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The Effects of Syllable Boundary, Stop Consonant Closure Duration, and VOT on VCV Coarticulation

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The Effects of Syllable Boundary, Stop Consonant Closure Duration, and VOT on VCV Coarticulation

by

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Dedication

To my parents

Eram Farsad and Hassan Modarresi Ghavami

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The Effects of Syllable Boundary, Stop Consonant Closure Duration, and VOT on VCV Coarticulation

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This study investigated whether the vocalic gestures in VCV sequences are produced with a single diphthongal movement as predicted by the superimposition model of coarticulation or as separate events as predicted by a phoneme-by-phoneme view. ‘Troughs’ or discontinuities in anticipatory vowel-to-vowel coarticulation during the closure period of bilabial stops in symmetrical VCV sequences have provided evidence in favor of a phoneme-by-phoneme view. This investigation sought to uncover the acoustic correlates of troughs in VCV utterances produced by five English and two Persian speakers.

Acoustic evidence for troughs was found in frequency changes of F2 transitions in symmetrical [V.bV] and [V.p^{h}V] sequences. F2 transitions indicative of tongue-related trough effects were influenced by the syllabic

affiliation of the intervocalic stop and to a lesser degree by its voicing properties. Changes in consonantal closure duration did not elicit troughs.

Locus equations (LE) were employed as a second methodology to uncover the acoustic correlates of troughs in a variety of consonantal and vocalic contexts. LE slopes capture CV coarticulation. Troughs would be expected to lower slope values. Consistently lower LE slopes at the CV_2 interface were observed with closed versus open and voiceless versus voiced stops. LE slopes remained stable across changes in consonantal closure duration.

Bidirectional V-to-V coarticulatory effects were also explored. The superimposition model predicts no changes in V-to-V coarticulation as a function of the syllabic affiliation, closure duration, and the voicing properties of an intervocalic stop. Results showed reduced anticipatory V-to-V effects in closed versus open, geminate versus singleton, and voiceless versus voiced conditions in English and with lesser degrees of consistency in Persian. Increased carry-over V-to-V effects were observed in closed versus open syllables in English and in voiceless versus voiced conditions in Persian. Carry-over effects were generally smaller in geminate versus singleton utterances in English and Persian and across voiceless versus voiced stops in English.

The results of this study support a phoneme-by-phoneme view of segmental organization in which vocalic and consonantal gestures are distinct, but temporally and spatially overlapping events and affect one another in varying degrees based on the degree of their overlap.

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Chapter 1: Introduction

Two different views exist as to the characterization of gestures in VCV utterances. One view, known as the superimposition model, is that there are two gestures in a VCV sequence; a diphthongal vocalic gesture and a consonantal gesture that is superimposed on the diphthongal gesture. This view of segmental organization is intended to account for vowel-to-vowel coarticulatory effects. Another view of segmental organization, referred to as the phoneme-by-phoneme[1] model in this study, is that a VCV sequence is composed of three successive gestures that overlap in time. Vowel-to-vowel coarticulation is accounted for by the temporal overlap of the vocalic gestures. The first view of segmental organization is challenged by an articulatory phenomenon known as the 'trough'. Troughs represent discontinuities in anticipatory vowel-to-vowel coarticulation and are not expected to occur if the vowels are produced in a diphthongal gesture. On the other hand, the second view of segmental organization can account for the occurrence of troughs as they represent the relaxation phase of the first vocalic gesture in a VCV sequence. The main goal of the present study was to investigate the acoustic properties of segments in VCV utterances to determine whether such properties provide support for a continuous diphthongal gesture for the vowels in such sequence or two distinct gestures.

This chapter begins with an overview of the pioneering studies on coarticulation. Section 1.2 provides a definition of the term 'coarticulation' and its

[1] The term phoneme is used to imply the distinctness of successive articulatory gestures and not their underlying form.

different types. Since the superimposition model was originally developed to account for vowel-to-vowel coarticulatory effects, an overview of the studies on vowel-to-vowel coarticulation and theories presented to account for this phenomenon are presented in section 1.3. In section 1.4, I have provided a detailed review of the studies documenting troughs and how this phenomenon can be explained by the current theories of the segmental organization of speech. The goals and the organization of the present study are discussed in section 1.5.

1.1. PIONEERING STUDIES ON COARTICULATION

Before the advent of modern speech analysis tools, scholars considered speech to be composed of discrete and distinguishable sounds that came one after the other in the string of speech as the letters of the alphabet do in writing. The general belief was that each sound has a static phase and is connected to adjacent sounds by short terminal glides which allow speech to be produced in a continuous manner (Sievers, 1876). Nevertheless, phoneticians were at the same time aware of the shortcomings of this view. For instance, Sievers (1876) had noticed that the characteristics of a segment can be anticipated during the production of preceding sounds as long as they are not in conflict with the requirements of the sound being produced. Paul (1898) had also noticed that words cannot be broken down into sounds corresponding to the letters of the alphabet. Rather he believed that each word is composed of an infinite number of sounds that cannot be dissected in any possible way (Kühnert and Nolan, 1999:11).

When speech analysis tools became available in the late 19th and early 20th century, scholars began to find evidence in favor of their speculations on sound interaction. Using quantitative scientific methods, early investigators such as Grützner (1879), Lenz (1888), Viëtor (1894, 1898), Rousselot (1897-1901, 1901-1908), and Scripture (1902) recognized that speech cannot be dissected into distinguishable sounds. Rather, speech is a continuously changing process in which the articulatory movements overlap in time and sounds fuse into each other (Hardcastle, 1981: 51).

Menzerath and de Lacerda (1933) were first to use the term 'koartikulation' to refer to the complex interweaving of simultaneous movements in speech. They specifically used this term to refer to the anticipation of an upcoming segment during the production of a sound. Menzerath and de Lacerda (1933) believed that 'coarticulation' was one of the major principles governing speech and a general organizational principle of articulatory control (Kühnert et al. 1999: 14-15).

The term 'coarticulation' has become widely spread in phonetics since the publication of two papers by Öhman in 1966 and 1967 (Laver, 1994:379). This term has, however, gained a broader meaning than what Menzerath and de Lacerda (1933) originally intended.

1.2. COARTICULATION: DEFINITION AND TYPES

In present-day literature, the term 'coarticulation' is used in a broad sense to refer to the pervasive, systematic and reciprocal influences among contiguous and often non-contiguous speech segments (Farnetani & Recasens; 1999: 31). Coarticulatory effects are of two basic types depending on their direction; they can be anticipatory or perseveratory. In anticipatory coarticulation, the production of a sound is affected by upcoming segment(s). An example in English is lip rounding during the production of [s] in the word 'soup' [sup] in anticipation of the upcoming [u]. Anticipatory influences are also called right-to-left, forward, or regressive coarticulation (Laver, 1994: 379).

In perseveratory coarticulation, the production of a sound is affected by previous segment(s). An example in English is the palatalization of the final velar consonant in the word 'cheek' [tʃik^y] under the persisting influence of the preceding front vowel [i]. Perseveratory influences are also referred to as left-to-right, carry-over, retentive, backward, or progressive coarticulation (Laver, 1994: 379). In the present study, I have used the terms anticipatory and carry-over to refer to these two types of coarticulation.

Anticipatory co-articulation is considered to reflect properties of speech planning, while carryover co-articulation has been ascribed to mechanical and inertial factors. However, considering the extent of carry-over coarticulation, it has been suggested that carryover co-articulation cannot simply be assumed to result from mechanical or inertial effects (Fowler, 1993).

1.3. ANTICIPATORY AND CARRY-OVER VOWEL-TO-VOWEL COARTICULATION

Numerous studies have shown that in V_1CV_2 sequences the production of each vowel is influenced by the other across the intervening consonant and that this influence is observable in the speech signal. In section 1.3.1, I will review the major works that have documented such vowel-to-vowel effects. Section 1.3.2 includes a review of the theories presented to explain vowel-to-vowel coarticulation.

1.3.1. Studies on Vowel-to-Vowel Coarticulation

Rousselot, who was among the first to investigate speech instrumentally, was also first to notice vowel-to-vowel coarticulatory effects. Rousselot (1897-1901: 947) observed that in a VCu sequence lip rounding for /u/ can start during the production of the first vowel (Kühnert & Nolan, 1999: 12).

Another early documentation of vowel-to-vowel coarticulation was made by Laclotte (1899). In his investigation of /eli/ and /ela/ sequences, Laclotte (1899) observed that in the production of /e/ the tongue was in a higher position when the second vowel was /i/ compared to when the second vowel was /a/. The same pattern was seen with /ebi/ versus /eba/ and /venti/ versus /venta/ (Scripture, 1902: 372).

Serious study of vowel-to-vowel effects began after Öhman published his two famous articles on vowel-to-vowel coarticulation in 1966 and 1967. Öhman (1966) performed an acoustic as well as an articulatory study of VCV sequences in Swedish and an acoustic study of comparable VCV sequences uttered by English and Russian speakers. Öhman (1966) observed that in Swedish and English VCV utterances the terminal frequency values of formant transitions are not only dependent on the medial C, but on the formant pattern of the trans-consonantal vowel.

Since Öhman presented the results of his study, a considerable number of articulatory as well as acoustic studies have documented vowel-to-vowel coarticulatory effects. Vowel-to-vowel coarticulation has been observed acoustically in the transitions (Perkell, 1969; Kent, 1972; Kent & Moll, 1972; Butcher & Weiher, 1976; Purcell, 1979) as well as in the steady-state portions of V_1 and V_2 in V_1CV_2 sequences (Fowler, 1981a; Recasens, 1984, 1987; Magen, 1984, 1985, 1997; Manuel, 1990; Whalen, 1990). Many studies have shown that vowel-to-vowel coarticulation is sensitive to speaking rate (Hertich & Ackerman, 1995), vowel inventory (Manuel & Krakow, 1984; Manuel 1990), consonant inventory (Hussein, 1990; Recasens, 1987), and the direction of coarticulation (Hussein, 1990; Browman & Goldstein, 1986, Van Berbem, 1994, Hertich & Akerman, 1995).

1.3.2. Vowel-to-Vowel Coarticulation: Theories and Predictions

In order to account for vowel-to-vowel coarticulation, Öhman (1966, 1967) proposed the 'superimposition' model. According to this model, a VCV utterance is not a linear sequence of three successive gestures. Rather, the vowels are produced in a single diphthongal movement and the consonantal gesture is superimposed on the vocalic diphthongal movement that is present during all of the consonantal gesture. A schematic representation of this view is shown in figure 1-1.

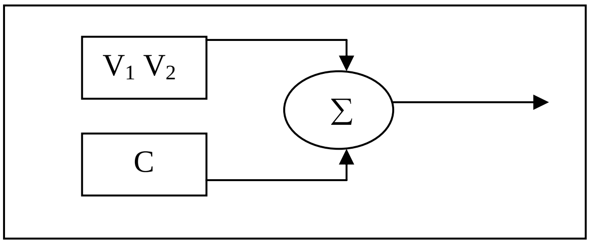


Figure 1-1. Schematic representation of gestural overlap according to the superimposition model (Öhman, 1967). Vowels are produced with a diphthongal movement and the consonantal gesture is superimposed on the diphthongal gesture.

Central to Öhman's model is the distinctness of the articulators involved in the production of vowels and consonants. Öhman (1966) proposed that physiologically the tongue involves three separate articulatory systems that execute invariant neural instructions through three independent articulatory channels. The apical and dorsal articulators are involved in the production of consonants, i.e. sounds described as dental, alveolar, retroflex, palatal and velar. The tongue-body articulator is, on the other hand, involved in the production of vowels. The distinctness of the articulators allows for the temporal overlap of vocalic and consonant gestures.

The superimposition model of Öhman is widely accepted as an explanation for vowel-to-vowel coarticulation. The early version of 'coproduction theory[2]' (Fowler, 1977, 1980) adopts a similar view of vowel-to-vowel

[2]The term 'coproduction' is specifically associated with the theory of coarticulation proposed by Fowler (1977; 1980) and developed later by other researchers at Haskins Laboratories. However, the term has been used in a broad sense in the literature to refer to all 'intrinsic-timing' theories in which segmental gestures contain temporal information and overlap in time. In this broad sense, Öhman's superimposition model is also considered to be a coproduction model in which the consonantal and diphthongal vocalic gestures overlap in time or are 'coproduced'. I have used the term coproduction in its specific sense in the present study to refer to the model proposed by researchers at Haskins Laboratories.

coarticulation. Like Öhman (1966), Fowler (1980) maintained that vowels and consonants are realized through the actions of different sets of muscles or coordinative structures and that this distinctness allows the temporal overlap or 'coproduction' of their respective gestures:

> "Consonants and vowels are distinguished by the coordinative structures that effect their realization … all vowels are the product of a single set of coordinative structures invoked just once at the onset of an utterance. These muscle systems effect a characteristic kind of gesture … that distinguishes vowels as a class of segment. Consonants are produced by (a variety of) coordinative structures different from those that invariantly underlie vowel production … (Fowler, 1980: 129)"

A later version of coproduction theory (Fowler & Saltzman, 1993) presented a different view of segmental organization. In this new view, the speech plan for a given utterance was defined as the set of activation waveforms for the gestures in the utterance as shown schematically in figure 1-2. The gestural activation waves were hypothesized to "[be] smoothly shaped and … display gradual implementation and relaxation phases…" (Fowler & Saltzman, 1993: 184). In this view of coproduction, the gestures for successive segments overlap in time irrespective of being a vowel or a consonant. Vowel-to-vowel coarticulation is accounted for by the temporal overlap or the coproduction of two distinct vocalic gestures.

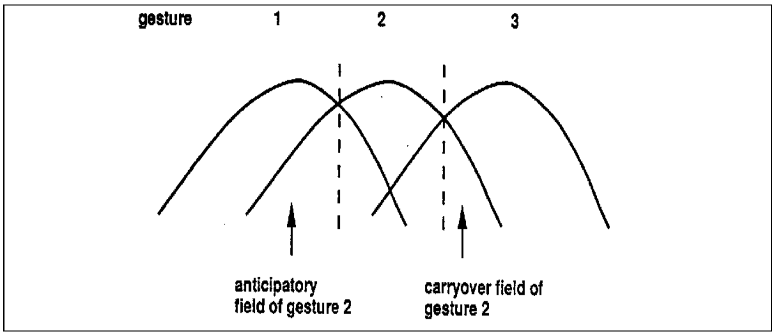


Figure 1-2. Schematic representation of activation waves of three overlapping gestures. Anticipatory and carryover coarticulatory fields of gesture 2 are indicated by arrows (Fowler & Saltzman, 1993)

This version of coproduction is reminiscent of an earlier model proposed by Joos (1948). In his ‘overlapping innervation wave’ theory, Joos proposed that each segment in a string is the result of an innervation wave that is sent from the speech center to the vocal organs. The innervations called ‘neuremes’ are static and invariable at higher levels of speech organization. They are sent simultaneously but separately along parallel paths to the speech organs. These waves overlap in time and wax and wane in a smooth manner as schematically shown in figure 1-3. According to this theory, the contextual variation of segments in articulatory and acoustic dimensions is the result of the temporal overlap of the innervation waves that bring them about.

