/ sequences as well. Although the low vowel [a] does not normally induce palatalization, epenthesis of the glide [j] sometimes takes place as a transitive sound between the alveolar and [a] in HI speech. In some cases, the syllable [puta] was realized as [put^{j}a] by speakers with HI causing further fronting of [u] anticipatorily.

An overview of V-to-V coarticulation in both F1 and F2 formant frequencies shows that HI high vowels [i] and [u] compared with the corresponding NH vowels are more susceptible to influences from the transconsonantal vowel in tongue front/back displacement than jaw/tongue height movement. Although relatively limited differentiation in lingual position along the front/back axis has been reported between /i/ and /u/ in English (e.g., Stein, 1980), the speakers with HI participating in our study display significant V-to-V effects in the horizontal dimension. Tye-Murray (1987) also reports contextual influences on horizontal tongue dorsum position before the high [i] for two American intelligible deaf speakers. Conversely, the open vowel [a] seems almost equally susceptible in jaw/tongue height displacement for both groups but relatively less influenced in tongue front/back movement for the HI than the NH group. Hence, depending on fixed vowel context, HI speech shows more or less transconsonantal influence than that found in NH speech.

As documented by Harris et al. (1985) using electromyography, the visible articulator, i.e., the jaw, that is mainly associated with the F1, displays a relatively normal activity in HI speech, while the temporal alignment of tongue and jaw activity is more variable than normal which could account partly for differences between HI and NH coarticulatory patterns. An interesting finding of the present study concerns coarticulatory direction; V-to-V coarticulation across alveolar consonants was found more prominent in HI than NH speech in the anticipatory direction, especially in the F2 formant frequency. This result may be related to increased palatalization during alveolar production in HI speech requiring stronger anticipation of the whole CV_2 syllable. This interpretation is in line with Okalidou & Harris (1999) who find more intervocalic anticipatory coarticulation in the alveolar context in HI than NH speech. In a [əCV] sequence produced by deaf speakers, instead of three distinct coproduced gestures, the researchers infer “a single extended gesture” from schwa to vowel accompanied by a transient gesture of elevation and lowering of the jaw/tongue complex for the intervening consonantal constriction (Okalidou & Harris, 1999:408). The undifferentiated tongue gestures in their study are also documented in reduced anticipatory and carryover HI C-to-V effects as compared to effects in NH speech.

However, in our study C-to-V effects are not as reduced; significant C-to-V effects are located on HI [a] and [u] midpoint from the two alveolars. Nevertheless, C-to-V effects are mainly anticipatory, while for the NH group they are significant in both directions. The differential results of the two studies may be associated with subjects’ characteristics and language differences. Although both studies look into profound hearing impairment, the subjects in Okalidou and Harris study have a PTA of more than 106 dB, while the subjects of the present study have a PTA of 91 to 104 dB. This implies different use of residual hearing in each case. In addition, the language under examination is American English in the first case and Greek in the second. Due to these and other differences, e.g., speech therapy protocols, type of schooling, hearing aid use, speakers in the two studies may be assumed to display different articulatory strategies. A major difference is that they produce a fronted [u] in our study, while [u] remains in a posterior position in the Okalidou & Harris study. Moreover, consonant constrictions are characterized as “less adequate than their hearing counterparts in /ədud/ and /ədid/” (Okalidou & Harris, 1999:407); especially in the case of /ədud/, the [u]-target is preserved instead of showing /d/ effects. In the present study, consonant constrictions do not seem to be less adequate, as C-to-V effects are significant, but are different than the NH ones (see section 6.3.1). Speakers with HI in our study seem to produce overall more constrained alveolars than normal, i.e., alveolars with more tongue dorsum contact than normal, which accounts for the strong preference to the anticipatory component in both C-to-V and V-to-V effects. This is also reflected in longer pre-consonantal vowel durations in anticipation of the alveolars and especially the fricative (see section 6.2.3) and by EPG data (Nicolaidis, 2004) revealing more constrained alveolar production for speakers with HI, two of which also particulate in the current study .

6.4.2. Temporal Extent of V-to-V Coarticulation in HI vs. NH Speech

In the above section, NH and HI coarticulatory patterns were discussed on the basis of F1 and F2 V-to-V effects measured at V_1 offset and V_2 onset. In this section we discuss the temporal extent of anticipatory and carryover V-to-V coarticulation in HI and NH speech. For this reason, effects were also measured at V_1 midpoint and onset as well as V_2 midpoint and offset (six points in the disyllable). (See also Appendix 2.4.: Coarticulation Tables, Hearing & Context –F1 and Hearing & Context –F2).

An interesting finding is that, although C-to-V effects are overall significant at vowel midpoint in F1 and F2 frequencies, V-to-V effects barely reach vowel midpoint in either the anticipatory or the carryover direction for both groups. This holds for all vocalic and consonantal contexts for the NH group, while there are few exceptions for the HI group; namely, in [ipa]-[ipi], [ipu]-[ipi] and [ipa]-[apa][41] sequences, significant V-to-V effects in the F2 frequency were detected up to V_1 midpoint or as early as V_1 onset. We note that in all cases the extended effects are anticipatory and they occur in the bilabial context. Hence, the bilabial seems to allow vocalic anticipation that reaches further back in the aforementioned HI disyllables. This result argues against claims for reduced anticipation in HI speech (e.g., Waldstein & Baum, 1991) and is in line with Okalidou & Harris (1999) who report significant V-to-V effects as early as schwa onset for deaf speakers, although their results refer to the alveolar environment only. In the F1 axis, we observe that the NH group shows significant V-to-V effects at the fixed vowel [u] onset and offset, but not at the vowel midpoint in [upu]-[apu], [upu]-[ipu] and [upi]-[upu] sequences. The HI group, similarly, demonstrates effects at the vowel start and end in [asa]-[isa] pairs.

In the alveolar context, significant F2 anticipatory V-to-V effects appear at V_1 midpoint or V_1 onset for the HI group of this study, e.g., in [ita]-[iti] and [isa]-[isi] pairs respectively, but not at V_1 offset. Similarly, in [iti]-[uti] sequences we also note that carryover effects appear at the offset of V_2, suggesting that the alveolar stop does not allow [i] backing from [u] earlier in the vowel. We, thus, observe that in the fixed [i] context, the two alveolars do not allow significant V-to-V coarticulation near

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[41] In [api]-[apa] sequences anticipatory V-to-V effects, although sizeable, are statistically significant at V2 midpoint but not at V2 offset.

consonantal constriction. This occurrence may be related to the stronger palatalization of [i] + [alveolar consonant] mentioned earlier, that resists significant backing from [a] and [u]. Nicolaidis (1997) reports greater effects in lingual anteriority and in some cases lingual raising at the onset than the offset of the pre-consonantal vowel and at the offset than the onset of the post-consonantal vowel in an EPG investigation of NH Greek /VsV/ and /VtV/ sequences. The reverse evolution of effects is interpreted on the basis of large constraints and relative invariance at and near constriction and release for the consonant (Fujimura, 1981). This occurrence is reaching significance only for the HI group in the present study possibly due to increased palatal contact during HI compared with NH alveolar production. In addition, a different technique was adopted in the two studies. Articulatory variability has been found twice as large as acoustic variability (Maeda, 1991) and coarticulation effects are often not reflected in acoustical measurements as in other types of physiological measurements, e.g., cinefluorography (Gay, 1974) and ultrasound (Zharkova, 2007).

As stated above, there is an overall tendency for the vocalic centre to remain relatively uninfluenced from the transconsonantal vowel. This tendency is slightly more pronounced in the NH group, although the HI group follows this general pattern as well. A rather limited range of V-to-V coarticulatory effects has been documented in other studies on normal speech (Gay, 1974, 1977a; Öhman, 1966; Carney & Moll, 1971), although long-range effects have also been reported (Magen, 1989). Recasens et al. (1997) found relatively short [a]-to-[i] F2 effects in both directions (8.00 and 18.00 ms across [p], 2.00 and 12.00 ms across [s]), while [i]-to-[a] F2 effects were extended over [p] anticipatorily (78.00 ms), but quite limited temporally in the carryover direction (18.00 ms), while the opposite holds in the [s] environment (17.44

and 66.00 ms respectively)[42]. Hence, our results are overall in line with Recasens et al. (1997) regarding the temporally limited effects in the fixed [i] context; however, anticipatory effects on fixed [a] over the bilabial and carryover effects over the fricative were not found as temporally extended as reported by Recasens.

According to Recasens (1999), increased gestural conflict and large articulatory distance between consonant and vowel may cause early onset time of C-to-V coarticulation and, as a consequence, later onset time of V-to-V coarticulation. The onset of anticipatory coarticulation, being more influenced by gestural formation, is more immediately related to the constraints of the intervening consonant and can be more precisely predicted, whereas the offset of carryover coarticulation is more variable as it reflects mechanico-inertial contextual factors. Such clear patterns could not be discerned in our data. In agreement with our findings, Fowler & Brancazio (2000) also report that the temporal extent of V-to-V coarticulation in NH American English sequences of the form /əCV/ did not show any indication of modulation due to the degree of coarticulation resistance of the consonant, i.e., /b/, /v/, /ð/, /d/, /z/, /ʒ/ and /g/. Although there were effects on magnitude, the researchers found no differences in the temporal onset of anticipatory V-to-V effects as a function of coarticulatory resistance.

Another reason for lack of effects on the temporal extent of V-to-V articulation in relation to consonantal coarticulatory aggression in our study could be the nature of the selected consonantal context; the alveolar stop [t] and the Greek fricative [s] are not as constrained as dorsopalatal consonants (also used in the Recasens studies) that display stronger tendencies in temporal extent and coarticulatory direction. Additionally, measurements were made at three specific

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[42] The values cited here are taken from Recasens et al. (1997), TABLE I (p. 551) and TABLE II (p. 552). The [t] context was not included in their study.

temporal points in the vowel, hence, although effects do not reach statistical significance at the exact midpoint, we cannot preclude that statistically significant effects extend farther than the transitions and into the steady-state of the opposite vowel. Moreover, in some sequences, although sizeable effects are located at vowel midpoint, increased variability, probably due to large number of speakers, contexts and tokens, rules out statistical significance. An additional factor that could have contributed the lack of significant effects is the type of post-hoc test employed for this study, i.e., Tukey. This test is considered conservative as it does not locate many statistical differences (Vlahavas, 2012).

Our results concerning reduced NH V-to-V coarticulation at vowel midpoint in the F1 axis are in accordance with Okalidou and Koenig (1999), who carried out an acoustic study of V-to-V coarticulation in Greek and English. Nevertheless, the authors report significant V-to-V effects at vowel midpoint in the F2 axis which were not located in our NH data. However, their study includes the mid vowels [e] and [o] that show more within-category variability than point vowels [i, a, u] examined exclusively in the current study (Stevens, 1989; Perkell & Cohen, 1989). The scarcity of temporally extended V-to-V effects in our data may seem in disagreement with Manuel and Krakow (1984), advocating high degree of V-to-V coarticulation in languages with a small vowel inventories. The data reported here reveal that large V-to-V effects in size are located in many contexts at V_1 offset and/or V_2 onset, but coarticulation magnitude decreases significantly towards the midpoint. Manuel and Krakow's hypothesize that languages with fewer vowels receive more transconsonantal vowel influence because each vowel is allocated a relatively large vowel area; nonetheless, as they themselves state, "there are language particular determinants of distribution that are not predictable solely by the number of vowels"

(p. 77). Therefore, some five-vowel languages could allocate more space to individual vowels thus allowing more extensive V-to-V effects, while others may not. As discussed in section 2.4.1., perceptual experiments have shown that Greek listeners seem to be stricter in identifying stimuli as native Greek vowels when compared with American listeners (Hawks & Fourakis, 1995) and reject a large number of synthetic tokens as not possible Greek vowels (Botinis et al., 1997). Therefore, each Greek vowel requires being within a certain frequency range to ensure distinctiveness. This need for perceptual clarity may limit coarticulatory influences. Data on the comparison of V-to-V coarticulatory patterns in Greek and English reported by Okalidou and Koenig (1999) also reveal no language differences in the size of individual vowel areas, indicating that, although Greek has a less crowded vowel inventory, individual vowel areas were not found expanded in relation to the English ones.

Less V-to-V coarticulation has also been found in languages with sparser vowel spaces than English (Beddor et al., 2002; Choi & Keating, 1990). In addition, vowel density has been found not to correlate with cross-linguistic coarticulatory differences between Korean and Japanese (Han, 2007) as well as Cantonese and Beijing Mandarin (Mok, 2006). Other factors besides phonemic contrasts may influence language-specific V-to-V coarticulation, such as syllable structure and rhythmic language patterns. Stressed-timed languages, such as English, with complex syllable structure, display increased vowel reduction (Roach, 1982) and may allow more extensive V-to-V coarticulation than languages classified as less stress-timed, such as Greek (Baltazani, 2007). Mok (2010) argues that languages with simple syllable structure may allow less V-to-V coarticulation than languages with complex syllable structure; the functional load on the vowel is heavier in the first case, while in the second case, consonants carry more cues and vowels are allowed more variation. Finally, an additional factor that could be related to the reduced amount of effects in the present data is syllable type. The material used was in the form of open syllables (CVCV). Less coarticulation overall has been found in open vs. closed syllables in American English (Modarresi et al., 2004) and Thai (Mok, 2010).

Duration has been documented to influence vowel production (e.g., Fourakis, 1991; Lindblom, 1963; Moon & Lindblom, 1994), but the effect of duration specifically on V-to-V coarticulation has not been studied as thoroughly. In the current study, although HI vowel durations are overall longer, there are few cases (see above) where longer V-to-V effects occur for the HI group in comparison to the NH group. Shorter phoneme durations or faster production rate do not result in greater coarticulation or more normal-like coarticulatory patterns in deaf speech (Okalidou & Harris, 1999; Okalidou, 2002). In NH speech, vowel duration was not found to influence V-to-V coarticulation in Thai (Mok, 2011). In their study of interarticulator programming in NH American English VCV sequences consisting of bilabial consonants [p, b] and point vowels [i, a, u], Löfqvist and Gracco (1999:1875) report that "there is a temporal window before the oral closure for the stop during which the tongue movement can start", otherwise perceptual clarity is compromised. According to the authors, reports of anticipatory tongue movements spanning large temporal intervals in NH speech (e.g., Magen, 1997) only involve vowels with no clear articulatory specification like the schwa. In the present study, the temporal extent of coarticulatory patterns is overall similar for the HI and the NH group, minus the few aforementioned instances. Thus, despite differences in absolute vowel duration, interarticulator timing may not deviate appreciably for the speakers with HI participating in this study, a remark also made earlier on the basis of V-to-V durational effects found in HI speech that generally resemble the NH pattern (section 6.2.4.). However, an investigation including measurement of consonant durations and relative durational patterns will elucidate the issue further.

6.4.3. Stress and V-to-V Coarticulation in HI vs. NH Speech

Regarding stress effects on V-to-V coarticulation, a fairly systematic pattern can be observed for vowels [i] and [a] of the NH group, while the stress influence on [u] coarticulation is more variable. In both F1 and F2 axes, NH vowels [i] and [a] receive more V-to-V effects when stressed, while the pattern for [u] is different in the two axes and the two coarticulatory directions. More specifically, the high back vowel [u] receives more lowering effects in the post-consonantal position when stressed and in the pre-consonantal position when unstressed, while in the F2 axis, [u] receives more V-to-V effects pre-consonantally when stressed and post-consonantally when unstressed. As illustrated earlier (see section 4.2.), stressed [i] and [a] are more peripheral, especially in the post-consonantal position, than their unstressed counterparts, thus coarticulatory influence may be the result of the larger distance between vowels in the acoustic space. On the other hand, the quality of high back vowel [u] does not show significant stress effects, and a more variable pattern concerning the influence of stress on V-to-[u] coarticulation is noted.

For the HI group, stress effects in the F1 axis are found in the fixed [a] context only, as F1 coarticulation only occurs on HI [a], and effects resemble the NH pattern, i.e., the stressed [a] receives overall more raising effects from the high vowels than its unstressed counterpart. In the F2 axis, the HI stress effect pattern follows the corresponding NH one in the anticipatory direction, i.e., more effects on stressed vowels, while in the carryover direction unstressed vowels display more V-to-V coarticulation. A possible interpretation for the opposing patterns of the two groups in the carryover direction may be related to the absence of position effects on unstressed HI vowels. As shown earlier (section 4.2.), the NH unstressed vowels are more peripheral pre- than post-consonantally, whereas positional effects are not as pronounced for the HI stressed vs. unstressed. Thus, the unstressed post-consonantal HI vowels are slightly more peripheral within the HI vowel system so as to show V-to-V carryover effects, whereas the NH vowels are possibly too central to display such effects.

Overall, Greek NH stressed vowels seem to be more coarticulated than unstressed ones. Although Fowler (1981a) documents consistent coarticulatory effects of a stressed vowel on a preceding or following unstressed transconsonantal vowel in English NH speech, these results concern influence from the point vowels on the medial vowel /ʌ/, which is subject to more reduction than Greek point vowels, and the material refers only to the bilabial context. Nicolaidis (1997) reports more variable stress influence on V-to-V effects in the environment of coronal consonants in Greek, underlining that contextual effects seem to moderate stress effects on V-to-V coarticulation. In agreement with Huffman (1986) and Farnetani et al. (1985), our results also indicate that V-to-V effects are primarily dependent on vocalic and consonantal context and secondarily on stress placement. A recent study carried out by Agwuele (2005) on American English also provides evidence of V-to-V coarticulatory effects from the unstressed on the stressed vowel. Contrary to expectations, in /V_1#CV_2/ sequences, persistent carryover effects of an unstressed V_1 unto a stressed V_2 were documented across the syllabic boundary.

Additionally, an examination of stress effects on V-to-V coarticulation in Cantonese and Beijing Mandarin revealed that effects of stress and direction were not consistent (Mok & Hawkins, 2004). The researchers report slightly more V-to-V coarticulation on unstressed vowels, but exceptions were common, and conclude that stress does not have a uniform effect on the degree of V-to-V coarticulation in the two languages. Stress effects on V-to-V coarticulation may present a variable picture in Greek as, compared to English, stress affects Greek vowel quality to a lesser degree (Arvaniti, 2007). As Mok and Hawkins (2004) argue, stress-based languages are expected to show more V-to-V coarticulation on their unstressed vowels than less stress-based languages.

6.4.4. Gender and V-to-V Coarticulation in HI vs. NH Speech

In this section, gender effects on V-to-V coarticulation in the two hearing groups are discussed. Significant V-to-V effects were located in both genders of the NH and HI groups; however, different trends concerning gender and coarticulation can be discerned within the two hearing groups.

Regarding the NH group, larger anticipatory V-to-V effects in both F1 and F2 frequencies occurred for NH female than male speakers. The female predominance is more evident in the F1 axis in the fixed [a] context across all consonants. Conversely, carryover V-to-V effects are more evenly distributed between the two NH gender groups in F1, but greater V-to-V coarticulation was located in F2 for the female group. As far as the HI group is concerned, a different trend is observed; V-to-V effects in both directions were found larger for the HI male group. The gender preference is more clearly manifested in the anticipatory direction and especially in the F2 axis, where it occurs in all vocalic and consonantal contexts.

One possible interpretation for the prevalence V-to-V effects in NH female coarticulation is related to differences in acoustic distance among female vowels as compared with male vowels. As expounded earlier (section 5.3.), there is a pronounced difference between NH female and male vowels in absolute vowel distance in both F1 (i.e., [a-i] and [a-u] distance) and F2 (i.e., [i-u] and [i-a]) axes which might partly explain the female predominance in NH V-to-V coarticulation. That is, an expanded acoustic space for the female group could provide a larger vowel area and thus, greater room for contextual variance. After normalization, the vowel means of the two NH genders almost coincide, but variability is consistently higher for NH female speakers. Thus, after reducing anatomical/physical variation, female speakers still display greater dispersion, a finding also reported by other researchers (Henton, 1995; Bradlow et al., 1996; Yang, 1996; Pierrehumbert, Bent, Munson, Bradlow & Bailey, 2004; Heffernan, 2007). Hence, differences beyond those associated with anatomy, e.g., sociophonetic, may relate to greater variability in female vowel production which is also manifested in greater V-to-V influences.

It is noteworthy that, in line with evidence from other languages (e.g., Hillenbrand et al., 1995, for American English; Simpson, 1998, for German; Ericsdotter & Ericsson, 2001, for Swedish; Simpson, 2001, for American English diphthongs and Simpson, 2002, for American English vowel sequences), Greek female vowels were found longer than male vowels (section 6.2.1). However, they still show more coarticulation in magnitude of effects than male vowels at vowel onset and offset, and differences in temporal extent were not located between the two NH genders. Simpson’s (2002, 2003) work on gender-specific articulatory-acoustic relations has shown that speed and temporal extent of tongue dorsum movement is actually longer for male speakers, despite their shorter vowel durations. Although further investigation of the correlation between relative duration and coarticulation patterns is required, this could be preliminary indication that longer segmental durations do not necessarily result in reduced coarticulation in NH female speech.

As regards the association of gender differences in vowel space and variability with gender patterns in HI V-to-V coarticulation, the difference between the absolute acoustic distance among HI female vowels vs. that among HI male vowels is even more pronounced than the corresponding NH gender difference in the F1 axis, but less prominent in the F2 axis (section 5.3.2). Hence, absolute vowel distance cannot account for the HI gender pattern in V-to-V coarticulation. After normalization, HI male vowels display overall higher variability than HI female vowels and much higher variability than the corresponding NH vowels. Conversely, female vowels in the NH and the HI group show relatively similar variability. Therefore, an opposing variability pattern emerges for the two genders in the two hearing groups which could be related to the differential V-to-V coarticulatory patterns. As stated earlier, the male speakers with HI participating in this study had a lower average level of intelligibility which could also play a role in the gender-specific pattern we observe here. It is also interesting to note that the difference in gender-specific coarticulation patterns between the two hearing groups is more prominent in the anticipatory direction in both F1 and F2 frequencies, which has been traditionally associated with pre-programming strategies (Henke, 1966; Daniloff & Hammarberg, 1973; Kent & Minifie, 1977; Recasens, 1984b).

An acoustic investigation of VCV productions of 5 male and 5 female NH American English speakers, focusing on anticipatory V-to-V coarticulation relative to variation due to intervening consonant and individual speaker carried out by Cole et al. (2010) revealed that speaker gender accounted for 63.2% of F1 and 36% of F2 variation, while further speaker differences accounted for an additional 19% of F1 and 5% of F2 variance. In that study, speaker was clearly the most important source of variation for F1 and for a substantial portion of F2 variation (p. 179). Attempting to answer why female NH speakers and male HI speakers in the current study show an indication of increased anticipation of V_2, we should take into account that, besides gender-specific strategies, speaker-specific strategies are at play as well. Larger subject groups are required in order to arrive at still tentative conclusions, and individual coarticulatory patterns need to be studied in order to disentangle the relative contribution of various factors influencing a phenomenon as complicated as coarticulation, especially in HI speech which is characterized by such variability that urged Huntington et al. (1968:157) to comment that “deaf speakers are no more like each other than they are like normal speakers”.

6.4.5. Intelligibility and V-to-V Coarticulation in HI vs. NH Speech

As expounded earlier (sections 3.4. and 6.1.3.), following an intelligibility experiment, the nine speakers with HI were divided into three groups according to their intelligibility score: intel group 1 (very high intelligibility, > 90%) consisting of two female speakers, intel group 2 (high intelligibility, > 80%) including 2 female and 3 male speakers, and intel group 3 (medium intelligibility, > 60%) comprising two male speakers. In this section effects of intelligibility level are discussed in relation to V-to-V effects located in each intelligibility group relative to the NH group.

Compared with all three intelligibility groups, the NH group displays V-to-V effects in more fixed vowel and consonantal contexts, in the carryover direction in the F2 frequency and in both directions in the F1 frequency. The very high intelligibility group (intel group 1) shows the least F1 & F2 coarticulation of all groups, contrary to expectations. The highly intelligible group (intel group 2) shows significant anticipatory F2 V-to-V effects in more contexts than the NH group. These are mostly fixed high vowel and alveolar contexts, i.e., [itu]-[iti], [uti]-[utu] and [usi]-[usu] pairs. Increased anticipatory coarticulation has been documented in alveolar contexts in sequences produced by American English speakers with HI (Okalidou & Harris, 1999), although their intelligibility level was relatively lower than that of our intel group 2. Moreover, the intel group 2 manifests greater magnitude of V-to-V effects than the NH group in some cases where both groups show significant coarticulation, e.g., in [asa]-[isa] and [ata]-[atu] pairs for F1, and [ipa]-[apa] pairs for F2. However, the fact that a less intelligible group, i.e., intel group 2, shows more coarticulation than intel group 1 does not mean that its coarticulatory patterns always resemble the NH pattern. As commented in section 5.4.2., the coarticulatory pattern of intel group 2 resembles the NH pattern in F1 but not in F2, where it displays coarticulation in more contexts, especially alveolars, and of greater magnitude than normal. Finally, the medium intelligibility group (intel group 3) shows overall less V-to-V coarticulation in F1 and F2 frequencies than both the NH and the intel group 2, and their significant effects occur mostly over alveolars.

In a previous chapter (section 4.3.2.), we reported that the intel group 1 has the longest vowel durations while the intel group 2 the shortest. As mentioned before, the speech of one of the subjects of the intel group 1, namely HI_01, is slow and deliberate, and her consonantal durations were found significantly longer than normal in an electropalatographic study (Nicolaidis, 2007). Prolonged duration might not be detrimental to intelligibility, but it could diminish the influence from the transconsonantal vowel. More evidence towards this direction is provided in the aforementioned study, where speaker HI_01 showed a quite constrained production of the alveolars, small vocalic effects on [t] and no effects on [s] (Nicolaidis, 2007). Highly constrained consonants that do not allow V-to-C effects, have also been associated with absence of V-to-V effects (Recasens, 1987).

This subject's speech was slow and hyperarticulated possibly in at attempt to ensure perceptual clarity on the part of the listener, and her intelligibility score revealed that she succeeded in that goal. It has been hypothesized that NH clear speech would be produced with less coarticulation, as it is characterized by longer sound segment durations or lower movement velocities. However, in their study of variation in anticipatory coarticulation in [iC_nu] sequences (where n=1-3 consonants) with changes in clarity and rate, Matthies et al. (2001) investigated the aforementioned hypothesis and found that overall NH subjects systematically increased the consonant-string duration to achieve clarity, but the amount of anticipatory coarticulation did not vary as consistently, since a lot of individual variability was observed. They comment that "the effect of speech rate and clarity on coarticulation reflects the simultaneous expression of a number of influences" (p. 351). An investigation of coarticulation in slow NH speech conducted by Hertrich & Ackermann (1995) also showed that anticipatory V-to-V coarticulation in NH speech did not significantly depend on speech rate, as opposed to carryover V-to-V coarticulation. Additionally, high individual variability of anticipatory V-to-V coarticulation was revealed in a relatively homogenous group of NH speakers, which was interpreted as an indication that anticipatory coarticulation reflects individual planning strategies. Moreover, the premise that reduced coarticulation of deaf speakers may be a byproduct of slow speaking rate was not validated by the findings of Okalidou & Harris' (1999) study. Therefore, further examination of this speaker's individual duration and coarticulatory patterns is needed so as to find out whether reduced V-to-V effects correlate with segmental durations and relative durational patterns in her speech.

We must note here that the intel group 1 consists of two female subjects and the intel group 3 of two male subjects. Therefore, a reasonable question would be whether these differences in coarticulation vs. intelligibility are also related to gender. As discussed in the previous section, although the NH female group shows overall more V-to-V coarticulation, no similar trend was observed for the HI female; on the contrary, the HI male group seemed to coarticulate more than the female. Since the intelligibility groups are not balanced for gender, we cannot safely dismiss the gender factor from the correlation between intelligibility and coarticulation. Moreover, there is the issue of the number of subjects in each intelligibility group. The high intelligibility group (intel 2) was found to exhibit the most effects of the three HI groups, but it also consists of five subjects, while the other two groups have two subjects each. In addition, the intel group 2 displayed coarticulatory effects more comparable in number of contexts and size to the NH, which also consists of five subjects, than the other two intelligibility groups. However, the NH group still demonstrated fewer effects than the intel group 2 in certain cases, despite the same number of subjects in these two groups. Although coarticulation exhibited by a group may not be directly related to the gender of the subjects or their average intelligibility or total number of subjects, the fact that our groups are not balanced for these factors poses certain limitations.

In summary, no direct relationship between intelligibility and coarticulation can be discerned from the results of the present study. The HI group that most resembles F1 NH coarticulation is the high intelligibility group (intel 2), although in F2 it surpasses the NH coarticulation in degree and number of contexts. The medium intelligibility group (intel 3) displays significant F1 and F2 coarticulation in very few contexts, while the very high intelligibility group (intel 1) shows the least coarticulation. However, the relationship between coarticulation and intelligibility requires further investigation. A design including a wider range of speech intelligibility levels, balanced for gender and number of subjects may reveal a more systematic relationship between the two variables.

6.5. General Discussion

One of the major aims of the present thesis has been the investigation of coarticulation in NH and HI speech viewed from the theoretical standpoint of coproduction. Three vocalic and three consonantal contexts were studied in combination so as to examine the coarticulation resistance of these segments and make inferences about intergestural blending and coordination from acoustic consequences in speech acquired with vs. without auditory feedback. The bilabial [p] was selected as a context where minimal spatial perturbations are expected from its gestural and temporal overlap with abutting vowels, due to its sharing only one articulator, i.e., the jaw, with preceding and subsequent vocalic gestures. The alveolars [t] and [s] were selected so as to look into the degree of spatial overlap occurring when the intervening consonant shares both articulators, i.e., jaw and tongue, with surrounding vowels. The blending influence of the overlapping of gestures as deduced from the acoustic outcome would provide information about the articulatory realization of the consonantal and vocalic segments and their coarticulatory resistance or adaptability in relation to each other. Thus, coarticulatory patterns would bring out similarities and differences in articulatory strategies adopted by speakers with NH in comparison to those of speakers who have acquired speech in absence or profound loss of hearing, effectively influencing the coordination of their articulators and resulting in partly differential speech production characteristics.

In general, reduced vocalic contrast, higher acoustic variability, longer durations and differential effect of gender and stress on the acoustic characteristics of vowels and coarticulation were located for the HI group, but both the acoustic characteristics and overall coarticulatory patterns found in HI speech did not severely deviate from normal. That is, the overall trends were similar for the two groups. This outcome is most probably associated with the high speech intelligibility of the individuals comprising the HI group of this study. The mean group score of the nine speakers with HI at the intelligibility test was 88%. Hence, the results must be viewed in light of the fact that they refer to an acoustic investigation of speech produced by talkers with profound hearing loss, yet highly intelligible. Despite the similar overall picture, an important difference between the two groups is that the prominence of contextual and stress influence occurs on the second syllable (post-consonantally) in NH speech, whereas such effects are particularly pronounced in the first syllable (pre-consonantally) in HI speech.