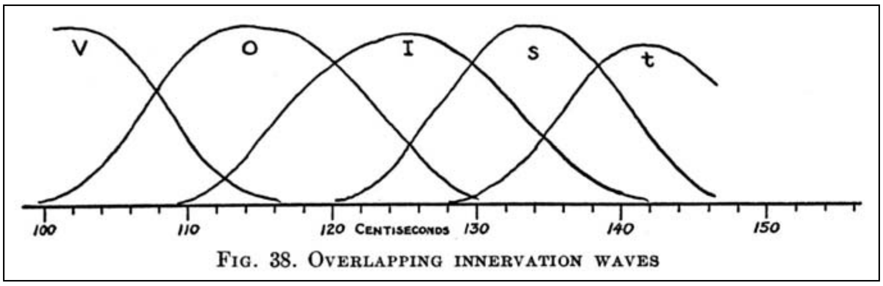


Figure 1-3. Schematic representation of overlapping innervation waves (from Joos, 1948). The innervation waves sent to the peripheral organs overlap in time irrespective of the quality of the segment being produced.

Although Joos did not specifically discuss vowel-to-vowel coarticulation, his model accounts for vowel-to-vowel coarticulatory effects by the temporal overlap of distinct vocalic gestures.

The superimposition and Haskins' coproduction models are the two models that specifically address vowel-to-vowel coarticulation. However, other theories of coarticulation can explain this phenomenon following their general account of coarticulation. In Browman and Goldstein's (1986; 1989; 1992) articulatory phonology, utterances are viewed as 'constellations' of gestures that can overlap in time. Gestures as abstract characterizations of articulatory events have intrinsic duration. In the making up of an utterance, these gestures have to be 'phased' with one another and organized into larger units. Since gestures have internal duration, they may overlap in time resulting in coarticulatory effects. In articulatory phonology as in the overlapping innervation wave theory and Haskins' coproduction model, vowel-to-vowel coarticulation is accounted for by the temporal overlap of vocalic gestures. Vocalic gestures in a VCV utterance are phased with one another and with the consonantal gesture. Vocalic gestures may or may not overlap depending on their intrinsic duration as well as the intrinsic duration of the consonantal gesture.

To summarize, models such as the superimposition, coproduction, overlapping innervation wave, and articulatory phonology all account for coarticulation by assuming a temporal overlap to exist between adjacent gestures. In the superimposition model and earlier version of coproduction theory, vowel-to-vowel coarticulation is accounted for by assuming a temporal overlap to exist between one single diphthongal vocalic gesture and a consonantal gesture. In the overlapping innervation wave theory, the later version of coproduction, and in articulatory phonology, vowel-to-vowel coarticulation is accounted for by assuming a temporal overlap to exist between two distinct vocalic gestures that at the same time overlap with a consonantal gesture.

Not all theories of coarticulation account for vowel-to-vowel coarticulation through the assumption of temporal overlap between vocalic gestures. For instance, in the 'window model' (Keating, 1990), vowel coarticulation is accounted for by the interpolation between vocalic windows. In this model, segments are defined in terms of articulatory or acoustic 'windows' that consist of all the spatial values each segment can assume in different contexts. A sequence of segments is translated into a sequence of non-overlapping windows for each articulatory or acoustic dimension. Coarticulation is accounted for by the operation of an interpolation process that occurs between adjacent windows and consists of finding a path through the windows. Thus, the articulatory or acoustic value for each segment is determined by the path that connects it smoothly to the next window. In a VCV sequence, where the vowels are associated with narrow windows and consonants with broad windows for a given vocalic articulatory or acoustic dimension, vowel-to-vowel coarticulation can be accounted for by the interpolation between vocalic windows through a broad consonantal window.

The main interest of the present study is the predictions that the mainstream theories of coarticulation make regarding VCV sequences where the two vowels are identical and share all features. The superimposition model predicts that the articulators involved in the production of the vowels maintain their position throughout the production of the consonant. That is because the two vowels are programmed together in a single diphthongal movement and if they share all features, the shared articulators have to be activated only once and have to remain in position even during the production of the intervocalic consonant. The earlier version of coproduction model makes a similar prediction.

However, the overlapping innervation wave theory and the later version of coproduction make a different prediction regarding symmetrical VCV sequences. These models predict that the articulators involved in the production of the vowels maintain their position only if the temporal overlap of the vocalic gestures is total or if the periods of maximum activation coincide. Otherwise, a break will occur in articulator activity as gestures go through periods of activation and deactivation.

In gestural phonology, if the two vocalic gestures overlap in time or if the gesture for V_2 starts as soon as the V_1 gesture ends, a maintained articulation will be observed throughout the utterance. However, if the two gestures do not overlap in time, a break in articulator activity will be seen. In other words, the maintained position of the articulators throughout the utterance depends on the temporal relationship between the vocalic gestures.

In the window model, since the two vowels are associated with identical windows for a given dimension, the interpolation path goes through the vocalic and consonantal windows in a straight line. Thus, no change is observed in the given articulatory or acoustic dimension throughout the utterance.

To summarize, the models of coarticulation can be divided into two groups when it comes to their predictions with regard to VCV sequences where the two vowels share all features. One group predicts that in a symmetrical VCV sequence the articulators involved in the production of the vowels remains in position throughout the utterance. Another group allows maintained articulator position only when the gestures overlap to a considerable degree. When the intended amount of overlap is not present, a break is expected to occur in articulatory movement.

Kinematic studies on symmetrical and nonsymmetrical VCV sequences have documented a phenomenon known as the 'trough' effect. This articulatory phenomenon represents a break in anticipatory coarticulation as predicted by the second group mentioned above. Section 1.4 provides a review of the major works that have documented troughs.

1.4. ARTICULATORY TROUGHS

Studies have shown that, contrary to the predictions of the superimposition and window models, the articulators involved in the production of the vowels in symmetrical VCV sequences do not maintain their position throughout the utterance. Rather, they deviate from their assumed position for the first vowel and resume it again during the consonantal constriction despite an upcoming identical vowel. This discontinuity in anticipatory coarticulation (Perkell, 1986) has come to be known as the 'trough effect' (Gay, 1977) and has been documented in numerous kinematic studies.

At the same time that Öhman had published his two articles on vowel-to-vowel coarticulation, Houde (1967) reported the results of a cineradiographic study of articulatory movements during labial closure in symmetrical ([bibi, baba, bubu]) and non-symmetrical ([bubi, bibu]) sequences. He observed active tongue lowering during labial closure as shown in figure 1-4.

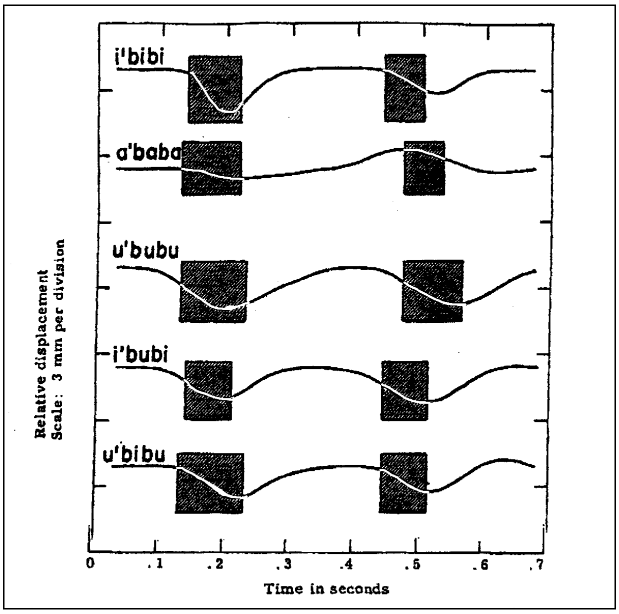


Figure 1-4. Cineradiographic records of tongue movement in symmetrical and nonsymmetrical sequences (Houde, 1967). Consonantal closure periods are shown by shaded boxes. The records show active tongue body movement during the production of the consonants.

In figure 1-4 the shaded boxes indicate stop closure periods. As the top three rows of the cineradiographic records in this figure show, the tongue deviated from V_1 position during the closure for /b/ despite an upcoming identical vowel. Similarly in the nonsymmetrical sequences shown in the last two rows, the tongue deviated from its high position despite an up coming high vowel. These results are especially interesting considering that the tongue is not involved the production of /b/ and hence is not expected to displace from its position as predicted by the superimposition and window models.

Gay (1974a) replicated Houde's (1967) results in an electromyographic (EMG) study of the activity of the genioglossus[3] muscle during the production of /ipi/ and /iti/ sequences. The averaged EMG data of this study showed de-activation of the genioglossus muscle during the production of the bilabial and alveolar stops as shown in figure 1-5 below. The results also indicated that each vowel in the VCV sequences was associated with a distinct muscular activation.

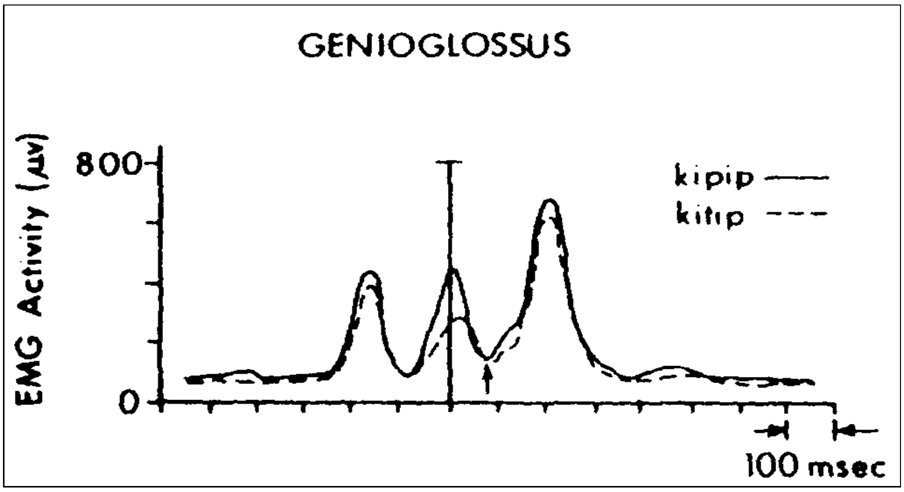


Figure 1-5. Averaged EMG activity of genioglossus muscle for the utterances /kipip/ and /kitip/. The first peak of muscle activity is associated with the initial /k/. The vertical line indicates the time of voicing onset for the first vowel (Gay, 1978). The records show distinct tongue body activity for each of the two vowels.

In a subsequent investigation, Gay and Ushijima (1974) studied the activity of the genioglossus muscle during the production of VCV sequences in normal and fast speech of American English speakers. As with previous studies,

[3] The genioglossus muscle is responsible for bunching and protruding the tongue and is thus involved the production of high front vowels.

the EMG records showed genioglossus relaxation during the production of the intervocalic consonant in /ipip/ and /itip/ sequences in both normal and fast speech.

Bell-Berti and Harris (1974) also performed an EMG study of /ipi/ sequences with varying stress patterns, where a cessation of genioglossus muscle activity between the two high front vowels was observed. Figure 1-6 illustrates the results of this study for /ípi/ and /ipí/ sequences. Although the degree of muscle activity shows differences as a function of stress, both utterances show troughs and distinct peaks of genioglossus activity.

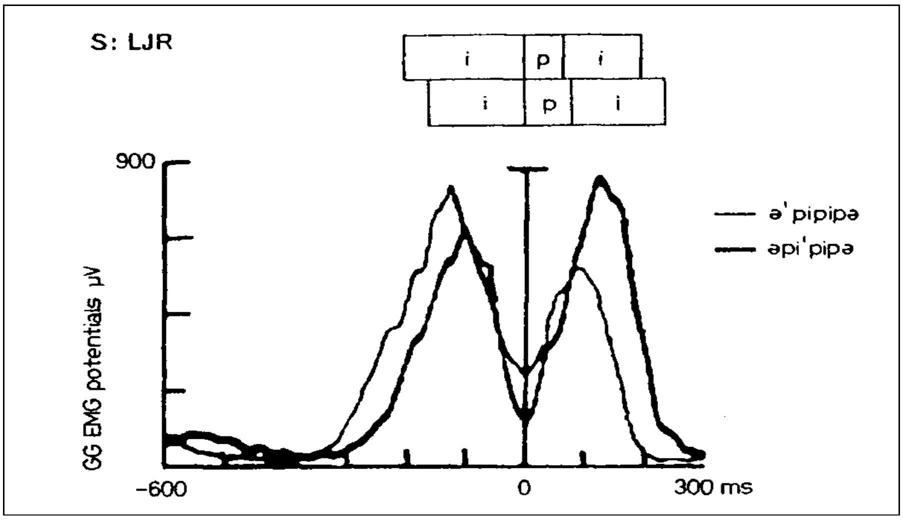


Figure 1-6. Averaged EMG activity of the genioglossus muscle during the production of [ipi] sequences shows a trough and distinct muscle activations for the two vowels. Zero on the x axis represents [p] closure (from Bell-Berti and Harris 1974).

In an examination of x-ray images taken from a Swedish speaker during the production of VbV and VpV utterances, Lindblom and Sussman (2002) and Lindblom et al. (2002) found further evidence of troughs. Figure 1-7 shows time series plots of jaw and tongue height in the x-ray pictures taken during the production of [a:ba:p^{h}a:ɹ] and [i:bi:p^{h}i:l] sequences. In each plot, filled triangles show jaw movement/opening (mm) and filled circles show jaw-based tongue height (mm). As these x-ray tracings show, the tongue did not maintain its position throughout the utterances. Rather, it lowered during the production of /b/ and /p^h/ in the [i:bi:p^{h}i:l] sequence while the jaw opening remained relatively stable. A similar pattern was observed during the production of [b] in the [a:ba:p^{h}a:ɹ] sequence, where considerable tongue lowering was observed relative to jaw movement. Another instance of tongue lowering was observed towards the end of the second [a:] into [p^h] closure.

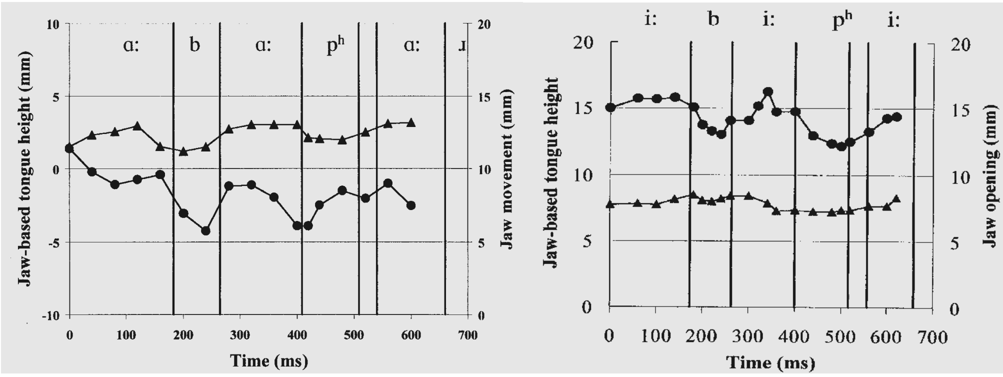


Figure 1-7. Time series plots of jaw-based tongue height in millimeters (circles) and jaw opening in millimiters (triangles) for the utterances [a:ba:p^{h}a:ɹ] and [i:bi:p^{h}i:l] produced by a Swedish speaker. Traces show a decline in tongue height during consonantal closure despite a relatively fixed jaw position. (Lindblom & Sussman, 2002; Lindblom et al., 2002).