The relative prevalence of anticipatory vs. carryover V-to-V effects in HI speech occurs mainly in fixed high vowel and alveolar contexts. Additionally, C-to-V fronting effects from the two alveolars on the back vowels are again more prominent anticipatorily. Moreover, HI high vowels are longer before the alveolars than the bilabial stop which is not the case for NH high vowels. All these findings indicate a different alveolar articulation, possibly more constrained in terms of tongue dorsum involvement than normal, which influences the preceding vowel. Thus, the first-syllable vowel is significantly affected both in duration and in quality as it anticipates the highly demanding alveolar consonant. Between the two HI alveolars, [s] was found more constrained than [t] as it seemed to cause longer pre-consonantal durations, more extensive fronting C-to-V effects and allowed slightly less V-to-V effects than HI [t]. On the other hand, the relative coarticulatory aggression of NH [t] and [s] was not significantly different. A C-to-V directionality preference was not manifested by the two NH alveolars denoting that the consonantal influence spanning the symmetrical VCV was similar in the two directions in NH speech. Conversely, the alveolar influence was significantly reduced in the carryover direction in HI speech.

The lower degree of C-to-V_2 coarticulation may suggest greater overlap between the consonantal and subsequent vocalic gesture, in that, the two are more ‘merged’ than normal. According to the DAC model, C-to-V coarticulatory effects are maximal when gestural antagonism is maximal. Hence, greater C-to-V_1 than C-to-V_2 effects suggests more gestural competition between the consonant and the preceding than the following vowel. It could be that the CV_2 in HI speech is more overlapped, because V_2 is more centralized and can adapt to the consonantal place of articulation more readily. According to Recasens (1987), a highly constrained CV_2 sequence is not expected to exhibit much carryover V-to-V coarticulation, as also confirmed by our data.

Moreover, the articulatory realization of the HI alveolars could be different from normal so that increased anticipation is required. Within the DAC framework, consonants produced with the tongue front and involving little tongue dorsum activation, e.g., [t], do not induce especially prominent anticipatory consonantal effects. On the other hand, prominent tongue front raising anticipation is required for more constrained consonants, like the NH Catalan [s]. The results of the current study suggest that the NH Greek [s] is not as constrained as reported in other languages, as it does not favour either C-to-V coarticulatory direction and allows more V-to-V effects across than predicted by the DAC model. However, the HI alveolars clearly favour the anticipatory direction in C-to-V effects suggesting that they are thus more constrained than NH alveolars, in agreement with EPG findings that showed greater tongue dorsum contact during the production of [s], [t] and [n] by Greek speakers with HI (Nicolaidis, 2004).

According to Recasens (2005), consonants that favour anticipation prevent V_1 carryover effects from occurring, as V_1 carryover influence conflicts with consonantal anticipation. Indeed, V_1 carryover influence in HI speech is significantly reduced as compared with that found in NH speech. This occurrence is especially noted in high vowel contexts that may tend to form a palatalized CV_2 syllable resisting V_1 influence. Conversely, V_2 influence on V_1 is increased across alveolars in HI speech. This finding can thusly be explained within the DAC framework and has been also documented in previous studies regarding American HI speech (Okalidou & Harris, 1999). In the fixed [a] context, V-to-V coarticulatory directionality resembles the NH pattern, in that significant carryover effects were located. In this case, the CV_2 syllable, i.e., /ta/ or /sa/, may not be as heavily palatalized due to the lowered tongue dorsum for the production of the low vowel. Hence, CV_2 anticipation is not as robust and V_1 carryover is more salient.

The account adopted here for the interpretation of coarticulatory directionality in NH and HI speech is based on the degree of articulatory constraint and the gestural compatibility between adjacent segments in VCV sequences as put forth by the DAC model. Regarding directionality trends in NH speech, variability has been documented depending on context, language and speaker (section 2.2.1.4). A trend for carryover predominance in V-to-V coarticulation across bilabials and dentoalveolar stops has been reported for various languages, e.g., English (Bell-Berti & Harris, 1976; Magen, 1984a; Manuel & Krakow, 1984), Catalan (Recasens, 1987), Italian (Farnetani et al., 1985; Farnetani, 1990). Similarly, Greek NH V-to-V coarticulation showed a preference towards the carryover level, in agreement with previous acoustic investigations of Greek NH V-to-V coarticulation (Okalidou & Koenig, 1999; Asteriadou, 2008). Concerning lingual fricatives, although their articulatory demands require strong anticipation, there is evidence of carryover V-to-V effects across [z] and [ʃ] in [i] and [a] contexts in Italian (Farnetani & Faber, 1992) and predominance of vowel-dependent effects in [s] and [ʃ] contexts in German and English (Hoole et al., 1993). Opposite trends have also been documented across languages, hence coarticulatory directionality has been characterised as a language-specific property of how articulatory programming is organised (Recasens, 1987).

On the basis of the present data, V-to-V coarticulatory effects in Greek seem to favour the carryover component in bilabial and alveolar stop as well as in alveolar fricative contexts. The preference of HI coarticulation towards the anticipatory component may be associated with higher demands placed upon the intervening alveolar consonants as discussed above. Traditionally, the anticipatory component has been thought to reflect articulatory pre-programming, while the carryover process has been mainly attributed to mechanical inertial constraints (e.g., Recasens, 1987; Whalen, 1990). Hence, more prominent anticipation could be related to a different planning strategy adopted by the speakers with HI in order to meet the demands of the gestural formation of a more constrained consonant or a more heavily palatalized CV_2 syllable. However, further investigation of coarticulation in more contexts and by more speakers with HI is required so as to verify the premise that speakers with HI plan utterances differently than speakers with NH.

An important issue that needs to be taken under consideration is that, besides language-specific, coarticulatory patterns are to a great extent speaker-specific. High individual variability has been located in V-to-V anticipatory coarticulation patterns among speakers with NH (e.g., Perkell & Matthies, 1992; Hoole et al., 1993; Johnson et al., 1993; Hertrich & Ackermann, 1995). Coarticulatory variability is bound to be even higher in speakers with HI whose speech is generally characterized by instability of articulatory gestures (Rubin, 1985; Harris et al., 1985; McGarr & Campbell, 1995). Our findings on acoustic variability agree with these claims. In addition, the analysis of coarticulation according to intelligibility level revealed different patterns in each intelligibility group which are associated with different strategies adopted by the speakers comprising each group. For example, the degree of V-to-V coarticulation was found particularly low in the very high intelligibility group, a result that may be attributed to hyperarticulation shown by one of the two speakers of the group in her attempt to achieve successful communication. More extensive contact during closures in lingual stops due to emphasis ("*deeper contact hypothesis*") have been shown to limit anticipatory coarticulation in NH speech (Lindblom et al., 2007; Lindblom et al., 2009) and increased effort in clear speaking conditions, although to a small extent, reduce the amount of anticipatory coarticulation (Matthies et al., 2001). If hyperarticulation has an effect, albeit small, on coarticulation in NH speech, in HI speech such an effect may be increased due to the longer segmental durations and the different interarticulatory organization from normal (McGarr & Campbell, 1995).

As expounded above, our findings indicate that speakers with HI may produce more overlapped CV sequences composed of gestures that involve tongue tip and/or dorsum activation. Such coarticulatory patterns have been reported for developing speech (Nittrouer, 1993) and suggest that full control of the various parts of the tongue for successful speech production may be difficult to master. A recent ultrasound study of V-to-C coarticulation on the Scottish English fricative [ʃ] provides evidence that children coarticulate more than adults, and supports Nittrouer's idea that children produce the CV syllable as a syllable-sized unit (Zharkova, Hewlett & Hardcastle, 2011). Regarding the bilabial context, V-to-V effects over [p] were found overall relatively reduced for the HI group, although not to the extent documented in previous studies in English (e.g., Okalidou & Harris, 1999). Evidence from cinefluorographic studies indicate that speakers with HI may not move their articulators toward the open posture involved in vowel production throughout consonantal stop closure which could limit V-to-V influence (Tye-Murray, 1987). A similar observation has been made concerning NH developing speech; children have not yet learnt to take advantage of the independence of tongue and lips, e.g., in the syllable /pi/, so as to start executing the vowel gesture while their lips are closed (Goodell & Studdert-Kennedy, 1993). As a consequence, CV syllables with bilabials are less coarticulated.

Regarding NH speech, the observed C-to-V and V-to-V patterns fall largely within the predictions of the DAC model, with the exception of the coarticulatory behaviour of two segments, namely, the high front [i] and the fricative [s]. Both segments have been generally assigned very high DAC values. The high front [i], as a palatal vowel requiring maximal tongue dorsum raising, has been characterized as highly constrained “in much the same way as alveolopalatal consonants” (Recasens & Espinosa, 2009:2289) and assigned a DAC value of 3. However, in the current study, the amount of V-to-V coarticulation on [i] may suggest a relatively less constrained articulation of the high front vowel in Greek, in agreement with Nicolaidis’ (1997) claim. Similar results were also obtained acoustically by Asteriadou (2008). This vowel was found quite susceptible to the coarticulation influence of the back vowels [a] and [u] along the front/back dimension, although the effects occurred almost exclusively in the bilabial context. In addition, its acoustic variability was slightly higher than that of [u]. However, [i] was found the most resistant among the point vowels to coarticulatory raising/lowering effects. The existence of the Greek front mid vowel [e] may limit a vertical influence for reasons of perceptual clarity. Conversely, the long distance between [i] and [u] allows for more backing of the front vowel.

The lingual fricative [s], is considered highly constrained due to the manner requirements for the formation of a narrow central groove for airflow passage and has been given a DAC value of 3 (Recasens et al., 1997) and more recently a DAC value of 4 (Recasens, 2005). Yet, the current analysis showed that fronting and raising C-to-V effects on the back vowels are induced to a similar degree by [s] and [t] in NH speech. Moreover, both consonants seemed to block or allow V-to-V effects to a comparable extent overall depending on the vocalic context. Although an examination of V-to-C effects is required so as to gain more insight into the two consonants' coarticulatory resistance, the present results indicate a lower degree of constraint for the Greek [s] and possibly a higher one for [t] than postulated by the general DAC scale. Such language-specific modifications are expected within the DAC framework, since the degree of constraint for each segment is not the only factor influencing the amount of coarticulation resistance displayed by a segment, or rather the degree of constraint itself and, thus, the actual realization of the segment could be determined by numerous factors. One of these factors is phonological contrast which, to a certain extent, depends on the phonemic inventory of a language and places output constraints on segments in order to ensure distinctiveness (Manuel & Krakow, 1984; Manuel, 1987; 1990). In the case of the Greek [s], the lack of a contrastive fricative in the same region, such as [ʃ], may allow greater coarticulatory variability, as displayed by EPG data (Nicolaidis, 1997). Besides phonological contrast, additional factors may influence the degree and extent of coarticulation. These factors cannot always be predicted or interpreted on the basis of grammar or anatomy. According to Disner (1983), the exact phonetic implementation of a segment cannot be predicted solely on the basis of the phonemic inventory of a language. On the same note, Ladefoged (1983) maintains that there is not always a physiological or phonetic explanation about how a phoneme is produced in a certain language. Hence, more research is necessary in order to uncover language-specific coarticulatory behaviours and adjust the DAC scale to the segments of a particular language.

As far as HI speech is concerned, a different realization of vowels and consonants from normal is observed and, as a corollary, differences in coarticulatory patterns are located. These differences in production between HI and NH speech are related to differences in perception due to lack of auditory feedback. Overall, the point vowels as produced by speakers with HI were found more variable and centralized compared with the NH point vowels. This finding falls within the predictions of the DIVA model (Guenther, 1995; Guenther et al., 1998), according to which the vocalic and consonantal goals the speaker uses in order to plan articulatory movements are auditory-based. Thus, perception influences production. In hearing loss, perception is compromised and the regions in the auditory-temporal space that determine production goals are less refined. Consequently, phonemic contrast can be reduced or lost. Discrimination of contrast has been correlated with contrast production in both NH (Perkell, Guenther, et al., 2004; Perkell, Matthies, et al., 2004) and HI speech (Vick et al., 2001). According to the DIVA model, speakers who perceive contrast are more likely to produce it, and the finer their perception of acoustic phonetic detail, the further apart their goal regions will be spaced. The results of the current study suggest that speakers with profound HI produce more converged vowel subspaces and overall their vowels are more susceptible to coarticulatory and acoustic variability than NH vowels.

Regarding the production of HI consonants, inferences may be made on the basis of acoustic analysis of of C-to-V and V-to-V coarticulatory patterns. The results suggest that they are more constrained, perhaps covering a wider palatal region than normal. At the same time, HI coarticulatory patterns suggest larger variability in alveolar production. That is, HI alveolar consonants may show more variation than normal in front/back placement of the tongue depending on the frontness or backness of the following high vowel. EPG findings about increased consonantal variability in Greek HI speech that suggest reduced articulatory precision and control lend support to our claim (Nicolaidis, 2004). A tendency for greater area of linguapalatal contact during sibilant [s] and [ʃ] production indicating less precise articulator configuration has also been reported for American HI speech (McGarr et al., 2004). Moreover, Okalidou (1996) documents backing of [d] in /dud/ rather than fronting of [u] suggesting variable placement of the tongue for the alveolar stop in American deaf speech. Hence, increased linguapalatal contact frequently co-occurs with articulatory instability in HI speech. In Greek, although the groove location and width of [s] are less critical than in languages that contrast alveolar and postalveolar fricatives, articulatory variability needs to be maintained within certain limits so as to differentiate [s] from [x] or [ç], as commented by Nicolaidis (2004). Similarly, the tongue needs to be correctly positioned for the production of the Greek alveolar [t] and its distinction from [k] or [c].

In accordance with the DIVA model, speakers with normal hearing gradually acquire speech sound representation and develop a feedforward control system through the fine-tuning of auditory and somatosensory information. After maturation their speech production mechanism ceases to require moment-to-moment auditory feedback, although it is still needed for continual tuning and maintenance of contrast. Conversely, speakers with congenital profound hearing loss do not manage to obtain the spatio-temporal auditory goals through audition. Lack of auditory feedback not only impedes the development of a mature and complete internal model as described above for the NH speakers, but also precludes its stability as auditory information cannot be used in order to tune and maintain contrasts.

6.6. Implications for Speech Habilitation

The present acoustic analysis revealed certain issues in the speech production of individuals with HI, such as vowel centralization and increased acoustic variability leading to partial overlap between vowel categories along the front/back dimension, and coarticulatory patterns suggesting less precise tongue configuration during alveolar consonant production possibly due to more constrained gestures resulting from greater linguapalatal contact. The predominance of the anticipatory component in C-to-V and V-to-V coarticulation in V_1CV_2 sequences with alveolar consonants suggests extensive overlap of CV_2 probably due to less control over the different tongue articulators, i.e., tongue tip/blade and body.

On the basis of the above, speech therapy should primarily concentrate on enhancement of vowel contrast, correct tongue placement for alveolars and, last but not least, the coproduction of sequences containing lingual consonants so as to practise the differentiation of tongue articulators and their well-timed coordination in vowel-consonant-vowel production. Traditional speech therapy techniques involving the provision of oral instructions and tactile cues about articulatory positions and their sequencing, and phonetic drills including disyllables with various consonant-vowel combinations may prove beneficial for the differentiation of the tongue articulators and the coordination between tongue and jaw. Moreover, the visual display of acoustic speech signals could assist in remediation. Visual speech representation can supplement conventional therapy by providing a reference for sounds and their combination the speakers can work towards, as well as feedback on their own productions.

In order to improve coproduction, vocabulary exercises containing sound sequences as well as isolated segments need to be selected and practised. A speech training system that visualizes speech, built to practise phonemes in isolation as well as in sequences, words, minimal pairs and sentences has been developed for European languages and includes a database editing module that allows the construction of a Greek vocabulary (Vicsi et al., 2000). The type of display is especially appropriate for sibilants; it contains exercises with fricatives presented in CV, VCV, VC and VC-VC-VC sequences. Such exercises can be incorporated in conventional therapy and help establish and maintain articulatory skills, while offering motivation to speakers with HI who can see the acoustic outcome of their production through visual feedback.

A tool that has been used in the assessment and treatment of speech disorders associated with hearing impairment with encouraging results is electropalatography (EPG). EPG visualizes the location and timing of tongue-hard palate contact during continuous speech (Hardcastle, Gibbon & Jones, 1991). In addition to targeting specific articulatory postures, it can also help establish a sound in various vocalic contexts, thus developing coarticulatory skills (Johnson, Goldberg & Mathers, 1984). The lingual fricative [s] has been documented as the least correctly produced consonant (Dagenais & Critz-Crosby, 1991) and one of the least-improving consonants with traditional speech therapy (Bernhardt, Gick, Bacsfalvi & Ashdown, 2003). However, great gains for sibilants have been reported for speakers with HI after the use of EPG, and visual feedback has been found especially useful in establishing new articulatory patterns (Dagenais, 1992; Williams & Bernhardt, 1998; Bernhardt et al., 2003). Concerning the alveolar [t], its placement has been shown to improve as a result of treatment for the alveolar [s] (Bernhardt et al., 2003).

Tongue position and movement can also be displayed in real time with ultrasound, a non-invasive articulatory technique, providing information about the full tongue contour (Stone, 2005; Zharkova & Hewlett, 2009). Research has shown that gains in speech production training are faster when ultrasound feedback complements traditional principles and practices of therapy (Bernhardt et al., 2005; Bacsfalvi, Bernhardt & Gick, 2007; Adler-Bock et al., 2007). Improvement of tongue grooving for sibilant production at single word level is documented, although traditional treatment methods are recommended in order to integrate the phone into words, sentences and conversation. Additionally, reduced variability and greater tongue movements in the oral cavity for vowel production were noted when EPG and ultrasound were employed for the speech habilitation of adolescents with hearing impairment (Bernhardt et al., 2008).

Regarding the increased acoustic variability of HI vowels, Okalidou (2002) notes that it does not necessarily suggest articulatory instability in speech production and could be the natural outcome of prolonged segmental durations. Thus, it is important to identify the cause of variability so as to adopt the appropriate protocol in therapy. According to the author, the differential diagnosis may be carried out by an acoustic examination at two speaking rates, i.e., normal and fast. If normal-like coarticulatory patterns emerge at fast rate, then variability may be attributed to prolonged durations, and therapy can focus on increasing the speaking rate. If patterns become aberrant at fast rate, then variability could be associated with articulatory instability, hence exercises should include articulation drills that promote learning through repetition.

Moreover, it is essential to develop and keep practising the speech perception abilities of the speaker with HI. Besides providing visual, tactile or somatosensory feedback in general, it is essential, even in profound hearing loss, to utilize any existing residual hearing, as audition has a primary sensorimotor role in the development of speech as well as in the refining and maintenance of the speech production mechanism in adulthood (Lane et al., 2007). Consequently, early fitting and consistent use of sensory aids along with auditory and language training are crucial parameters of the overall speech habilitation program. The Ling method (1976, 1989) has been used extensively for speech rehabilitation of children with HI and encourages auditory-oral training. This method targets the ‘phonetic’ as well as the ‘phonologic’ level of speech. At the ‘phonetic’ level, practice includes both nonsegmental aspects of speech such as respiration, voicing, intensity, pitch as well as segmental speech patterns such as vowel and consonant targets. The ‘phonologic’ level refers to the carryover use of the above nonsegmental and segmental speech patterns from one context to another and into everyday language (Pratt & Tye-Murray, 2009).

Special attention must be paid to suprasegmental aspects of speech in therapy (sections 2.3.2.2. and 2.3.3). Sentence rhythm and prosody are important factors influencing the blending of segments. Although segmental errors have been found to have a greater effect on intelligibility than suprasegmental errors (Monsen, 1978; Maasen & Povel, 1985), coordination of articulatory movements over time has been shown to significantly influence intelligibility (Osberger & Levitt, 1979). Speech should embody both correct prosody and segmental elements, which means that training in segmentals should not overshadow practice in rhythm and prosody. A level of high intelligibility cannot be reached, unless respiration, voice and articulation function in tandem as three inter-connected speech supporting systems. Last but not least, it is important that therapy protocols are flexible; speech production training must be tailored according to the specific needs of the individual in therapy (Clark, 2003).

6.7. Limitations and Avenues for Future Research

Among the basic aims of this thesis has been the investigation of V-to-V coarticulation in Greek HI and NH speech, so as to provide insight into the interarticulatory coordination and articulatory strategies in the speech of individuals with normal hearing and profound hearing loss. The evidence buttressing our findings was obtained through acoustic analysis. Based on acoustic data we attempted to make inferences about possible movements and posturing of the articulators, i.e., the tongue tip, the tongue body, the lips and the jaw. However, an acoustic outcome is associated with a number of articulatory combinations due to compensation (Maeda, 1991). Therefore, our interpretations in terms of articulatory movement and coordination are only tentative.

Additional physiological techniques, such as electropalatography (EPG), electromyography (EMA/EMMA) and ultrasound, should be used to complement acoustic examination. Thus, patterns of tongue-palate contact as well as the whole tongue contour position need to be associated with acoustic parameters. Each technique emphasizes different aspects of speech which is a multi-dimensional phenomenon; hence, the concurrent examination of more than one type of data is required in order to reach more definite conclusions about the coarticulatory behaviour of phonemes and their relative resistance/aggression in HI and NH speech. For example, recent ultrasound findings suggest that, contrary to the DAC model, an alveolar consonant, e.g., [t], can be regarded as less coarticulation resistant than a low back vowel, e.g., [ɑ], if the displacement of the whole midsagittal contour is examined with ultrasound rather than only tongue-palate contact with EPG (Zharkova, 2007).

Another important issue requiring serious consideration is that of variability, grouping of subjects and statistical treatment of the data. The issue of variability in production has been underlined in the literature of normal speech and especially that of hearing impaired speech. Speaker-specific articulatory strategies have been documented in both types of speech as well as token-to-token variability within a speaker. For this thesis, the 5 NH speakers and 9 speakers with HI were treated as two groups in our statistical analyses. For this reason, particular effort was made to examine a number of subjects as large as possible. On the other hand, the substantial number of acoustic measurements (6,480 formant measurements per subject) and the strict criteria for participation in the HI group limited the number of appropriate candidates (section 3.2.1.1). In addition, to compose a HI group as homogeneous as possible, we carried out an additional experiment of speech intelligibility. Thus, coarticulatory patterns were further examined according to level of speech intelligibility (section 3.4). Nevertheless, our results must still be interpreted with caution. Individual coarticulatory patterns need to be examined as well, so as to confirm the general patterns emerging from groups. Our findings also need to be confirmed by research in more vocalic and consonantal contexts involving a larger number of subjects.

Due to the aforementioned paucity of acceptable candidates for participation in the HI group, the intelligibility groups of the study were not equal in number of subjects and were not balanced for gender (section 3.4.6). This issue was taken into account in the discussion of the results (sections 6.1.3. and 6.4.5.), and poses certain limitations to the interpretation of the findings relative to these factors. However, tentative conclusions can be drawn so as to formulate a basis for hypotheses that will be tested in the future with research especially designed to address these questions.

Literature on Greek HI speech is very limited in general. The present study constitutes the first attempt to explore coarticulation in Greek HI speech with respect to various factors. A factor we did not include in our current design, but aspire to in a future investigation, is the method of primary communication (oral vs. sign or total) and the educational setting of the speaker with HI. To our knowledge, there are no Greek studies addressing the relationship between oral vs. sign/total communication or mainstream vs. special education setting and oral speech production of Greek speakers with HI in terms of acoustic/articulatory characteristics or speech intelligibility level. As far as the literature is concerned, some researchers claim that implanted children who use oral communication and are placed in mainstream schools demonstrate higher level of performance on speech perception measures or display higher intelligibility than do children who use total communication or attend schools for the deaf (John et al., 1976; Staller et al., 1991; Osberger et al., 1991; Sommers, 1991; Osberger, Maso & Sam, 1993; Dowell et al., 1995; 1997; Svirsky et al., 2000; Sarant et al., 2001; Tobey et al., 2003; Girgin & Özsoy, 2008), while others maintain that there is no empirical evidence suggesting that the use of sign language impairs the ability or motivation to acquire spoken language (Marschark, 2001) and that bilingual programs contribute to improved spoken language abilities (Wilbur, 2000) as well as literacy, communication and social-emotional development (Preisler & Ahlstroem, 1997; Preisler et al., 2002). Although this question lies beyond the scope of the current study, the investigation of such issues should be undertaken in the future by researchers in Greece. If the ultimate goal is successful communication and self-realization for the speaker with HI, then research in this area is of paramount importance, as it has serious implications in matters of clinical practice as well as educational policy.

Chapter 7

Conclusions

The main focus of the current study has been the acoustic exploration of coarticulation effects, both in degree and temporal extent, in the speech of Greek young adult male and female individuals with normal hearing (NH) and hearing impairment (HI), and the manner in which certain variables, i.e., vocalic and consonantal context, stress, syllable position, as well as gender and intelligibility, influence coarticulation. The investigation of coarticulatory patterns aimed at elucidating differences and similarities in articulatory strategies adopted by the two hearing groups, namely, the NH and the HI group, as inferred by the spectrographic analysis, and thus broadening our knowledge base on the speech production of individuals with profound hearing loss which is fairly limited for languages other than English. The NH and HI data is considered in light of the coproduction framework and, in particular, the Degree of Articulatory Constraint (DAC) model.

The speech of five talkers with NH, two male and three female, and nine talkers with HI, five male and four female, was analyzed acoustically using the LPC method in Praat. In particular, formant frequencies F1 and F2 at vowel onset, midpoint and offset, and duration measurements of the Greek point vowels [i, a, u] in disyllables of the form [pV_1CV_2] with consonants [p, t, s] stressed on the first or the second vowel were carried out. The data was treated statistically with analysis of variance (ANOVA), and Tukey post-hoc tests were employed to locate within- and across-group differences. In order to include speech intelligibility level as a factor in the statistical design, an additional experiment with 54 naïve listeners who judged 101 words and 25 phrases produced by the speakers with HI was conducted.

Besides reporting the degree and temporal evolution of coarticulatory patterns, among the main goals of the study was also to provide an acoustic description in terms of vowel space, distribution and duration of the three point vowels in the two hearing groups and to look into the influence of the aforementioned factors, i.e., gender, intelligibility, context, stress and syllable position, on static acoustic characteristics. To this end, formant frequencies F1 and F2 at the vowel midpoint only as well as vowel duration of the three point vowels in symmetrical bilabial disyllables of the form [pVpV] were measured and treated statistically. The bilabial context was selected as a neutral consonantal environment since the tongue is fairly unconstrained during the production of [p].

The analysis revealed that the high back rounded vowel [u], as produced by the speakers with HI, deviates the most from its NH counterpart, in that, a more anterior and closer constriction than normal was located. As a consequence, [y]-like productions of the vowel [u] were recurrently found in the HI data. On the other hand, the high front vowel [i] was realized more posteriorly than normal, although differences between mean values of NH and HI [i] were eliminated after normalization. However, both HI high vowels display higher acoustic variability in comparison with the corresponding NH vowels, which results in some overlap between the two vowel subspaces. The mid low vowel [a] resembles its NH counterpart the most, both in terms of mean value and acoustic variability. The foregoing suggests more problematic tongue placement by the speakers with HI along the front/back dimension, reflected in F2 frequency, than along the high/low dimension, presented in F1 frequency, possibly due to the greater audibility of the latter and visibility of articulators, i.e., jaw and lips, associated with the vertical dimension, as reported extensively in the literature. Due to the restricted F2 frequency range, the HI vowel space appears reduced by 28% compared with the NH one, after normalization.

Regarding gender, female vowels of both the NH and the HI group form a larger vowel space than male vowels, as expected. However, the two hearing groups differ in their patterns of acoustic variability as a function of gender. More specifically, NH female vowels were found consistently more variable than NH male vowels, as reported for other languages; however, such a consistent gender pattern was not located for the speakers with HI, probably due to the overall greater and speaker-specific variability characterizing HI speech. The analysis showed less tight within-category clustering for male speakers compared with female speakers with HI, which could be related to their overall lower intelligibility level.

The results of the intelligibility experiment showed that the nine speakers with HI participating in the present study are very intelligible as a group (mean group score 88%). Their high level of speech intelligibility is probably associated with background factors such as early fitting and consistent use of hearing aids, almost exclusive use of oral communication, continual speech training of an early onset and placement in mainstream education. The HI group was further divided into three intelligibility groups: intel group 1 (very high intelligibility, > 90%) consisting of two female speakers, intel group 2 (high intelligibility, > 80%) including 2 female and 3 male speakers, and intel group 3 (medium intelligibility, > 60%) comprising two male speakers. Intelligibility level did not correlate with average degree of hearing loss. Interestingly, [u] fronting and vowel space shrinking was found to vary directly as a function of intelligibility level; that is, the lower the intelligibility level, the more anteriorly [u] is realized, the higher the overlap between [i] and [u] subspaces and, thus, the greater the vowel space reduction. Nevertheless, acoustic variability does not seem to vary inversely with intelligibility level, since the very high and the medium intelligibility group display less variability than the high intelligibility group, although the uneven composition of the groups in terms of gender and number of subjects may have interfered with the outcome.

Stress influences the quality of the three point vowels of the two hearing groups in a similar way, although the effect was found slightly greater for the HI group. In particular, for both groups, stressed [a] was found more open and anterior, and stressed [i] more fronted than their unstressed counterparts, while [u] was not significantly affected. Therefore, absence of stress resulted in a 24.8% vowel space reduction for the NH group and a slightly higher reduction of 28.4% for the HI group, probably associated with a more pronounced shift along the F1 axis in HI vowels due to stress, also documented in other studies. Moreover, a differential pattern of stress effects on pre- and post-consonantal vowels was observed in the two hearing groups. For both groups, stressed vowels appear more peripheral post-consonantally; however, the absence of stress results in more vowel reduction post-consonantally for the NH group, while for the HI group greater reduction is located pre-consonantally. Hence, the first syllable appears to be less stable in HI speech, which could indicate that speakers with HI do not apply initial articulatory strengthening to the same degree as speakers with NH, in order to provide more cues, important for word identification, to the listener.

An examination of point vowel duration as a function of the aforementioned factors showed that both hearing groups follow the universal trend for intrinsic vowel duration, i.e., [a] > [u] > [i]. In line with existing literature, the HI point vowels were found longer in comparison with the corresponding NH vowels. Moreover, the HI group follows the NH trend for greater female vs. male vowel duration, albeit to a lesser extent. A comparison between gender groups also showed that the temporal difference between NH and HI vowels is greater in the male than the female group. However, both these findings concerning duration vs. gender could be related to intelligibility differences between the two HI gender groups or to speaker-specific characteristics not necessarily associated with gender. Regarding speech intelligibility level, its relationship with segmental duration does not appear to be a direct one, as the very high intelligibility group displays the longest point vowels among the three intelligibility groups. The vowel durations of the high intelligibility group are the shortest and, therefore, closest to the NH vowel durations. As above, this result could be influenced by gender, since the very high intelligibility group consists solely of female speakers; hence there might be a gender-related trend for longer vowel durations for this group. Future research with HI groups balanced for both gender and speech intelligibility level could help disentangle the relative effect of these two factors on vowel duration.

Furthermore, the vowels of both hearing groups showed significant durational shortening in the absence of stress, occurring at a slightly greater degree for NH vowels. Moreover, unstressed high vowels [i] and [u] display more durational shortening in the absence of stress than the low vowel [a] in both groups. Regarding the interaction of stress and syllable position, the two hearing groups also show similar patterns, albeit with differences in degree of effects. In particular, the NH trend involves greater stressed-vowel-lengthening and unstressed-vowel-shortening in the second syllable position. The former occurrence is twice more prominent than the latter in NH speech, and has been associated with the preservation of normal speech rhythm in Greek. The HI group follows this pattern as far as the stressed-vowel lengthening is concerned, albeit to a lesser extent than normal, but not the unstressed-vowel shortening. Hence, speakers with HI seem to follow the type of effect that is more prominent in NH speech. The fact that unstressed-vowel shortening occurs in the first syllable more frequently in HI than NH speech could also be associated with the relative instability of the first syllable in HI speech mentioned above. Regarding the two genders, female speakers in both groups differentiate between their stressed and unstressed vowels more extensively than male speakers, although this difference is more pronounced in the HI group. Overall, the female HI group seems to follow the NH duration pattern more closely, especially the stress and syllable position effects of significance in NH speech, while the male HI group displays more differential patterns than normal. As mentioned above, this could be related to the lower intelligibility level or speaker-specific characteristics of the male participants with HI of the study.