Troughs are not limited to tongue activity during consonantal production. In an EMG study of the activity of orbicularis oris[4] during the production of /utup/ sequences, Gay (1977a) reported an interruption in muscle activity during the closure for the medial /t/ as shown in figure 1-8 below. Again, these results contradict the prediction of the superimposition and feature-spreading models in that the rounding activity of the lips is not continuous throughout the utterance and that the two vowels are associated with distinct muscle activities.

[4] Orbicularis oris is an oval ring of muscle encircling the mouth and is involved in different lip movements including lip closure, lip rounding, and lip protrusion.

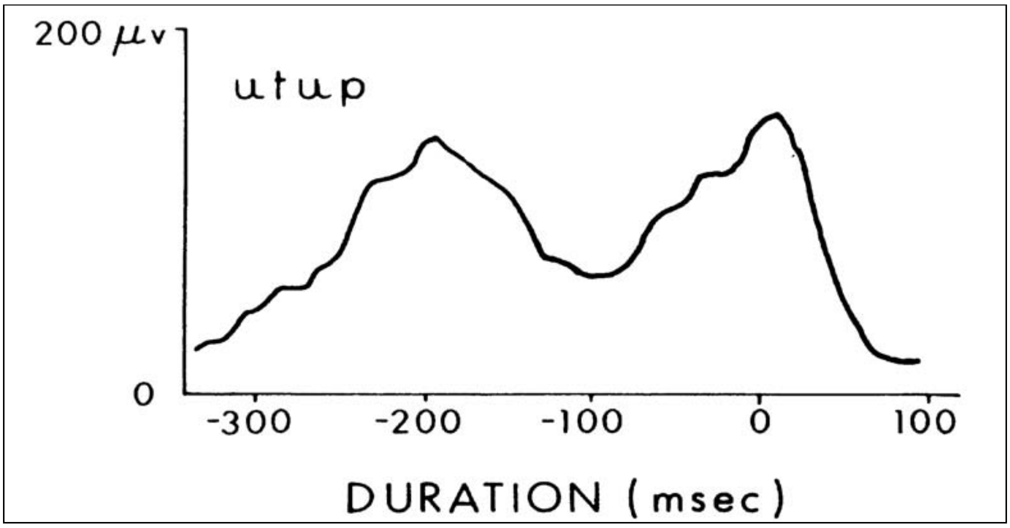


Figure 1-8. Averaged orbicularis oris muscle activity during the production of /utu/ sequences (from Gay, 1977a). The records show two distinct peaks of muscle activity for the two flanking vowels.

Mc Allister (1978) and Engstrand (1980) also observed active lip retraction in a series of electromyographic (EMG) studies of lip activity during stop closure of /uCu/ sequences.

Studies have also shown that troughs are sensitive to the phonetic properties of the intervocalic consonant. For instance, Engstrand (1989) in an EPG investigation of /ibi/ and /ipi/ sequences produced by Swedish speakers showed a clear voicing effect on the extension of EPG contact area for /b/ and /p/. Greater troughs were observed during the production of /p/ compared to /b/. The duration of the troughs were not however significantly different as a function of voicing. Engstrand (1989) concluded that the difference between /b/ and /p/ in terms of troughs can be a consequence of different aerodynamic requirements for the two consonants. In a more recent EPG data, Engstrand (unpublished data) found no difference between /b/ and /p/ in the magnitude of troughs.

Harris and Bell-Berti (1984) also investigated the sensitivity of troughs to the phonetic properties of the intervocalic consonant. Their aim was to determine whether troughs are markers of syllable boundary irrespective of the phonetic properties of the intervocalic consonant. According to Kozhevnikov and Chistovich (1965), a C_nV sequence forms an articulatory syllable in that the anticipatory effects of V can be detected during the production of the first consonant in a consonantal cluster preceding the vowel, but not earlier. Since troughs represent discontinuities in anticipatory coarticulation, Harris and Bell-Berti (1984) hypothesized that they mark syllable boundary. A lateral view cineradiographic study of tongue movement in [ihi], [iʔi], and [ipi] utterances showed evidence of tongue body movement during [p], but not consistently during [h] and not at all during [ʔ] production. An x-ray study of lip protrusion in [utu] and [uʔu] sequences showed evidence of lip retraction during [t], but not during [ʔ]. Harris and Bell-Berti (1984) maintained that troughs are positive articulatory requirements for the consonants for which they occur and not syllable boundary markers.

Scholars have also investigated the effect of intervocalic consonant duration on the production of troughs. For instance, Gay (1978) in an EMG study of the activity of orbicularis oris in uCu, uCCu, and uCCCu sequences observed troughs during consonantal constriction irrespective of the number of intervening consonants. Gay (1978) observed a relaxation in muscle activity as early as the closure for the first consonant and an immediate resumption of activity during the production of the consonants. Figure 1-9 shows the averaged EMG data of /utu/ and /ukstu/ sequences from Gay’s (1978) study showing discontinuities in muscle activity irrespective of the number of consonants that intervene between the two vowels.

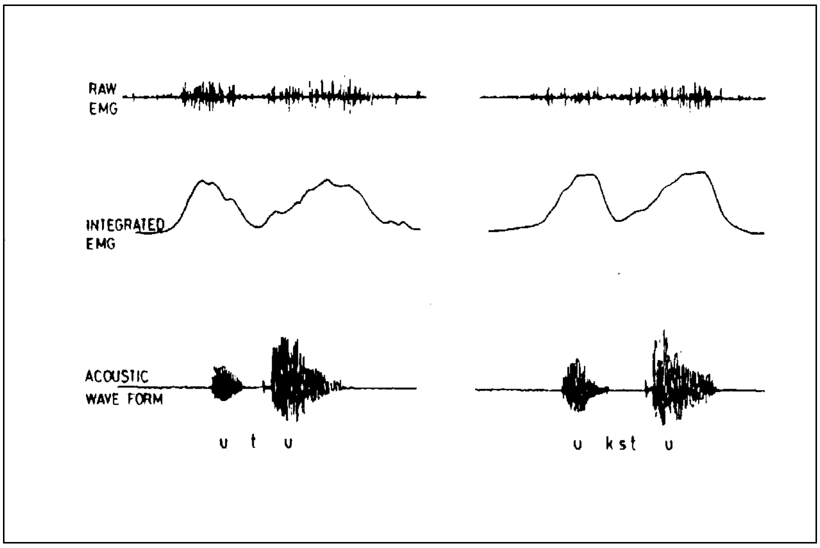


Figure 1-9. Orbicularis oris muscle activity for /utu/ and /ukstu/ utterances shows discontinuities in muscle activity (from Gay, 1978).

Phoneticians have also investigated the universality of troughs. Perkell (1986) studied lower lip protrusion movement for the vowel /u/ in /uC_nu/ utterances produced by French, Spanish, and American English speakers. The intervocalic consonant in these sequences consisted of one to three coronal consonants (/t, s, n, l, sl, sn, ns, nl, ln, nst, lst/) presumably neutral with regard to lip protrusion. The lower lip movement traces showed a trough for English and

Spanish speakers in all consonantal contexts. The utterances produced by French speakers showed troughs only during the production of /s/ and the sequences containing /s/. As with Gay's (1978) study, there were no obvious effects of consonant sequence size on the magnitude of troughs. Following Engstrand (1980) and Harris and Bell-Berti (1984), Perkell (1986) suggested that acoustic and/or aerodynamic requirements for consonantal production might be responsible for the occurrence of troughs in French during the production of /s/. Perkell's explanation seems to suggest that troughs do not normally occur, unless language-specific acoustic or aerodynamic requirements make it necessary.

Boyce (1988, 1990) also compared the occurrence of troughs in English and Turkish. She studied upper and lower lip protrusion movement and performed an EMG study of the activity of the orbicularis oris muscle in real and nonsense VC_nV sequences produced by Turkish speakers and in identical nonsense sequences produced by English speakers. The utterances contained all combinations of rounded and unrounded vowels and the intervocalic consonants consisted of one to three non-labial consonants. In utterances produced by Turkish speakers, lip movement records and EMG results showed plateaus i.e. maintained articulator position during consonantal closure. The results obtained from English speakers, on the other hand, showed troughs. Boyce (1990) concluded that the phonology of each language plays an important role in the production of troughs. Troughs do not occur in languages such as Turkish that have vowel harmony. Since the phonological system of such languages requires the vowels in an utterance to share features, and that vowels are tightly bonded together, troughs are not observed. However, in a language such as English where the phonology of the language does not require the vowels to share features, troughs do occur.

McAllister and Engstrand (1992) also performed a cross-linguistic EPG study of linguopalatal contact in /ipi/ sequences produced by English, French, German, Irish, and Swedish speakers. The results of their investigation are shown in figure 1-10 below. This study showed clear troughs during the production of /p/ in all languages except in French.

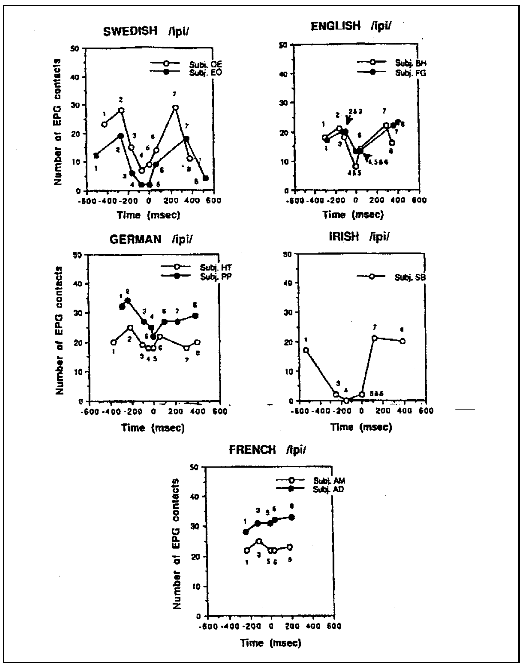


Figure 1-10. Average number of EPG contacts over time for the utterance /ipi/ produced by Swedish, English, German, Irish, and French (McAllister & Engstrand, 1992).

The results obtained by McAllister and Engstrand (1992) indicated that the average length of the utterances were shorter for both French speakers compared to other speakers. Based on this observation, McAllister and Engstrand (1992) suggested that the increased rate of the French utterances could have increased the temporal overlap of the vocalic gestures and caused a substantial reduction in the trough-like pattern observed with other speakers. This explanation is, however, compatible with Gay and Ushijima's (1974) results, where a trough was observed in normal and fast speech of English speakers.

To summarize, contrary to the predictions of the superimposition and window models, cineradiographic, EPG, EMG, and x-ray data have shown that the articulators involved in the production of V_1 in V_1CV_2 sequences do not maintain their position during the production of the intervocalic consonant. Rather, in many languages and with many intervocalic consonants the articulators relax from their position during consonantal constriction and resume their position by the time the constriction is removed producing a trough in articulatory movement.

Scholars have attempted to explain troughs. Many phoneticians suggest that troughs fulfill acoustic, aerodynamic, and perceptual requirements for consonants for which they occur. Others have shown that troughs are not related to the properties of consonants, but have to do with linguistic requirements on vowels; troughs are sensitive to language-specific requirements on vowel harmony and diphthongization. Some scholars have suggested that troughs indicate requirements for syllabic organization (Perkell, 1986). On the other hand, studies have shown that troughs do not occur during the production of all consonants in syllable-initial position (Engstrand, 1980; Harris and Bell-Berti, 1984). Moreover, the fact that troughs are not observed in all languages indicates that they cannot be considered as universal markers of syllable boundary.

A possible explanation for troughs emerges from the view that speech is planned as a sequence of overlapping gestures that go through phases of implementation/activation and relaxation/deactivation as stipulated by Joos (1948) and Fowler and Saltzman (1993). Troughs in tongue body and lip activity represent the relaxation phase of the corresponding gesture. In other words, when the temporal overlap between two vocalic gestures in a VCV sequence is not total, troughs, i.e. discontinuities in anticipatory coarticulation are expected to occur as the gestures go through a deactivation phase.

1.5. GOALS AND ORGANIZATION OF THE STUDY

The main question addressed in this investigation is whether the vowels in a VCV sequence are produced in a single diphthongal movement as predicted by the superimposition model or are distinct events as predicted by the phoneme-by-phoneme view of segmental organization. If the vowels are realized through a diphthongal movement troughs do not occur and changes in the temporal properties of the intervocalic consonant are not expected to affect vowel-to-vowel coarticulation. On the other hand, if vowels are distinct events, troughs are expected to occur and changes in the temporal characteristics of the intervocalic consonant are expected to affect vowel-to-vowel coarticulation.

In the present study, VCV utterances produced by American English and Persian speakers are investigated to answer the following questions:

(a) Is it possible to detect the effects articulatory troughs in the acoustic signal?

(b) Since troughs represent kinematic discontinuities in anticipatory coarticulation, are their acoustic correlates enhanced when V_2 in V_1CV_2 sequences is temporally removed from V_1, as in geminate [VC.CV] sequences and in voiceless aspirated contexts?

(c) Can troughs be more easily observed in the acoustic signal, if the syllable boundary is altered as in closed [VC.V] utterances?

The answer to these questions is intended to provide an answer to the main question asked above, i.e. if vowels are produced in a diphthongal gesture or if they represent two distinct but overlapping events.

According to the superimposition model, the vowels in a VCV sequence are timed with relative to one another irrespective of the intervocalic consonant. Thus, no changes are expected to be observed in V-to-V coarticulatory effects as a function of the syllabic affiliation, closure duration, and the voicing properties of the intervocalic stop consonant. According to a phoneme-by-phoneme view, on the other hand, the vowels and consonants in a VCV sequence are all timed relative to one another. Thus, V-to-V coarticulation is expected to be affected by the syllabic affiliation, closure duration, and the voicing properties of the intervocalic stop consonant. These expectations are also evaluated as a secondary investigation in this study.

The organization of this dissertation is as follows: in chapter 2 the experimental methods and statistical tools employed to investigate troughs in the acoustic signal are described. Since the effects of stop consonant closure duration and VOT on the production of troughs are of interest in this study, stop consonant closure duration and VOT measurement results are presented in chapter 3. Troughs, their acoustic consequences, and the effects of syllable boundary, stop closure duration, and VOT on troughs are investigated in selected symmetrical VCV sequences in chapter 4. The results obtained in chapter 4 serve as a basis for a more extensive investigation of troughs in a variety of VCV contexts using the locus equation paradigm in chapter 5. Chapter 6 deals with the effects of the temporal properties of the intervocalic consonant on vowel-to-vowel coarticulation. Conclusions and discussions appear in chapter 7.

Chapter 2: Methodology and Statistical Tools

This chapter consists of two main sections. In section 2.1 the experimental methods employed in this study are described. Section 2.2 deals with the statistical tools used to analyze the obtained data.

2.1. METHODOLOGY

2.1.1. Subjects

Five male speakers of American English and two male speakers of Persian between the ages of 27 and 38 participated in this study. All subjects except for one were students at the University of Texas at Austin. The native speakers of English came from all parts of the United States and spoke other languages such as Spanish, Portuguese, French, German, and Arabic as a second language with varying degrees of fluency. One Persian speaker spoke the Tehrani dialect of Persian, while the second speaker showed traces of the dialects spoken in western Iran. Both Persian speakers spoke English as a second language.

In the presentation of the results, the English speakers are referred to as E#1 through E#5 and the Persian speakers as P#1 and P#2.

2.1.2. Speech Samples

In order to study the effects of the syllabic affiliation of the intervocalic consonant on VCV co-articulation, vowel-consonant-vowel nonsense tokens with the syllable boundary falling at two different positions were devised as described in (1) and (2) in the following list. Furthermore, to investigate the effect of consonantal closure duration on VCV co-articulation, a third set of tokens with geminate intervocalic consonants was devised as described in (3) below:

(1) Open/Singleton $[C_iV_1.C_iV_2]$ tokens in which the syllable boundary fell before C,

(2) Closed $[tV_1C.V_2t]$ (English) or $[dV_1C.V_2t]$ (Persian) tokens in which the syllable boundary fell after C, and

(3) Geminate[5] $[tV_1C_i.C_iV_2t]$ (English) or $[dV_1C_i.C_iV_2t]$ (Persian) tokens in which C was produced with relatively long closure durations.

In the discussion of the results, I have referred to the tokens in (1) above as open syllables when I have discussed them in relation to closed syllable forms. When discussing the same tokens in relation to geminate utterances, I have referred to them as singleton utterances.

The consonant /t/ was chosen as the initial and final consonants in closed and geminate utterances to facilitate utterance production for the speakers.

Since the effect of Voice Onset time (VOT) on the enhancement of troughs and on V-to-V coarticulation was also of interest, voiced and voiceless aspirated stop consonants of English and Persian were used as medial consonants in all token types. These included /b,p,d,t,k,g/ for English and /b,p,d̪,t̪,k,g/ for

[5] The term geminate is used to refer to intervocalic stop consonants with relatively long closure durations. This term is not used in a phonological sense.

Persian. The V_1 and V_2 contexts included all combinations of /i,e,æ,u,ɔ/ for English and /i,ɛ,æ,u,o,ɒ/ for Persian. All stimuli were bisyllabic nonsense words put in the carrier sentence "*Say* ----- *again*" for English and "inǰɒ ----- nɛvɛštɛ." ("---- is written here") for Persian.

English and Persian stimuli were read from two separate lists in English and Persian orthography respectively, where tokens appeared in IPA transcription. Subjects were asked to read the list three times aloud and in a careful manner. No instruction was given to subjects regarding stress. Persian subjects produced all tokens with stress on the second syllable, following the stress pattern of nouns in Persian. As for the English speakers, open/singleton utterances were produced with stress on the first syllable. Closed and geminate utterances were either stressed on the second syllable or both syllables were given equal stress. This observation was confirmed by two native speakers of American English who listened to a random collection of actual tokens for stress assignment.

In total, each English speaker produced 1350 tokens (6 stop consonants * 5 V_1 contexts * 5 V_2 contexts * 3 syllable shapes * 3 repetitions). Each Persian speaker produced 1944 tokens (6 stop consonants * 6 V_1 contexts * 6 V_2 contexts * 3 syllable shapes * 3 repetitions). One repetition of the closed syllable token types produced by speaker P#1 had to be discarded all together, as the release burst of the syllable-final consonant was either non-existent or too noisy to allow accurate measurement. In total, the corpus of this study included 10,458 tokens; 6750 and 3708 tokens for English and Persian speakers respectively.

2.1.3. Recording and Digitizing

Subjects were recorded in a sound attenuated room using high-quality microphones (SHURE SM58, SHURE BG3.1, or Radio Shack unidirectional dynamic microphone IMP 5000) and Marantz cassette recorders (model PMD 201 and PMD 507).

The recorded signal was digitized using a Power Macintosh 7100/80 at 16 bits with a 20 kHz sampling rate. The SoundScope/16 speech analysis software (version 1.44, GW Instruments, Inc.) was used for all display, editing, playback, and measurement procedures. The FFT spectra were calculated with 1024 points using a filter setting of 45 Hz. LPC spectra were calculated with 25 coefficients and a 20ms frame length using 512 points. Spectrograms were generated with a 150 Hz filter setting and 1024 FFT points.

2.1.4. Measurements and Data Sample Points

2.1.4.1. Formant Measurements

The effects of syllable boundary, consonantal closure duration, and VOT on troughs as well as on V-to-V coarticulation were investigated by measuring changes in second formant (F2) frequency. All measurements and analysis procedures were identical, as far as possible, to those previously described in Sussman et al. (1991; 1997).

The second formant (F2) frequency was measured at the following points:

1. <u>F2 vowel.</u> The second formant was measured at the steady state of V_1 and V_2 in all tokens. F2 vowel values were means obtained from wide-band

spectrographic display, narrow-band Fast Fourier Transform (FFT), and Linear Predictive Coding (LPC) spectra.

On the spectrographic display, the criterion for determining vowel steady state was basically visual. If the formant was visually steady all throughout the vowel, the mid point formant frequency was taken as F2 vowel. If the formant pattern was diagonally rising or falling, again a visual midpoint was taken. Finally, if the formant pattern was either “U-shaped” or the inverse, a “minimum” or “maximum” frequency was respectively taken as F2 vowel. The different F2 orientations and the points at which F2 vowel was measured in each case are shown in figure 2-1 below.

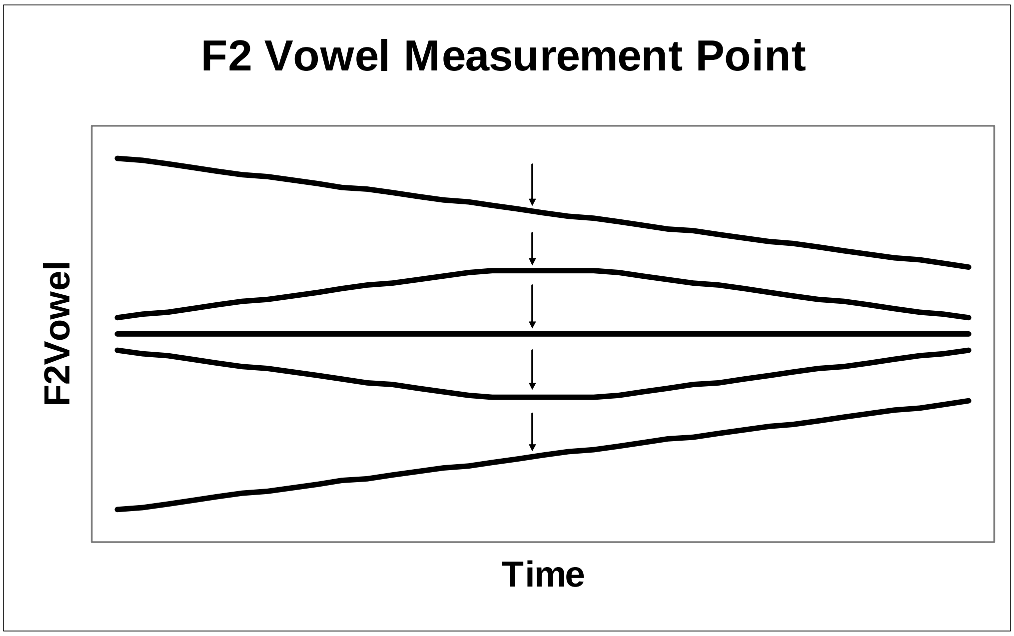


Figure 2-1. Second formant visual midpoint was taken as F2 vowel regardless of formant orientation.

FFT and LPC readouts were taken from spectral windows corresponding to F2 vowel midpoint determined by positioning the marker on the spectrographic display. In such readouts, F2 vowel value was taken from the second spectral peak on the FFT and LPC windows.

2. F2 offset. F2 offset was measured at the last pitch period of V_1 before the stop closure by placing the cursor on the last pitch period of V_1 on the wide-band spectrographic display. Frequency read-outs were taken from the spectrographic display and checked against the frequency of the second FFT spectral peak as shown in figure 2-2.

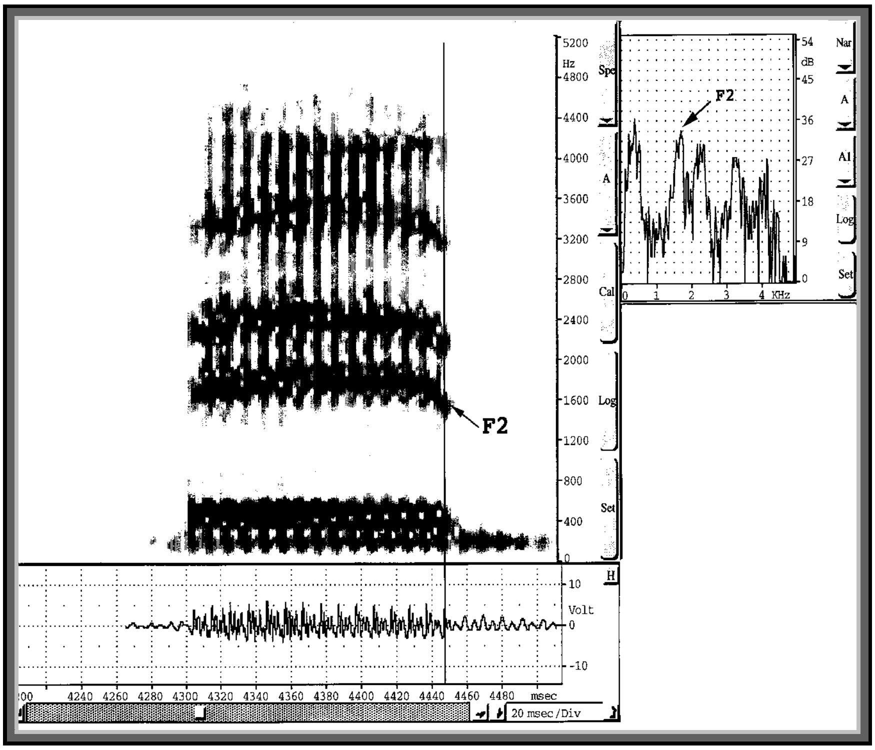


Figure 2-2. F2 offset was measured at the last pitch period of V_1 on the spectrographic display corresponding to the second spectral peak shown at the top right corner.

3. <u>F2 onset.</u> Different procedures were used to measure the F2 onset depending on the syllabic position and the voicing properties of the intervocalic stop.

In open [$C_iV_1.C_iV_2$] and geminate [$tV_1C.CV_2t$] tokens where C was a voiced stop, F2 onset was measured at the first pitch period of V_2 after the release of the intervocalic stop by positioning the cursor on the wide-band spectrographic display. F2 onset frequency values were obtained from spectrographic read-outs and checked against the frequency of the second spectral peak on the FFT window as shown in figure 2-3.

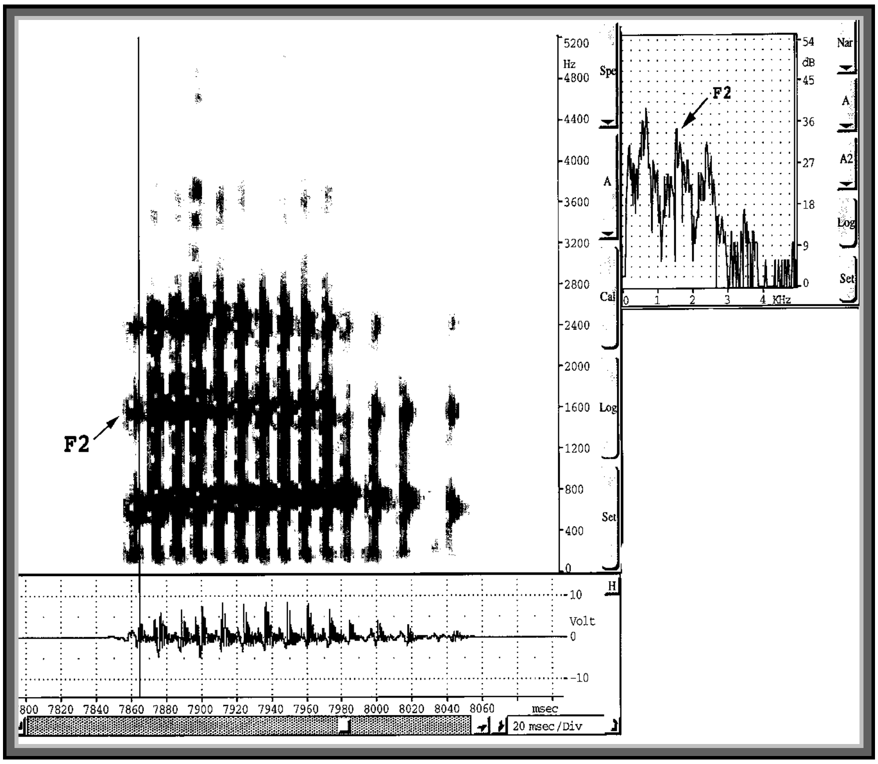


Figure 2-3. F2 onset was measured at the first pitch period of V_2 on the spectrographic display matched with the second spectral peak shown at the top right corner in open/singleton and geminate utterances.

Following Sussman and Shore (1996), in order to establish comparable measurement loci for F2 onset for voiceless aspirated stops in open/singleton and geminate utterances, V_2 second formant was traced back through the aspiration period on the spectrographic display. The earliest visible F2 resonance, after the burst release, which was judged to continue into the F2 of the vowel, was taken as

F2 onset. Spectrographic readouts of F2 onset were subsequently checked against the frequency of the second spectral peak on the corresponding narrow-band FFT window as shown in figure 2-4.

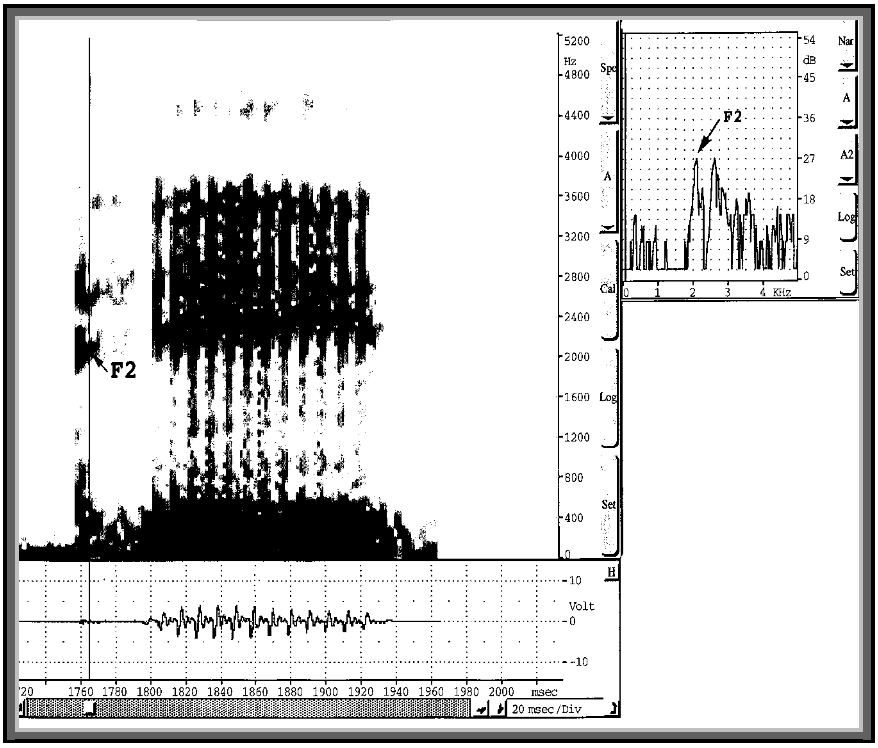


Figure 2-4. F2 onset for aspirated stops was determined by tracing F2 of the vowel through the aspiration period up to the stop release. Spectrographic measurements were checked against second spectral peak values shown at the top right corner.