Following an investigation of the effect of the medial consonant on the preceding and following vowel duration in symmetrical disyllables of the type [pVCV], similar trends were found post-consonantally between the two hearing groups, but differences were located pre-consonantally. Post-consonantally, all three vowels, and especially the close vowels, are longer after the bilabial stop [p] than the alveolar stop [t] and the fricative [s] for both groups. Pre-consonantally, the NH [a] is longer before the fricative [s] than the two stops, while the close vowels are longer before the bilabial stop but not significantly. Hence, the effect of consonant type on vowel duration depends on the quality of the vowel, in line with previous literature on Greek. Conversely, all three HI point vowels were found longer before the fricative [s]. The differential NH and HI vowel duration patterns in the pre-consonantal position may be related to difficulty in fricative production by speakers with HI, as evident in previous literature. In particular, speakers with HI may require additional time in anticipation of the fricative which may result in prolonged vowels before this consonant.

Finally, V-to-V durational effects were found in disyllables of the form [pV_1pV_2]. In both groups, lengthening effects on the low vowel [a] from the close vowels [i] and [u] were located, albeit to a lesser extent in the HI group, indicative of a compensatory strategy for maintaining relatively stable disyllable duration. Concerning the close vowels, shortening effects from [a] were found in both groups; however, in this case, the HI group displays more effects than the NH group, probably because HI close vowels are longer than NH vowels and can allow for more extensive shortening.

Subsequent to the investigation of acoustic characteristics in NH and HI speech, consonant-to-vowel (C-to-V) and vowel-to-vowel (V-to-V) coarticulation was examined. Consonant-to-vowel effects from the two alveolars [t] and [s] were measured in F1 and F2 frequencies at the temporal midpoint of the vowels [i, a, u] produced by the two hearing groups, employing the bilabial context as a neutral base for comparison. Overall, the HI group followed the C-to-V coarticulatory pattern in both the F1 and F2 axes, albeit presenting differences in coarticulatory magnitude, coarticulatory directionality and relative coarticulation aggression between the two alveolars. More specifically, the results revealed no substantial effects in vowel height for the NH vowels, whereas significant raising of the low vowel [a] from the fricative [s] was found for the HI group. Additionally, substantial fronting of the vowels [a] and [u] from the two alveolars in both hearing groups was observed, although the fronting was significantly more pronounced from the fricative than the stop on the HI

[u]. Consequently, the two alveolars seem to display a relatively similar degree of coarticulatory aggression for the speakers with NH, but differential degree of aggression for the speakers with HI, which could be related to the more constrained production of the HI fricative compared with the NH fricative, covering a wider area of the palate and including more extensive front placement than normal. Greater involvement of the tongue dorsum in fricative production could also require a higher mandible position, accounting for the raised HI [a] in the fricative environment, as opposed to the absence of consonantal effects on the height of NH [a].

Regarding coarticulatory resistance displayed by the point vowels, for both groups, the front vowel [i] was found less influenced by consonantal context, an expected outcome on account of its articulatory proximity to the alveolars. Between the two non-front vowels, the vowel [u] presented more extensive fronting due to its more posterior position than [a] in both hearing groups. However, the difference is more prominent in the NH group, since [u] in HI speech is already significantly fronted as mentioned above. It is noted that, although C-to-V effects were larger in size for the NH group in absolute values, the HI group displayed significant anticipatory C-to-V coarticulation as well.

Concerning the relative prominence of the two coarticulatory directions, the anticipatory component was found more robust in HI C-to-V coarticulation, while a directionality preference was not observed for the NH group. The prominence of anticipatory consonantal effects in HI speech may be related to higher manner requirements for the production of alveolars, and especially the fricative, compared with the demands placed on the tongue dorsum for the less constrained NH fricative. This hypothesis is also supported by the vowel duration pattern observed in HI speech, that is, all three HI vowels were found longer before the fricative, which does not occur for NH [i] and [u]. Longer vowel duration pre-consonantally could indicate additional time required for a more demanding consonantal constriction for the speakers with HI.

Lack of stress was found to cause greater fronting effects from the alveolars on the point vowels of both hearing groups, although the influence was more pronounced on the NH vowels. On the other hand, significant raising of the unstressed [a] in the fricative context occurred only for the HI group. Hence, lack of stress causes more prominent C-to-V effects in height rather than in front/back tongue placement for the HI group in relation to the NH group, as predicted on the basis of previous studies. Vowel duration could also play a role in the different degree of stress influence on consonant-dependent effects in the two hearing groups, in that, NH vowels showed more extensive shortening in the absence of stress. Thus, consonantal influence on the longer HI vowels might have waned before reaching the temporal midpoint. However, this assumption requires further examination.

Vowel-to-vowel coarticulation was investigated in size at V_1 offset and V_2 onset and temporal extent (onset, midpoint and offset of V_1 and V_2) across the three consonantal contexts, the bilabial plosive [p], the alveolar plosive [t] and the alveolar fricative [s]. Overall, the HI group follows the V-to-V pattern displayed by the NH group, in that, basic raising and fronting/effects are present on the vowels of both hearing groups; however, the HI group shows also trends that differ from the normal pattern. Although coarticulatory magnitude is smaller for the HI group, which was expected on the basis of the shorter articulatory distance between the HI vowels, statistically significant coarticulation is displayed in contexts where no effects were located for the NH group. Hence, according to the present data, speakers with HI do not necessarily coarticulate less than speakers with NH, they coarticulate either more or less depending on vocalic and consonantal context.

In particular, the majority of differences between HI and NH coarticulation are exhibited in the fixed high vowel contexts, i.e., [i] and [u]. Both HI high vowels show less coarticulation in height, whereas they are relatively more susceptible to contextual effects in the front/back dimension than the corresponding NH vowels. This result may seem unexpected, but it is interpretable if we consider that the consonantal contexts in which increased coarticulation for the speakers with HI occurs are alveolar and the coarticulatory direction is predominantly anticipatory. As discussed earlier, EPG studies (Nicolaidis, 2004, 2007) have shown that increased palatalization takes place during HI alveolar consonant production. Palatalization is bound to be further intensified in sequences composed of an alveolar + high vowel (e.g., /V*ti*/, /V*tu*/, /V*si*/, /V*su*/), creating a highly overlapped syllable inducing substantial effects on the preceding vowel. Hence, the anticipatory component is more salient in HI V-to-V coarticulation. On the other hand, carryover V-to-V effects are clearly prominent in NH speech.

Therefore, speakers with HI display more anticipatory coarticulation effects along the front/back dimension in fixed high vowel contexts across the two alveolars than the speakers with NH, in agreement with findings on American English deaf speech (Okalidou & Harris, 1999). The NH high vowels show more effects in height than the HI high vowels; these effects occur only across the bilabial, in line with the DAC model. The NH [i] was found overall less coarticulation resistant than the DAC model predicts, which agrees with previous claims about the variability of the Greek [i] in line with Manuel and Krakow's (1984) postulations about languages with smaller vowel inventories allowing more freedom for contextual coarticulation. The

NH [u] received significant lowering effects, in the bilabial environment only, from both [a] and [i]. The dissimilatory [i]-to-[u] lowering effects could be attributed to reasons of perceptual clarity or they could be the result of a trough causing [u]-raising in /upu/ sequences. In addition, [u] was fronted significantly only from [i] across all consonants. Similarly, the NH low mid vowel [a] was found significantly fronted by [i] in all consonantal environments. Hence, the Greek NH high front [i], although not as coarticulation resistant, displays substantial coarticulatory aggression. Overall, in NH speech, [i] is relatively more susceptible than [u] to V-to-V effects in the F2, while [u] seems to receive more effects in the F1. Between the non-front vowels, [a] shows far more coarticulatory variability than [u] in the F1, but the two vowels present a similar degree of coarticulatory resistance in the F2. In HI speech, coarticulatory variability decreases in F2 as follows: [i] > [u] > [a], while in F1, [a] is the only vowel showing effects.

Among the three point vowels, the low vowel [a] seems to be the one showing more similarities in HI and NH V-to-V coarticulation, in that, for both hearing groups, it receives significant raising effects from the high vowels and fronting effects from [i]. Moreover, it is the only HI point vowel not presenting anticipatory fronting effects, but rather showing carryover effects resembling the NH pattern. As mentioned above, this vowel was also found more like the NH one in terms of acoustic characteristics (mean formant values, acoustic variability and duration). Due to lack of auditory feedback, speakers with HI tend to depend on visual articulators, i.e., the jaw and lips, hence the production of a vowel like [a], that does not require relatively such exact tongue dorsum placement in relation to the palate, may be easier to produce. However, an exaggerated dependency on jaw displacement for articulatory performance in HI speech may again lead to differential patterns. The slightly more pronounced anticipatory component in HI [a] raising effects and the increased stress effects on the height of HI [a] due to greater jaw opening than normal may constitute evidence towards that direction.

The permissiveness to V-to-V effects exhibited by the three consonantal contexts differed slightly between the two groups, but was also variable within each group depending on fixed vowel context. For the NH group, in line with the DAC model, the bilabial context generally allowed more V-to-V coarticulation, especially in high vowel contexts, and more particularly in the fixed [i] context. The two NH alveolars showed comparable blocking or promoting of effects, the latter occurring in fixed non-front vowel contexts, i.e., [a] and [u]. On the other hand, the alveolar consonants seemed to allow for more V-to-V coarticulation in HI speech, especially anticipatorily in fixed high vowel contexts. According to earlier studies, HI alveolars, although more constrained in terms of palatal contact, tend to show increased articulatory instability. Thus, their realization could be influenced by the vocalic environment more so than NH alveolar consonants, rendering them more permissive to V-to-V effects depending on the quality of the vowel that precedes and follows them. An examination of V-to-C effects would be required to confirm this claim, as it would complement C-to-V and V-to-V coarticulation data.

Regarding the temporal extent of V-to-V coarticulation, an overall tendency for absence of coarticulatory influence was observed at the vowel midpoint in both hearing groups, except for very few cases in HI coarticulation. In general, although C-to-V effects were significant at the midpoint, the vocalic centre seemed unaffected by the flanking vowel across all three consonants. According to Manuel and Krakow's (1984) hypothesis, we would expect a longer range of V-to-V coarticulation for a language like Greek with a sparse vowel system. However, perceptual constraints aiming at communicative efficiency could be at play, limiting the range of influence. Thus, in agreement with findings on the perceptual mapping of Greek vowels indicating a maximally rather than sufficiently contrastive vowel organization (Hawks & Fourakis, 1995), both NH and HI point vowels do not seem to allow for the expected variance based on the density of the Greek vowel system. This result may also be associated with the claim that Greek is less stress-timed and simpler in syllable structure than other languages, which places more functional weight on Greek vowels, thus restricting V-to-V coarticulation. An investigation of effects at shorter temporal steps might uncover more details about the exact temporal span of V-to-V coarticulation in Greek.

Moreover, concerning the temporal examination of effects, there were some instances of reverse evolution of V-to-V coarticulation for speakers with HI, i.e., blocking of V-to-V effects at the temporal point nearest the flanking vowel and appearance of effects farther into the vowel. Specifically, the anticipatory backing effects of [a] on [i] and the carryover backing influence of [u] on [i] over the alveolars [t] and [s] were not found significant near the consonant, but at the vocalic midpoint or, even farther, at the other end of the vowel. It is noteworthy that these instances occur in sequences composed of an alveolar + [i] which are generally heavily palatalized in HI speech, and could be related to large constraints at and near the alveolar constriction and release. However, there were also few cases where HI V-to-V coarticulation spanned almost the whole vowel. These instances involve the fixed [i] context as well, and are observed in both directions, but they occur in the bilabial environment only. In NH speech, no such temporally extended effects are noted, possibly indicating higher coarticulatory variability of the HI [i] than normal across the bilabial. Nonetheless, coarticulation along the time domain was overall more limited than expected for both groups.

In general, for both groups, V-to-V coarticulation seems to be primarily moderated by context and direction and secondarily by stress. An investigation of the effect of stress on V-to-V coarticulation along both formant axes in HI and NH speech showed that, in the anticipatory direction the effect of stress is variable for both groups depending on vocalic and consonantal context, while in the carryover direction, the stress factor influences coarticulation differently in the two groups especially along the F2 dimension. Specifically, a tendency for NH vowels [i] and [a] to present more V-to-V coarticulatory effects when stressed was observed, whereas more effects were located on the corresponding HI vowels when unstressed, especially in F2. This stress-related coarticulatory pattern was more evident in the carryover direction for both groups, but especially for the HI group. Unstressed HI vowels were found more peripheral than their stressed counterparts post-consonantally, which may account for increased V-to-V effects in the carryover direction for the HI group. On the other hand, for the NH group, it is the stressed vowels that are more peripheral than their unstressed counterparts post-consonantally, possibly allowing more room for carryover coarticulatory influence on stressed vowels instead. Moreover, the finding that unstressed NH vowels do not show relatively greater coarticulation than stressed ones may be associated with the less stress-based rhythm of the Greek language. This pattern may not be followed by speakers with HI because their unstressed vowels are longer than normal and hence more fully articulated and more peripheral, allowing for more coarticulatory effects than NH unstressed vowels.

Regarding gender, a prevalence of V-to-V effects was located in female NH speech, whereas more coarticulation was found in male HI speech. Larger coarticulatory effects for NH female speakers may be associated with their expanded acoustic space and higher acoustic variability, even after normalization, relative to those of NH male speakers. On the other hand, higher variability was observed for HI male vowels than HI female and NH male vowels. However, this result may also relate to speaker-specific rather than gender-specific strategies influencing the V-to-V coarticulation pattern displayed by the groups, and especially the HI group as HI coarticulation is characterized by great speaker-specific variability.

Finally, the examination of V-to-V coarticulation in relation to speech intelligibility level revealed that the two variables are not directly related. More specifically, the very high intelligibility group displayed almost no V-to-V effects, the medium intelligibility group presented effects in very few contexts, while the group with a high intelligibility level, i.e., intermediate among the three groups, displayed the most coarticulation which in certain contexts surpassed NH coarticulation in degree and number of contexts. As mentioned earlier, the high intelligibility group also presented higher acoustic variability during vowel production than the other two HI groups, most resembling the NH vowel variability and vowel durations closest to normal. Despite showing more coarticulation than the other two, not all coarticulatory patterns presented by this group are normal-like. Lack of V-to-V effects for the very high intelligibility group could be associated with an exaggerated effort to articulate clearly and thus limiting contextual influence, although further investigation with carefully balanced groups in gender and number of subjects, as well as examination of individual coarticulatory patterns, are needed to arrive at firmer conclusions.

An overview of the findings indicates that the speech of the HI group participating in the current study shows a lot of similarities with that of the NH group in terms of the acoustic characteristics of vowels and general coarticulation patterns; yet, significant differences are located that involve reduced vocalic contrast, greater vowel acoustic variability, longer vowel durations, differential effect of gender and stress on the acoustic characteristics of vowels and coarticulation, and a predominance of anticipatory coarticulation in alveolar contexts. Owing to lack of auditory feedback, speakers with profound hearing loss may develop an internal model (DIVA) that differs from that of speakers with normal hearing, consequently affecting various characteristics of their speech, such as contrast, variability and coarticulation. As they cannot fully utilize audition, they need to rely on other types of feedback, e.g., visual or tactile, that is less accurate or different in nature. Hence, visible aspects of their articulation, such as jaw movement, may appear less problematic. However, visible articulators could also be used more extensively than normal, in opposition to the less visible tongue. The closer to NH production and the more normal-like V-to-V patterns of [a] compared with those of the high vowels support the first part of the argument. At the same time, the increased stress effects on [a], probably due to exaggerated jaw lowering, speak in favour of the second part of the argument. Reduced contrast along the front/back dimension and greater than normal lingual coarticulation suggest insufficient control of the tongue articulators which significantly influences coarticulatory directionality. The majority of the findings are well accounted for by the Degree of Articulatory Constraint model (DAC) (Recasens et al., 1997) that is based on the coproduction framework. Overall, our findings suggest that HI alveolars are more constrained than normal. As a result, they display more extensive overlap with the following vowel, and thus require stronger anticipation and induce prominent coarticulatory effects on the preceding vowel.

Appendices

Methodology

Appendix 1.1.: Questionnaire

The following questionnaire was given in Greek to the HI who wished to participate in the experiment. It was completed before the recording, so as to confirm that they met certain requirements set to ensure group homogeneity and to gather important information relative to the analysis and discussion of the results.

1. Full name.

……………………………………………………………………………………………………

2. Date of birth.

……………………………………………………………………………………………………

3. Where were you born and raised?

……………………………………………………………………………………………………

4. What is your level and field of study?

……………………………………………………………………………………………………

5. What is your profession?

……………………………………………………………………………………………………

6. What is/was your parents' profession;

……………………………………………………………………………………………………

7. Do you have an audiogram? When did you have it done?

……………………………………………………………………………………………………

8. Is your hearing loss acquired or hereditary?

……………………………………………………………………………………………………

9. Do you know the cause of your hearing loss?

……………………………………………………………………………………………………

10. When was your hearing impairment first diagnosed?

……………………………………………………………………………………………………

11. Was there any other illness diagnosed besides hearing impairment?

……………………………………………………………………………………………………

12. Do you wear hearing aids? In both ears?

……………………………………………………………………………………………………

13. When did you first have hearing aids fitted? Both ears?

……………………………………………………………………………………………………

14. Do you wear hearing aids all the time? If not, how often?

……………………………………………………………………………………………………

15. Have you ever had speech therapy? If yes, for how long and how often?

……………………………………………………………………………………………………

16. Which primary school and high school did you attend?

……………………………………………………………………………………………………

17. Did you also attend a supporting class or did you have parallel support in the mainstream class?

……………………………………………………………………………………………………

18. Do you know/use sign language?

……………………………………………………………………………………………………

19. If yes, how often do you use it?

……………………………………………………………………………………………………

20. How often do you use oral communication (with family, friends)?

……………………………………………………………………………………………………

21. Do you feel comfortable using oral communication?

……………………………………………………………………………………………………

Appendix 1.2.: Consent Form

The following two-page form was prepared for every subject. The first page provides information about the experiment, the procedure and the aims of the study and ensures the anonymity of the participants. The second page is the consent form that the subjects sign. The subjects kept the first page and the researcher the second page.

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ

ΤΜΗΜΑ ΑΓΓΛΙΚΗΣ
ΤΟΜΕΑΣ ΘΕΩΡΗΤΙΚΗΣ ΓΛΩΣΣΟΛΟΓΙΑΣ
Τηλ: 2310 99 7457/7479
Fax: 2310 99 7432
540 06 Θεσσαλονίκη

Όνομα ερευνήτριας: Άννα Σφακιανάκη
Τηλ.: ______________
Όνομα επιβλέπουσας καθηγήτριας: Κατερίνα Νικολαΐδου
Τηλ.: ______________

Τίτλος: «Ακουστικά χαρακτηριστικά του λόγου Ελλήνων με φυσιολογική ακοή και βαρηκοΐα/κώφωση»

Αγαπητέ/ή κ.
Σας παρακαλώ να συμμετάσχετε στην έρευνά μου. Αυτή η έρευνα εξετάζει τα ακουστικά χαρακτηριστικά λόγου Ελλήνων με φυσιολογική ακοή και βαρηκοΐα/κώφωση.

Στο πείραμα αυτό θα συμμετάσχουν περίπου είκοσι άτομα με βαρηκοΐα/κώφωση και δέκα άτομα με φυσιολογική ακοή. Αν συμφωνήσετε να λάβετε μέρος, θα σας ζητηθεί να διαβάσετε κάποιες λέξεις και μικρές φράσεις που θα είναι γραμμένες σε μορφή λίστας. Η συνολική διάρκεια του πειράματος θα είναι περίπου 40 λεπτά. Ο λόγος σας θα ηχογραφηθεί σε φορητό κομπιούτερ με τη βοήθειά ενός μικροφώνου. Τα δεδομένα θα αποθηκευτούν σε ψηφιακή μορφή. Το όνομά σας δε θα αναφερθεί (ίσως μόνο τα αρχικά) και οι πληροφορίες για το άτομό σας δε θα αποκαλυφθούν. Η ανάλυση του λόγου σας θα βοηθήσει να κατανοήσουμε καλύτερα πώς αρθρώνουν άτομα με φυσιολογική ακοή και με βαρηκοΐα. Ακόμα, η δημιουργία μιας φωνητικής βάσης δεδομένων της Ελληνικής θα συντελέσει στην προώθηση της έρευνας της ελληνικής γλώσσας. Αν το επιθυμείτε, θα σας αποσταλεί μια περίληψη των ευρημάτων της έρευνας.
Η συμμετοχή σ'αυτή την έρευνα είναι εθελοντική. Μπορείτε να αρνηθείτε να λάβετε μέρος ή να αποσυρθείτε οποιοδήποτε στιγμή.

Η έρευνα αυτή γίνεται μέσα στα πλαίσια διδακτορικής διατριβής που εκπονείται στο Τμήμα της Αγγλικής Γλώσσας και Φιλολογίας, στον Τομέα Θεωρητικής και Εφαρμοσμένης Γλωσσολογίας του Αριστοτελείου Πανεπιστημίου Θεσσαλονίκης.

Με τιμή,
Άννα Σφακιανάκη

ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ
Τμήμα Αγγλικής Γλώσσας και Φιλολογίας
Τομέας Θεωρητικής και Εφαρμοσμένης Γλωσσολογίας

ΕΝΤΥΠΟ ΣΥΓΚΑΤΑΘΕΣΗΣ

Ο σκοπός της έρευνας και αυτό που μου ζητείται μου έχουν εξηγηθεί ικανοποιητικά.

Συμφωνώ με τις λεπτομέρειες σχετικά με τη συμμετοχή μου σ'αυτή την έρευνα.

Κατανοώ ότι η συμμετοχή μου είναι εντελώς εθελοντική και ότι έχω το δικαίωμα να αποσυρθώ από το πείραμα οποιαδήποτε στιγμή.

Κατανοώ ότι ο λόγος μου θα ηχογραφηθεί και θα αποθηκευτεί για να αναλυθεί ακουστικά. Κατανοώ ότι το ακριβές όνομά μου δε θα χρησιμοποιηθεί.

Έχω λάβει αντίγραφο αυτού του εντύπου συγκατάθεσης.

Υπογραφή: ____

Ονοματεπώνυμο: ____

Ημερομηνία: ____

Όνομα επιβλέπουσας καθηγήτριας: Κατερίνα Νικολαΐδου
Τηλ.: _______________

Όνομα ερευνήτριας: Άννα Σφακιανάκη
Τηλ.: _______________

The Acoustic Experiment

Appendix 1.3.: Material

The recording material consists of two lists. List 1 contains 27 /pV_1CV_2/ sequences with stress on the first syllable and List 2 includes 27 sequences with stress on the second syllable. Each phrase was repeated 10 times, thus each final list had 270 sentences in total which had been randomized before the recording. The disyllables within the carrier phrase "ˈleʝe _____ ˈpali" (Say _____ again.) are presented below. The lists were given to the subjects in Greek writing only. The parentheses after each phrase are added here and contain the target disyllable.

List 1

1. Λέγε πάπα πάλι. (ˈpapa)
2. Λέγε πάπι πάλι. (ˈpapi)
3. Λέγε πάπου πάλι. (ˈpapu)
4. Λέγε πίπι πάλι. (ˈpipi)
5. Λέγε πίπα πάλι. (ˈpipa)
6. Λέγε πίπου πάλι. (ˈpipu)
7. Λέγε πούπου πάλι. (ˈpupu)
8. Λέγε πούπα πάλι. (ˈpupa)
9. Λέγε πούπι πάλι. (ˈpupi)
10. Λέγε πάτα πάλι. (ˈpata)
11. Λέγε πάτι πάλι. (ˈpati)
12. Λέγε πάτου πάλι. (ˈpatu)
13. Λέγε πίτι πάλι. (ˈpiti)
14. Λέγε πίτα πάλι. (ˈpita)
15. Λέγε πίτου πάλι. (ˈpitu)
16. Λέγε πούτου πάλι. (ˈputu)
17. Λέγε πούτα πάλι. (ˈputa)
18. Λέγε πούτι πάλι. (ˈputi)
19. Λέγε πάσα πάλι. (ˈpasa)
20. Λέγε πάσι πάλι. (ˈpasi)
21. Λέγε πάσου πάλι. (ˈpasu)
22. Λέγε πίσι πάλι. (ˈpisi)
23. Λέγε πίσα πάλι. (ˈpisa)
24. Λέγε πίσου πάλι. (ˈpisu)
25. Λέγε πούσου πάλι. (ˈpusu)
26. Λέγε πούσα πάλι. (ˈpusa)
27. Λέγε πούσι πάλι. (ˈpusi)

List 2

1. Λέγε παπά πάλι. (paˈpa)
2. Λέγε παπί πάλι. (paˈpi)
3. Λέγε παπού πάλι. (paˈpu)
4. Λέγε πιπί πάλι. (piˈpi)
5. Λέγε πιπά πάλι. (piˈpa)
6. Λέγε πιπού πάλι. (piˈpu)
7. Λέγε πουπού πάλι. (puˈpu)
8. Λέγε πουπά πάλι. (ˈpupa)
9. Λέγε πουπί πάλι. (puˈpi)
10. Λέγε πατά πάλι. (paˈta)
11. Λέγε πατί πάλι. (paˈti)
12. Λέγε πατού πάλι. (paˈtu)
13. Λέγε πιτί πάλι. (piˈti)
14. Λέγε πιτά πάλι. (piˈta)
15. Λέγε πιτού πάλι. (piˈtu)
16. Λέγε πουτού πάλι. (puˈtu)
17. Λέγε πουτά πάλι. (puˈta)
18. Λέγε πουτί πάλι. (puˈti)
19. Λέγε πασά πάλι. (paˈsa)
20. Λέγε πασί πάλι. (paˈsi)
21. Λέγε πασού πάλι. (paˈsu)
22. Λέγε πισί πάλι. (piˈsi)
23. Λέγε πισά πάλι. (piˈsa)
24. Λέγε πισού πάλι. (piˈsu)
25. Λέγε πουσού πάλι. (puˈsu)
26. Λέγε πουσά πάλι. (puˈsa)
27. Λέγε πουσί πάλι. (puˈsi)

Appendix 1.4.: Disyllable Pairs

The material presented above contained disyllables which were subsequently paired so as to measure V-to-V coarticulatory effects. The tables below display the disyllables used for executing pairwise comparisons (F1 & F2 comparisons) or subtractions (ΔF1 & ΔF2 values) depending on the type of V-to-V effect, the direction and the stress condition.

1) /i/ on /a/

ANTICIPATORY	CARRYOVER
1) ˈpapa – ˈpapi	1) ˈpapa – ˈpipa
2) paˈpa – paˈpi	2) paˈpa – piˈpa
3) ˈpata – ˈpati	3) ˈpata – ˈpita
4) paˈta – paˈti	4) paˈta – piˈta
5) ˈpasa – ˈpasi	5) ˈpasa – ˈpisa
6) paˈsa – paˈsi	6) paˈsa – piˈsa

2) /u/ on /a/

ANTICIPATORY	CARRYOVER
1) ˈpapa – ˈpapu	1) ˈpapa – ˈpupa
2) paˈpa – paˈpu	2) paˈpa – puˈpa
3) ˈpata – ˈpatu	3) ˈpata – ˈputa
4) paˈta – paˈtu	4) paˈta – puˈta
5) ˈpasa – ˈpasu	5) ˈpasa – ˈpusa
6) paˈsa – paˈsu	6) paˈsa – puˈsa

3) /a/ on /i/

ANTICIPATORY	CARRYOVER
1) ˈpipi – ˈpipa	1) ˈpipi – ˈpapi
2) piˈpi – piˈpa	2) piˈpi – paˈpi
3) ˈpiti – ˈpita	3) ˈpiti – ˈpati
4) piˈti – piˈta	4) piˈti – paˈti
5) ˈpisi – ˈpisa	5) ˈpisi – ˈpasi
6) piˈsi – piˈsa	6) piˈsi – paˈsi

4) /u/ on /i/

ANTICIPATORY	CARRYOVER
1) ˈpipi – ˈpipu	1) ˈpipi – ˈpupi
2) piˈpi – piˈpu	2) piˈpi – puˈpi
3) ˈpiti – ˈpitu	3) ˈpiti – ˈputi
4) piˈti – piˈtu	4) piˈti – puˈti
5) ˈpisi – ˈpisu	5) ˈpisi – ˈpusi
6) piˈsi – piˈsu	6) piˈsi – puˈsi

5) /a/ on /u/

ANTICIPATORY	CARRYOVER
1) ˈpupu – ˈpupa	1) ˈpupu – ˈpapu
2) puˈpu – puˈpa	2) puˈpu – paˈpu
3) ˈputu – ˈputa	3) ˈputu – ˈpatu
4) puˈtu – puˈta	4) puˈtu – paˈtu
5) ˈpusu – ˈpusa	5) ˈpusu – ˈpasu
6) puˈsu – puˈsa	6) puˈsu – paˈsu

6) /i/ on /u/

ANTICIPATORY	CARRYOVER
1) ˈpupu – ˈpupi	1) ˈpupu – ˈpipu
2) puˈpu – puˈpi	2) puˈpu – piˈpu
3) ˈputu – ˈputi	3) ˈputu – ˈpitu
4) puˈtu – puˈti	4) puˈtu – piˈtu
5) ˈpusu – ˈpusi	5) ˈpusu – ˈpisu
6) puˈsu – puˈsi	6) puˈsu – piˈsu

Appendix 1.5.: Script

A script was written for automatic formant and duration measurements in Praat. Information and values up to “preEmphasis” differed depending on disyllable, subject gender, etc. An example is given below for the analysis of the disyllable /’papa/ by female subject HI_01.

```
filePrefix$ = "_papa_"
filePostfix$ = "_HI_01"
numberOfSoundFiles = 10
numberOfFormants = 5
maximumFormant = 5500
# windowLength for F1start, F1end, F2start, F2end
windowLength1 = 0.015
# windowLength for F1mid, F2mid
windowLength2 = 0.025
preEmphasis = 50

for i to numberOfSoundFiles
    if i < 10
    wavFileName$ = filePrefix$+"0"+"'i'"+filePostfix$+".wav"
    textGridFileName$ = filePrefix$+"0"+"'i'"+filePostfix$+".TextGrid"
    else
    wavFileName$ = filePrefix$+"'i'"+filePostfix$+".wav"
    textGridFileName$ = filePrefix$+"'i'"+filePostfix$+".TextGrid"
    endif
    if fileReadable(wavFileName$)
        Read from file... 'wavFileName$'
        Read from file... 'textGridFileName$'
    endif
endfor

for i to numberOfSoundFiles
    if i < 10
        soundName$ = filePrefix$+"0"+"'i'"+filePostfix$
    else
        soundName$ = filePrefix$+"'i'"+filePostfix$
    endif

    if fileReadable(soundName$+".wav")
        if autoFormant$="yes"
            select Sound 'soundName$'
            # We create another sound in order to create another formant with
            # a different windowLength for the mid points
            Copy... 'soundName$'_MidPoint
            select Sound 'soundName$'
            To Formant (burg)... 0.01 numberOfFormants maximumFormant windowLength1 preEmphasis
            select Sound 'soundName$'_MidPoint
            To Formant (burg)... 0.01 numberOfFormants maximumFormant windowLength2 preEmphasis
        endif
    endif
endfor
for i to numberOfSoundFiles
```

```
    if i < 10
        soundName$ = filePrefix$+"0"+"'i'"+filePostfix$
    else
        soundName$ = filePrefix$+"'i'"+filePostfix$
    endif
    if fileReadable(soundName$+".wav")
        select TextGrid 'soundName$'

        tierNumber=1

            numberOfIntervals = Get number of intervals... tierNumber
            for interval to numberOfIntervals
                select TextGrid 'soundName$'
                labelOfInterval$ = Get label of interval... tierNumber interval

                # If we find vowel intervals...
                if left$(labelOfInterval$,1) = "a" or left$(labelOfInterval$,1) = "i"
or left$(labelOfInterval$,1) = "u"
                    startPoint = Get starting point... tierNumber interval
                    endPoint = Get end point... tierNumber interval
                    duration = endPoint - startPoint
                    midPoint = (startPoint + endPoint) / 2
                    select Formant 'soundName$'
                    f1start = Get value at time... 1 startPoint Hertz Linear
                    f1end = Get value at time... 1 endPoint Hertz Linear
                    f2start = Get value at time... 2 startPoint Hertz Linear
                    f2end = Get value at time... 2 endPoint Hertz Linear

                    select Formant 'soundName$'_MidPoint
                    f1mid = Get value at time... 1 midPoint Hertz Linear
                    f2mid = Get value at time... 2 midPoint Hertz Linear
                    if mid$(labelOfInterval$,2,1) = "1"

    filename$="out"+filePrefix$+right$(filePostfix$,5)+"_v1.txt"
                    else

    filename$="out"+filePrefix$+right$(filePostfix$,5)+"_v2.txt"
                    endif
                    fileappend                                  'filename$'
'labelOfInterval$"tab$"startPoint:3"tab$"endPoint:3"tab$"duration:3"tab$"midPoint:3"tab$"f1start:0"tab
$"f1mid:0"tab$"f1end:0"tab$"f2start:0"tab$"f2mid:0"tab$"f2end:0"newline$'
                    select Formant 'soundName$'
                    select TextGrid 'soundName$'
                endif

                # If we find "p", "t" or "s" consonant intervals
                if left$(labelOfInterval$,1) = "p" or left$(labelOfInterval$,1) = "t"
or left$(labelOfInterval$,1) = "s"
                    startPoint = Get starting point... tierNumber interval
                    endPoint = Get end point... tierNumber interval
                    duration = endPoint - startPoint

    filename$="out"+filePrefix$+right$(filePostfix$,5)+"_c.txt"
                    fileappend                                  'filename$'
'labelOfInterval$"tab$"duration:3"newline$'
                    select TextGrid 'soundName$'
                endif
            endfor
    endif
endfor
```

The Intelligibility Experiment

The Intelligibility Experiment consisted of 101 words and 25 sentences. The two lists were randomized for every HI subject.