Following the same reasoning, in closed syllable forms, F2 onset was measured at the release of the syllable-final stop as shown in figure 2-5, despite the fact that a period of pause intervened between the release of the stop and the following vowel. Similar procedures were used to measure F2 onset at the release of the voiced and voiceless stops in syllable-final position. In both cases, F2 onset was measured at the release of the stop by positioning the cursor on the spectrogram. Like other cases, the spectrographic values were checked against the frequency of the second spectral peak on the FFT window.

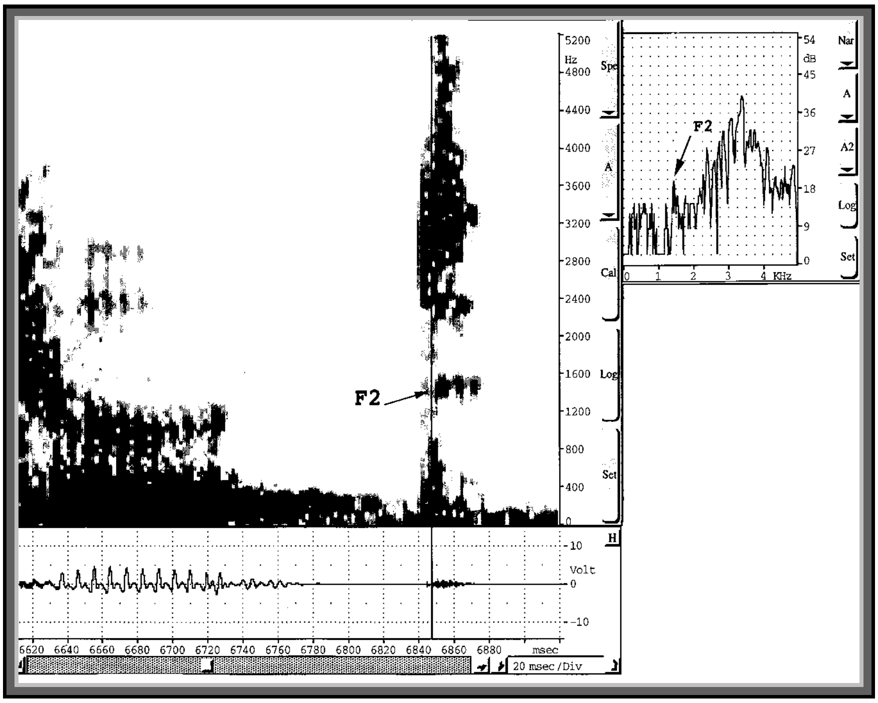


Figure 2-5. F2 onset was measured at the release of syllable final stop in closed syllable forms. Spectrographic measurements were matched with corresponding spectral F2 peaks shown at the top right corner.

2.1.4.2. Rate and Duration of F2 Transition

In the acoustic investigation of lingual troughs, rate and duration of F2 transition at the VC and CV boundaries of [ibi] and [ipi] sequences were taken as the acoustic cues to troughs. Rate of F2 transition was defined as the amount of change in F2 frequency over time (ms) and was measured using spectrographic and wave form displays.

The procedures employed to measure rate and duration of F2 transition at the VC boundary of an [ibi] sequence are shown in figure 2-6. In order to determine the extent of F2 frequency change at this boundary, a marker was placed on the last F2 steady state striation pulse of the vowel and another on the last F2 resonance before consonantal closure as observable on the spectrographic display. F2 frequency of these two points was obtained from spectrographic read-outs and their difference in frequency was calculated as the extent of F2 transition. The distance between the two markers was taken as the duration of F2 transition and was measured using the wave form. Extent of frequency change divided by the duration of transition was taken as rate of F2 transition (Hz/ms) at this boundary.

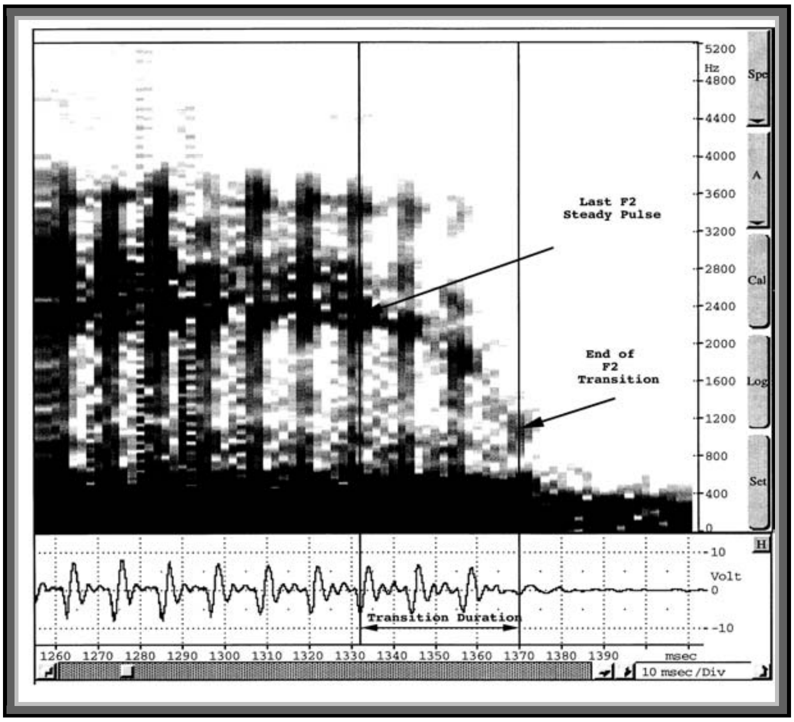


Figure 2-6. Rate of F2 transition at the VC boundary of [iCi] sequences was determined by dividing the amount of F2 frequency change at this boundary by the duration of frequency change. The duration of frequency change was measured using the waveform.

Similar procedures were used to determine rate of F2 transition at the CV boundary of [ibi] and [ipi] sequences as shown in figure 2-7. A marker was placed on the earliest F2 resonance at stop release. Another marker was placed on the first F2 steady state striation pulse of the vowel as observable on the spectrographic display. F2 frequency of these two points was obtained from spectrographic read-outs and their difference in frequency was calculated as the extent of F2 transition at the CV boundary. The distance between the two markers was taken as the duration of F2 transition and was measured using the wave form.

The extent of F2 frequency change divided by the duration of transition was taken as rate of F2 transition (Hz/ms) at the CV boundary.

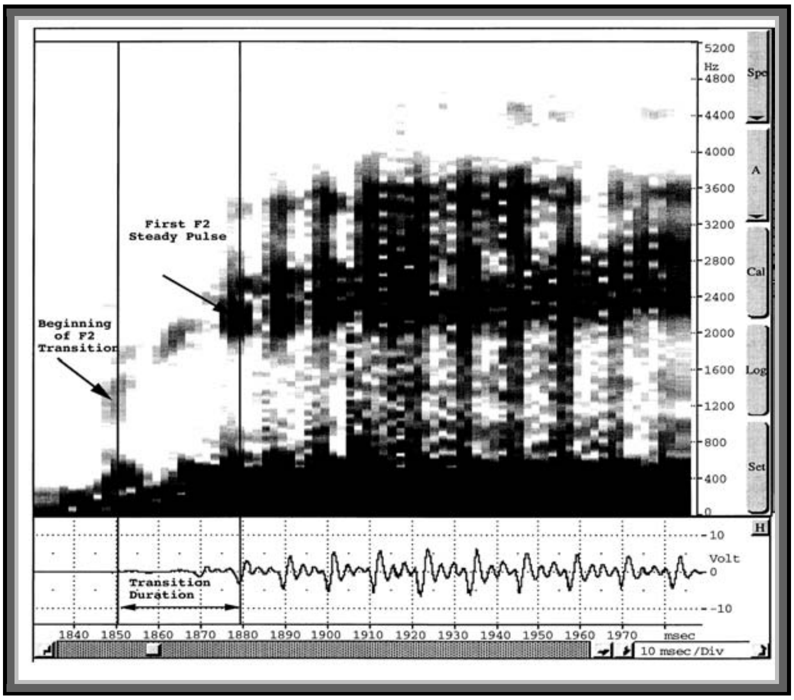


Figure 2-7. Rate of F2 transition at the CV boundary of [iCi] sequences was determined by dividing the amount of F2 frequency change at this boundary by the duration of frequency change. The duration of frequency change was measured using the waveform.

2.1.4.3. Duration Measurements

Since the effects of consonantal closure duration and VOT on troughs and on V-to-V coarticulation constituted the main focus of this study, intervocalic stop consonant closure duration and the delay time between the release of the intervocalic stop and the beginning of V_2 were measured using wave forms.

In all token types, the duration of stop closure was determined by measuring the duration of the waveform from the last pitch period of V_1 up to the release of the stop as marked by the burst transient. Figures 2-8 through 2-10 show the portion of the waveform that was measured to determine stop closure duration for all token types.

The nature of the delay time between the release of the stop and the start of V_2 was different in open/singleton and geminate forms compared to closed syllable forms. In the case of all voiced and voiceless aspirated intervocalic stops of in open/singleton and geminate forms, this delay time corresponded to voice onset time (VOT), i.e. the interval between the release of the stop consonant and the start of voicing for the following vowel as shown in figures 2-8 and 2-9.

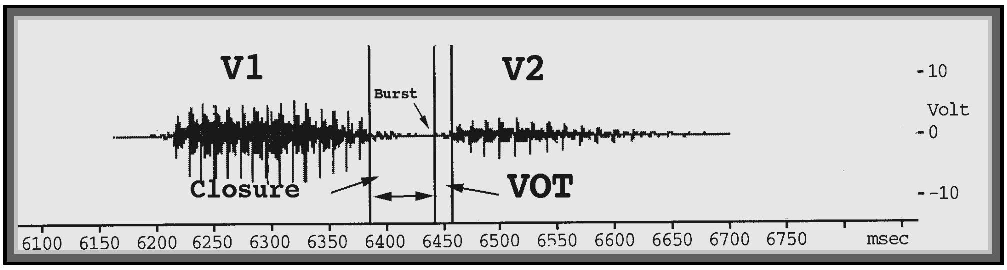


Figure 2-8. Intervocalic voiced stop closure and VOT duration as measured in open/singleton and geminate forms.

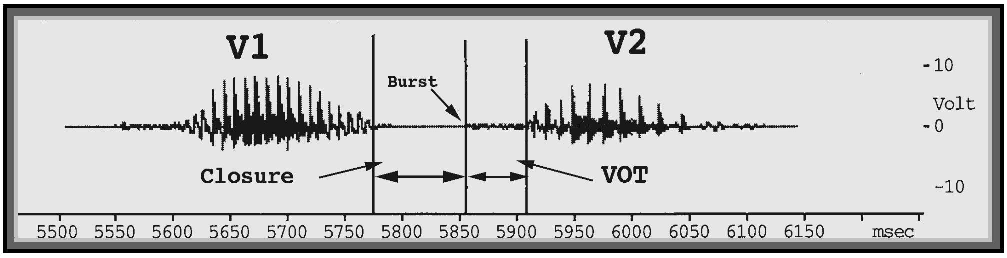


Figure 2-9. Intervocalic voiceless aspirated stop closure and VOT duration as measured in open/singleton and geminate forms.

It should be noted that, in some of the open/singleton utterances where the intervocalic consonant was voiced, voicing was present throughout the stop closure. In such cases, the gap between the release of the stop and the beginning of V_2 was taken as VOT, although voicing had been present before the stop closure. The reason was that the temporal distance between the end of V_1 and the beginning of V_2 was the main interest of this study and not the actual voice onset time.

In the case of closed syllable forms, the delay time corresponded to a period of pause between the release of the syllable-final consonant and the subsequent vowel-initial syllable as shown in figure 2-10.

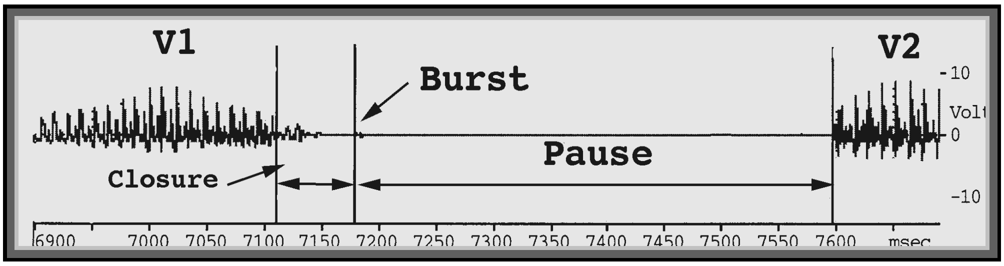


Figure 2-10. Intervocalic stop closure and pause duration as measured in closed syllable forms.

2.2. STATISTICAL TOOLS

I have employed three different statistical tools in analyzing the results obtained in the present study: Independent-Samples *t*-Test, Bivariate Regression Analysis, and Repeated-Measures ANOVA. The software program Microsoft Excel version 10.0 was used for regression analysis and Statview version 5.0 for independent samples t-test, repeated-measures ANOVA, and descriptive statistics.

2.2.1. Independent-Samples *t*-Test

Independent-samples *t*-test is used to compare the means of two independent samples to determine whether the difference between the two sample means is statistically significant. In the present study, *t*-tests were employed to determine the statistical significance of the difference between stop consonant closure duration of singleton versus geminate utterances and between the closure durations of voiced versus voiceless stops. The significance of the difference between voice onset time of voiced and voiceless aspirated stops were also determined using *t*-tests. Also, the statistical significance of changes observed in anticipatory and carry-over vowel-to-vowel coarticulation as a function of syllabification, consonantal closure duration, and voice onset time were determined by *t*-tests.

2.2.2. Bivariate Regression Analysis: Locus Equations

Troughs and the effects of syllable boundary, stop consonant closure duration, and VOT on troughs were investigated on a macro level at the CV boundary of all token types included in this study using the locus equation (LE) paradigm.

Numerous studies (Lindblom, 1963; Neary & Shammass, 1987; Krull, 1988, 1989; Sussman, 1989; Matthews, 1990; Sussman, 1991; Sussman, 1994; Sussman et al. 1991; Sussman et al. 1993; Sussman & Shore, 1996) have established that plotting onset frequencies of F2 transitions of CV sequences along the *y* axis and their corresponding mid vowel frequencies on the *x* axis results in frequency coordinates that are tightly clustered and linearly correlated and fit by a straight regression line of the form F2 onset = k * F2 vowel + c, where *k* and *c* are slope and y-intercept respectively. The frequency scatterplots thus obtained are called "locus equations" after Lindblom (1963).