Appendix 1.6.: Material

Words

1) ˈpçata (dishes)
2) arˈkuða (bear -noun)
3) luˈluði (flower)
4) ˈtreçi (runs -3rd person)
5) ˈciknos (swan)
6) ʝaˈʎa (glasses)
7) paɣoˈto (ice cream)
8) maˈçeri (knife)
9) taˈksi (taxi)
10) stratjoˈtaci (toy soldier)
11) ˈpezun (they play)
12) viˈvlio (book)
13) sxoˈlio (school)
14) ariθˈmos (number)
15) neˈro (water)
16) ˈfandazma (ghost)
17) kaˈrekla (chair)
18) karaˈmela (candy)
19) avˈɣo (egg)
20) ˈkaɟelo (banister)
21) ˈscilos (dog)
22) sfiˈrixtra (whistle -noun)
23) ˈxtipise (knocked -3rd person)
24) siˈmea (flag)
25) zoˈni (belt)
26) ˈθalasa (sea)
27) ðelˈfini (dolphin)
28) θerˈmometro (thermometer)
29) ˈkastro (castle)
30) ˈxoma (soil -noun)
31) ˈiʎos (sun)
32) foˈtça (fire)
33) kuˈzina (kitchen)
34) ˈtsanda (bag)
35) ˈvrisi (tap)
36) kaˈpnos (smoke)
37) ˈðaxtilo (finger)
38) ˈlimni (lake)
39) ˈlampa (lamp)
40) ˈdzami (glass)
41) erɣoˈstasio (factory)
42) xoˈndri (fat -female)
43) aˈɣori (boy)
44) ˈɣlosa (tongue)

45) ˈfusces (bubbles)
46) θraˈnio (desk)
47) paˈputsi (shoe)
48) kuˈbja (buttons)
49) fliˈdzani (cup)
50) ˈporta (door)
51) buˈkali (bottle)
52) ɣlifiˈdzuri (lolly pop)
53) ˈcimata (waves)
54) vroˈçi (rain)
55) ˈðrakos (dragon)
56) roˈloi (clock)
57) paˈlto (coat)
58) ˈroða (wheel)
59) aɣeˈlaða (cow)
60) ˈnaftis (sailor)
61) psiˈɉio (fridge)
62) kaˈrotsi (carriage)
63) zɣuˈra (curly –neutral, pl.)
64) ˈftçari (shovel)
65) ðjavazi (reads -3rd person)
66) aeroˈplano (airplane)
67) ˈspiti (house)
68) aftoˈkinito (car)
69) kaˈlaθi (basket)
70) afˈtça (ears)
71) ˈbala (ball)
72) ʎoˈndari (lion)
73) moˈro (baby)
74) sfiˈri (hammer)
75) ˈpsari (fish)
76) ˈpetres (rocks)
77) ˈkaθete (sits -3rd person)
78) ˈespase (broke -3rd person)
79) ˈaɲɟelos (angel)
80) feˈgari (moon)
81) ˈkuɲes (seesaw)
82) kaˈfes (coffee)
83) çeˈlona (turtle)
84) kliˈði (key)
85) kaˈravi (boat)
86) ˈksilo (wood)
87) ˈdzaki (fireplace)
88) tiˈɣani (frying pan)
89) karˈfi (nail)
90) ˈɣata (cat)
91) tsuˈliθra (slide)
92) pexniðja (toys)
93) skaˈmni (stool)
94) kreˈvati (bed)
95) ˈsinefo (cloud)
96) mixaˈni (engine)
97) duˈlapa (wardrobe)
98) veˈlona (needle)

99) psaˈliði (scissors)

100) ˈɣrama (letter)

101) ceˈri (candle)

Sentences

1) to aˈɣori ðjaˈvazi viˈvlia sto sxoˈlio (The boy reads books in school.)

2) ˈʝemisa to buˈkali me neˈro (I filled the bottle with water.)

3) afˈti i ˈɣata ɲauˈrizi ðinaˈta (This cat meows loudly.)

4) to moˈro ˈklei ˈmesa stin ˈkuɲa (The baby is crying in the cradle.)

5) to ˈpsari zi ˈmesa sti ˈθalasa (The fish live in the sea.)

6) ˈçonize ˈolo to proˈi (It snowed all morning.)

7) ˈesfikse ta ˈɟemja tu aˈloɣu (He tightened the reins of the horse.)

8) i fotˈça sto ˈdzaki ˈiçe ˈzvisi (The fire at the fireplace had gone out.)

9) to ʎoˈndari ˈksaplose sta ˈxorta (The lion lay on the grass.)

10) ˈleroses to ˈkitrino ˈforema (You stained the yellow dress.)

11) ˈrotisa ti miˈtera mu to ˈvraði (I asked my mother at night.)

12) o uraˈnos ˈʝemise aˈsterja (The sky filled with stars.)

13) ˈekane mja meˈɣali ˈgafa sti ðuˈʎa (He made a big blunder at work.)

14) min ˈanɟiksis to tiˈɣani ʝaˈti ˈcei (Don’t touch the frying pan because it’s hot.)

15) θiˈmame to paraˈmiθi me to ˈkastro (I remember the castle fairy tale.)

16) ˈotan ˈʎoni to ˈçoni ˈʝinete neˈro (When ice melts it turns into water.)

17) ˈkane mja ˈtumba sto ˈpatoma (Do a turnover on the floor.)

18) ˈexase ʝaˈti ˈiçe ˈɟiɲa (He lost because of bad luck.)

19) to aeroˈplano ˈmbice sta ˈsinefa (The aeroplane entered the clouds.)

20) ˈndiθice vjastiˈka ce ˈefiʝe ˈɣriɣora (He/she dressed hastily and left quickly.)

21) me to ˈuzo meˈθas ˈefkola (You get drunk easily on uzo.)

22) ziˈtuse na ton ði ˈenas ˈfilos tu (A friend of his came looking for him.)

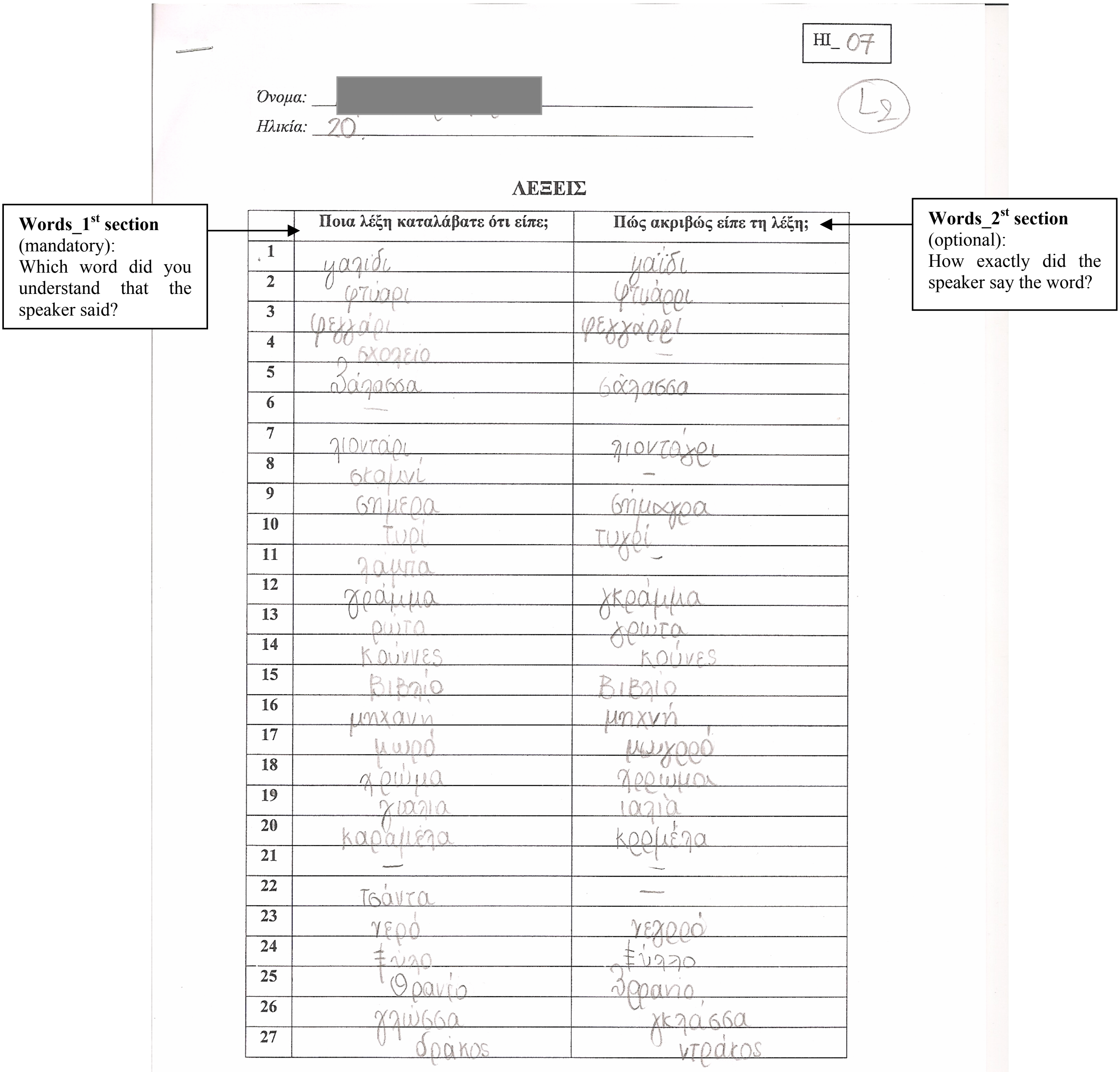
23) to roˈloi ˈxtipise meˈsanixta (The clock struck midnight.)

24) ˈekana poˈla ˈlaθi sta ˈɲata mu (I made many mistakes when I was young.)

25) greˈmizun to paˈʎo mu ˈspiti (My old house is being torn down.)

Appendix 1.7.: Answer Sheet

The listeners were provided with an answer sheet which contained two parts, one for words (below) and one for sentences (see next page). Each part contained two sections. The first section (for words, the left column and for sentences, the first row) was used for scoring the HI subjects' intelligibility. The second section (for words, the right column and for sentences, the second row) was optional and listeners had the chance to write in Greek spelling how the subject produced the item, especially if it sounded "strange" to them. The first page of the first part (words) and the first page of the second part (sentences) completed by a listener are presented below.



HI_ 07

L2

Όνομα: [redacted]

Ηλικία: 20

ΛΕΞΕΙΣ

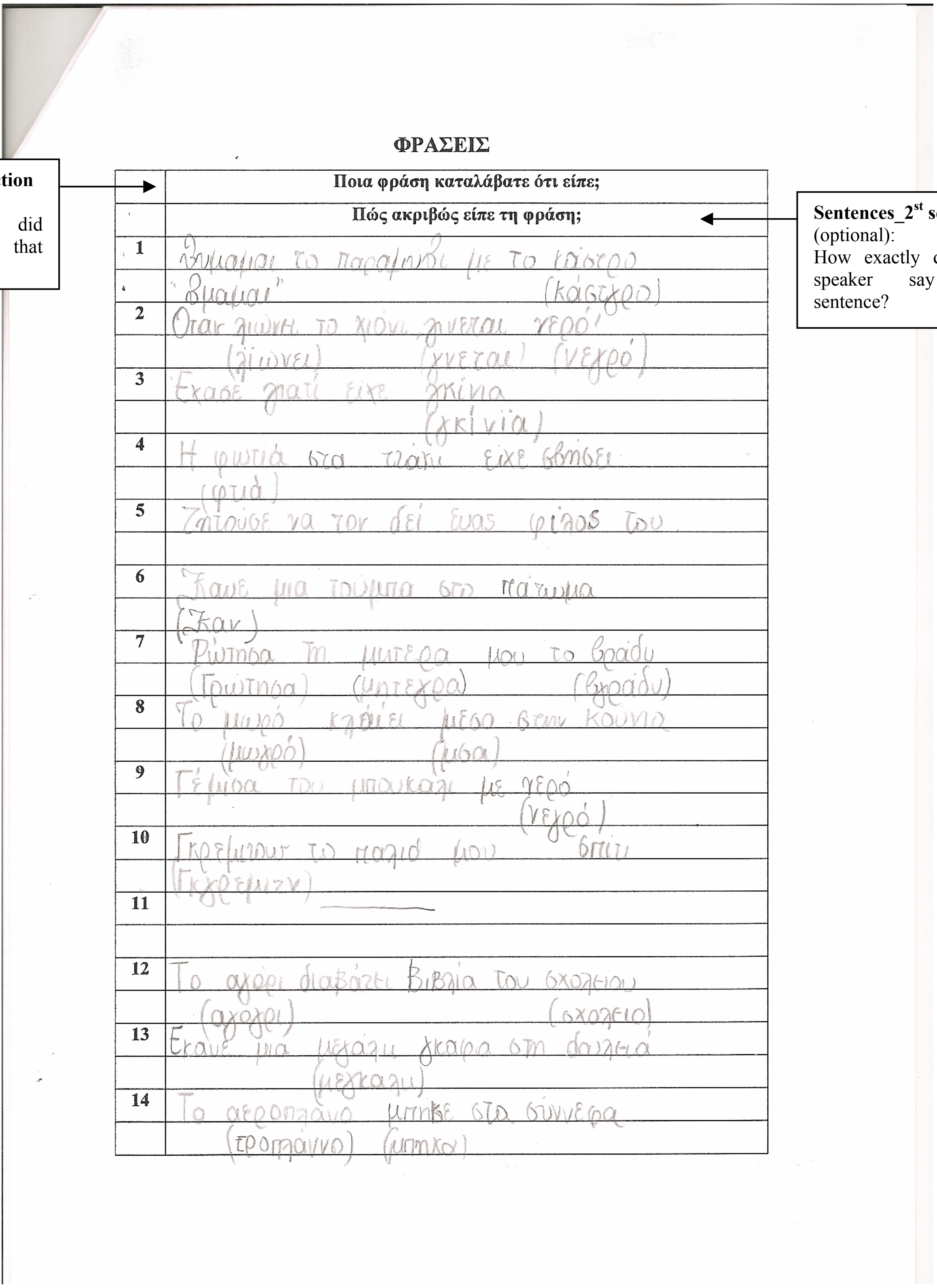
Words_1st section (mandatory): Which word did you understand that the speaker said?

Words_2st section (optional): How exactly did the speaker say the word?

	Ποια λέξη καταλάβατε ότι είπε;	Πώς ακριβώς είπε τη λέξη;
1	γαλίδι	γαΐδι
2	φτύαρι	φτυάρρι
3	φεγγάρι	φεγγάρρι
4	σχολειο	—
5	θάλασσα	σάλασσα
6	—	
7	λιοντάρι	λιοντάγρι
8	σταμνί	—
9	σήμερα	σήμαγρα
10	τυρί	τυγρί
11	λάμπα	—
12	γράμμα	γκράμμα
13	ρώτα	γρώτα
14	κούννες	κούνες
15	βιβλίο	βιβλίο
16	μηχανή	μηχνή
17	μωρό	μωγρό
18	χρώμα	χρρωμα
19	γυαλια	ιαλιά
20	καραμέλα	κρρμέλα
21	—	—
22	Τσάντα	—
23	νερό	νεγρό
24	ξύλο	ξύλλο
25	θρανίο	ζρανιο
26	γλώσσα	γκλάσσα
27	δράκος	ντράκος

Sentences_1st section (mandatory):
Which sentence did you understand that the speaker said?

Sentences_2nd section (optional):
How exactly did the speaker say the sentence?



ΦΡΑΣΕΙΣ

	Ποια φράση καταλάβατε ότι είπε;
	Πώς ακριβώς είπε τη φράση;
1	Θυμαμαι το παραμυθι με το κάστρο
	“θμαμαι” (κάστγρο)
2	Οταν λιώνει το χιόνι γινεται νερό
	(λίωνει) (γνεται) (νεγρό)
3	Εχασε γιατί είχε γκίνια
	(γκίνια)
4	Η φωτιά στα τζάκι είχε σβήσει
	(φτιά)
5	Ζητούσε να τον δεί ενας φίλος του.
6	Έκανε μια τουμπα στο πάτωμα
	(Έκαν)
7	Ρώτησα τη μητερα μου το βραδυ
	(Γρώτησα) (μητεγρα) (βγραδυ)
8	Το μωρό κλαίει μεσα στην κούνια
	(μωγρό) (μσα)
9	Γέμισα του μπουκαλι με νερό
	(νεγρό)
10	Γκρεμιζουν το παλιό μου σπίτι
	(Γκγρεμιζν)
11	———
12	Το αγόρι διαβάζει Βιβλία του σχολειου
	(αγογρι) (σχολειο)
13	Εκανε μια μεγάλη γκαφα στη δουλειά
	(μεγκαλη)
14	Το αεροπλανο μπηκε στα σύννεφα
	(εροπλάινο) (μπηκο)

Appendix 1.8.: Scoring Sheet

The information from the listeners' answer sheets concerning each subject were transferred to the subject's scoring sheet below. The score was averaged over 6 listeners. The number before the item denotes the order in which that item was played back for this subject (HI_01).

		HI_01	L1	L2	L3
1	18	πιάτα			
2	98	αρκούδα			
3	42	λουλούδι			
4	3	τρέχει			
5	70	κύκνος			
6	26	γυαλιά			
7	12	παγωτό			
8	75	μαχαίρι			
9	73	ταξί			
10	90	στρατιωτάκι			
11	7	παίζουν			
12	25	βιβλίο			
13	53	σχολείο			
14	100	αριθμός			
15	41	νερό			
16	57	φάντασμα			
17	19	καρέκλα			
18	39	καραμέλα			
19	94	αυγό			
20	45	κάγκελο			

21	11	σκύλος			
22	101	σφυρίχτρα			
23	5	χτύπησε			
24	78	σημαία			
25	79	ζώνη			
26	83	θάλασσα			
27	93	δελφίνι			
28	35	θερμόμετρο			
29	14	κάστρο			
30	15	χώμα			
31	47	ήλιος			
32	49	φωτιά			
33	31	κουζίνα			
34	13	τσάντα			
35	76	βρύση			
36	60	καπνός			
37	61	δάχτυλο			
38	71	λίμνη			
39	68	λάμπα			
40	51	τζάμι			
41	97	εργοστάσιο			
42	33	χοντρή			
43	21	αγόρι			
44	91	γλώσσα			
45	20	φούσκες			
46	59	θρανίο			
47	72	παπούτσι			
48	92	κουμπιά			
49	85	φλυτζάνι			

50	99	πόρτα			
51	29	μπουκάλι			
52	2	γλειφιτζούρι			
53	46	κύματα			
54	67	βροχή			
55	34	δράκος			
56	64	ρολόι			
57	58	παλτό			
58	77	ρόδα			
59	80	αγελάδα			
60	40	ναύτης			
61	28	ψυγείο			
62	10	καρότσι			
63	56	σγουρά			
64	16	φτυάρι			
65	24	διαβάζει			
66	69	αεροπλάνο			
67	88	σπίτι			
68	36	αυτοκίνητο			
69	38	καλάθι			
70	95	αυτιά			
71	8	μπάλα			
72	32	λιοντάρι			
73	9	μωρό			
74	54	σφυρί			
75	23	ψάρι			
76	6	πέτρες			
77	27	κάθεται			
78	17	έσπασε			

79 81 άγγελος			
80 74 φεγγάρι			
81 4 κούνιες			
82 50 καφές			
83 44 χελώνα			
84 87 κλειδί			
85 48 καράβι			
86 89 ξύλο			
87 84 τζάκι			
88 30 τηγάνι			
89 55 καρφί			
90 22 γάτα			
91 1 τσουλήθρα			
92 62 παιχνίδια			
93 63 σκαμνί			
94 86 κρεβάτι			
95 66 σύννεφο			
96 65 μηχανή			
97 37 ντουλάπα			
98 43 βελόνα			
99 52 ψαλίδι			
100 96 γράμμα			
101 82 κερί			
TOTAL			
Ζητούσε να τον δει ένας φίλος του.			
Το αεροπλάνο μπήκε στα σύννεφα.			
Έκανα πολλά λάθη στα νιάτα μου.			
Μην αγγίξεις το τηγάνι γιατί καίει.			
Το μωρό κλαίει μέσα στην κούνια.			

Κάνε μια τούμπα στο πάτωμα.			
Το λιοντάρι ξάπλωσε στα χόρτα.			
Με το ούζο μεθάς εύκολα.			
Λέρωσες το κίτρινο φόρεμα.			
Γκρεμίζουν το παλιό μου σπίτι.			
Ρώτησα τη μητέρα μου το βράδυ.			
Χιόνιζε όλο το πρωί.			
Η φωτιά στο τζάκι είχε σβήσει.			
Το ρολόι χτύπησε μεσάνυχτα.			
Το ψάρι ζει μέσα στη θάλασσα.			
Γέμισα το μπουκάλι με νερό.			
Έκανε μια μεγάλη γκάφα στη δουλειά.			
Όταν λιώνει το χιόνι γίνεται νερό.			
Έχασε γιατί είχε γκίνια.			
Έσφιξε τα γκέμια του αλόγου.			
Ο ουρανός γέμισε αστέρια.			
Ντύθηκε βιαστικά και έφυγε γρήγορα.			
Θυμάμαι το παραμύθι με το κάστρο.			
Αυτή η γάτα νιαουρίζει δυνατά.			
Το αγόρι διαβάζει βιβλία στο σχολείο.			
TOTAL			

Results

Appendix 2.1.: Statistical Analyses Results –Main factors

F1, F2, ΔF1 & ΔF2 vs. hearing

F1

hearing: start: F(1, 15035)=723.566, p<.0001, mid: F(1, 15036)=463.775, p<.0001, end: F(1, 15035)=1894.647, p<.0001

gender: start: F(1, 15035)=7216.933, p<.0001, mid: F(1, 15036)=12347.468, p<.0001, end: F(1, 15035)=3953.509, p<.0001

measured vowel: start: F(2, 15035)=29312.838, p<.0001, mid: F(2, 15036)=67791.626, p<.0001, end: F(2, 15035)=16073.460, p<.0001

transconsonantal vowel: start: F(2, 15035)=145.068, p<.0001, mid: F(2, 15036)=24.286, p<.0001, end: F(2, 15035)=88.013, p<.0001

consonant: start: F(2, 15035)=713.810, p<.0001, mid: F(2, 15036)=96.190, p<.0001, end: F(2, 15035)=260.888, p<.0001

stress: start: F(1, 15035)=308.298, p<.0001, mid: F(1, 15036)=1608.664, p<.0001, end: F(1, 15035)=654.720, p<.0001

position: start: F(1, 15035)=1338.740, p<.0001, mid: F(1, 15036)=31.505, p<.0001, end: F(1, 15035)=525.218, p<.0001

F2

hearing: start: F(1, 15039)=288.124, p<.0001, mid: F(1, 15045)=156.453, p<.0001, end: F(1, 15038)=4.528, p<.05

gender: start: F(1, 15039)=6966.822, p<.0001, mid: F(1, 15045)=9549.159, p<.0001, end: F(1, 15038)=4546.601, p<.0001

measured vowel: start: F(2, 15039)=39535.110, p<.0001, mid: F(2, 15045)=75450.424, p<.0001, end: F(2, 15038)=21187.576, p<.0001

transconsonantal vowel: start: F(2, 15039)=248.406, p<.0001, mid: F(2, 15045)=87.853, p<.0001, end: F(2, 15038)=182.284, p<.0001

consonant: start: F(2, 15039)=3135.212, p<.0001, mid: F(2, 15045)=872.675, p<.0001, end: F(2, 15038)=2623., p<.0001
stress: mid: F(1, 15045)=50.672, p<.0001, end: F(1, 15038)=87.891, p<.0001
position: start: F(1, 15039)=6549.934, p<.0001, mid: F(1, 15045)=110.368, p<.0001, end: F(1, 15038)=7463.397, p<.0001

ΔF1

hearing: start: F(1, 9969)=35.129, p<.0001, mid: F(1, 9971)=10.583, p<.01, end: F(1, 9969)=41.361, p<.0001

gender: start: F(1, 9969)=8.365, p<.01, mid: F(1, 9971)=43.110, p<.0001, end: F(1, 9969)=63.270, p<.0001

V-to-V: start: F(5, 9969)=224.606, p<.0001, mid: F(5, 9971)=38.675, p<.0001, end: F(5, 9969)=104.943, p<.0001

consonant: start: F(2, 9969)=32.570, p<.0001, mid: F(2, 9971)=16.949, p<.0001, end: F(2, 9969)=25.088, p<.0001

direction: start: F(1, 9969)=63.251, p<.0001, mid: F(1, 9971)=5.289, p<.05, end: F(1, 9969)=148.451, p<.0001

stress: mid: F(1, 9971)=6.644, p<.05

ΔF2

hearing: end: F(1, 9973)=25.994, p<.0001
gender: mid: F(1, 9973)=43.110, p<.0001
V-to-V: start: F(5, 9974)=250.911, p<.0001, mid: F(5, 9973)=107.408, p<.0001, end: F(5, 9973)=171.980, p<.0001
consonant: start: F(2, 9974)=39.850, p<.0001, end: F(2, 9973)=8.871, p<.0001
direction: start: F(1, 9974)=29.657, p<.0001, end: F(1, 9973)=6.254, p<.05

F1, F2, ΔF1 & ΔF2 vs. intelligibility

F1

intelligibility: start: F(3, 15035)=323.740, p<.0001, mid: F(3, 15036)=512.168, p<.0001, end: F(3, 15035)=699.003, p<.0001

gender: start: F(1, 15035)=7121.582, p<.0001, mid: F(1, 15036)=10233.652, p<.0001, end: F(1, 15035)=3397.882, p<.0001

measured vowel: start: F(2, 15035)=29419.908, p<.0001, mid: F(2, 15036)=75434.059, p<.0001, end: F(2, 15035)=14674.011, p<.0001

transconsonantal vowel: start: F(2, 15035)=104.618, p<.0001, mid: F(2, 15036)=23.390, p<.0001, end: F(2, 15035)=97.459, p<.0001

consonant: start: F(2, 15035)=901.739, p<.0001, mid: F(2, 15036)=119.855, p<.0001, end: F(2, 15035)=395.149, p<.0001

stress: start: F(1, 15035)=415.063, p<.0001, mid: F(1, 15036)=1816.581, p<.0001, end: F(1, 15035)=728.312, p<.0001

position: start: F(1, 15035)=1311.437, p<.0001, mid: F(1, 15036)=127.678, p<.0001, end: F(1, 15035)=801.367, p<.0001

F2

intelligibility: start: F(3, 15039)=353.269, p<.0001, mid: F(3, 15045)=145.940, p<.0001, end: F(3, 15038)=60.764, p<.0001

gender: start: F(1, 15039)=5181.914, p<.0001, mid: F(1, 15045)=8692.412, p<.0001, end: F(1, 15038)=3679.970, p<.0001

measured vowel: start: F(2, 15039)=38257.502, p<.0001, mid: F(2, 15045)=83353.345, p<.0001, end: F(2, 15038)=19386.949, p<.0001

transconsonantal vowel: start: F(2, 15039)=104.618, p<.0001, mid: F(2, 15045)=23.390, p<.0001, end: F(2, 15038)=97.459, p<.0001

consonant: start: F(2, 15039)=3175.688, p<.0001, mid: F(2, 15045)=312.906, p<.0001, end: F(2, 15038)=2927.538, p<.0001

stress: start: F(1, 15039)=9.673, p<.01, mid: F(1, 15045)=32.975, p<.0001, end: F(1, 15038)=127.587, p<.0001

position: start: F(1, 15039)=7980.078, p<.0001, mid: F(1, 15045)=312.906, p<.0001, end: F(1, 15038)=10790.197, p<.0001

ΔF1

intelligibility: start: F(3, 9969)=16.989, p<.0001, mid: F(3, 9971)=9.986, p<.0001, end: F(3, 9969)=17.773, p<.0001

gender: start: F(1, 9969)=6.024, p<.05, mid: F(1, 9971)=25.987, p<.0001, end: F(1, 9969)=25.987, p<.0001

V-to-V: start: F(5, 9969)=151.586, p<.0001, mid: F(5, 9971)=30.924, p<.0001, end: F(5, 9969)=115.365, p<.0001

consonant: start: F(2, 9969)=19.382, p<.0001, mid: F(2, 9971)=9.798, p<.0001, end: F(2, 9969)=12.407, p<.0001

direction: start: F(1, 9969)=38.988, p<.0001, end: F(1, 9969)=148.753, p<.0001

stress: mid: F(1, 9971)=4.557, p<.05

ΔF2

intelligibility: start: F(3, 9974)=3.782, p<.05, mid: F(3, 9973)=8.446, p<.0001, end: F(3, 9973)=10.144, p<.0001

gender: start: F(1, 9974)=7.179, p<.01, mid: F(1, 9973)=17.428, p<.0001

V-to-V: start: F(5, 9974)=192.722, p<.0001, mid: F(5, 9973)=101.708, p<.0001, end: F(5, 9973)=191.607, p<.0001

consonant: start: F(2, 9974)=22.928, p<.0001, end: F(2, 9973)=8.042, p<.0001

direction: start: F(1, 9974)=17.805, p<.0001, mid: F(1, 9973)=5.121, p<.05, end: F(1, 9973)=29.391, p<.0001

Duration vs. hearing

hearing: F(1, 15055)=2761.851, p<.0001
gender: F(1, 15055)=1017.189, p<.0001
measured vowel: F(2, 15055)=980.457, p<.0001
transconsonantal vowel: F(2, 15055)=102.171, p<.0001
consonant: F(2, 15055)=9.239, p<.0001
stress: F(1, 15055)=11173.162, p<.0001
position: F(1, 15055)=1381.068, p<.0001

Duration vs. intelligibility

intelligibility: F(3, 15055)=1296.272, p<.0001
gender: F(1, 15055)=901.845, p<.0001
measured vowel: F(2, 15055)=1096.757, p<.0001
transconsonantal vowel: F(2, 15055)=128.658, p<.0001
consonant: F(2, 15055)=25.663, p<.0001
stress: F(1, 15055)=12946.179, p<.0001
position: F(1, 15055)=1291.553, p<.0001

Appendix 2.2.: ANOVA Tables & Statistics Plots –Main factors & interactions

-ON CD-ROM/separate file-

CONTENTS

F1 & F2 vs. hearing

F1 & F2 vs. intelligibility

Duration

ΔF1 & ΔF2 vs. hearing

ΔF1 & ΔF2 vs. intelligibility

Appendix 2.3.: V-to-V Coarticulation Tables

Statistical significance within group is denoted with asterisks and between groups with crosses. There are three levels of significance:

[*] or [$^{+}$] for p<.05, [**] or [$^{++}$] for p<.01 and [***] or [$^{+++}$] for p<.0001

Hearing & Context –F1

Context			NH			HI		
V-to-V	**direction**	**C**	**start**	**mid**	**end**	**start**	**mid**	**end**
/a/-to-/i/	anticipatory	p						
		t						
		s						
	carryover	p	***					
		t						
		s						
/u/-to-/i/	anticipatory	p						
		t						
		s						
	carryover	p						
		t						
		s						
/i/-to-/a/	anticipatory	p						
		t						***
		s						
	carryover	p	***			**		
		t	***					
		s	***			***		***
/u/-to-/a/	anticipatory	p						***
		t			*			***
		s			***			***
	carryover	p	***			$^{++}$***		
		t	***			$^{+}$***		
		s	***			***		
/a/-to-/u/	anticipatory	p			***			
		t						
		s	*					
	carryover	p	***		***			
		t						
		s						*
/i/-to-/u/	anticipatory	p	***		***			
		t						
		s						
	carryover	p	***		**			
		t						
		s						

Hearing & Context –F2

Context			NH			HI		
V-to-V	direction	C	start	mid	end	start	mid	end
/a/-to-/i/	anticipatory	p				**	*	***
		t					**	
		s				*		
	carryover	p	**					
		t						
		s						***
/u/-to-/i/	anticipatory	p			***		*	$^{+}$**
		t						*
		s						**
	carryover	p	***			***		
		t	*					*
		s				***		***
/i/-to-/a/	anticipatory	p					*	
		t						
		s						
	carryover	p	*			***		
		t	***			$^{+}$***		
		s	***					
/u/-to-/a/	anticipatory	p						
		t						
		s						
	carryover	p						
		t						
		s						
/a/-to-/u/	anticipatory	p						
		t						**
		s						***
	carryover	p						
		t						
		s						
/i/-to-/u/	anticipatory	p						
		t						***
		s						***
	carryover	p	***					
		t	***					
		s	*					

Stress & Context –F1

Context				NH			HI		
V-to-V	**direction**	**stress**	**C**	**start**	**mid**	**end**	**start**	**mid**	**end**
/a/-to-/i/	anticipatory	stressed	p						
			t						
			s						
		unstressed	p						
			t						
			s						
	carryover	stressed	p	***					
			t						
			s						
		unstressed	p						
			t						
			s						
/u/-to-/i/	anticipatory	stressed	p						
			t						
			s						
		unstressed	p						
			t						
			s						
	carryover	stressed	p						
			t						
			s						
		unstressed	p						
			t						
			s						
/i/-to-/a/	anticipatory	stressed	p						
			t						**
			s						
		unstressed	p						
			t						
			s						
	carryover	stressed	p	**					*
			t						
			s	**					***
		unstressed	p						
			t						
			s				*		

Context				NH			HI		
V-to-V	**direction**	**stress**	C	**start**	**mid**	**end**	**start**	**mid**	**end**
/u/-to-/a/	anticipatory	stressed	p						
			t						***
			s			***			$^{+}$***
		unstressed	p						***
			t						*
			s						*
	carryover	stressed	p	***			$^{++}$***		
			t	***					
			s	***			***		
		unstressed	p	***					
			t	*					
			s	**			**		
/a/-to-/u/	anticipatory	stressed	p						
			t						
			s						
		unstressed	p			*			
			t						
			s						
	carryover	stressed	p	***					
			t						
			s						
		unstressed	p						
			t						
			s						
/i/-to-/u/	anticipatory	stressed	p						
			t						
			s						
		unstressed	p	*		***			
			t						
			s						
	carryover	stressed	p	*					
			t						
			s						
		unstressed	p						
			t						
			s						

Stress & Context –F2

Context				NH			HI		
V-to-V	direction	stress	C	start	mid	end	start	mid	end
/a/-to-/i/	anticipatory	stressed	p						**
			t						
			s						
		unstressed	p				**	**	**
			t						
			s						
	carryover	stressed	p						*
			t						
			s						***
		unstressed	p				**		
			t						
			s						***
/u/-to-/i/	anticipatory	stressed	p			*			
			t						
			s						
		unstressed	p			**	*		
			t						
			s						**
	carryover	stressed	p	***					
			t						
			s						
		unstressed	p	***			+***		
			t						*
			s				**		***
/i/-to-/a/	anticipatory	stressed	p						
			t						
			s						
		unstressed	p						
			t						
			s						
	carryover	stressed	p						
			t	**					
			s	***					
		unstressed	p				*		
			t	**					
			s	***					

Context				NH			HI		
V-to-V	**direction**	**stress**	**C**	**start**	**mid**	**end**	**start**	**mid**	**end**
/u/-to-/a/	anticipatory	stressed	p						
			t						
			s						
		unstressed	p						
			t						
			s						
	carryover	stressed	p						
			t						
			s						
		unstressed	p						
			t						
			s						
/a/-to-/u/	anticipatory	stressed	p						
			t						
			s			*			**
		unstressed	p						
			t						
			s						
	carryover	stressed	p						
			t						
			s						
		unstressed	p						
			t						
			s						
/i/-to-/u/	anticipatory	stressed	p						
			t						***
			s			**			***
		unstressed	p						
			t						
			s						
	carryover	stressed	p						
			t	***					
			s						
		unstressed	p						
			t	**					
			s	**					

Gender & Context –F1

Context				NH			HI		
V-to-V	**direction**	**gender**	**C**	**start**	**mid**	**end**	**start**	**mid**	**end**
/a/-to-/i/	anticipatory	male	p						
			t						
			s						
		female	p						
			t						
			s						
	carryover	male	p						
			t						
			s						
		female	p	***					
			t						
			s						
/u/-to-/i/	anticipatory	male	p						
			t						
			s						
		female	p						
			t						
			s						
	carryover	male	p						
			t						
			s						
		female	p						
			t						
			s						
/i/-to-/a/	anticipatory	male	p						
			t						
			s						
		female	p						
			t						
			s			**			
	carryover	male	p	**			**		
			t						
			s	**			***		
		female	p						**
			t						
			s						***

Context				NH			HI		
V-to-V	**direction**	**gender**	**C**	**start**	**mid**	**end**	**start**	**mid**	**end**
/u/-to-/a/	anticipatory	male	p						***
			t						***
			s						
		female	p			**			
			t			**			***
			s			***			
	carryover	male	p	***					
			t	**					
			s	***					
		female	p	***					
			t	**					
			s	***					
/a/-to-/u/	anticipatory	male	p						*
			t						
			s						
		female	p						
			t						
			s						
	carryover	male	p	***		***			
			t						
			s						***
		female	p	*					
			t						
			s						
/i/-to-/u/	anticipatory	male	p			**			
			t						
			s						
		female	p						
			t						
			s						
	carryover	male	p						
			t						
			s						
		female	p	**					
			t						
			s						

Gender & Context –F2

Context				NH			HI		
V-to-V	**direction**	**gender**	**C**	**start**	**mid**	**end**	**start**	**mid**	**end**
/a/-to-/i/	anticipatory	male	p						***
			t						
			s						
		female	p						
			t					*	
			s				**		
	carryover	male	p						**
			t						
			s						**
		female	p						
			t						
			s						***
/u/-to-/i/	anticipatory	male	p						
			t					*	***
			s						
		female	p				***		
			t						
			s						
	carryover	male	p	***					
			t						
			s				**		
		female	p	***			$^{++}$***		
			t						
			s						**
/i/-to-/a/	anticipatory	male	p						
			t						
			s						
		female	p						
			t						
			s						
	carryover	male	p				***	*	
			t	*					
			s	**					
		female	p						
			t	***			**		
			s	***					

Context				NH			HI		
V-to-V	**direction**	**gender**	**C**	**start**	**mid**	**end**	**start**	**mid**	**end**
/u/-to-/a/	anticipatory	male	p						
			t						***
			s						
		female	p						
			t						
			s						
	carryover	male	p						
			t						
			s						
		female	p	**					
			t						
			s						
/a/-to-/u/	anticipatory	male	p						
			t						**
			s						
		female	p						
			t						
			s						
	carryover	male	p						
			t						
			s						
		female	p						
			t						
			s						
/i/-to-/u/	anticipatory	male	p						
			t						***
			s						**
		female	p						
			t						
			s			**			
	carryover	male	p	**					
			t	**					
			s						
		female	p						
			t	***					
			s						

Intelligibility & Context –F1

Context			Intel 1			Intel 2			Intel 3		
V-to-V	**direction**	**C**	**start**	**mid**	**end**	**start**	**mid**	**end**	**start**	**mid**	**end**
/a/-to-/i/	anticipatory	p									
		t									
		s									
	carryover	p									
		t									
		s									
/u/-to-/i/	anticipatory	p									
		t									
		s									
	carryover	p									
		t									
		s									
/i/-to-/a/	anticipatory	p									
		t						**			
		s									
	carryover	p				**					
		t									
		s				***		***			
/u/-to-/a/	anticipatory	p						***			
		t						***			***
		s						***			
	carryover	p				***			*		***
		t				**					
		s				***					
/a/-to-/u/	anticipatory	p									
		t									
		s									
	carryover	p									
		t									*
		s									***
/i/-to-/u/	anticipatory	p									
		t									
		s									
	carryover	p									
		t									
		s									

Intelligibility & Context –F2

Context			Intel 1			Intel 2			Intel 3		
V-to-V	**direction**	**C**	**start**	**mid**	**end**	**start**	**mid**	**end**	**start**	**mid**	**end**
/a/-to-/i/	anticipatory	p					***	***			
		t					*				
		s	***								
	carryover	p				***	*	***			
		t									
		s			***			***			
/u/-to-/i/	anticipatory	p					***	**			
		t						**			
		s									**
	carryover	p				***		**			
		t			**						
		s			***				*		
/i/-to-/a/	anticipatory	p									
		t									
		s									
	carryover	p				**					
		t				**					
		s									
/u/-to-/a/	anticipatory	p									
		t									
		s									
	carryover	p									
		t									
		s									
/a/-to-/u/	anticipatory	p									
		t									
		s		***	***						
	carryover	p									
		t									
		s									
/i/-to-/u/	anticipatory	p									
		t						*			
		s						*			
	carryover	p									
		t									
		s				*					

References

Abelin, A., Landberg, I. & Persson, L. (1980). A study of anticipatory labial coarticulation in the speech of children. *Phonetic Experimental Research at the Institute of Linguistics Working Papers, 2,* 2-18. University of Stockholm. Retrieved from http://www2.ling.su.se/fon/perilus/

Abraham, S. (1989). Using a phonological framework to describe speech errors of orally trained, hearing-impaired school-agers. *Journal of Speech and Hearing Disorders, 54,* 600-609.

Adank, P., Smits, R. & van Hout, R. (2004). A comparison of vowel normalization procedures for language variation research. *Journal of the Acoustical Society of America, 116*(5), 3099-3107.

Adler-Bock, M., Bernhardt, B., Gick, B. & Bacsfalvi, P. (2007). The use of ultrasound in remediation of /r/ in adolescents. *American Journal of Speech-Language Pathology, 16,* 128-139.

Agwuele, A. H. (2005). *Effect of stress and rate on coarticulation: An analysis of the variability of F2-onsets.* Doctoral Dissertation. The University of Texas at Austin, Texas. Retrieved from Dissertations & Theses: Full Text. (Publication No. AAT 3205963).

Al-Bamerni, A. & Bladon, A. (1982). One-stage and two-stage patterns of velar coarticulation. *Journal of the Acoustical Society of America, 72,* S104.

Alfonso, P. J., & Baer, T. (1982). Dynamics of vowel articulation. *Language and Speech, 25,* 151-173.

Allen, G. D. & Andorfer, P. M. (2000). Production of sentence-final intonation contours by hearing impaired children. *Journal of Speech, Language and Hearing Research, 43,* 411-455.

Ando, K. & Canter, G. J. (1969). A study of syllabic stress in some English words as produced by deaf and normally hearing speakers. *Language and Speech, 12,* 247-255.

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 & Hearing Disorders, 29*, 156-170.

Arvaniti, A. (1991). *The Phonetics of Modern Greek rhythm and its phonological implications.* Doctoral Dissertation. University of Cambridge, Cambridge, UK.

Arvaniti, A. (1994). Acoustic features of Greek rhythmic structure. *Journal of Phonetics, 22,* 239-268.

Arvaniti, A. (2000). The phonetics of stress in Greek. *Journal of Greek Linguistics, 1,* 9-38.

Arvaniti, A. (2007). Greek Phonetics: The State of the Art. *Journal of Greek Linguistics, 8,* 97-208.

Asteriadou, I. (2008). *An acoustic study of vowel-to-vowel coarticulation in Greek.* Unpublished Master's Thesis. Aristotle University of Thessaloniki.

Bacsfalvi, P., Bernhardt, B. & Gick, B. (2007). Ultrasound and electropalatography as adjuncts to speech therapy for vowels with adolescents with severe hearing impairment. *Advances in Speech-Language Pathology, 9,* 36-45.

Baltazani, M. (2007). Prosodic rhythm and the status of vowel reduction in Greek. *Selected Papers on Theoretical and Applied Linguistics from the 17th International Symposium on Theoretical and Applied Linguistics, 1,* 31-43. Department of Theoretical & Applied Linguistics, Aristotle University of Thessaloniki.

Barzaghi, L. & Madureira, S. (2005). Production and perception of stop consonants by a hearing-impaired Brazilian subject. Poster presented at *Phonetics and Phonology in Iberia (PaPI) 2005*, Barcelona. Retrieved from http://webs2002.uab.es/ filologiacatalana /papi/prog.html

Baum, S. R. & Waldstein R. S. (1991). Perseveratory coarticulation in the speech of profoundly hearing-impaired and normally-hearing children. *Journal of Speech and Hearing Research, 34,* 1286-1292.

Beckman, M. E., Edwards, J. R. & Fletcher, J. (1992). Prosodic structure and tempo in a sonority model of articulatory dynamics. In G. Doherty & D. R. Ladd (Eds.), *Papers in Laboratory Phonology II: Segment, Gesture and Tone,* 68-86. Cambridge: CUP.

Beddor, P. S., Harnsberger, J. D. & Lindemann, S. (2002). Language-specific patterns of vowel-to-vowel coarticulation: Acoustic structures and their perceptual correlates. *Journal of Phonetics, 30,* 591-627.

Bell-Berti, F. & Harris, K. (1974): More on the motor organization of speech gestures. *Status Report on Speech Research*, *SR-37/38,* 73-77. Haskins Laboratories.

Bell-Berti, F. & Harris, K. (1979). Anticipatory Coarticulation: Some implications from a study of lip-rounding. *Journal of the Acoustical Society of America, 65*(5), 1268-1270.

Bell-Berti, F. & Harris, K. (1981). A temporal model of speech production. *Phonetica, 38*, 9-20.

Bell-Berti, F. & Harris, K. (1982). Temporal patterns of coarticulation: lip rounding. *Journal of the Acoustical Society of America, 71*(2), 449-454.

Bell-Berti, F., & Krakow, R. (1991). Anticipatory velar lowering: A coproduction account. *Journal of the Acoustical Society of America, 90*(1), 112-123.

Bell-Berti, F., Krakow, R., Gelfer, C. & Boyce, S. (1995). Anticipatory and carryover effects: implications for models of speech production. In Bell-Berti, F. & L. J. Raphael, *Producing Speech: Contemporary Issues. For Katherine Safford Harris,* 77-97. New York: AIP Press.

Benguerel, A. P. & Cowan, H. A. (1974). Coarticulation of upper lip protrusion in French. *Phonetica, 30,* 41-55.

Beňuš, Š. & Mády, M. (2010). Effects on lexical stress and speech rate on the quantity and quality of Slovak vowels. In *Proceedings of Speech Prosody 2010, 5th International Conference,* 100185, 1-4. Chicago, Illinois. Retrieved from http://aune.lpl.univ-aix.fr/ ~sprosig/sp2010/papers/100185.pdf

Bernhardt, B., Gick, B., Bacsfalvi, P. & Ashdown, J. (2003). Speech Habilitation of hard of hearing adolescents using electropalatography and ultrasound as evaluated by trained listeners. *Clinical Linguistics and Phonetics, 17*(3), 199-216.

Bernhardt, B., Bacsfalvi, P., Gick, B., Radanov, B. & Williams, R. (2005). Exploring electropalatography and ultrasound in speech habilitation. *Journal of Speech-Language Pathology and Audiology, 29,* 169-182.

Bernhardt, B., Bacsfalvi, P., Adler-Bock, M., Shimizu, R., Cheney, A., Giesbrecht, N., O'Connell, M., Sirianni, J. & Radanov, B. (2008). Ultrasound as visual feedback in speech habilitation: Exploring consultative use in rural British Columbia, Canada. *Clinical Linguistics and Phonetics, 22*(2), 149-162.

Bladon, R. & Al-Bamerni, A. (1976). Coarticulation resistance in English /l/. *Journal of Phonetics, 4,* 137-150.

Boersma, P. & Weenink, D. (2011). Praat: doing phonetics by computer [Computer Program]. Version 5.2.19. Retrieved from http://www.praat.org.

Bohn, O., Flege, J. E. & Dagenais, P. A. (1991). Differenzierung und Variabilität der Zungenpositionen bei der Artikulation Deutscher Vokale. *Zeitschrift für Dialektologie und Linguistik, Beihefte 72,* 1-26.

Boone, D. (1966). Modification of the voices of deaf children. *The Volta Review, 68*, 686-692.

Boothroyd, A. (1969). *Distribution of hearing levels in the student population of the Clarke School for the Deaf.* Northampton, Mass.: Clarke School for the Deaf.

Boothroyd, A. (1983). Evaluation of speech. In I. Hochberg, H. Levitt & M. J. Osberger (Eds.), *Speech of the Hearing-impaired: Research, Training, and Personal Preparation,* 181-193. Baltimore: University Park Press.

Boothroyd, A. (1984). Auditory perception of speech contrasts by subjects with sensorineural hearing loss. *Journal of Speech and Hearing Research, 27*, 128-134.

Boothroyd, A. (1985). Evaluation of speech production in the hearing-impaired. Some benefits of forced-choice testing. *Journal of Speech and Hearing Research, 28,* 185-196.

Boothroyd, A. (1988). Hearing aids, cochlear implants, and profoundly deaf children. In E. Owens & D. K. Kessler (Eds.), *Cochlear implants in young deaf children*, 81-99. Boston, MA: College Hill Press.

Boothroyd, A., Nickerson, R. & Stevens, K. (1974). *Temporal patterns in the speech of the deaf: A study in remedial training.* Northampton: Mass.: Clarke School for the Deaf.

Botinis, A., Fourakis, M. & Hawks, J. W. (1997). A perceptual study of the Greek vowel space using synthetic stimuli. *Proceedings of the 5th European Conference on Speech Communication and Technology (EUROSPEECH '97) 3,* 1307-1310, Rhodes, Greece.

Botinis, A. (1989). *Stress and prosodic structure in Greek: A phonological, acoustic, psychological and perceptual study.* Lund: Lund University Press.

Botinis, A., Fourakis, M. & Katsaiti, M. (1995). Acoustic characteristics of Greek vowels under different prosodic conditions. *Proceedings of the 13th International Congress of Phonetic Sciences, 4,* 404-407. Stockholm, Sweden.

Botinis, A., Fourakis, M. & Prinou, I. (1999). Prosodic effects on segmental durations in Greek. *Proceedings of the 6th European Conference on Speech Communication and Technology (EUROSPEECH '99), 6,* 2475-2478. Budapest, Hungary.

Boucher, K. R. (2007). *Patterns of anticipatory coarticulation in adults and typically developing children.* Unpublished Master's Thesis. Bringham Young University. Retrieved from http://printfu.org/kurtt+boucher

Boyce, S. (1990). Coarticulatory organization for lip rounding in Turkish and English. *Journal of the Acoustical Society of America, 88*(6), 2584-2595.

Bradlow, A. R. (1995). A comparative acoustic study of English and Spanish vowels. *Journal of the Acoustical Society of America, 97*(3), 1916-1924.

Bradlow, A. R., Torretta, G. M. & Pisoni, D. B. (1996). Intelligibility of normal speech I: Global and fine-grained acoustic-phonetic talker characteristics. *Speech Communication, 20,* 255-272.

Brannon, J. (1964). *Visual feedback of glossal motions and its influence upon the speech of deaf children*. Doctoral Dissertation. Northwestern University.

Browman, C. P., & Goldstein, L. M. (1986). Towards an articulatory phonology. *Phonology Yearbook, 3,* 219-252.

Browman, C. P., & Goldstein, L. M. (1993). Dynamics and Articulatory Phonology. *Status Report on Speech Research, SR-113,* 51-62.

Browman, C. P., & Goldstein, L. M. (1995). Gestural syllable positional effects in American English. In Bell-Berti, F. & Raphael, L. J. (Eds.), *Producing speech: Contemporary issues. For Katherine Safford Harris,* 19-33. New York: AIP Press. Retrieved from web.haskins.yale.edu/Reprints/HL0969.pdf

Brunner, J., Hoole, P. & Perrier, P. (2007). Articulatory optimisation in perturbed vowel articulation. *Proceedings of the 14th International Congress of Phonetic Sciences*, ID 1408, 497-500. Saarbrücken.

Butcher, A. (1989). Measuring coarticulation and variability in tongue contact patterns. *Clinical Linguistics and Phonetics, 3,* 39-47.

Butcher, A. & Weiher, E. (1976). An electropalatographic investigation of coarticulation in VCV sequences. *Journal of Phonetics, 4,* 59-74.

Byrd, D. (1992). Preliminary results on speaker-dependent variation in the TIMIT database. *Journal of the Acoustical Society of America, 92*(1), 593-596.

Byrd, D. (1994). Relations of sex and dialect to reduction. *Speech Communication, 15,* 39-54.

Calvert, D. R. (1961). *Some acoustic characteristics of the speech of profoundly deaf individuals.* Doctoral Dissertation. Stanford University, Stanford, California.

Calvert, D. R. (1962). Deaf voice quality: a preliminary investigation. *The Volta Review, 64,* 402-403.

Calvert, D. R. & Silverman, S. R. (1983). *Speech and deafness*. Washington, DC: Alexander Graham Bell Association for the Deaf.

Campbell, M. M., Boothroyd, A., McGarr, N. S. & Harris, K. S. (1992). Articulatory compensation in hearing-impaired speakers. *Journal of the Acoustical Society of America, 91*(4), 2362.

Carney, P. J. & Moll, K. L. (1971). A cinefluorographic investigation of fricative consonant-vowel coarticulation. *Phonetica*, *23,* 193-202.

Carlson, G. S. & Bernstein, J. (1988). *A voice-input communication aid.* Final Report of Contract N01-NS-5-2394 submitted to the National Institute of Neurological and Communicative Disorders and Stroke (April, 1988). SRI International, Menlo Park, CA.

Carr, J. (1953). An investigation of the spontaneous speech sounds of five-year-old deaf-born children. *Journal of Speech and Hearing Disorders, 18,* 22-29.

Chiang, W. & Chiang, F. (2005). Vowel dispersion in Truku. *Concentric: Studies in Linguistics, 31*(1), 21-45. Retrieved from http://ir.lib.ntnu.edu.tw/retrieve/19621/ntnulib_ja_B0203_3101_021.pdf

Cho, T. (2004). Prosodically conditioned strengthening and vowel-to-vowel coarticulation in English. *Journal of Phonetics, 32*(2)*,* 141-176.

Choi, J. D. & Keating, P. (1990). Vowel-to-vowel coarticulation in three Slavic languages. *UCLA Working Papers in Phonetics*, *78,* 78-86. UC Los Angeles: Department of Linguistics. Retrieved from: http://escholarship.org/uc/item/8j00q68c

Chung, H., Kim, K. & Huckvale, M. (1999). Consonantal and prosodic influences on Korean vowel duration. *Proceedings of Eurospeech 1999.* Retrieved from https://iris.ucl.ac.uk/ research

Clark, J. G. (1981). Uses and abuses of hearing loss classification. *American Speech-Language-Hearing Association, 23,* 493-500.

Clark, G. (2003). *Cochlear implants –Fundamentals & Applications.* New York: Springer-Verlag.

Clumeck, H. (1976). Patterns of soft palate movement in six languages. *Journal of Phonetics, 4,* 337-351.

Cohn, A. C. (1993). Nasalization in English: phonology or phonetics. *Phonology, 10,* 43-81.

Coimbra, B., Jesus, L. M. T. & Couto, P. (2011). Vowel Acoustics in Normal and Hearing Impaired Children with Cochlear Implant. *International Journal of Pediatric Otorhinolaryngology, 75*(S1), 46. Retrieved from http://www.ieeta.pt/~lmtj/lmtj/ CoimbraJesusCouto2011b.htm

Cole, J., Linebaugh, G., Munson, C. M. & McMurray, B. (2010). Unmasking the acoustic effects of vowel-to-vowel coarticulation: A statistical modeling approach. *Journal of Phonetics, 38,* 167-184.

Crouter, L. (1963). *A cinefluorographic comparison of selected vowels spoken by deaf and hearing subjects.* Unpublished Master's Thesis. University of Kansas.

Crystal, T. H. & House, A. S. (1988). The duration of American-English stop consonants: an overview. *Journal of Phonetics, 16,* 285-295.

Dagenais, P. A. (1992). Speech training with glossometry and palatometry with profoundly impaired children. *The Volta Review, 94,* 261-282.

Dagenais, P. A. & Critz-Crosby, P. (1991). Consonant lingual-palatal contacts produced by normal-hearing and hearing-impaired children. *Journal of Speech, Language & Hearing Research, 34,* 1423-1435.

Dagenais, P. A. & Critz-Crosby, P. (1992). Comparing tongue positioning by normal-hearing and hearing-impaired children during vowel production. *Journal of Speech and Hearing Research, 35*(1), 35-44.

Daniloff, R. & Hammarberg, R. (1973). On defining coarticulation. *Journal of Phonetics, 1,* 239-248.

Daniloff, R. & Moll, K. (1968). Coarticulation of lip rounding. *Journal of Speech and Hearing Research, 11,* 707-721.

Davis, B. L. & MacNeilage, P. F. (1995). The articulatory basis of babbling. *Journal of Speech and Hearing Research, 38,* 1199-1211.

Dauer, R. M. (1980a). *Stress and rhythm in Modern Greek.* Doctoral Dissertation. University of Edinburgh, Edinburgh, UK.

Dauer, R. M. (1980b). The reduction of unstressed high vowels in Modern Greek, *Journal of the International Phonetic Association, 10,* 17-27.

de Jong, K. J. (1995). The supraglottal articulation of prominence in English: Linguistic stress as localized hyperarticulation. *Journal of the Acoustical Society of America, 97*(1), 491-504.

Delattre, P. (1951). The physiological interpretation of sound spectrograms. *Publications of the Modern Language Association*, *66*(5), 864-875.

Di Simoni, F. G. (1974). Influence of consonant environment on duration of vowels in the speech of three-, six- and nine-year old children. *Journal of the Acoustical Society of America, 55,* 362-363.

Diakoumakou, E. (2005). Coarticulatory nasalization in Modern Greek: Evidence for a link between coarticulation and syllable structure. *Journal of the Acoustical Society of America, 117*(4), 2459-2459.

Diehl, R. L. (2008). Acoustic and auditory phonetics: the adaptive design of speech sound systems. *Philosophical Transactions of the Royal Society B Biological Sciences, 363,* 965-978. Retrieved from http://rstb.royalsocietypublishing.org/content/363/1493/965.full.pdf+html

Diehl, R. L. & Kluender, K. R. (1989). Reply to commentators. *Ecological Psychology, 1*(2), 195-225. Retrieved from http://www.cps.utexas.edu/Research/Diehl/pdf/Diehl%20&%20Kluender%201989b.pdf

Diehl, R. L., Lotto, A. J. & Holt, L. L. (2004). Speech perception. *Annual Review of Psychology, 55,* 149-179.

Diehl, R. L., Lindblom, B., Hoemeke, K. A. & Fahey, P. (1996). On explaining certain male-female differences in the phonetic realization of vowel categories. *Journal of Phonetics, 24,* 187-208.

Disner, S. F. (1983). Vowel quality: The relation between universal and language-specific factors. *Working Papers in Phonetics*, *58.* UC Los Angeles: Department of Linguistics, UCLA. Retrieved from: http://escholarship.org/uc/item/1wm9n05g

Dowell, R. C., Blamey, P. J., & Clark, G. M. C. (1995). Potential and limitations of cochlear implants in children. *Annals of Otology, Rhinology and Laryngology, 104*(2), (Suppl. 166), 324-327.

Dowell, R. C., Blamey, P. J., & Clark, G. M. (1997). Factors affecting outcomes in children with cochlear implants. In G. M. Clark (Ed.), *Cochlear implants: XVI World Congress of Otorhinolaryngology, Head and Neck Surgery,* 297-303. Bologna: Monduzzi Editore.

Dromey C. & Sanders, M. (2009). Intra-speaker variability in palatometric measures of consonant articulation. *Journal of Communication Disorders, 42,* 397-407.