Sample locus equation scatterplots are given in figures 2-11, 2-12, and 2-13 for each stop place of articulation. To generate a locus equation scatterplot, F2 onset values obtained from CV utterances where C is a fixed stop consonant are plotted against F2 vowel mid point values where V consists of all vocalic contexts. For instance, in tokens such as ‘deed, dead, dude’ F2 onset frequency of the initial /d/ in all three cases is plotted against the F2 vowel frequency of /i/, /ɛ/, and /u/. In these plots, F2 vowel is the independent variable and F2 onset is the dependent variable that varies as a function of the following vowel. A regression line is fit to the data points thus plotted and slope, y-intercept, and R^2 values of the regression equation are obtained. Detailed description of the procedures employed to derive locus equation scatterplot appear in Sussman et al. (1998).

In each plot, the regression equation and R^2 value are given in the top right-hand corner. The regression equation should be read as follows: F2 onset = k * F2 vowel + c, where *k* and *c* are slope and y-intercept respectively. Slope or the regression coefficient indicates how much change will occur in the predicted value y (F2 onset) for each 1-point change in *x* (F2 vowel). Y-intercept or regression constant determines the altitude of the regression line or the point at which the regression line crosses the *y* axis. R^2 or the coefficient of determination indicates the proportion of the total variance in *y* (i.e. F2 onset) that has been predicted by the variable *x* (i.e. F2 vowel). A R^2 value of 1.0 indicates that *x* and *y* are highly correlated and %100 of the total variance in *y* has been predicted by *x*. A R^2 value of zero indicates that *x* and *y* are not correlated and none of the variance in *y* is predicted by *x*.

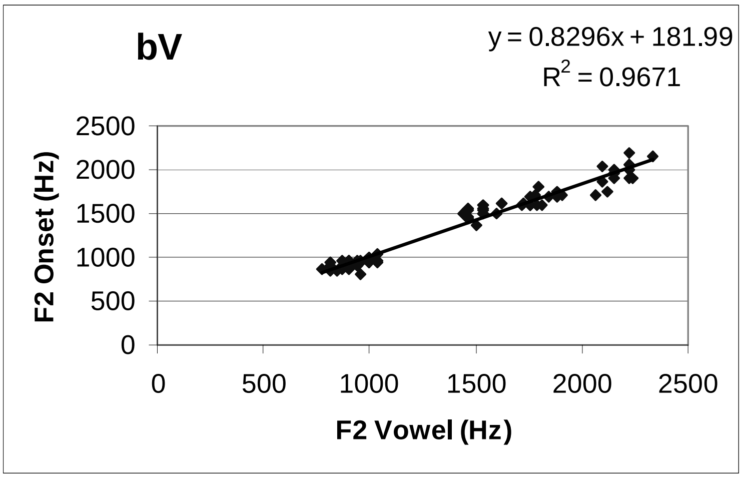


Figure 2-11. Locus equation scatter plot of [bV] combinations where V represents all vocalic contexts.

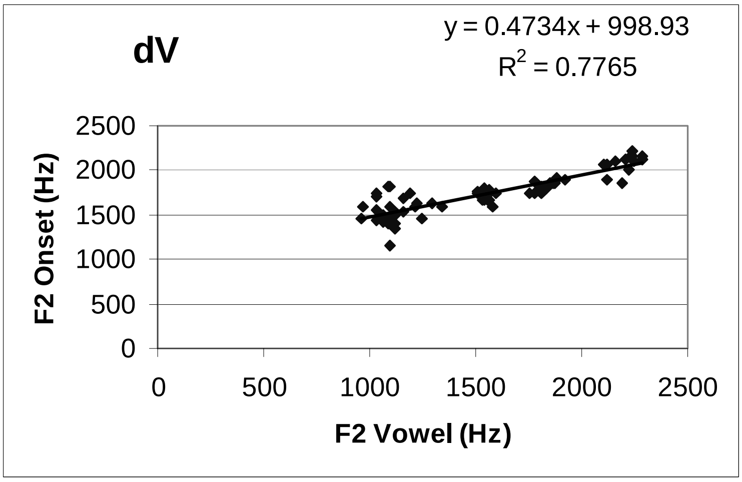


Figure 2-12. Locus equation scatterplot of [dV] combinations were V represents all vocalic contexts.

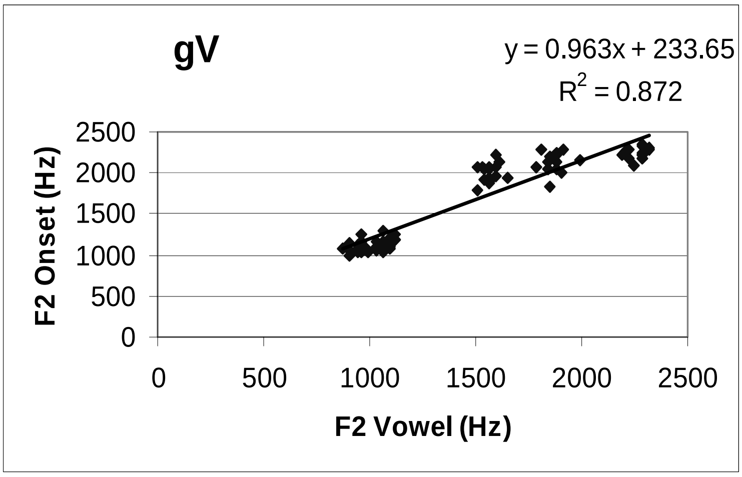


Figure 2-13. Locus equation scatterplot of [gV] sequences were V represents all vocalic contexts.

It has been suggested that the slope of locus equation regression line quantifies the extent of CV coarticulation (Krull, 1988). Figure 2-14 adopted from Krull (1988) shows extremes of CV coarticulation. The steep regression line in this figure shows cases where F2 onset frequency value is exactly the same as F2 vowel midpoint indicating maximum CV coarticulation. When F2 onset frequency value remains constant despite changes in F2 vowel frequency (1600 Hz in the example below), the regression line is completely flat, indicating the absence of CV coarticulation.

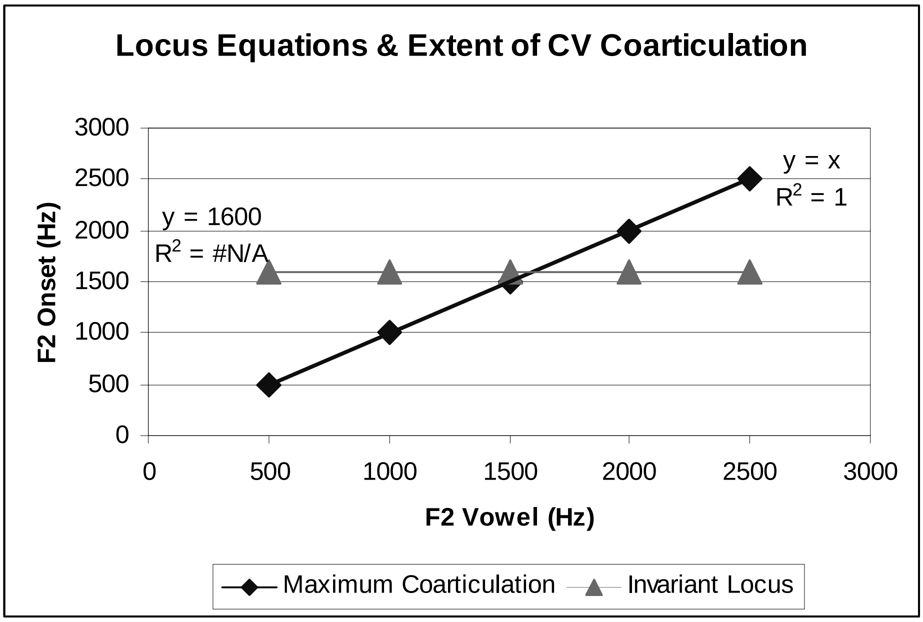


Figure 2-14. Locus equation slopes as indicators of the extent of CV coarticulation. A steep regression line indicates maximum CV coarticulation. A flat regression line indicates a lack of CV coarticulation or the existence of an invariant locus (adapted from Krull, 1988).

Besides indicating the extent of CV coarticulation, locus equation slope values are also established as 'relational invariants' capable of signaling stop place of articulation (Sussman, 1989; Sussman, 1991; Sussman et al. 1991; Sussman et al. 1993). Thus, the stability of the locus equation parameter across varying V_1 contexts and place of articulation was also investigated.

2.2.3. Repeated-Measures ANOVA

One-way analysis of variance (ANOVA) was used to determine the statistical significance of variations in locus equations slopes as a function of syllable form, consonantal closure duration, and VOT. In repeated-measures ANOVA, all the members of a sample are measured under a number of different conditions. As the sample is exposed to each condition in turn, the measurement of the dependent variable is repeated.

In the investigation of CV_2 coarticulation, two within-subject variables were considered: syllable form and manner. The ‘syllable form’ variable had three levels: open/singleton, closed, and geminate. The ‘manner’ variable had two levels: voiced unaspirated and voiceless aspirated. No between-subject variables existed in the present study. In order to investigate the stability of locus equation slopes as a function of place of articulation, the variable of ‘place’ with three levels of ‘bilabial’, ‘alveolar/dental, and ‘velar’ was also added. To summarize, the ANOVA had a 3 (syllable form)* 2 (manner)* 3 (place) design with repeated measures on the three variables. The significance level was set at .05.

Chapter 3: Stop Consonant Closure Duration and VOT

One of the purposes of this study was to determine the effects of stop consonant closure duration and VOT on troughs and on vowel-to-vowel coarticulation. For this reason, stop closure durations and VOT were measured in singleton and geminate forms. The results are presented in this chapter. In section 3.1, stop consonant closure durations in singleton versus geminate stops are given for American English and Persian speakers. In section 3.2, VOT measurements for voiced and voiceless aspirated stops produced by the two groups of speakers are presented. A summary of results appears in section 3.3.

Stop consonant closure and pause duration were also measured in closed syllable forms. Since vowel-to-vowel coarticulatory effects observed in these forms are partly explained by the duration of consonantal closure and pause, the results of these measurements are presented in chapter 6 where vowel-to-vowel coarticulation is discussed.

3.1. STOP CLOSURE DURATION

Stop closure duration was measured in singleton and geminate utterances produced by English and Persian speakers following the procedures described in section 2.1.4.3. The stop closure duration measurement results are provided in section 3.1.1 for English speakers and in section 3.1.2 for Persian speakers.

3.1.1. English

Average stop closure durations of all stop consonants in singleton and geminate tokens produced by English speakers are given in figure 3-1. The closure durations are mean values obtained from all English speakers of this study. In this figure, average closure durations of singleton and geminate stops are indicated by light and dark bars respectively. Average values represented by each bar appear next to the bars.

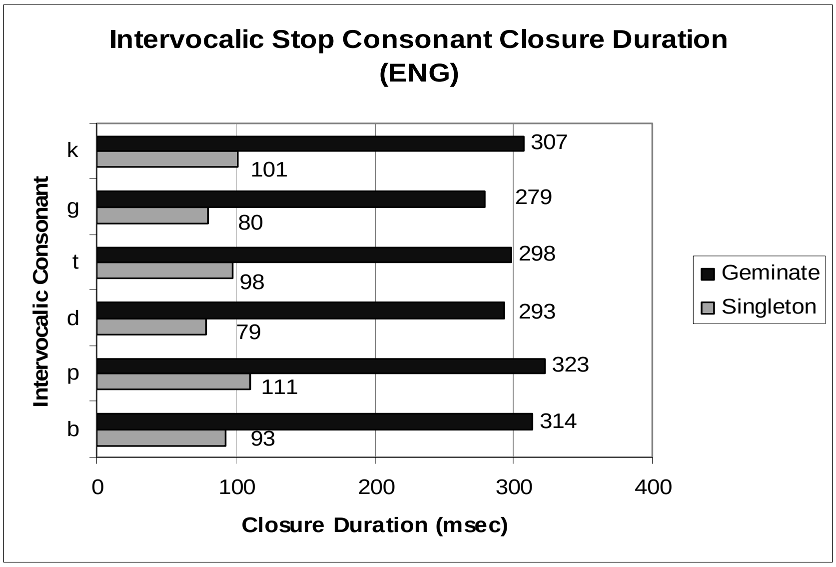


Figure 3-1. Average closure durations of singleton and geminate stop consonants of all places of articulation produced by English speakers.

On average, geminate stops of all places of articulation had closure durations three times as long as that of their singleton counterparts. The geminate/singleton closure duration ratios for each English speaker are given in table 3-1. Speakers showed variability in the geminate/singleton closure duration ratios. Three subjects produced geminate stops with closure durations that were 2.18-2.67 times longer than singleton stops. The other two subjects produced geminates with closure durations approximately four to five times longer than that of singleton stops. A paired t-test showed that the difference between closure durations of singleton and geminate stops was statistically highly significant for all places of articulation ($p<.0001$).

As the singleton/geminate ratios show, voiceless aspirated stops on average showed less increase in closure duration from singleton to geminate form compared to their voiced counterparts.

Subjects	**bb/b**	**pp/p**	**dd/d**	**tt/t**	**gg/g**	**kk/k**	**Mean**
E#1	2.33	2.09	2.80	2.73	2.08	1.87	**2.32**
E#2	5.26	3.66	6.45	4.02	7.35	4.36	**5.18**
E#3	2.39	2.26	2.45	1.95	2.02	1.99	**2.18**
E#4	4.75	4.03	4.35	4.44	4.95	4.30	**4.47**
E#5	2.58	2.91	2.97	1.96	2.76	2.86	**2.67**
Mean	**3.46**	**2.99**	**3.80**	**3.02**	**3.83**	**3.08**	**3.36**

Table 3-1. Geminate/singleton stop consonant closure duration ratios (English).

The closure durations of voiced stops were uniformly smaller than their voiceless aspirated counterparts in both singleton and geminate forms. The closures for voiceless aspirated stops were on average 19 ms and 14 ms longer than that of voiced stops in singleton and geminate forms respectively. The difference in the closure durations of voiced and voiceless aspirated singleton stops was highly significant for all places of articulation ($p<.0001$). This difference was also statistically significant for geminate voiced versus voiceless aspirated bilabial and velar stops ($p<.05$ for bilabials; $p<.0001$ for velars). The difference between the closure durations of /dd/ versus /tt/ was not statistically significant ($p=.2251$).

3.1.2. Persian

Average stop closure durations of all stop consonants in singleton and geminate tokens produced by the two Persian speakers of this investigation are given in figure 3-2. The closure durations represent mean values obtained from Persian speakers. Dark bars in this figure show closure duration of geminate stops and light bars indicate the duration of singleton stops. Average values represented by each bar appear next to the bars.