Edwards, J. R., Beckman, M. E. & Fletcher, J. (1991). The articulatory kinematics of final lengthening. *Journal of the Acoustical Society of America, 89,* 369-382.

Eleftheriades, O. (1985). *Modern Greek. A Contemporary Grammar*. Pacific Books Publishers.

Elliot, L. L. (1967). Descriptive analysis of audiometric and psychometric scores of students at a school for the deaf. *Journal of Speech and Hearing Research, 10,* 21-40.

Engstrand, O. (1988). Articulatory correlates of stress and speaking rate in Swedish VCV utterances. *Journal of the Acoustical Society of America, 83,* 1863-1875.

Erickson, D. (1998). Effects of contrastive emphasis on jaw opening. *Phonetica, 55,* 147-169.

Erickson, D. (2002). Articulation of extreme formant patterns for emphasized vowels. *Phonetica, 59,* 134-149. *Journal of the Acoustical Society of America, 106*(4), 2241.

Erickson, D., Fujimura, O. & Dang, J. (1999). Articulatory and acoustic characteristics of emphasized and unemphasized vowels. *Journal of the Acoustical Society of America, 106,* 2241.

Ericsdotter, C. & Ericsson, A. M. (2001). Gender differences in vowel duration in read Swedish: Preliminary results. In *Proceedings of Fonetik 2001, the XIVth Swedish Phonetics Conference, Working Papers, 49,* 34-37. Department of Linguistics, Lund University. Retrieved from http://www2.ling.su.se/fon/perilus/2001.htm

Fabricius, A., Watt, D. & Johnson, D. E. (2009). A comparison of three speaker-intrinsic vowel formant frequency normalization algorithms for sociophonetics. *Language Variation and Change, 21*(3), 413-435.

Fadiga, L., Fogazzi, L., Pavesi, G. & Rizzolatti, G. (1995). Motor facilitation during action observation: A magnetic stimulation study. *Journal of Neurophysiology, 7,* 2608-2611.

Fant, G. (1966). A note on vocal tract size factors and non-uniform F-pattern scalings. *Speech Transmission Laboratory - Quarterly Progress and Status Report, 7*(4), 22-30. Dept. of Speech Communication, KTH, Stockholm, Sweden. Retrieved from http://www.speech.kth.se/qpsr

Fant, G. (1975). Non-uniform vowel normalization. *Speech Transmission Laboratory - Quarterly Progress and Status Report, 16*(2-3), 1-19. Dept. of Speech Communication, KTH, Stockholm, Sweden. Retrieved from http://www.speech.kth.se/qpsr

Farnetani, E. (1990). V-C-V lingual coarticulation and its spatiotemporal domain. In W.J. Hardcastle & A. Marchal (Eds). *Speech production and speech modelling*, 93-130. Dordrecht: Kluwer Academic Publishers.

Farnetani, E. (1999). Coarticulation and connected speech processes. In W. J. Hardcastle & J. Laver (Eds.), *The Handbook of Phonetic Sciences*, 371-404. Oxford: Blackwell Publishers Ltd.

Farnetani, E., & Faber, A. (1991). Vowel production in isolated words and in connected speech: an investigation of the linguo-mandibular subsystem. *Proceedings of the ESCA workshop: phonetics and phonology of speaking styles: reduction and elaboration in speech communication,* Barcelona.

Farnetani, E., & Faber, A. (1992). Tongue-jaw coordination in vowel production: Isolated words versus connected speech. *Speech Communication, 11*(4-5), 401-410.

Farnetani, E. & Recasens, D. (1993). Anticipatory Consonant-to-Vowel coarticulation in the production of VCV sequences in Italian. *Language and Speech, 36*(2-3), 279-302.

Farnetani, E. & Recasens, D. (1999). Coarticulation models in recent speech production theories. In W.J. Hardcastle & N. Hewlett (Eds.), *Coarticulation: Theory, Data & Techniques*, 31-65, Cambridge: CUP.

Farnetani, E. & Recasens, D. (2010). Coarticulation and connected speech processes, In Hardcastle, W. J., Laver, J. & Gibbon, F. E. (Eds.), *The Handbook of Phonetic Sciences*, 316-352. (2nd ed.). Oxford: Wiley-Blackwell.

Farnetani, E. & Vayra, M. (1996). The role of prosody in the shaping of articulation in Italian CV syllables. In *Speech Production Modeling 1996: From Control Strategies to Acoustics,* 9-12. Retrieved from http://www.isca-speech.org/archive_open/spm_96/ sps6_009.html

Farnettani, E., Vagges, K. & Magno-Caldognetto, E. (1985). Coarticulation in Italian /VtV/ sequences: a palatographic study. *Phonetica, 42,* 78-99.

Flege, J. E. (1988). Effects of speaking rate on tongue position and velocity of movement in vowel production. *Journal of the Acoustical Society of America, 84,* 901-916.

Fletcher, J. & Daly, D. A. (1976). Nasalance and utterance of hearing-impaired speakers. *Journal of Communication Disorders, 9,* 63-73.

Fletcher, J. & Harrington, J. (1999). Lip and jaw coarticulation. In W.J. Hardcastle & N. Hewlett (Eds.), *Coarticulation: Theory, Data & Techniques*, 164-178. Cambridge: CUP.

Fletcher, S. G. & Newman, D. G. (1991). [s] and [ʃ] as a function of linguapalatal contact place and sibilant groove width. *Journal of the Acoustical Society of America, 89,* 850-858.

Flynn, N. & Foulkes, P. (2011). Comparing vowel formant normalization methods. *Proceedings of the 17th International Congress of Phonetic Sciences*, 683-686. Hong Kong.

Forner, L., & Hixon, T. (1977). Respiratory kinematics in profoundly hearing-impaired speakers. *Journal of Speech & Hearing Research, 66*, 373-408.

Fougeron, C. & Keating, P. A. (1997). Articulatory strengthening at edges of prosodic domains. *Journal of the Acoustical Society of America, 101*(6), 3728-3740.

Fourakis, M. (1986). An acoustic study of the effects of tempo and stress on segmental intervals in Modern Greek. *Phonetica, 43,* 172-188.

Fourakis, M. (1991). Tempo, stress, and vowel reduction in American English. *Journal of the Acoustical Society of America, 90*(4), 1816-1827.

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

Fowler, C. A. (1977). *Timing control in speech production*. Bloomington IN: Indiana University Linguistics Club.

Fowler, C. A. (1980). Coarticulation and theories of extrinsic timing. *Journal of Phonetics, 8,* 113-133.

Fowler, C. A. (1981a). Production and perception of coarticulation among stressed and unstressed vowels. *Journal of Speech Hearing Research, 24,* 127-139.

Fowler, C. A. (1981b). A relationship between coarticulation and compensatory shortening. *Phonetica, 38,* 35-50.

Fowler, C. A. (1983). Realism and unrealism: A reply. *Journal of Phonetics, 11*, 303-322.

Fowler, C. A. (1986). An event approach to the study of speech perception from a direct-realist perspective. *Journal of Phonetics, 14,* 3-28.

Fowler, C. A. (1990). Sound-producing sources as objects of perception: rate normalization and nonspeech perception. *Journal of the Acoustical Society of America, 88,* 1236-1249.

Fowler, C. A. (1991). Auditory perception is not special: We see the world, we feel the world, we hear the world. *Journal of the Acoustical Society of America, 89,* 2910-2915.

Fowler, C. A. (1996). Listeners do hear sounds, not tongues. *Journal of the Acoustical Society of America, 99,* 1730-1741.

Fowler, C.A. (2005). Parsing coarticulated speech in perception: Effects of coarticulation resistance. *Journal of Phonetics, 33,* 199-213.

Fowler, C.A. (2006). Compensation for coarticulation reflects gesture perception, not spectral contrast. *Perception & Psychophysics, 68,* 178-183.

Fowler, C. A. (2007). Speech production. In Gaskell, M.G. (Ed.), *The Handbook of Psycholinguistics*, 489-501. Oxford University Press.

Fowler, C. A. & Brancazio, L. (2000). Coarticulation resistance of American English consonants and its effects on transconsonantal vowel-to-vowel coarticulation. *Language and Speech, 43*(1), 1-41.

Fowler, C. A. & Galantucci, B. (2005). The relation of speech perception and speech production. In D. B. Pisoni & R. E. Remez (Eds.), *The Handbook of Speech Perception,* 633-652. Oxford: Blackwell Publishing Ltd.

Fowler, C. A., & Turvey, M. T. (1980). Immediate compensation in bite-block speech. *Phonetica, 37*, 306-326.

Fowler, C. A. & Saltzman, E. (1993). Coordination and coarticulation in speech production. *Language and Speech, 36,* 171-195.

Fowler, C. A., Brown, J. M. & Mann, V. A. (2000). Contrast effects do not underlie effects of preceding liquids on stop-consonant identification by humans. *Journal of Experimental Psychology: Human Perception & Performance, 26,* 877-888.

Fowler, C. A., Galantucci, B. & Saltzman, E. (2003). Motor theories of perception. In M. A. Arbib (Ed.), *The Handbook of Brain Theory and Neural Networks,* 705-707. (2nd ed.). Cambridge Mass: The MIT Press.

Fowler, C. A., Brown, J. M., Sabadini, L., Weihing, J. (2003). Rapid access to speech gestures in perception: Evidence from choice and simple response time tasks. *Journal of Memory & Language, 49,* 396-413.

Fry, D. B. (1955). Duration and intensity as physical correlates of linguistic stress. *Journal of the Acoustical Society of America, 27,* 765-768.

Fry, D. B. (1958). Experiments in the perception of stress. *Language and Speech. 1,* 126-152.

Fry, D. B. (1965). The dependence of stress judgements on vowel formant structure. In S. Karger (Ed.), *Proceedings of the 5th International Congress of Phonetic Sciences,* Munster, 306-311. Basil, New York.

Fuchs, S., Hoole, P., Brunner, J. & Inoue, M. (2004). The trough effect –An aerodynamic phenomenon? *Proceedings of From Sound to Sense: Fifty + Years of Discoveries in Speech Communication,* C25-C30. M.I.T., Cambridge, MA. Retrieved from http://www.rle.mit.edu/soundtosense/conference/pages/contributed.htm

Fuchs, S., Perrier, P., Geng, C. & Mooshammer, C. (2006). What role does the palate play in speech motor control? Insights from tongue kinematics for German alveolar obstruents. In Harrington, J. and Tabain, M. (Eds.), *Speech production: Models, Phonetic Processes and Techniques*, 149-164. New York: Psychology Press. Retrieved from http://susannefuchs.org/publications.html

Fujimura, O. (1981). Temporal organization of articulatory movements as a multidimensional phrasal structure. *Phonetica, 38,* 66-83.

Fujimura, O. (2000). The C/D model and prosodic control of articulatory behaviour. *Phonetica, 57,* 128-138.

Gabrielsson, D., Kirchner, S., Nilsson, K., Norberg, A. & Widlund, C. (2011). Anticipatory lip rounding – a pilot study using The Wave Speech Research System.

In Proceedings from Fonetik 2011, Quarterly Progress & Status Report, 37-40. Department of Speech, Music & Hearing, KTH, Stockholm. Retrieved from http://www.speech.kth.se/ fonetik2011/proceedings.pdf

Galantucci, B., Fowler, C. A., & Goldstein, L. (2009). Perceptuo-motor compatibility effects in speech. *Attention, Perception, & Psychophysics, 71*(5), 1138-1149. Retrieved from http://www.yu.edu/uploadedFiles/Faculty/Bruno_Galantucci/ A172RA_Manuscript.pdf

Galantucci, B., Fowler, C. A., & Turvey, M. T. (2006). The motor theory of speech perception reviewed. *Psychonomic Bulletin & Review, 13*(3), 361-377. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2746041/?tool=pmcentrez

Gay, T. (1974). A cinefluorographic study of vowel production. *Journal of Phonetics, 2,* 255-266.

Gay, T. (1975): Some electromyographic measures of coarticulation in VCV-utterances. *Status Report on Speech Research*, *SR-44,* 137-145. Haskins Laboratories.

Gay, T. (1977a). Articulatory movements in VCV sequences. *Journal of the Acoustical Society of America, 62*(1), 183-193.

Gay, T. (1977b). Cinefluorographic and electromyographic studies of articulatory organization. In M. Sawashima & F. S. Cooper (Eds.), *Dynamic aspects of speech production,* 85-102. Tokyo: University of Tokyo Press. Retrieved from http://www.haskins.yale.edu/Reprints/HL0227.pdf

Gay, T. (1978a). Articulatory units: segments or syllables? *Status Report on Speech Research*, *SR-54,* 53-63. Haskins Laboratories.

Gay, T. (1978b). Effect of speaking rate on vowel formant movements. *Journal of the Acoustical Society of America, 63,* 223-230.

Gay, T. (1981). Mechanisms of control of speech rate. *Phonetica, 38,* 148-158.

Geffner, D. S. (1980). Feature characteristics of spontaneous speech production in young deaf children. *Journal Communication Disorders, 13,* 443-454.

Geffner, D. S. & Rothman Freeman, L. (1980). Assessment of language comprehension of 6-year-old deaf children. *Journal of Communication Disorders, 13*(6), 455-470.

Gelfer, C. E., Bell-Berti, F., & Harris, K. S. (1989). Determining the extent of coarticulation: Effects of experimental design. *Journal of the Acoustical Society of America, 86*(6), 2443-2445.

Gibson, T. & Ohde, R. N. (2007). F2 locus equations: Phonetic descriptors of coarticulation in 17- to 22-month-old children. *Journal of Speech, Language and Hearing Research, 50,* 97-108.

Gilbert, H. R. (1975). Simultaneous oral and nasal airflow during stop consonant production by hearing-impaired speakers. *Folia Phoniatrica, 27,* 423-437.

Gilbert, H. R. & Campbell, M. I. (1978). Voice-onset time in the speech of hearing impaired individuals. *Folia Phoniatrica, 30,* 67-81.

Girgin, M. C. & Özsoy, B. (2008). The relationship between formant frequency and duration characteristics of vowels and speech intelligibility in Turkish hearing impaired children. *World Applied Sciences Journal, 4*(6), 891-899.

Goffman, L., Smith, A., Heisler, L. & Ho, M. (2008). The breadth of coarticulatory units in children and adults. *Journal of Speech, Language and Hearing Research, 51,* 1424-1437.

Gold, T. (1978). *Speech and hearing skills: A comparison between hard-of-hearing and deaf children*. Doctoral Dissertation. City University of New York.

Gold, T. (1980). Speech production in hearing-impaired children. *Journal of Communication Disorders, 13,* 397-418.

Goldstein, U. (1980). *An articulatory model for the vocal tracts of growing children*. Doctoral Dissertation. MIT, Cambridge.

Goodell, E. W. & Studdert-Kennedy, M. (1993). Acoustic evidence for the development of gestural coordination in the speech of 2-year-olds: A longitudinal study. *Journal of Speech and Hearing Research, 36,* 707-727.

Grosvald, M. (2009). Interspeaker variation in the extent and perception of long-distance vowel-to-vowel coarticulation. *Journal of Phonetics, 37*(2), 173-188.

Guenther, F. H. (1995). Speech sound acquisition, coarticulation, and rate effects in a neural network model of speech production. *Psychological Review, 102,* 594-621.

Guenther, F. H. (2001). Neural modelling of speech production. *Proceedings of the 4th International Nijmegen Speech Motor Conference*. Nijmegen, The Netherlands. Retrieved from http://speechlab.bu.edu/publications/ neuralModeling2001.pdf

Guenther, F. H., Gosh, S. S. & Tourville, J. A. (2006). Neural modelling and imaging of the cortical interactions underlying syllable production. *Brain and Language, 96,* 280-301.

Guenther, F. H., Hampson, M. & Johnson, D. (1998). A theoretical investigation of reference frames for the planning of speech. *Psychological Review, 105,* 611-633.

Guenther, F. H. & Perkell, J. (2004). A neural model of speech production and its application to studies of the role of auditory feedback in speech. In B. Maasen, R. Kent, H. F. M. Peters, P. Lieshout & W. Hulstijn (Eds.), *Speech motor control in normal and disordered speech*, 29-50. Oxford: Oxford University Press.

Hammarberg, R. (1976). The metaphysics of coarticulation. *Journal of Phonetics, 4,* 353-363.

Hammarberg, R. (1982). On redefining coarticulation. *Journal of Phonetics, 10,* 123-137.

Han, J. I. (2007). The role of vowel contrast in language-specific patterns of vowel-to-vowel coarticulation: Evidence from Korean and Japanese. *Proceedings of the 16th International Congress of Phonetic Sciences*, ID 1097, 509-512. Saarbrücken. Retrieved from http://www.icphs2007.de/conference/Papers/1097/1097.pdf

Hardcastle, W. J., Gibbon, F. E. & Jones, W. (1991). Visual display of tongue-palate contact: Electropalatography in the assessment and remediation of speech disorders. *British Journal of Disorders of Communication, 26,* 41-74.

Harrington, J., Fletcher, J. & Beckman, M. (2000). Manner and place conflicts in the articulation of accent in Australian Engish. In Pierrehumbert, B. (Ed.), *Papers in Laboratory Phonology V: Language acquisition and the lexicon,* 40-51. Cambridge: CUP.

Harris, M. S. & Umeda, N. (1974). Effect of speaking mode on temporal factors in speech. *Journal of the Acoustical Society of America, 56*(3), 1016-1018.

Harris, K. S., Rubin-Spitz, J. & McGarr, N. S. (1985). The role of production variability in normal and deviant developing speech. Proceedings of the Conference on the Planning and Production of Speech in Normal and Hearing-Impaired Individuals. *ASHA Reports, 15,* 50-57. Retrieved from http://www.haskins.yale.edu/Reprints/HL0513.pdf

Hawks, J. W. & Fourakis, M. (1995). Perception of synthetic vowels by native speakers of American English and Modern Greek. *Language and Speech, 38,* 237-252.

Hazan, V. & Markham, D. (2004). Acoustic-phonetic correlates of talker intelligibility for adults and children. *Journal of the Acoustical Society of America, 116*(5), 3108-3118.

Heffernan, K. (2007). Vowel dispersion as a determinant of which sex leads a vowel change. *Proceedings of the 16th International Congress of Phonetic Sciences*, ID 1120, 1485-1488. Saarbrücken.

Henke, W. (1966). *Dynamic articulatory model of speech production using computer simulation.* Doctoral Dissertation. MIT, Cambridge.

Henton, C. (1983). Changes in the vowels of Received Pronunciation. *Journal of Phonetics, 11,* 353-371.

Henton, C. (1992). The abnormality of male speech. In G. Wolf (Ed.), *New Departures in Linguistics,* 27-59. New York: Garland Publishing Co.

Henton, C. (1995). Cross-language variation in the vowels of female and male speakers. *Proceedings of the 13th International Congress of Phonetic Sciences*, *4,* 420-423. Stockholm.

Hertrich, I. & Ackermann, H. (1995). Coarticulation in slow speech: Durational and spectral analysis. *Language and Speech, 38*(2), 159-187.

Hickok, G. (2001). Functional Anatomy of Speech Perception and Speech Production: Psycholinguistic Implications. *Journal of Psycholinguistic Research, 30*(3), 225-235.

Hickok, G. & Poeppel, D. (2000). Towards a functional neuroanatomy of speech perception. *Trends in Cognitive Science, 4,* 131-138.

Hide, Ø., Gillis, S., Verhoeven, J., Govaerts, P. & De Maeyer, S. (2010). The role of reduced hearing and cochlear implants in children's production of word stress. [Abstract]. Oral presentation at the *13th Meeting of the International Clinical Phonetics and Linguistics Association* (*ICPLA*), 71, June 23-26, Oslo, Norway.

Higgins, M. B., Carney, A. E., & Schulte, L. (1994). Physiological assesment of speech and voice production of adults with hearing loss. *Journal of Speech and Hearing Research, 37*, 510-521.

Hillenbrand, J., Getty, L. A., Clark, M. J. & Wheeler, K. (1995). Acoustic characteristics of American English vowels. *Journal of the Acoustical Society of America, 97*(5), 3099-3111.

Holt, L. L., Lotto, A. J., Kluender, K. R. (2000). Neighbouring spectral content influences vowel identification. *Journal of the Acoustical Society of America, 108,* 710-722.

Hood, R. & Dixon, R. (1969). Physical characteristics of speech rhythm of deaf and normal-hearing speakers. *Journal of Communication Disorders, 2,* 20-28.

Hoole, P. & Kühnert, B. (1995). Patterns of lingual variability in German vowel production. *Proceedings of the 13th International Congress of Phonetic Sciences*, *2,* 442-445. Stockholm. Retrieved from http://www.phonetik.uni-muenchen.de/~hoole/pdf/ Hoole_ICPhS95.pdf

Hoole, P., Nguyen-Trong, N. & Hardcastle, W. (1993). A comparative investigation of coarticulation in fricatives: electropalatographic, electromagnetic, and acoustic data. *Language and Speech, 36*(2-3), 235-260.

House, A. S. (1961). On vowel duration in English. *Journal of the Acoustical Society of America, 33(9),* 1174-1178.

Howe, M. S. & McGowan, R. S. (2005). Aeroacoustics of [s]. *Proceedings: Mathematical, Physical and Engineering Sciences, 461*(2056), 1005-1028. Retrieved from http://www.jstor.org/stable/30046954

Hudgins, C. V. (1934). A comparative study of the speech coordinations of deaf and normal subjects. *Journal of Genetic Psychology, 44*, 1-48.

Hudgins, C. V. (1937). Voice production and breath control in the speech of the deaf. *American Annals of the Deaf, 82,* 338-363.

Hudgins, C. V. (1946). Speech breathing and speech intelligibility. *The Volta Review, 48*, 642-644.

Hudgins, C. V., & Numbers, F. C. (1942). An investigation of the intelligibility of the speech of the deaf. *Genetic Psychology Monograph, 25*, 289-392.

Huffman, M. (1986). Patterns of coarticulation in English. *UCLA Working Papers in Phonetics, 63*, 26-47. UC Los Angeles: Department of Linguistics. Retrieved from http://escholarship.org/uc/item/45k7g853

Huntington, D. A., Harris, K. S. & Sholes, G. N. (1968). An electromyographic study of consonant articulation in hearing-impaired and normal speakers. *Journal of Speech and Hearing Research, 11,* 147-158.

Huntington, D. A., Harris, K. S., Shankweiler, D. & Sholes, G. N. (1968). Some observations on monosyllabic production by deaf speakers and dysarthric speakers. *American Annals of the Deaf, 113,* 134-146.

Jacewicz, E., Fox, R. A. & Salmons, J. (2007). Vowel space areas across dialects and gender. *Proceedings of the 16th International Congress of Phonetic Sciences*, ID 1252, 1465-1468. Saarbrücken.

Jacewicz, E., Fox, R. A. & Salmons, J. (2007). Vowel duration in three American English dialects. *American Speech, 82,* 367-385.

Jacewicz, E., Fox, R. A. & Wei, L. (2010). Between-speaker and within-speaker variation in speech tempo of American English. *Journal of the Acoustical Society of America, 128*(2), 839-850.

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

John, J. E. J., Gemmill, J., Howarth, J. N., Kitzinger, M. & Sykes, M. (1976). Some factors affecting the intelligibility of deaf children’s speech. In S. D. G. Stephens (Ed.) *Disorders of Auditory Function II,* 187-196. London: Academic Press.

Johnson, K. (2006). Resonance in an exemplar-based lexicon: the emergence of social identity and phonology. *Journal of Phonetics, 34,* 485-499.

Johnson, K. & Martin, J. (2001). Acoustic vowel reduction in Creek: effects of distinctive length and position in the word. *Phonetica, 58,* 81-102.

Johnson, K., Ladefoged, P. & Lindau, M. (1993). Individual differences in vowel production. *Journal of the Acoustical Society of America, 94*(2), 701-714.

Johnston, R. G., Goldberg, L. R. & Mathers, P. L. (1984). Coarticulation: theory to therapy. In R. G. Daniloff (Ed.), *Articulation, Assessment and Treatment Issues.* San Diego: College Hill Press.

Jongman, A., Fourakis, M. & Sereno, J. A. (1989). The acoustic vowel space of Modern Greek and German. *Language and Speech, 32,* 221-248.

Joseph, B. & Philippaki-Warburton, I. (1987). *Modern Greek.* London: Croom Helm.

Jusczyk, P. W. (1997). *The discovery of spoken language.* Cambridge, MA: MIT Press.

Jusczyk, P. W. & Luce, P. A. (2002). Speech perception and spoken word recognition: Past and present. *Ear & Hearing, 23*(1), 2-40.

Jusczyk, P. W., Pisoni, D. B., Walley, A. & Murray, J. (1980). Discrimination of relative time onset of two-component tones by infants. *Journal of the Acoustical Society of America, 67,* 262-270.

Katz, W. F. & Bharadwaj, S. (2001). Coarticulation in fricative-vowel syllables produced by children and adults: a preliminary report. *Clinical Linguistics and Phonetics, 15*(1&2), 139-143.

Katz, W. F., Kripke, C. & Tallal, P. (1991). Anticipatory coarticulation in the speech of adults and young children: Acoustic, perceptual and video data. *Journal of Speech and Hearing Research, 34,* 1222-1232.

Keating, P. (1988). The window model of coarticulation: articulatory evidence. In *UCLA Working Papers in Phonetics*, *69,* 3-29. UC Los Angeles: Department of Linguistics. Retrieved from: http://escholarship.org/uc/item/713890f5

Keating, P. A., Lindblom, B., Lubker, J. & Kreiman, J. (1994). Variability in jaw height for segments in English and Swedish VCVs. *Journal of Phonetics, 22,* 407-422. Retrieved from http://www.linguistics.ucla.edu/people/keating/keatingetal_1994_jaw.pdf

Kelso, J. A. S., Saltzman, E. L. & Tuller, B. (1986). The dynamical perspective on speech production: Data and theory. *Journal of Phonetics, 14,* 29-59.

Kelso, J. A. S., Tuller, B., Vatikiotis-Bateson, E. & Fowler, C. A. (1984). Functionally specific articulatory cooperation following jaw perturbations during speech:

Evidence for coordinative structures. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 812-832.

Kelso, J. A. S., Vatikiotis-Bateson, E., Saltzman, E. L. & Kay, B. (1985). A qualitative dynamic analysis of reiterant speech production: Phase portraits, kinematics, and dynamic modeling. *Journal of the Acoustical Society of America, 77*(1), 266-280.

Kent, R. D. (1983). The segmental organization of speech. In P. MacNeilage (Ed.), *The production of speech*, 57-89. New York: Springer-Verlag.

Kent, R. D. & Minifie, F. (1977). Coarticulation in recent speech production models. *Journal of Phonetics, 5,* 115-133.

Kent, R. D., Miolo, G. & Bloedel, S. (1994). The intelligibility of children's speech: A review of evaluation procedures. *American Journal of Speech Language-Pathology, 3,* 81-93.

Khouw, E. & Ciocca, V. (2007). An acoustic and perceptual study of initial stops produced by profoundly hearing impaired adolescents. *Clinical Linguistics & Phonetics, 21*(1), 13-27.

Kiritani, S., Itoh, K., Hirose H. & Sawashima M. (1977). Coordination of the consonant and vowel articulations - X-ray microbeam study on Japanese and English. *Annual Bulletin of the Research Institute for Logopedics and Phoniatrics, 11,* 11-21.

Klatt, D. H. (1973). Interaction between two factors that influence vowel duration. *Journal of the Acoustical Society of America, 54*(4), 1102-1104.

Klatt, D. H. (1975). Vowel lengthening is syntactically determined in connected discourse. *Journal of Phonetics, 3,* 129-140.

Klatt, D. H. (1976). Linguistic uses of segmental duration in English: Acoustic and perceptual evidence. *Journal of the Acoustical Society of America, 59*(5), 1208-1221.

Kluender, K. R., Diehl, R. L. & Killeen, P. R. (1987). Japanese quail can learn phonetic categories. *Science, 237,* 1195-1197.

Koenig, L. & Okalidou, A. (2003). Stress effects on coarticulation in English and Greek. In *Proceedings of the 145th Meeting of the Acoustical Society of America, J.A.S.A. 113* (4), 2330 (A).

Kontosopoulos, N., Ksiromeritis, N. & Tsitsa, A. (1988). Akustikes erevnes epi ton ellinikon fthogon [Acoustic research on the Greek sounds]. *Glossologia, 5-6,* 103-122.

Kröger, B. J., Kannampuzha, J. & Neuschaefer-Rube, C. (2009). Towards a neurocomputational model of speech production and perception. *Speech Communication, 51,* 793-809.

Kühnert, B. & Nolan F. (1999). The origin of coarticulation. In W.J. Hardcastle & N. Hewlett (Eds.), *Coarticulation: Theory, Data & Techniques*, 7-30. Cambridge: CUP.

Kuehn, D. P. & Moll, K. L. (1976). A cineradiographic study of VC and CV articulatory velocities. *Journal of Phonetics, 4,* 303-320.

Kuhl, P. K. (1991). Human adults and human infants show a "perceptual magnet effect" for the prototypes of speech categories, monkeys do not. *Perception Psychophysics, 50,* 93-107. Retrieved from http://www.utdallas.edu/~assmann/aud6306/kuhl91.pdf

Kuhl, P. K. & Miller, J. D. (1975). Speech perception by the chinchilla: voiced-voiceless distinction in alveolar plosive consonants. *Science, 190,* 69-72.

Krull, D. (1989). Consonant-vowel coarticulation in spontaneous speech and in reference words. *Speech Transmission Laboratory - Quarterly Progress and Status Report, 30*(1), 101-105. Dept. of Speech Communication, KTH, Stockholm, Sweden.

Labov, W. (1970). The study of language in its social context. *Studium Generale, 23,* 30-87.

Labov, W. (1990). The intersection of sex and social class in the course of linguistic change. *Language Variation and Change, 2,* 205-254.

Ladefoged, P. (1980). What are linguistic sounds made of? *Language, 56*(3), 485-502.

Ladefoged, P. (1983). The limits of biological explanation in phonetics. In *UCLA Working Papers in Phonetics*, *57,* 1-10. UC Los Angeles: Department of Linguistics. Retrieved from: http://escholarship.org/uc/item/1kq6011w

Ladefoged, P. (2004). Phonetics and Phonology in the Last 50 years. In *UCLA Working Papers in Phonetics*, *103,* 1-11. UC Los Angeles: Department of Linguistics. Retrieved from: http://escholarship.org/uc/item/3xk6p6hj

Lane, H. & Perkell, J. S. (2005). Control of Voice-Onset Time in the Absence of Hearing: A Review. *Journal of Speech, Language, and Hearing Research, 48,* 1334-1343.

Lane, H., Denny, M., Guenther, F. H., Matthies, M. L., Menard, L., Perkell, J. S., Stockman, E., Tiede, M., Vick, J. & Zandipour, M. (2005). Effects of bite blocks and hearing status on vowel production. *Journal of the Acoustical Society of America, 118*(3), 1636-1646.

Lane, H., Matthies, M. L., Guenther, F. H., Denny, M., Perkell, J. S., Stockman, E., Tiede, M., Vick, J. & Zandipour, M. (2007). Effects of short- and long-term changes in auditory feedback on vowel and sibilant contrasts. *Journal of Speech, Language & Hearing Research, 50,* 913-927.

Lee, S-H. (1994). *A cross-linguistic study of the role of the jaw in consonant articulation.* Doctoral Dissertation. Ohio State University. Retrieved from http://etd.ohiolink.edu/ view.cgi?acc_num=osu1283177636

Leeper, H. A., Perez, D. M. & Mencke, E. O. (1980). The influence of utterance length upon bilabial closure duration of selected deaf children. *Journal of Communication Disorders, 13,* 373-383.