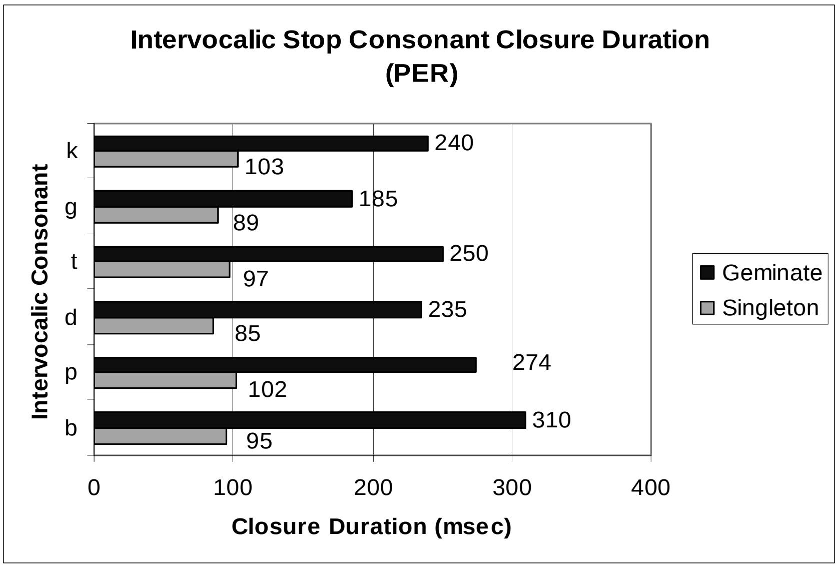


Figure 3-2. Average closure durations of singleton and geminate stop consonants of all places of articulation produced by Persian speakers.

The results in figure 3-2 show that geminate consonants of all places of articulation except for /b/ were more than two times longer than their singleton counterparts. Geminate /bb/ was more than three times longer than the singleton /b/. Table 3-2 shows the geminate/singleton stop duration ratios for all places of articulation as produced by Persian speakers. While speaker P#1 produced geminates with closure durations 1.09-2.39 times longer than singleton stops, for speaker P#2 geminate stops had closure durations 2.80-4.52 times longer than singleton stops. For speaker P#1, all voiced stops had closure durations longer than that of their voiceless aspirated counterparts. Speaker P#2 showed the same pattern with bilabials and dentals, but not with velars.

Subject	bb/b	pp/p	dd/d	tt/t	gg/g	kk/k	Mean
P#1	2.39	2.01	2.01	1.09	1.60	1.53	**1.77**
P#2	4.52	3.53	3.84	3.45	2.80	3.49	**3.61**
Mean	**3.46**	**2.77**	**2.93**	**2.27**	**2.20**	**2.51**	**2.69**

Table 3-2. Geminate/singleton stop consonant closure duration ratios (Persian).

A paired t-test showed that the difference in closure durations of singleton and geminate stops produced by Persian speakers was highly significant ($p<.0001$).

As the singleton/geminate ratios in table 3-2 show, voiceless aspirated stops on average showed less increase in closure duration from singleton to geminate form compared to their voiced counterparts. The only exception to this general pattern was observed with velar stops produced by P#2 where voiceless aspirated velars showed greater increase in closure duration from singleton to geminate form compared to their voiced counterpart.

The closure durations of voiced stops were smaller than their voiceless aspirated counterparts in both singleton and geminate forms. The only exception to this general pattern was observed with /bb/ versus /pp/, where the latter had smaller closure duration compared to the former. This effect was observed with both Persian speakers. Since tokens containing /bb/ were first in the list of tokens, this effect might have resulted from speakers' more careful and slower pronunciation of the tokens earlier in the list before a confident 'geminate' duration was achieved.

The difference in the closure durations of voiced and voiceless aspirated singleton stops was highly significant for all places of articulation ($p<.0001$). This difference was also statistically significant for geminate voiced versus voiceless aspirated stops ($p<.0001$ for bilabials and velars; $p<.05$ for dentals).

3.2. VOICE ONSET TIME

Voice Onset Time (VOT) was measured for voiced and voiceless aspirated stops in singleton and geminate utterances produced by American English and Persian speakers following the procedures described in section 2.1.4.3. VOT measurement results are provided in section 3.2.1 for English speakers and in section 3.2.2 for Persian speakers.

3.2.1. English

Average VOT values of voiced and voiceless aspirated stops produced by English speakers are given in figure 3-3. In this figure, average VOT values of voiced and voiceless aspirated singleton stops are given in the top graph and those of geminate stops are given in the bottom graph. Bilabial singleton and geminate stops are represented by the letters B and BB respectively. Alveolar singleton and geminate stops are represented by the letters D and DD respectively. Likewise, velar singleton and geminate stops are represented by the letters G and GG respectively. Dark bars show VOT durations for aspirated voiceless stops and light bars show VOT durations for voiced stops.

Averaging across singleton and geminate stops produced by English speakers, VOT of /p/, /t/, and /k/ was 3.04, 3.82, and 2.30 times longer than that of /b/, /d/, and /g/ respectively. A t-test showed that the difference between the VOT of voiced and voiceless aspirated stops in both singleton and geminate forms was highly significant ($p<.0001$).

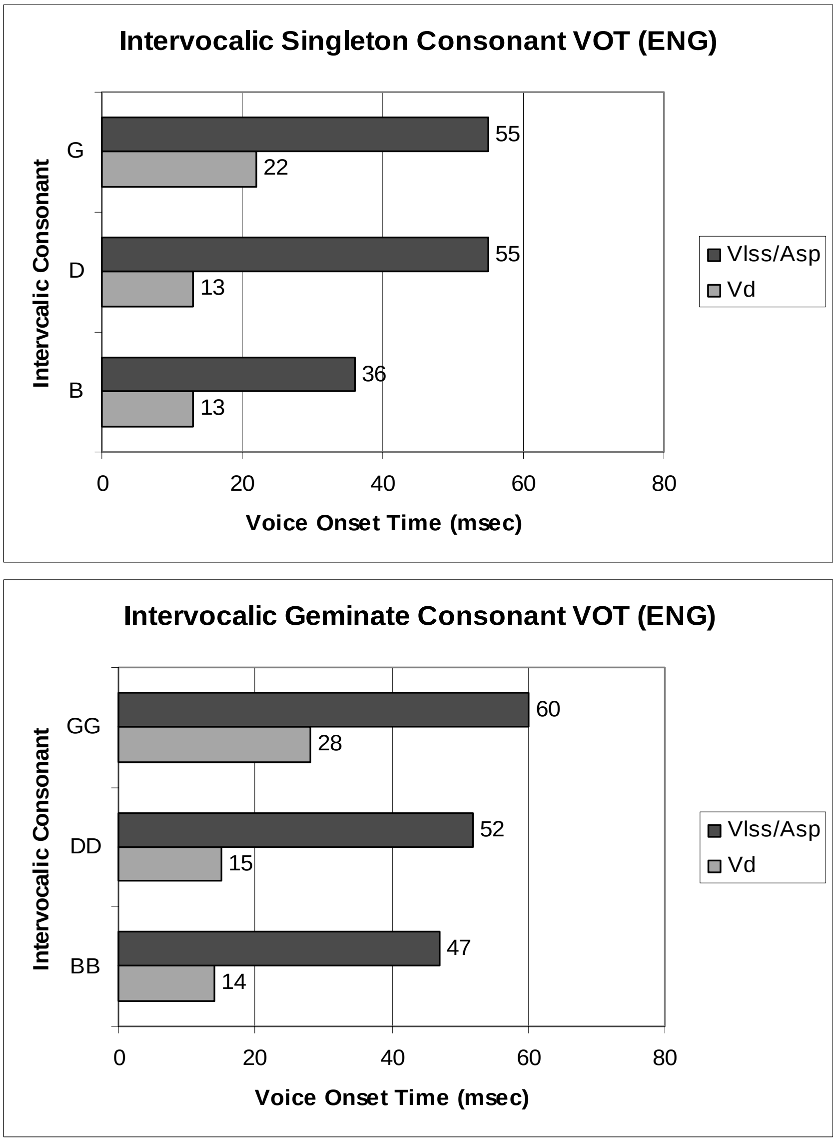
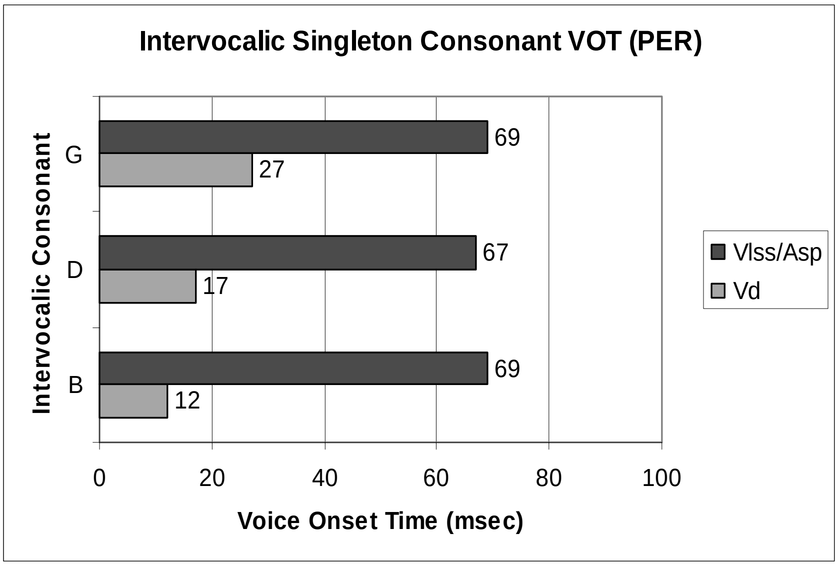


Figure 3-3. Average VOT of intervocalic singleton (top) and geminate (bottom) bilabial (B, BB), alveolar (D, DD), and velar (G, GG) stop consonants produced by five English speakers.

3.2.2. Persian

Average VOT values of voiced and voiceless aspirated stops produced by Persian speakers are given in figure 3-4. In this figure, average VOT values of voiced and voiceless aspirated singleton stops are given in the top graph and those of geminate stops are given in the bottom graph. The significance of the labels is identical with those in figure 3-3.

Averaging across singleton and geminate stops produced by Persian speakers, the VOT of /p/, /t/, and /k/ was 5.72, 4.11, and 2.47 times longer than that of /b/, /d/, and /g/ respectively. A t-test showed that the difference between the VOT of voiced and voiceless aspirated stops in both singleton and geminate forms was highly significant ($p<.0001$).



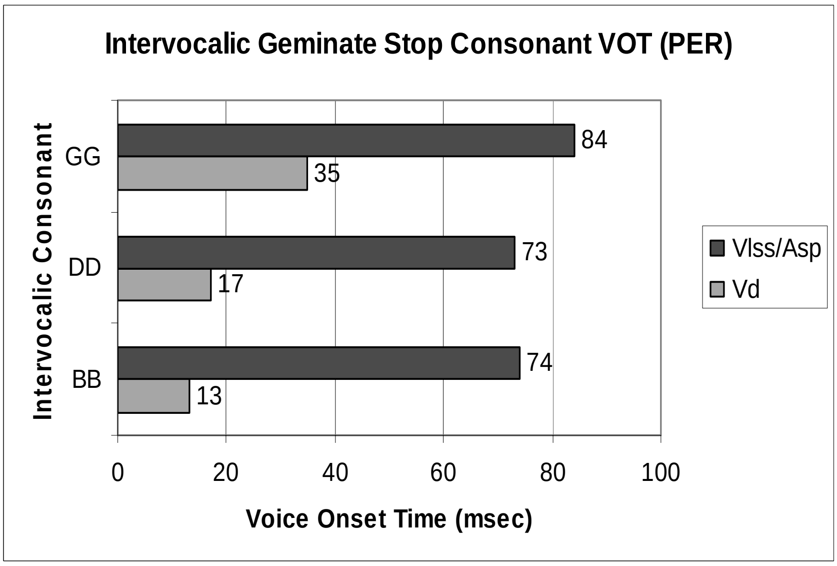


Figure 3-4. Average VOT of intervocalic singleton (top) and geminate (bottom) bilabial (B, BB), dental (D, DD), and velar (G, GG) stop consonants produced by two Persian speakers.

3.3. SUMMARY

Since the effects of consonantal closure duration and VOT on troughs and vowel-to-vowel coarticulation constitute the main focus of the present investigation, the closure duration of the intervocalic stops and their VOT were measured. The results of stop closure duration measurements indicated that the speakers of this study had successfully produced geminate[6] stops with closure durations considerably and significantly longer than that of singleton stops. In other words, the main purpose of introducing greater temporal distance between V_1 and V_2 in V_1CV_2 sequences was achieved.

The results of VOT measurements were expected as voiceless aspirated stops by definition have longer voice onset times compared to their voiced counterparts. Voiceless aspirated stops were not only different from their voiced counterparts in terms of VOT, but they were also different in terms of closure duration. The longer closure durations of voiceless aspirated versus voiced stops observed in this study were consistent with the findings of Lisker (1952; 1972), Malécot (1968), and Stathopoulos & Weismer (1983), where voiceless stops have been shown to have consistently greater closure durations than voiced stops in medial stressed position.

In the next three chapters, the effects of consonantal closure duration and VOT as well as the effects of syllable boundary on troughs and on vowel-to-

[6] It must be noted that in this study the term ‘geminate’ refers to stop consonants with closure durations significantly and relatively longer than singleton stops. This term is not used in a phonological sense.

vowel coarticulation are investigated considering the results obtained in this chapter.

Chapter 4: The Effects of Syllable Boundary, Stop Consonant Closure Duration, and VOT on Tongue Body Displacement

In this chapter, symmetrical VCV utterances are investigated acoustically to determine whether evidence of articulatory troughs appear in the acoustic signal. The results obtained in this chapter are expected to provide an answer to the main question addressed in this investigation, i.e. if the vowels in a VCV sequence are produced in a single diphthongal movement or if they are produced as separate articulatory events.

This discussion begins with an overview of the articulatory properties of troughs in section 4.1. The acoustic attributes of troughs and the effects of syllable boundary, stop closure duration, and voice onset time on these attributes are discussed in section 4.2. Discussions and conclusions appear in section 4.3.

4.1. ARTICULATORY CHARACTERISTICS OF TROUGHS

In chapter 1, an overview of the studies that have documented ‘troughs’ was presented. A trough has been described as an “apparent discontinuity in anticipatory coarticulation” (Perkell, 1986). This term refers to actual tongue body or lip displacement from the position required for the production of identical vowels in a symmetrical VCV sequence during the production of the intervocalic consonant. This term also refers to discontinuities in the activity of the underlying muscular control of the articulator involved in the production of the vowels during consonantal production. In this study, 'trough' is specifically used to refer to tongue body displacement during the production of an intervocalic stop.

Troughs have been mainly observed during the closure period of bilabial stops in VCV sequences where different articulators are involved in the production of the vowels and the consonant. The question to be addressed here is "where does the tongue go during the bilabial stop production?" In a Principal Components analysis on x-ray data from a Swedish speaker, Lindblom and Sussman (2002) showed that the tongue body contour of the vowels [i, u, a] changes in the direction of a neutral shape during the bilabial closure in symmetrical VCV sequences. This neutral shape was not fixed, but varied with the vocalic context. For example, in a sequence such as [i:bi:p^{h}i:l] the vertical component of the tongue contour was slightly lower and the horizontal component was slightly more retracted during bilabial closure than during the production of the vowels. In [a:ba:p^{h}a:l], the vertical component of tongue body contour was lower and the horizontal component was slightly more forward during the bilabial closure than during the production of the vowels. In both cases, the vertical component of the tongue contour was relatively lower during bilabial closure than during the production of the vowels. In both cases, the horizontal component showed a tendency towards a more central position.