Leeper, H. A., Perez, D. M. & Mencke, E. O. (1987). Influence of utterance length upon temporal measures of syllable production by selected hearing-impaired children. *Folia Phoniatrica, 39,* 230-243.

Lehiste, I. (1970). *Suprasegmentals.* Cambridge: MIT.

Lehiste, I. (1972). The timing of utterances and linguistic boundaries. *Journal of the Acoustical Society of America, 51,* 2018-2024.

Lehiste, I. (1976). Segmental features of speech. In N. J. Lass (Ed.), *Contemporary issues in experimental phonetics,* 225-239. New York: Academic.

Lengeris, A. (2011). Phonetic vowel reduction in Standard Modern Greek. [Abstract] Oral presentation at the *10th International Conference of Greek Linguistics,* 1-4 September, 2011, Democritus University of Thrace, Komotini. Retrieved from http://www.icgl.gr/

Levitt, H., Smith, C. R. & Stromberg, H. (1976). The structure of segmental errors in the speech of deaf children. In G. Fant (Ed.), *Proceedings of the Speech Communication Seminar*. New York: Wiley.

Liberman, A. M. (1970). The grammars of speech and language. *Cognitive Psychology, 1,* 301-323.

Liberman, A. M. (1996). *Speech: A special code*. Cambridge, MA: MIT Press.

Liberman, A. M. & Mattingly, I. G. (1985). The motor theory of speech perception revised. *Cognition, 21,* 1-36.

Liberman, A. M., Cooper, F.S., Shankweiler, D.P., Studdert-Kennedy M. (1967). Perception of speech code. *Psychological Review, 74,* 431-461.

Liberman, A. M., Delattre, P. & Cooper, F. S. (1952). The role of selected stimulus-variables in the perception of the unvoiced stop consonants. *The American Journal of Psychology, 65,* 497-516. Retrieved from http://www.haskins.yale.edu/Reprints/ HL0007.pdf

Liberman, A. M., Delattre, P. & Cooper, F. S. & Gerstman, L. J. (1954). The role of consonant-vowel transitions in the stop and nasal consonants. *Psychological Monographs, 68*(8), 1-13. Retrieved from http://www.haskins.yale.edu/Reprints/HL0011.pdf

Lieberman, P., & Blumstein, S. E. (1988). *Speech physiology, speech perception, and acoustic phonetics*. Cambridge: Cambridge University Press.

Liljencrants, J. & Lindblom, B. (1972). Numerical simulation of vowel quality systems: the role of perceptual contrast. *Language, 48,* 839-862.

Lindblom, B. (1963). Spectrographic study of vowel reduction. *Journal of the Acoustical Society of America, 35,* 1773-1781.

Lindblom, B. (1968). Temporal organization of syllable production. *Speech Transmission Laboratory - Quarterly Progress and Status Report, 9*(2-3), 1-5. Dept. of Speech Communication, KTH, Stockholm, Sweden. Retrieved from http://www.speech.kth.se/qpsr

Lindblom, B. (1983). Economy of speech gestures. In P. F. MacNeilage (Ed.), *The Production of Speech*, 217-245, New York: Springer-Verlag.

Lindblom, B. (1986). Phonetic universals in vowel systems. In J. Ohala & J. Jaeger (Eds.), *Experimental Phonology,* 13-44. New York: Academic.

Lindblom, B. (1989). Phonetic invariance and the adaptive nature of speech. In B.A. G. Elsendoom & H. Bouma (Eds.), *Working Models of Human Perception*, 139-173. London: Academic Press.

Lindblom, B. (1990). Explaining phonetic variation: a sketch of the H&H theory. In W. J. Hardcastle & A. Marchal (Eds.), *Speech Production and Speech Modelling*, 403-439. Dordrecht: Kluwer Academic Publishers.

Lindblom, B. & Studdert-Kennedy, M. (1967). On the role of formant transitions in vowel recognition. *Journal of the Acoustical Society of America, 42,* 830-843.

Lindblom, B., Sussman, H. M. & Agwuele, A. (2009). A duration-dependent account of coarticulation for hyper- and hypoarticulation. *Phonetica, 66*(3), 188-195.

Lindblom, B., Lubker, J. & Gay, T. (1979). Formant frequencies of some fixed-mandible vowels and a model of speech motor programming by predictive simulation. *Journal of Phonetics, 7*, 147-161.

Lindblom, B., Brownlee, S., Davis, B. & Moon, S. J., (1992). Speech Transforms. *Speech Communication, 11,* 357-368.

Lindblom, B., Agwuele, A., Sussman, H. M. & Cortes, E. E. (2007). The effect of emphatic stress on consonant vowel coarticulation. *Journal of the Acoustical Society of America, 121*(6), 3802-3813.

Ling, D. (1976). *Speech and the hearing-impaired child: Theory and practice.* Washington, CD: AG Bell Association.

Ling, D. (1989). *Foundations of spoken language for hearing-impaired children.* Washington, CD: Alexander Graham Bell Association for the Deaf.

Locke, J. (1983). *Phonological acquisition and change.* New York: Academic Press.

Löfqvist, A. & Gracco, V. L. (1999). Interarticulator timing in VCV sequences: Lip and tongue movements. *Journal of the Acoustical Society of America, 105*(3), 1864-1876.

Lubker, J. & Gay, T. (1982). Anticipatory labial coarticulation: experimental, biological, and linguistic variables. *Journal of the Acoustical Society of America, 71*(2), 437-448.

Luce, P. A. & Charles-Luce, J. (1985). Contextual effects on vowel duration, closure duration, and the consonant/vowel ratio in speech production. *Journal of the Acoustical Society of America, 78*(6), 1949-1957.

Maassen, B. & Povel, D. (1985). The effect of segmental and suprasegmental corrections on the intelligibility of deaf speech. *Journal of the Acoustical Society of America, 78*(3), 877-886.

Maassen, B., Nijland, L. & Terband, H. (2010). Developmental models of Childhood Apraxia of Speech. In B. Maassen & P. H. H. M. van Lieshout (Eds.), *Speech motor control: New developments in basic and applied research*, 243-258. Oxford: Oxford University Press.

MacNeilage, P. F. (1970). Motor control of serial ordering in speech. *Psychological Review, 77,* 182-196.

MacNeilage, P. F. & DeClark, J. L. (1969). On the motor control of coarticulation in CVC monosyllables. *Journal of the Acoustical Society of America, 45*(5), 1217-1233.

Mackridge, P. (1985). *The Modern Greek Language*. Oxford: Clarendon Press.

Maddieson, I. (1997). Phonetic universals. In W. J. Hardcastle & J. Laver (Eds.), *The Handbook of Phonetic Sciences,* 619-639. Oxford: Blackwell.

Maeda, S. (1991). On articulatory and acoustic variabilities. *Journal of Phonetics, 19,* 321-331.

Magen, H. S. (1984a). Vowel-to-vowel coarticulation in English and Japanese. *Journal of the Acoustical Society of America, 75,* S41.

Magen, H. S. (1984b). Variability in anticipatory and carryover vowel-to-vowel coarticulation. *Journal of the Acoustical Society of America, 77,* S98.

Magen, H. S. (1989). *An acoustic study of vowel-to-vowel coarticulation in English*, Doctoral Dissertation. Yale University, New Haven, CT.

Magen, H. S. (1997). The extent of vowel-to-vowel coarticulation in English. *Journal of Phonetics, 25,* 187-206.

Malikouti-Drachman, A. & Drachman, G. (1980). Slogan chanting and speech rhythm in Greek. In W. Dressler, O. Pfeiffer & J. Renisson (Eds.), *Phonologica 1980,* 283-292. Innsbruck: IBS.

Mangan, K. (1961). Speech improvement through articulation testing. *American Annals of the Deaf, 106,* 391-396.

Manuel, S. (1987). *Acoustic and perceptual consequences of vowel-to-vowel coarticulation in three Bantu languages.* Doctoral Dissertation. Yale University, New Haven, CT.

Manuel, S. (1990). The role of contrast in limiting vowel-to-vowel coarticulation in different languages. *Status Report on Speech Research, SR-103/104,* 1-20. Haskins Laboratories.

Manuel, S. (1999). Cross-language studies: relating language-particular coarticulation patterns to other language-particular facts. In W.J. Hardcastle & N. Hewlett (Eds.), *Coarticulation: Theory, Data & Techniques*, 179-198. Cambridge: CUP.

Manuel, S. & Krakow, R. (1984). Universal and language particular aspects of Vowel-to-Vowel Coarticulation. *Status Report on Speech Research, SR-77/78,* 69-78. Haskins Laboratories.

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,* 126-140.

Markides, A. (1983). *The speech of hearing-impaired children*. Manchester: Manchester University Press.

Marschark, M. (2001). *Language development in children who are deaf: A research synthesis.* ERIC ED 455620. Alexandria, VA: National Association of State Directors of Special Education.

Martony, J. (1968). On the correction of the voice pitch level for severely hard of hearing subjects. *American Annals of the Deaf, 113,* 195-202.

Massaro, D. W. (1989). Testing between the TRACE Model and the Fuzzy Logical Model of Speech perception. *Cognitive Psychology, 21*(3), 398-421.

Massaro, D. W., Chen, T. H. (2008). The motor theory of speech perception revisited. *Psychonomic Bulletin & Review, 15*(2), 453-457.

Matthies, M., Perrier, P., Perkell, J. S. & Zandipour, M. (2001). Variation in anticipatory coarticulation with changes in clarity and rate. *Journal of Speech, Language and Hearing Research, 44,* 340-353.

Mattys, S. L. (in press). Speech perception. To appear in D. Reisberg (Ed.), *Oxford Handbook of Cognitive Psychology*. Retrieved from http://psychology.psy.bris.ac.uk/ pdfs/svenmattys/Mattys,%20Speech%20Perception,%20OUP%202011.pdf

McAuliffe, M. J., Ward, E. C. & Murdoch, B. E. (2001). Tongue-to-palate contact patterns and variability of four English consonants in an /i/ vowel environment. *Logopedics Phoniatrics Vocology, 26,* 165-178.

McClelland, J. L. & Elman, J. L. (1986). The TRACE model of speech perception. *Cognitive Psychology, 18,* 1-86.

McCaffrey Morrison, H. (2008). The locus equation as an index of coarticulation in syllables produced by speakers with profound hearing loss. *Clinical Linguistics & Phonetics, 22*(9), 726-740.

McCaffrey, H. A. & Sussman, H. M. (1994). An investigation of vowel organization in speakers with severe and profound hearing loss. *Journal of Speech and Hearing Research, 37,* 938-951.

McGarr, N. (1978). *The differences between experienced and inexperienced listeners in understanding the speech of the deaf.* Doctoral Dissertation. City University of New York.

McGarr, N. (1981). The effect of context on the intelligibility of hearing and deaf children's speech. *Language and Speech, 24*(3), 255-264.

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

McGarr, N. S., & Campbell, M. (1995). Opening inroads to understanding articulatory organization in persons with hearing impairment. In K. S. Harris, F. Bell-Berti & L. J. Raphael (Eds.), *Producing speech: Contemporary issues. For Katherine Harris,* 433-454. New York: AIP Press.

McGarr, N. S., & Gelfer, C. (1983). Simultaneous measures of vowels produced by a hearing impaired speaker. *Language and Speech, 26,* 233-246.

McGarr, N. S. & Harris, K. (1980). Articulatory control in a deaf speaker. *Status Report on Speech Research, SR-63/64,* 309-332. Haskins Laboratories.

McGarr, N. S. & Osberger, M. J. (1978). Pitch deviancy and the intelligibility of deaf children's speech. *Journal of Communication Disorders, 11,* 237-248.

McGarr, N. S. & Löfqvist, A. (1982). Obstruent production in hearing-impaired speakers: Interarticulator timing and acoustics. *Journal of the Acoustical Society of America, 72*(1), 34-42.

McGarr, N. S., & Whitehead, R. (1992). Contemporary issues in phoneme production by hearing-impaired persons: physiological and acoustic aspects. *The Volta Review, 94*, 33-45.

McGarr, N., Raphael, L. J., Kolia, B., Vorperian, H. K. & Harris, K. (2004). Sibilant production in speakers who have hearing loss: electropalatographic and perceptual evidence. *The Volta Review, 104*(3), 119-140.

McGurk, H. & MacDonald, J. (1976). Hearing lips and seeing voices. *Nature, 264,* 746-748.

Mènard, L., Toupin, C., Thibeault, M., Noiray, A., Giroux, M. & Rousseau, M. C. (2010). A study of VCV coarticulation in 4-year-old children and adults. [Abstract]. Oral presentation at the *5th Ultrafest Conference*, March 19-21, Haskins Laboratories, New Haven, CT. Retrieved from http://www.haskins.yale.edu/conferences/UltrafestV/abstracts/Menard_etal.pdf

Mencke, E. O., Ochsner, G. J. & Testut, E. W. (1983). Listener judges and the intelligibility of deaf children. *Journal of Communication Disorders, 16*(3), 175-180.

Metz, D. E., Samar, V. J., Schiavetti, N., Sitler, R. & Whitehead, R. L. (1985). Acoustic dimensions of hearing impaired speakers' intelligibility. *Journal of Speech and Hearing Research, 17,* 386-398.

Metz, D. E., Whitehead, R., & Whitehead, B. (1984). Mechanics of vocal fold vibration and laryngeal articulation gestures produced by hearing-impaired speakers *Journal of Speech & Hearing Research, 27*, 62-69.

Miller, J. L. (1981). Effects of speaking rate on segmental distinctions. In Eimas, P. D. & Miller, J. L. (Eds.), *Perspectives on the study of speech,* 39-74. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Mok, P. K. P. (2006). *Influences on vowel-to-vowel coarticulation*. Doctoral Dissertation. University of Cambridge, Cambridge, UK.

Mok, P. K. P. (2007). Effects of syllable structure on V-to-V coarticulation (Thai vs English). *Proceedings of the 16th International Congress of Phonetic Sciences*, ID 1301, 421-424. Saarbrücken. Retrieved from http://www.cuhk.edu.hk/lin/people/peggy/ICPhS_07.pdf

Mok, P. K. P. (2010). Language-specific realizations of syllable structure and vowel-to-vowel coarticulation. *Journal of the Acoustical Society of America, 128*(3), 1346-1356.

Mok, P. K. P. (2011). Effects of vowel duration and vowel quality on vowel-to-vowel coarticulation. Language & Speech, 0023830911404961, first published on June 24, 2011 doi:10.1177/0023830911404961

Mok, P. K. P. & Hawkins, S. (2004). Effects of phonemic vs allophonic denstity and stress on vowel-to-vowel coarticulation in Cantonese and Beijing Mandarin. *Proceedings of the 4th International Symposium on Chinese Spoken Language Processing (ISCSLP).* 33-36. Hong-Kong. Retrieved from www.cuhk.edu.hk/lin/people/peggy/ISCSLP.pdf

Moll, K. & Daniloff, R. (1971). Investigation of the timing of velar movements during speech. *Journal of the Acoustical Society of America, 50,* 678-684.

Modarresi, G., Sussman, H., Lindblom, B. & Burlingame, E. (2004). An acoustic analysis of the bidirectionality of coarticulation in VCV utterances. *Journal of Phonetics, 32,* 291-312.

Monsen, R.B. (1974). Durational aspects of vowel production in the speech of deaf children. *Journal of Speech and Hearing Research, 17,* 386-398.

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

Monsen, R. B. (1976b). The production of English stop consonants in the speech of deaf children. *Journal of Phonetics*, *4,* 29-41.

Monsen, R. B. (1976c). Second formant transitions of selected consonant-vowel combinations in the speech of deaf and normally-hearing children. *Journal of Speech and Hearing Research, 19,* 279-289.

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

Monsen, R. B. (1979). Acoustic qualities of phonation in young hearing-impaired children. *Journal of Speech and Hearing Research, 22*, 270-288.

Monsen, R.B. (1983a). The oral speech intelligibility of hearing-impaired talkers. *Journal of Speech, Language & Hearing Research, 48,* 286-296.

Monsen, R.B. (1983b). Voice quality and speech intelligibility among deaf children. *American Annals of the Deaf, 128*(1), 12-19.

Morton, N. E. (1991). Genetic Epidemiology of Hearing Impairment. *Annals of the New York Academy of Sciences, 630*, 16-31.

Monsen, R. B., Engebretson, A. M., & Vemula, N. (1978). Some effects of deafness on the generation of voice. *Journal of the Acoustical Society of America, 66*, 1316-1324.

Moon, S-J. & Lindblom, B. (1994). Interaction between duration, context, and speaking style in English stressed vowels. *Journal of the Acoustical Society of America, 96*(1), 40-55.

Mooshammer, C. & Geng, C. (2008). Acoustic and articulatory manifestations of vowel reduction in German. *Journal of the International Phonetic Association, 38*(2), 117-136.

Mooshammer, C., Hoole, P. & Geumann, A. (2007). Jaw and Order. *Language and Speech, 50*(2), 145-176.

Most, T. (1999). Production and perception of syllable stress by children with normal hearing and children with hearing impairment. *The Volta Review, 101,* 51-70.

Munhall, K. & Löfqvist, A. (1992). Gestural aggregation in speech: Laryngeal gestures. *Journal of Phonetics, 20,* 111-126.

Naeser, M. A. (1970). Influence of initial and final consonants on vowel duration in CVC syllables. *Report from the project on language concepts and cognitive skills related to the acquisition of literacy, 130*. The University of Wisconsin. Retrieved from http://www.eric.ed.gov/ERICWebPortal/contentdelivery/servlet/ERICServlet?accno=ED042149

Nam, H., Goldstein, L., Browman, C., Rubin, P., Proctor, M. & Saltzman, E. (2007). *TADA: TAsk Dynamics Application Manual*. Haskins Laboratories, Inc. Retrieved from http://www.haskins.yale.edu/tada_download/doc/TADA_manual_v09.pdf

Nespor, M. & Vogel, I. (1989). On clashes and lapses. *Phonology, 6,* 69-116.

Nicolaidis, K. (1991). Coarticulatory strategies in Greek and English VCV sequences. *Proceedings of the 5th Symposium on the Description and/or Comparison of English and Greek*, 113-140. Aristotle University of Thessaloniki.

Nicolaidis, K. (1994). Aspects of lingual articulation in Greek: an electropalatographic study. In I. Philippaki-Warburton, K. Nicolaidis & M. Sifianou (Eds.), *Themes in Greek Linguistics,* 225-232, Amsterdam: John Benjamins.

Nicolaidis, K. (1997). *Sources of articulatory variability in Greek: an electropalatographic study*. Doctoral Dissertation. University of Reading, Reading, UK.

Nicolaidis, K. (1999). The influence of stress on V-to-V coarticulation: an electropalatographic study. *Proceedings of the 14th International Congress of Phonetic Sciences*. 1087-1090. San Francisco.

Nicolaidis, K. (2001). An electropalatographic study of Greek spontaneous speech. *Journal of the International Phonetic Association, 31*(1), 67-85.

Nicolaidis, K. (2002). Durational variability in Vowel-Consonant-Vowel sequences in Greek: The influence of phonetic identity, context and speaker. In M. Makri-Tsilipakou (Ed.), *Selected Papers on Theoretical and Applied Linguistics from the 14th International Symposium*, 280-294. April 20-22, 2000, Aristotle University of Thessaloniki.

Nicolaidis, K. (2003). Acoustic variability of vowels in Greek spontaneous speech. *Proceedings of the 15th International Congress of Phonetic Sciences*, 3221-3224. Universidad Autónoma de Barcelona.

Nicolaidis, K. (2004). Articulatory variability during consonant production by Greek speakers with hearing impairment: an electropalatographic study. *Clinical Linguistics & Phonetics, 18*(6-8), 419-432.

Nicolaidis, K. (2007). Aspects of spatio-temporal variability during consonant production by Greek speakers with hearing impairment. *Clinical Linguistics & Phonetics, 21*(6), 405-422.

Nicolaidis, K. & Rispoli, R. (2005). The effect of noise on speech production: An acoustic study. *Studies in Greek Linguistics, 25,* 415-426.

Nicolaidis, K. & Sfakianaki, A. (2007). An acoustic analysis of vowels produced by Greek speakers with hearing impairment. *Proceedings of the 16th International Congress of Phonetic Sciences*, ID 1358, 1969-1972. Saarbrücken.

Nittrouer, N. (1985). *The role of coarticulation in the perception of speech by young children (3-7 years).* Doctoral Dissertation. City University of New York Graduate Center.

Nittrouer, N. (1993). The emergence of mature gestural patterns is not uniform: Evidence from an acoustic study. *Journal of Speech and Hearing Research, 36,* 959-972.

Nittrouer, N., Studdert-Kennedy, M. (1987). The role of coarticulatory effects in the perception of fricatives by children and adults. *Journal of Speech and Hearing Research, 30,* 319-329.

Nittrouer, N., Studdert-Kennedy, M. & McGowan, R. S. (1989). The emergence of phonetic segments: Evidence from the spectral structure of fricative-vowel syllables spoken by children and adults. *Journal of Speech and Hearing Research, 32,* 120-132.

Nittrouer, N., Studdert-Kennedy, M. & Neely, S. T. (1996). How children learn to organize their speech gestures: Further evidence from fricative-vowel syllables. *Journal of Speech and Hearing Research, 39,* 379-389.

Nober, E. H. (1967). Articulation of the deaf. *Exceptional Children, 33,* 611-621.

Noiray, A. & Mènard, L. (2010). Measures of lingual coarticulation in children. Oral presentation at the *CPMSP2 2010,* International Summerschool, 27th Sept -1st Oct, Berlin. Retrieved from http://summerschool2010.danielpape.info/pres/pr_noirey_gross.pdf

Nord, L. (1974). Vowel reduction-centralization or contextual assimilation? In G. Fant (Ed.), *Speech Communication II,* 149-154. Stockholm: Almwvist & Wiskell.

Nord, L. (1986). Acoustic studies of vowel reduction in Swedish. *Speech Transmission Laboratory - Quarterly Progress and Status Report, 27*(4), 19-36. Dept. of Speech Communication, KTH, Stockholm, Sweden.

Nordström, P.-E. (1977). Female and infant vocal tracts simulated from male area functions. *Journal of Phonetics, 5,* 81-92.

Norris, D., McQueen, J. M. (2008). Shortlist B*:* A Bayesian Model of Continuous Speech Recognition. *Psychological Review, 115*(2), 357-395.

Norris, D., McQueen, J. M. & Cutler, A. (2000). Merging information in speech recognition: Feedback is never necessary. *Behavioral & Brain Sciences, 23,* 299-370.

Northern, J. L., & Downs, M. P. (2002). *Hearing in children* (5th ed.). USA: Lippincott Williams & Wilkins.

Nittrouer, S. (2009). *Early Development of Children with Hearing Loss*. Dan Diego: Plural Publishing.

Ohala, J. (1996). Speech perception is hearing sounds, not tongues. *Journal of the Acoustical Society of America, 99,* 1718-1725.

O'Halpin, R. (1997). Contrastive stress in the speech of profoundly deaf children: a preliminary investigation. *The Volta Review, 99,* 89-103.

Öhman, S. (1966). Coarticulation in VCV utterances: Spectrographic measurements. *Journal of the Acoustical Society of America, 39,* 151-168.

Okalidou, A. (1996). *Coarticulation in hearing and deaf talkers.* Doctoral Dissertation. City University of New York.

Okalidou, A. (2002). *Varikoia-kofosi. Meleti tis paragogis tou logou kai therapeutiki paremvasi.* [Hearing impairment-deafness. A study of speech production and therapeutic intervention]. Athina: Ellinika Grammata.

Okalidou, A. & Harris, K. S. (1999). A comparison of intergestural patterns in deaf and hearing adult speakers: Implications from an acoustic analysis of disyllables. *Journal of the Acoustical Society of America, 106*(1), 394-410.

Okalidou, A. & Koenig, L. L. (1999). Patterns of vowel-to-vowel coarticulation in Greek and English. In *Proceedings of the 137th Meeting of the Acoustical Society of America, JASA, 105*(2), pt. 2, 1094 (A).

Oller, D. K., Jensen, H. T. & Lafayette, R. H. (1978). The relatedness of phonological processes of a hearing-impaired child. *Journal of Communication Disorders, 11*(2-3), 97-105.

Orr, R. (2005). Phonetic vowel reduction in Danish. Paper presented at *Linguistics at Santa Cruz Annual Conference*, UC Santa Cruz. Retrieved from http://ling.ucsc.edu/ news_events/lasc05/randall_orr_abstract.pdf

Osberger, M. J. (1978). *The effect of timing errors on the intelligibility of deaf children's speech.* Doctoral Dissertation. The City University of New York.

Osberger, M. J. (1981). Fundamental frequency characteristics of the speech of the hearing impaired. *Journal of the Acoustical Society of America, 69*, S68 (A).

Osberger, M. J. & Levitt, H. (1979). The effect of timing errors on the intelligibility of deaf children's speech. *Journal of the Acoustical Society of America, 66,* 1316-1324.

Osberger, M. J., & McGarr, N. (1982). Speech production characteristics of the hearing impaired. *Status Report on Speech Research, SR-69*, 227-288. Haskins Laboratories.

Osberger, M. J., Maso, M. & Sam, L. K. (1993). Speech intelligibility of children with cochlear implants, tactile aids, or hearing aids. *Journal of Speech and Hearing Research, 36,* 186-203.

Osberger, M. J., Robbins, A. M., Lybolt, J., Kent, R. D. & Peters, J. (1986). Speech evaluation. In M.J. Osberger (Ed.), *Language and learning skills of hearing-impaired students.* ASHA Monographs 23, 24-31. Rockville, MD: American Speech-Language-Hearing Association.

Osberger, M. J., Miyamoto, R. T., Zimmerman-Phillips, S., Lemink, J., Stroer, B., Firszt, J. B. & Novak, M. A. (1991). Independent evaluation of the speech perception abilities of children with the Nucleus 22-channel cochlear implant system. *Ear and Hearing, 12*(Suppl.), 66S-80S.

Ozbič, M. & Kogovšek, D. (2008). An acoustic comparison of formant frequencies in individuals with normal hearing, profound and severe hearing impairment. *Investigationes Linguisticae, XVI,* 150-162. Poznań. Retrieved from http://www.inveling.amu.edu.pl/

Ozbič, M. & Kogovšek, D. (2010). Vowel formant values in hearing and hearing-impaired children: A discriminant analysis. *Deafness & Education International, 12*(2), 99-128(30).

Palethorpe, S., Beckman, M., Fletcher, J. & Harrington, J. (1999). The contribution of schwa vowels to the prosodic accent contrast in Australian English. *Proceedings of the 14th International Congress of Phonetic Sciences*, 695-698. San Francisco.

Parkhurst, B. & Levitt, H. (1978). The effect of selected prosodic errors on the intelligibility of deaf speech. *Journal of Communication Disorders, 11,* 249-256.

Perkell, J. (1969). *Physiology of speech production*. Cambridge: M.I.T.

Perkell, J. (1986). Coarticulation strategies: Preliminary implications of a detailed analysis of lower lip protrusion movements. *Speech Communication, 5,* 47-68.

Perkell, J. S. (1990). Testing theories of speech production: Implications of some detailed analyses of variable articulatory data. In W.J. Hardcastle & A. Marchal (Eds.), *Speech Production and Speech Modelling,* 263-288. Dordrecht: Kluwer.

Perkell, J. S. (2006). Sensorimotor control of speech production: models and data. *Proceedings of the International Speech Communication Association Workshop on Experimental Linguistics,* 45-52. Athens. Retrieved from http://www.isca-speech.org/archive_open/exling_2006/exl6_045.html

Perkell, J. S. & Chiang, C. (1986) Preliminary support for a "hybrid model" of anticipatory coarticulation. *Proceedings of the 12th International Congress of Acoustics*, A3-6. Toronto: Canadian Acoustical Association.

Perkell, J. S. & Cohen, M. H. (1989). An indirect test of the quantal nature of speech in the production of /i/, /a/ and /u/. *Journal of Phonetics, 17,* 123-133.

Perkell, J. S. & Matthies, M. L. (1992). Temporal measures of anticipatory coarticulation for the vowel /u/: Within- and cross-subject variability, *Journal of the Acoustical Society of America, 91*(5), 2911-2925.

Perkell, J. S. & Nelson, W. L. (1985). Variability in production of the vowels /i/ and /a/. *Journal of the Acoustical Society of America, 77*(5), 1889-1895.

Perkell, J. S., Guenther, F. H., Lane, H., Matthies, M. L., Perrier, P., Vick, J., Wilhelms-Tricarico, R. & Zandipour, M. (2000). A theory of speech motor control and supporting data from speakers with normal hearing and with profound hearing loss. *Journal of Phonetics, 28,* 233-272.

Perkell, J. S., Matthies, M. L., Guenther, F. H., Tiede, M., Zandipour, M., Stockmann, E. & Marrone, N. (2003). Sensory goals for speech movements: Cross-subject relations among production, perception and the use of articulatory saturation effect. *Proceedings of the 6th International Seminar on Speech Production*, 219-224. Sydney.

Perkell, J. S., Guenther, F. H., Lane, H., Matthies, M. L., Stockmann, E., Tiede, M. & Zandipour, M. (2003). Cross-subject relations between measures of vowel production and perception. *Proceedings of the 15th International Congress of Phonetic Sciences*, 439-442. Universitat Autònoma de Barcelona, Barcelona, Spain.

Perkell, J. S., Guenther, F. H., Lane, H., Matthies, M. L., Stockmann, E., Tiede, M. & Zandipour, M. (2004). The distinctness of speakers' productions of contrasting vowels is related to the acuity of their discrimination of the contrasts. *Journal of the Acoustical Society of America, 116,* 2338-2344.

Perkell, J. S., Matthies, M. L., Tiede, M., Zandipour, M., Stockmann, E. & Marrone, N., Lane, H. & Guenther, F. H. (2004). The distinctness of speakers' productions of /s/ and /ʃ/ is related to their discrimination of the contrast and use of an articulatory saturation effect. *Journal of Speech, Language and Hearing Research, 47,* 1259-1269.

Peterson, G. E. & Lehiste, I. (1960). Duration of syllable nuclei in English. *Journal of the Acoustical Society of America, 32*(6), 693-703.

Philippaki-Warburton, I. (1992). *Isagogi sti Theoritiki Glossologia.* [Introduction to Theoretical Linguistics]. Athens: Nefeli.

Picheny, M. A., Durlach, N. I. & Braida, L. D. (1985). Speaking clearly for the hard of hearing I: Intelligibility differences between clear and conversational speech. *Journal of Speech and Hearing Research, 28*(1), 96-103.

Pierrehumbert, J. B., Bent, T., Munson, B., Bradlow, A. R. & Bailey, J. M. (2004). The influence of sexual orientation on vowel production. *Journal of the Acoustical Society of America, 116*(4), 1905-1908.

Pisoni, D. B. (1977). Identification and discrimination of the relative onset time of two component tones: implications for voicing perception in stops. *Journal of the Acoustical Society of America, 61,* 1352-1361.

Pisoni, D. B. (1980). Variability of vowel formant frequencies and the quantal theory of speech: a first report, *Phonetica, 37,* 285-305.

Port, R. F. (1981). Linguistic timing factors in combination. *Journal of the Acoustical Society of America, 69*(1), 262-274.

Pratt, S. R. (2005). Aural habilitation update: The role of auditory feedback on speech production skills of infants and children with hearing loss. *ASHA Leader, 10*(4), 8-9, 32-33.

Pratt, S. R. & Tye-Murray, N. (2009). Speech impairment secondary to hearing loss. In M. R. McNeil (Ed.), *Clinical Management of Sensorimotor Speech Disorders* (2nd ed.). New York, NY: Thieme Medical Publishers, Inc.

Preisler, G. M. & Ahlstroem, M. (1997). Sign language for hard-of-hearing children –A hindrance or a benefit for their development? *European Journal of Psychology of Education, 2,* 465-477.

Preisler, G. M., Tvingstedt, A.-L. & Ahlström, M. (2002). A psychosocial follow-up study of deaf preschool children using cochlear implants. *Child: Care, Health & Development, 28*(5), 403-418.

Raphael, L. J., Dorman, M. F. & Geffner, D. (1977). Voicing-conditioned durational differences in vowels and consonants in the speech of three- and four-year old children. *Status Report on Speech Research, SR-50*, 115-122. Haskins Laboratories. Retrieved from http://www.haskins.yale.edu/SR/ StatusReportArchive.html

Raphael, L. J., Bell-Berti, F., Collier, R. & Baer, T. (1978). Tongue position in rounded and unrounded front vowel pairs. *Status Report on Speech Research, SR-54*, 227-288. Haskins Laboratories. Retrieved from http://www.haskins.yale.edu/SR/ StatusReportArchive.html

Rawlings, C. (1935). A comparative study of the movements of the breathing muscles in speech and quiet breathing of deaf and normal subjects. *American Annals of the Deaf, 80,* 147-156.

Recasens, D. (1984a). V-to-C coarticulation in Catalan VCV sequences: an articulatory and acoustical study. *Journal of Phonetics, 12,* 61-73.

Recasens, D. (1984b). Vowel-to-vowel coarticulation in Catalan VCV sequences. *Journal of the Acoustical Society of America, 76*(6), 1624-1635.

Recasens, D. (1985). Coarticulatory patterns and degrees of coarticulatory resistance in Catalan CV sequences. *Language and Speech, 28*(2), 97-114.

Recasens, D. (1987). An acoustic analysis of V-to-C and V-to-V coarticulatory effects in Catalan and Spanish VCV sequences. *Journal of Phonetics, 15,* 299-312.

Recasens, D. (1989). Long range coarticulation effects for tongue dorsum contact in VCVCV sequences. *Speech Communication, 8,* 293-307.

Recasens, D. (1990). An Electropalatographic and Acoustic Study of Consonant-to-Vowel Coarticulation. *Status Report on Speech Research*, *SR-101/102,* 130-148. Haskins Laboratories. Retrieved from http://www.haskins.yale.edu/SR/StatusReportArchive.html

Recasens, D. (1999). Lingual coarticulation. In W.J. Hardcastle & N. Hewlett (Eds.), *Coarticulation: Theory, Data & Techniques*, 80-104. Cambridge: CUP.

Recasens, D. (2002a). An EMA study of VCV coarticulatory direction. *Journal of the Acoustical Society of America, 111*(6), 2828-2841.

Recasens, D. (2002b). Patterns of jaw coarticulatory direction and linguomandibular coordination in VCV sequences, *Papers on Phonetics and Phonology: The Articulation, Acoustics and Perception of Consonants*, *ZAS Papers in Linguistics*, *28,* 83-92, Zentrum für Allgemeine Sprachwissenschaft, Berlin.

Recasens, D. (2005). An interpretation of patterns of VCV coarticulation according to a model of articulatory constraints. Oral presentation at *PaPI 2005, Phonetics and Phonology in Iberia.* Universitat Autònoma de Barcelona. Retrieved from webs2002.uab.es/filologiacatalana/papi/files/recasens.ppt

Recasens, D. (2010). Lingual kinematics and coarticulation for alveolopalatal and velar consonants in Catalan. *Journal of the Acoustical Society of America, 127*(5), 3154-3165.

Recasens, D. & Espinosa, A. (2009). An articulatory investigation of lingual coarticulatory resistance and aggressiveness for consonants and vowels in Catalan. *Journal of the Acoustical Society of America, 125*(4), 2288-2298.

Recasens, D. & Pallarès, M. D. (2000). A study of F1 coarticulation in VCV sequences. *Journal of Speech, Language & Hearing Research*, *43,* 501-512.

Recasens, D., Pallarès, M. D. & Fontdevila, J. (1995). Co-articulatory variability and articulatory-acoustic correlations for consonants. *European Journal of Disorders of Communication, 30,* 203-212.

Recasens, D., Pallarès, M. D. & Fontdevila, J. (1997). A model of lingual coarticulation based on articulatory constraints. *Journal of the Acoustical Society of America, 102*(1), 544-561.

Reilly, A. P. (1979). Vowel duration in the speech of hearing and deaf children. *Journal of the Acoustical Society of America, 65*(S1), S69.

Repp, B. H. (1986). Some observations on the development of anticipatory coarticulation. *Journal of the Acoustical Society of America, 79*(5), 1616-1619.

Rietveld, A. C. M. & Koopmans-van Beinum, F. J. (1987). Vowel reduction and stress. *Speech Communication, 6,* 217-229.

Rizzolatti, G. & Arbib, M.A. (1998). Language within our grasp. *Trends in Neuroscience, 21,* 188-194.

Roach, P. (1982). On the distinction between stress-timed languages and syllable-timed languages. In D. Crystal (Ed.), *Linguistic Controversies: Essays in honour of F.R. Palmer,* 73-79. London: Arnold.

Roeser, R. J. & Downs, M. P. (2004). *Auditory disorders in school children: the law, identification, remediation*. New York: Thieme.

Rosenblum, L. D. (2005). Primacy of multimodal speech perception. In D. B. Pisoni & R. E. Remez (Eds.), *The Handbook of Speech Perception,* 51-78. Oxford: Blackwell. Retrieved from www.sbmu.ac.ir/SiteDirectory/RehabilitationSchool/Documents/The Handbook of Speech Perception.pdf

Rothman, H. B. (1976). A spectrographic investigation of consonant-vowel transitions in the speech of deaf adults. *Journal of Phonetics, 4,* 129-136.

Rubin, J. A. (1985). *Static and dynamic information in vowels produced by the hearing impaired.* Bloomington, Indianna: Indianna University Linguistics Club.

Ryalls, J. & Larouche, A. (1992). Acoustic integrity of speech production in children with moderate and severe hearing impairment. *Journal of Speech and Hearing Research, 35,* 88-95.

Ryalls, J. & Lieberman, P. (1982). Fundamental frequency and vowel perception. *Journal of the Acoustical Society of America, 72*(5)*,* 1631-1634.

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*(2), 99-114.

Ryalls, J., Baum, S., Samuel, R., Larouche, A., Lacoursière, N. & Garceau, J. (1993). Anticipatory co-articulation in the speech of young normal and hearing-impaired French Canadians. *European Journal of Disorders of Communication*, *28,* 87-101.

Saltzman E.L. & Kelso, J. A. S. (1987). Skilled action: a task-dynamic approach. *Psychological Review, 94,* 84-106.

Saltzman E.L. & Munhall, K. (1989). A dynamic approach to gestural patterning in speech production. *Ecological Psychology, 1,* 333-382.

Saltzman, E, Löfqvist, A, & Mitra, S. (2000). 'Glue' and 'clocks': intergestural cohesion and global timing. In: Broe, M.B., & Pierrehumbert, J.B. (Eds.), *Papers in Laboratory Phonology V: Acquisition and the Lexicon,* 88-101. London: Cambridge University Press.

Samar, V. J., Metz, D. E., Schiavetti, N., Sitler, R. W. & Whitehead, R. L. (1989). Articulatory dimensions of hearing-impaired speakers' intelligibility: Evidence from a time-related aerodynamic, acoustic, and electroglottographic study. *Journal of Communication Disorders, 22,* 243-264.

Sander, E. (1972). When are speech sounds learned? *Journal of Speech and Hearing Disorders, 37,* 55-63.

Sarant, J. Z., Blamey, P. J., Dowell, R. C., Clark, G. M. & Gibson, W. P. R. (2001). Variation in speech perception scores among children with cochlear implants. *Ear and Hearing, 22*(1), 18-28.

Savy, R. & Cutugno, F. (1998). Hypospeech, vowel reduction, centralization: How do they interact in diaphasic variations? *Proceedings of the 16th International Congress of Linguistics.* Retrieved from: http://www3.unisa.it/uploads/1580/c_s_par.pdf

Schwartz, M. (1969). Influence of vowel environment on the duration of /s/ and /ʃ/. *Journal of the Acoustical Society of America, 46,* 480-481.

Schwartz, M. (1972). Influence of utterance length upon bilabial closure duration from /p/. *Journal of the Acoustical Society of America, 51,* 666.

Sereno, J. & Lieberman, P. (1987). Developmental aspects of lingual coarticulation. *Journal of Phonetics, 15,* 247-257.

Sereno, J., Baum, S., Marean, G. & Lieberman, P. (1987). Acoustic analyses and perceptual data on anticipatory labial coarticulation in adults and children. *Journal of the Acoustical Society of America, 81,* 512-519.

Sfakianaki, A. (1999). *The acoustic characteristics of Greek vowels produced by adults and children.* Unpublished Master's Thesis. University of Reading, Reading, UK.

Shadle, C. H. & Scully, C. (1995). An articulatory-acoustic-aerodynamic analysis of [s] in VCV sequences. *Journal of Phonetics, 23,* 53-66.

Shadle, C. H., Dobelke, C. U. & Scully, C. (1992). Spectral analysis of fricatives in vowel context. *Journal de Physique IV Colloque C1, Supplèment au Journal de Physique III, 2*(C1), 295-298.

Shaiman, S. (1989). Kinematic and electromyographic responses to perturbation of the jaw. *Journal of the Acoustical Society of America, 86*(1), 78-88.

Sharf, D. J. (1964). Vowel duration in whispered and in normal speech. *Language and Speech, 7,* 89-97.

Sharkey, S. & Folkins, J. (1985). Variability of lip and jaw movements in children and adults: implications for the development of speech motor control. *Journal of Speech and Hearing Research, 28,* 3-15.

Shukla, R. S. (1989). Phonological space in the speech of the hearing impaired. *Journal of Communication Disorders, 22,* 317-325.

Šimko, J., Cummins, F. & Beňus, Š. (2011). An analysis of the relative timing of coarticulated gestures within VCV sequences. *Proceedings of the 17th International Congress of Phonetic Sciences*, 1850-1853. Hong Kong.

Simpson, A. P. (1998). *Phonetische Datenbanken des Deutschen in der empirischen Sprachforschung under phonologischen Theoriebildung.* Arbeitsberichte des Instituts für Phonetik und digitale Sprachverarbeitung der Universität Kiel (AIPUK) 33.

Simpson, A. P. (2000). Gender-specific differences in the articulatory and acoustic realization of interword vowel sequences in American English. In P. Hoole, M. Honda & C. Mooshammer (Eds.), *5th Seminar on Speech Production: Models and Data*, 209-212. Kloster Seeon. Retrieved from http://www.personal.uni-jena.de/~x1siad/ publications.html

Simpson, A. P. (2001). Dynamic consequences of differences in male and female vocal tract dimensions. *Journal of the Acoustical Society of America, 109*(5), 2153-2164.

Simpson, A. P. (2002). Gender-specific articulatory-acoustic relations in vowel sequences. *Journal of Phonetics, 30,* 417-435.

Simpson, A. P. (2003). Possible articulatory reasons for sex-specific differences in vowel duration. In *Proceedings of the 6th International Seminar on Speech Production*. 261-266. Macquarie University, Sydney. Retrieved from http://www.personal.uni-jena.de /~x1siad/publications.html

Simpson, A. P. (2009). Phonetic differences between male and female speech. *Language and Linguistics Compass, 3/2,* 621-640. Retrieved from http://linguistics-compass.com/ phonetics-phonology/

Simpson, A. P. (2011). Is there a relationship between acoustic vowel space size and fundamental frequency? *Proceedings of the 17th International Congress of Phonetic Sciences*, 1854-1857. Hong Kong.

Simpson, A. P. & Ericsdotter, C. (2003). Sex-specific durational differences in English and Swedish. *Proceedings of the 15th International Congress of Phonetic Sciences*, 1113-1116. Universitat Autònoma de Barcelona, Barcelona, Spain.

Simpson, A. P. & Ericsdotter, C. (2007). Sex-specific differences in f0 and vowel space. *Proceedings of the 14th International Congress of Phonetic Sciences*, ID 1333, 933-935. Saarbrücken.

Smith, C. R. (1975). Residual hearing and speech production in deaf children. *Journal of Speech and Hearing Research, 18,* 773-794.

Soderstrom, M., Seidl, A., Kemler, N. D. & Jusczyk, P. W. (2003). The prosodic bootstrapping of phrases: Evidence from prelinguistic infants. *Journal of Memory and Language, 49,* 249-267.

Somers, M. (1991). Speech perception abilities of children with cochlear implants or hearing aids. *American Journal of Otology, 12*(Suppl.), 174-178.

Sperry, R. W. (1952). Neurology and the mind-body problem. *American Scientist, 40,* 291-331.

Stach, B. A. (1998). *Clinical Audiology: An Introduction*. (2nd ed). London: Singular Publishing Ltd.

Staller, S. J., Beiter, A. L., Brimacombe, J. A., Mecklenburg, D. J. & Arndt, P. (1991). Pediatric performance with the Nucleus 22-channel cochlear implant system. *American Journal of Otology, 12*(Suppl.), 126-136.

Stathopoulos, E., Duchan, J., Sonnenmeier, R. & Bruce, N. (1986). Intonation and pausing in deaf speech. *Folia Phoniatrica, 38,* 1-12.

Stein, D. (1980). *A study of articulatory characteristics of deaf talkers.* Doctoral Dissertation. University of Iowa.

Stevens, K. N. (1972). The quantal nature of speech. In E. David & P. Denes (Eds.), *Human Communication: A Unified View,* 51-66. New York: McGraw-Hill.

Stevens, K. N. (1989). On the quantal nature of speech. *Journal of Phonetics, 17,* 3-45.

Stevens, K. N. & House, A. S. (1963). Perturbation of vowel articulation by consonantal context: An acoustical study. *Journal of Speech Hearing Research, 6,* 111-128.

Stevens, K. N. & Klatt, D. H. (1974). Role of formant transitions in the voiced-voiceless distinction for stops. *Journal of the Acoustical Society of America, 55,* 653-659.

Stevens, K. N., Nickerson, R. S. & Rollins, A. M. (1978). On describing the suprasegmental properties of the speech of deaf children. In D. McPherson & M. Davids (Eds.), *Advances in prosthetic devices for the deaf: A technical workshop,* 134-155. Rochester, N.Y.: National Technical Institute for the Deaf.

Stevens, K. N., Nickerson, R. S. & Rollins, A. M. (1983). Suprasegmental and postural aspects of speech production and their effect on articulatory skills and intelligibility. In I. Hochberg, H. Levitt & M. J. Osberger (Eds.), *Speech of the hearing impaired: Research, training, and personnel preparation*, 35-51. Baltimore: University Park Press.

Stevens, K. N., Nickerson, R. S., Boothroyd, A. & Rollins, A. M. (1976). Assessment of nasalization in the speech of deaf children. *Journal of Speech and Hearing Research, 19,* 393-416.

Stoel-Gammon, C. & Dunn, C. (1985). *Normal and disordered phonology in children.* Austin, TX: Pro-Ed.

Stone, M. (1981). Evidence for a rhythm pattern in speech production: observations of jaw movement. *Journal of Phonetics, 9,* 109-120.

Stone, M. (1990). A three-dimensional model of tongue movement based on ultra-sound and x-ray microbeam data. *Journal of the Acoustical Society of America, 87,* 2207-2217.

Stone, M. (2005). A guide to analyzing tongue motion from ultrasound images. *Clinical Linguistics and Phonetics, 19,* 455-502.

Stone, M., Faber, A., Raphael, L., & Shawker, T. (1992). Cross-sectional tongue shape and lingua-palatal contact patterns in [s], [ʃ], and [l]. *Journal of Phonetics, 20,* 253-270.

Strange, W., Weber, A., Levy, E. S., Sharifo, V., Hisagi, M., Nishi, K. (2007). Acoustic variability within and across German, French, and American English vowels: Phonetic context effects. *Journal of the Acoustical Society of America, 122*(2), 1111-1128.

Subtelny, J. D., Whitehead, R. L. & Orlando, N. S. (1980). Description and evaluation of an instrumental problem to improve the speech and voice diagnosis of the hearing-impaired. *The Volta Review, 82,* 85-95.

Subtelny, J. D., Li, W., Whitehead, R. & Subtelny, J. D. (1989). Cephalometric and cineradiographic study of deviant resonance in hearing-impaired speakers. *Journal of Speech and Hearing Disorders, 54,* 249-263.

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 & Hearing Research, 35,* 574-579.

Summers, W. V. (1987). Effects of stress and final-consonant voicing on vowel production: Articulatory and acoustic analyses. *Journal of the Acoustical Society of America, 82,* 847-863.

Sussman, H. M. (1989). Neural coding of relational invariance in speech: Human language analogs to the barn owl. *Psychological Review, 96*(4), 631-642.

Sussman, H. M. & Westbury, J. R., (1981). The effects of antagonistic gestures on temporal and amplitude parameters of anticipatory labial coarticulation. *Journal of Speech and Hearing Research, 24,* 16-24.

Sussman, H. M., MacNeilage, P. F. & Hanson, R. J. (1973). Labial and mandibular dynamics during the production of bilabial consonants: Preliminary observations. *Journal of Speech and Hearing Research, 16,* 397-420.

Sussman, H. M., Bessell, N., Dalston, E. & Majors, T. (1997). An investigation of stop place of articulation as a function of syllable position: A locus equation perspective. *Journal of the Acoustical Society of America, 101*(5), 2826-2838.

Sussman, H. M., Duder, C., Dalston, E. & Cacciatore, A. (1999). An acoustic analysis of the development of CV coarticulation: A case study. *Journal of Speech, Language and Hearing Research, 42,* 1080-1096.

Sussman, H. M., Minifie, F. D., Buder, E. H., Stoel-Gammon, C. & Smith, J. (1996). Consonant-vowel interdependencies in babbling and early words: Preliminary examination of a locus equation approach. *Journal of Speech and Hearing Research, 39,* 424-433.

Svirsky, M. A., Chin, S. B., Miyamoto, R. T., Sloan, R. B. & Caldwell, M. D. (2000). Speech intelligibility of profoundly deaf pediatric hearing aid users. *Volta Review, 102*(4), 175-198.

Tabain, M., Breen, G. & Butcher, A. (2004). VC vs. CV syllables: A comparison of Aboriginal languages with English. *Journal of the International Phonetic Association, 34*(2), 175-200. Retrieved from http://dspace.flinders.edu.au/xmlui/handle/2328/14408

Tatham, M. A. A. (1970). A speech production model for synthesis by rule. *Working Papers in Linguistics, 6,* 66-87, Computer and Information Sciences Research Center, Ohio State University.

Tatham, M. & Morton, K. (2005). *Developments in speech synthesis.* West Sussex, UK: John Wiley & Sons.

Terband, H. (2011). *Speech motor control in relation to phonology: neurocomputational modelling of disordered development.* Doctoral Dissertation. University of Groningen. Retrieved from http://dissertations.ub.rug.nl/FILES/faculties/medicine/2011/h.r.terband

Thomas, W. (1963). Intelligibility of the speech of deaf children. *Proceedings of the International Congress on the Education of the Deaf, Doc. 106,* 245-261. Washington DC: Library of Congress.

Thomas, E. R. & Tyler, K. (2007). NORM: The vowel normalization and plotting suite. [Online Resource: http://ncslaap.lib.ncsu.edu/tools/norm/]

Tiffany, W. R. (1959). Non-random sources of variation in vowel quality. *Journal of Speech and Hearing Research, 2,* 305-317.

Tilsen, S. (2007). Vowel-to-vowel coarticulation and dissimilation in phonemic-response priming. *UC Berkeley Phonology Lab Annual Report,* 416-458. Retrieved from http://linguistics.berkeley.edu/phonlab/annual_report/documents/2007/Tilsen.pdf

Tobey, E. A. (1993). Speech production. In R. S. Tyler (Ed.), *Cochlear Implants: Audiological Foundations*. London: Whurr Publishers.

Tobey, E. A., Geers, A. E., Brenner, C., Altuna, D., Gabbert, G. (2003). Factors associated with development of speech production skills in children implanted by age five. *Ear and Hearing, 24*(1), 36-45.

Traunmüller, H. (1984). Articulatory and perceptual factors controlling the age- and sex-conditioned variability in formant frequencies of vowels. *Speech Communication, 3,* 49-61.

Tseng, S.-C. (2011). Speech production of Mandarin-speaking children with hearing impairment and normal hearing. *Proceedings of the 17th International Congress of Phonetic Sciences*, 2030-2033. Hong Kong.

Tserdanelis, G. (2003). Phonetic variation in syntactically ambiguous sentences. *Studies in Greek Linguistics, 23,* 931-942.

Tuller, B. & Kelso, J. A. S. (1984). The timing of articulatory gestures: Evidence for relational invariants. *Status Report on Speech Research, SR-79/80,* 49-64. Haskins Laboratories.

Tuller, B. & Kelso, J. A. S. (1990). Phase transitions in speech production and their perceptual consequences. In M. Jeannerod (Ed.), *Attention and Performance XIII,* 429-452. Hillside, NJ: Lawrence Erlbaum.

Tuller, B., Harris, K. S., & Gross, B. (1981). Electromyographic study of the jaw muscles during speech. *Journal of Phonetics*, *9,* 175-188. Retrieved from http://www.haskins.yale.edu/Reprints/HL0341.pdf

Turner, G., Tiaden, K. & Weismer, G. (1995). The influence of speaking rate on vowel space and speech intelligibility for individuals with amyotropic lateral sclerosis. *Journal of Speech and Hearing Research, 38,* 1001-1013.

Turvey, M. T. (1990). Coordination. *American Psychologist, 45,* 938-953.

Tye, N., Zimmermann, G. N. & Kelso, J. A. S. (1983). "Compensatory articulation" in hearing impaired speakers: a cinefluorographic study. *Journal of Phonetics, 11,* 101-115.

Tye-Murray, N. (1987). Effects of vowel context on the articulatory closure postures of deaf speakers. *Journal of Speech, Language and Hearing Research, 30,* 99-104.

Tye-Murray, N. (1992). Articulatory organizational strategies and roles of audition. *The Volta Review, 94,* 243-259.

Tye-Murray, N. & Folkins, J. W. (1990). Jaw and lip movements of deaf talkers producing utterances with known stress patterns. *Journal of the Acoustical Society of America, 87*(6), 2675-2683.

Tye-Murray, N. & Woodworth, G. (1989). The influence of final-syllable position on the vowel and word duration of deaf talkers. *Journal of the Acoustical Society of America, 85*(1), 313-321.

Umeda, N. (1977). Consonant duration in American English. *Journal of the Acoustical Society of America, 61*(3), 846-858.

Vakalos, A. E. (2009). *Akustiki phonitiki meleti tis paragogis kai anagnorisis ton fonienton se varikoa atoma.* [Vowel production and recognition in hearing loss]. Doctoral Dissertation. Aristotle University of Thessaloniki, Thessaloniki.

Vakalos, A., Iliadou, V., Eleytheriades, N., Iliades, T. & Fourakis, M. (2003). Vowel space in Greek running speech. Oral presentation at the *6th European Federation of Audiology Societies Congress (EFAS)*, Crete, Greece.

Vandam, M., Ide-Helvie, D. & Moeller, M. P. (2011). Point vowel duration in children with hearing aids and cochlear implants at 4 and 5 years of age. *Clinical Linguistics & Phonetics, 25*(8), 689-704.

Van Tassel, D. J. (1980). Perception of second formant transition by hearing impaired persons. *Ear and Hearing, 1,* 130-136.

Van Santen, J. P. H. (1992). Contextual effects on vowel duration. *Speech Communication, 11,* 513-546.

Vick, J., Lane, H., Perkell, J. S., Matthies, M. L., Gould, J. & Zandipour, M. (2001). Covariation of cochlear implant users' perception and production of vowel contrasts and their identification by listeners with normal hearing. *Journal of Speech, Language and Hearing Research, 44,* 1257-1267.

Vicsi, K., Roach P., Öster, A-M., Kacic, Z., Barczikay, P., Tantos, A., Csatari, F., Bakcsi, Z. & Sfakianaki, A. (2000). A Multimedia Mutlilingual Teaching and Training System for Speech Handicapped Children. *International Journal of Speech Technology, 3*(3/5), 290-300.

Viswanathan, N., Fowler, C. A. & Magnuson, J. S. (2009). A critical examination of the spectral contrast account of compensation for coarticulation. *Psychonomic Bulletin & Review, 16*(1), 74-79. Retrieved from http://www.haskins.yale.edu/Reprints/HL1565.pdf

Vlahavas, G. (2012). Efarmosmeni statistiki me xrisi tou paketou Minitab [Applied Statistics using the Minitab package]. Thessaloniki: Tziolas Publications.

Waldstein, R. S. & Baum, S. R. (1991). Anticipatory coarticulation in the speech of profoundly hearing-impaired and normally hearing children. *Journal of Speech & Hearing Research, 34,* 1276-1285.

Watt, D. & Fabricius, A. (2002). Evaluation of a technique for improving the mapping of multiple speakers' vowel spaces in the F1-F1 plane. In D. Nelson (Ed.), *Leeds Working Papers in Linguistics and Phonetics, 9,* 159-173. Retrieved from http://www.leeds.ac.uk/linguistics/WPL/WP2002/Watt_Fab.pdf

Watt, D. & Fabricius, A. (2011). A measure of variable planar locations anchored on the centroid of the vowel space: A sociophonetic research tool. *Proceedings of the 17th International Congress of Phonetic Sciences*, 2102-2105. Hong Kong.

Whalen, D. H. (1990). Coarticulation is largely planned. *Journal of Phonetics, 18,* 3-35.

Whitehead, R. L. (1983). Some respiratory and aerodynamic patterns in speech of the hearing impaired. In I. Hochberg, H. Levitt & M. J. Osberger (Eds.), *Speech of the hearing impaired: Research, training, and personnel preparation*, 97-116. Baltimore: University Park Press.

Whitehead, R. L. & Barefoot, S. M. (1983). Airflow characteristics of fricative consonants produced by normally hearing and hearing-impaired speakers. *Journal of Speech and Hearing Research, 26,* 185-194.

Whitehead, R. L. & Jones, K. O. (1976). Influence of consonant environment on duration of vowels produced by normal-hearing, hearing-impaired and deaf adult speakers. *Journal of the Acoustical Society of America, 60*(2), 513-515.

Whitehead, R. & Jones, K. (1978). The effect of vowel environment on duration of consonants produced by normal-hearing, hearing-impaired and deaf adult speakers. *Journal of Phonetics, 6,* 77-81.

Whiteside, S. P. (1996). Temporal-based acoustic-phonetic patterns in read speech: Some evidence for speaker sex differences. *Journal of the International Phonetic Association, 26,* 23-40.

Wickelgren, W. A. (1965). Distinctive features and errors in short-term memory for English consonants. *Journal of the Acoustical Society of America, 38*, 583-588.

Wickelgren, W. A. (1969). Context-sensitive coding, associative memory, and serial order in (speech) behaviour. *Psychological Review, 76*(1), 1-15.

Wilbur, R. (2000). The use of ASL to support the development of English and literacy. *Journal of Deaf Studies and Deaf Education, 5,* 81-104.

Willemain, T. & Lee, F. (1971). Tactile pitch feedback for deaf speakers. *The Volta Review, 73,* 541-533.

Williams, R. & Bernhardt, B. (1998). Speech treatment outcomes as determined by unfamiliar listeners. Poster presented at the *ASHA Convention 1998*, San Antonio, TX.

Wold, D.C., Evans, C.R., Montague, J.C. & Dancer, J.E. (1994). A pilot study of SPINE test scores and measures of tongue deviancy in speakers with severe-to-profound hearing loss. *American Annals of the Deaf*, *139*(3), 352-357.

Yang, B. (1996). A comparative study of American English and Korean vowels produced by male and female speakers. *Journal of Phonetics, 24,* 245-261.

Yang, D., Xu, B. & Wang X. (2010). Speech visualization based on improved spectrum for deaf children. *Proceedings of Control and Decision Conference (CCDC), 2010 Chinese,* 10.1109/CCDC.2010.5498359, 4377-4380. 26-28 May, 2010, Xuzhou.

Zandipour, M., Guenther, F. H., Perkell, J. S., Perrier, P., Payan, Y. & Badin, P. (2004). Vowel-vowel planning in acoustic and muscle space. *Proceedings of From Sound to Sense: Fifty + Years of Discoveries in Speech Communication,* M.I.T., Cambridge, MA. Retrieved from https://netfiles.uiuc.edu/cls/www/course/ling591ema/readings/Zandipourmovement3_24.pdf

Zee, E. & Lee, W-S. (2011). Spectral characteristics of the male and female vowels in Yongding Hakka Chinese. *Proceedings of the 17th International Congress of Phonetic Sciences*, 2256-2259. Hong Kong.

Zharkova, N. (2007). Quantification of coarticulatory effects in several Scottish English phonemes using ultrasound. *QMU Speech Science Research Centre Working Papers*, WP-13, 1-19. Retrieved from http://www.qmu.ac.uk/ssrc/pubs/Zharkova_WP13_2007.pdf

Zharkova, N. (2008). An EPG and ultrasound study of lingual coarticulation in vowel-consonant sequences. In R. Sock, S. Fuchs & Y. Laprie (Eds.), *Proceedings of the 8th International Seminar on Speech Production 2008,* 241-244. Strasbourg, France. Retrieved from http://issp2008.loria.fr/Proceedings/PDF/issp2008-54.pdf

Zharkova, N. (2010). Consonant-specific coarticulation in children and adults. [Abstract]. Oral presentation at the *5th Ultrafest Conference*, March 19-21, Haskins Laboratories, New Haven, CT. Retrieved from http://www.haskins.yale.edu/conferences/UltrafestV/ abstracts/zharkova.PDF

Zharkova, N. & Hewlett, N. (2009). Measuring lingual coarticulation from midsagittal tongue contours: description and example calculations using English /t/ and /a/. *Journal of Phonetics, 37,* 248-256.

Zimmerman, G. & Rettaliata, P. (1981). Articulatory patterns of an adventitiously deaf speaker: Implications for the role of auditory information in speech production. *Journal of Speech, Language & Hearing Research, 24,* 169-178.

Zharkova, N., Hewlett, N. & Hardcastle, W. J. (2008). An ultrasound study of lingual coarticulation in children and adults. In R. Sock, S. Fuchs & Y. Laprie (Eds.), *Proceedings of the 8th International Seminar on Speech Production 2008,* 161-164. Strasbourg, France. Retrieved from http://issp2008.loria.fr/Proceedings/PDF/issp2008-34.pdf

Zharkova, N., Hewlett, N. & Hardcastle, W. J. (2011). Coarticulation as an indicator of speech motor control development in children: An ultrasound study. *Motor Control, 15,* 118-140. Retrieved from www.qmu.ac.uk/casl/staff/nzharkova/Zharkova_et_al_Motor_Control_2011.pdf

Zsiga, E. C. (1994). Acoustic evidence for gestural overlap in consonant sequences. *Journal of Phonetics, 22,* 121-140.