The neutral position for the tongue is usually assumed to be the position it takes during the production of a schwa. Considering that schwa is a "targetless" vowel completely assimilated to its vocalic context (Fowler, 1981a; Alfonso & Baer, 1982; Browman & Goldstein, 1992; Van Bergem, 1994), it can be concluded that the relatively lower and more central position of the tongue in the context of [i] and the relatively lower and more central position of the tongue in the context of [a] are the neutral positions of the tongue in those contexts. To summarize, the tongue body appears to move to a neutral position during the stop closure period, but this neutral position is context dependent.

Lingual troughs are subtle events. In the pioneering study of Houde (1967) previously described in section 1.4.1, the largest degree of tongue lowering occurred during the closure of the first [b] in [íbibi] sequences (see figure 1-4). Using the scales provided in the figure, the calculated time for the tongue to reach its lowest point during the closure for [b] was 70.56 milliseconds. During this time period, the tongue was calculated to have lowered 1.94 mm. It took an additional 88.2 ms for the tongue to resume its high position for the production of the second [i]. In total, the calculated time from the beginning of tongue deactivation to its return to V_2 position was 158.76 ms.

In the x-ray study of tongue body movement in Lindblom & Sussman (2002) and Lindblom et al. (2002), the amount of tongue lowering in the [i:bi:p^hi:l] utterance was approximately 3 mm during [b] and 4mm during [p^h] closure (see figure 1-7). Using the time scale provided in figure 1-7, the total calculated time from the beginning of tongue deactivation to its return to V_2 position was approximately 200 ms when the intervocalic consonant was [b] and 260 ms when it was [p^h]. Thus, although it took the tongue body a relatively long time to relax from its position for V_1 and resume it again for V_2, the amount of absolute tongue lowering during bilabial closure was minimal in both studies. The subtlety of troughs is one of the factors that make it difficult to detect their effects on the acoustic signal. The second factor is that troughs occur during the closure of intervocalic stops which is characterized by silence in the acoustic signal. For example, in Houde's (1967) study shown in figure 1-4, maximum tongue lowering (trough) occurred during bilabial stop closure. Likewise, in the time series plots in figure 1-7, maximum tongue displacement occurred during bilabial stop closure, except in one case where maximum trough occurred at V_2C_2 boundary in the [a:ba:p^{h}a:ɹ] sequence.

Although maximum tongue body displacement occurs during intervocalic stop consonant closure, tongue body displacement generally starts before the closure and its recovery from maximum displacement generally continues after the closure is removed. For instance, the cineradiographic records of tongue movement in symmetrical and nonsymmetrical VCVCV sequences in figure 1-4 showed that tongue lowering started before both bilabial closures in [ububu] and [ibubi] sequences. Tongue elevation for post-consonantal vowels started either during consonantal closure or shortly after the closure was removed. Likewise, tongue body deactivation started before [p^h] closure in [a:ba:p^{h}a:ɹ] and [i:bi:p^{h}i:l] sequences in figure 1-7. In the EMG records shown in figure 1-6, genioglossus muscle deactivation started before consonantal closure. Figure 1-10 also shows that the number of EPG contact points started to decrease immediately after maximum tongue contact for the vowel [i] was made and began to increase at the release of [p^h] closure in all languages that showed evidence of troughs.

To summarize, lingual troughs last relatively long, but are, nevertheless, subtle articulatory events that mainly occur during intervocalic stop consonant closure in symmetrical VCV utterances. Tongue body displacement from the position required for the two vowels in such sequences can start during the production of the first vowel. Tongue body recovery from maximum displacement can continue after the consonantal closure is removed.

4.2. ACOUSTIC CORRELATES OF TROUGHS

It is not possible to investigate troughs acoustically during stop consonant closure as this period is marked by silence in the acoustic signal. Nevertheless, considering that tongue body displacement can start during V_1 production, it is theoretically possible to observe its effects in V_1C formant transitions. Likewise, since the tongue may still be recovering from its neutral position and on its way to the target position for V_2 after consonantal closure is removed, the effects of tongue movement towards its target are expected to be observable in CV_2 formant transitions as well.

In VCV sequences, vowel formants change in frequency at consonantal boundaries. Changes in formant frequencies reflect the effects of different articulators as they move from one position to the next. When the two vowels are identical, changes in vowel formant frequencies at the consonantal boundaries can be the result of different movement patterns depending on whether the tongue body remains in position for the production of the two vowels or goes through a deactivation-reactivation[7] phase. For example, in a [ibi] sequence, where the articulator involved in the production of the vowels is different from the articulator involved in the production of the consonant, changes in the formant frequencies of the vowels at the consonantal boundaries can reflect two different movement patterns. If the tongue body remains in the high front position required for the production of [i] all throughout the utterance, changes in the formant frequencies of the vowel at VC and CV boundaries will be due to lip closure and lip opening only. On the other hand, if the tongue body starts to relax from its high front position as the lips start to make a labial closure, then changes in the formant frequencies of the vowel at the VC boundary will be due to lip as well as tongue body movement. Likewise, as the tongue starts to resume its position for the second vowel at the opening of the lips, changes in the formant frequencies at the CV boundary will be due to lip as well as tongue body movement.

Thus, the main task in the acoustic investigation of troughs is to determine whether the formant transitions at VC and CV boundaries reflect the movement of the lips only or those of the lips and the tongue body. In this study, the acoustic consequences of lip versus lip and tongue body movement on the second formant (F2) transitions are discussed for symmetrical V_1CV_2 sequences, where the consonant was a bilabial stop. The reason for restricting the consonantal context to bilabial stops is that these consonants do not involve the tongue body in their production and provide the optimal context for a diphthongal vowel-to-vowel movement to occur. The vocalic context is also limited to two extreme cases, i.e.

[7] In this study, deactivation and reactivation are used to refer to tongue body relaxation from a vocalic configuration during stop consonant closure and the resumption of the same configuration shortly afterwards.

the high front vowel [i] and the mid back vowel [ɔ] for English and low back vowel [ɒ] for Persian speakers. The acoustic consequences of lip versus lip and tongue body movement for symmetrical [iCi] utterances are discussed in section 4.2.1. The acoustic consequences of lip versus tongue body movement for [ɔCɔ] and [ɒCɒ] sequences are discussed in section 4.2.2.

4.2.1. The Acoustic Correlates of Troughs in [iCi] Utterances

In order to determine whether changes in second formant frequencies at the VC and CV boundaries of [iCi] utterances of this study were due to lip movement only or to lip and tongue body movement, it is necessary to know the properties and the significance of F2 for the vowel [i]. When the tongue body is in a high and fronted position as required for the production of the vowel [i], the vocal tract resonances are similar to the resonances of a two-tube model as shown in figure 4-1. The vocal tract is divided into two tubes or cavities when the vowel [i] is being produced: a front cavity and a back cavity. Each one of these two cavities has its own resonances. The lowest resonance of a back cavity with the length of 8 cm is 2188 Hz which is the second formant of [i]. This resonance is unaffected by changes such as lip closure/opening in the front cavity. The lowest resonance of a front cavity with the length of 6 cm is 2917 Hz, which is the third formant of [i]. This resonance is affected by lip closing/opening. When the tongue is in position for [i] and the lips close for a bilabial stop, the front cavity which had the resonances of a tube open at both ends for the production of [i], will have the resonances of a tube open at one end and closed at the other. The lowest resonance of this tube will be 1459 Hz. Thus, this resonance will be F2 and the resonance of the back cavity will be F3 at the lip closure and at lip opening (Stevens, 1998: 342). To summarize, although F2 is a back cavity resonance for [i], it becomes a front cavity resonance at labial closure/opening due to changes in the resonance properties of the front cavity. Thus, mere closing and opening of the lips results in a sharp decrease in F2 frequency of [i] at the VC boundary and a sharp increase in F2 frequency at the CV boundary.

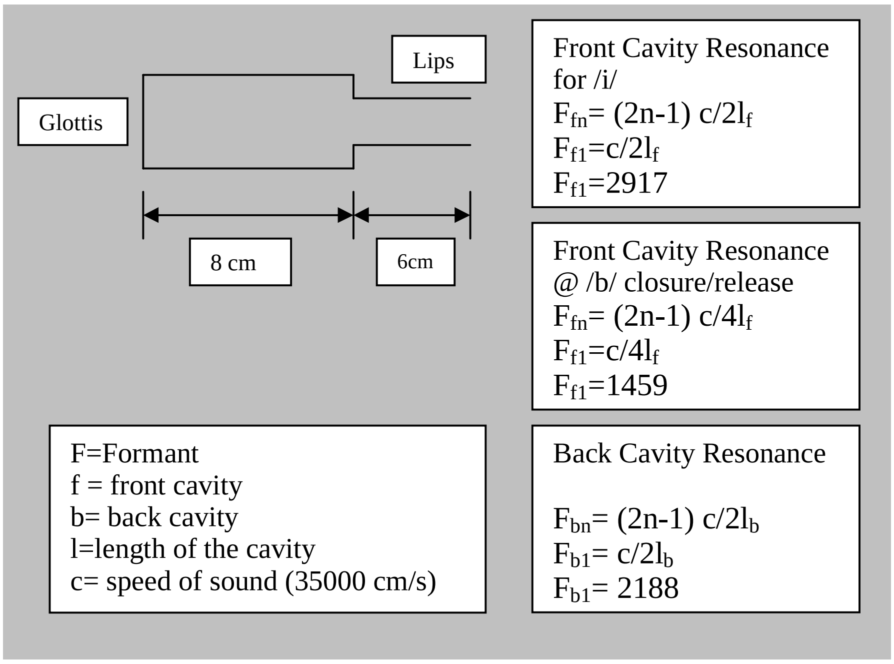


Figure 4-1. A two-tube resonator modeling vocal tract configuration for [i]. The lowest resonance of the back and front cavities are calculated. The lowest resonance of the front cavity when the lips are closed is also calculated.

Assuming the tongue body to be in position for the vowel [i] at the release of a bilabial closure, Stevens (1998: 341) calculated formant frequency changes as shown in figure 4-2 below. As this figure shows, F2 increases extensively within a short period of time after the release of the intervocalic bilabial stop. The fast and extensive increase in F2 frequency is due to the rapid increase in the labial cross-sectional area in the magnitude of 100 cm^2/s.

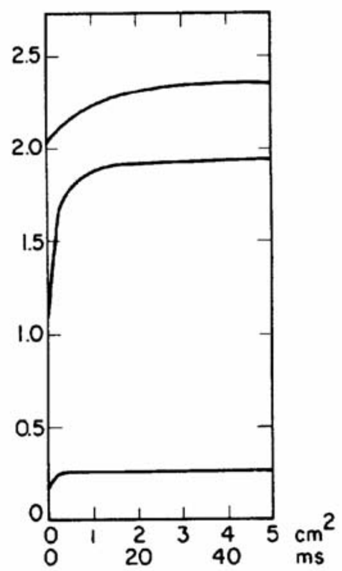


Figure 4-2. Formant frequency changes as the lips open to a vocal tract configuration for the vowel [i] (Stevens, 1998:341).

The same pattern was observed by Lindblom et al. (2002) when a [bi] sequence was simulated using the APEX articulatory model[8]. APEX simulation of a [bi] sequence is shown on the left graph in figure 4-3. This simulation was also based on assuming a 100cm^2/s increase in labial cross-sectional area at the release of [b] closure. Using APEX, formant transitions were also simulated for a [bi] sequence where the tongue body was not in position for the vowel [i] at the release of [b], but was in a neutral position (i.e. the vocal tract configuration for a schwa). The rate of increase in the labial cross-sectional area was again taken to be 100cm^2/s at the release of [b] closure. These formant transitions are shown in the right graph in figure 4-3. As this graph shows, formant movements were less abrupt and lasted longer compared to when the tongue is in position for [i] at the release of a bilabial closure. The extent of F2 transition is basically the same in both cases. The difference is in the time it takes for the transitions to be completed. The fast formant transitions end within 10 ms after the release of the bilabial stop. On the other hand, slower formant transitions last more than 20 ms.

[8] The APEX articulatory model was developed as a joint project at the Department of Linguistics at Stockholm University and Department of Speech, Music, and Hearing at the Royal Institute of Technology, Sweden.

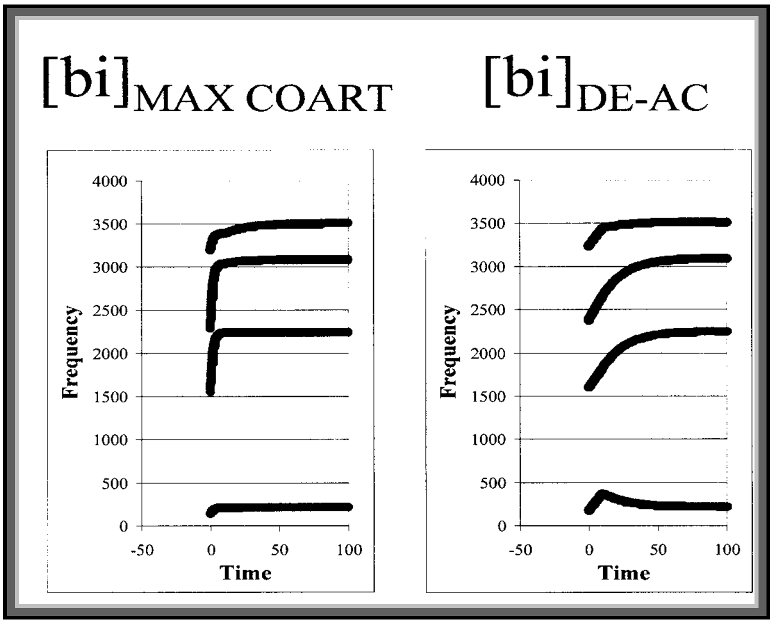


Figure 4-3. Apex-simulated formant transitions for [bi] when the tongue body is in position for [i] at the release of [b] (left) compared to when the tongue body is in position for a schwa at the release of [b] (right) (Lindblom, et al. 2002).

In the first 5 to 10 milliseconds after the release of an initial bilabial closure rapid changes in formant frequencies are largely due to changes in lip opening only. Nevertheless, after this first stage, the movement of the lips is relatively slow and changes in formant frequencies are principally due to concurrent changes in other parts of the vocal tract (Fujimura, 1961).

Thus, taking F2 transition at the V_1C boundary to be the mirror image of the F2 transition at the CV_2 boundary, fast F2 transitions that occur within 5-10 milliseconds are due to lip movement only as the tongue body remains in position for the vowel [i]. In other words, in the acoustic signal, fast F2 transitions from and into [i] reflect articulatory plateaus or maintained tongue body position throughout symmetrical VCV sequences. On the other hand, relatively slow F2 transitions that last longer than 10 milliseconds are due to lip as well as tongue body movement as the tongue body displaces from the position for the vowel [i] and resumes it again. In other words, in the acoustic signal slower F2 transitions from and into [i] are assumed to reflect articulatory troughs.

To summarize, two factors have to be considered in determining whether troughs or plateaus occur during the production of [iCi] utterances: (a) duration of F2 transition and (b) rate of F2 transition. Rate and duration of F2 transition of [i] into and from a bilabial closure are discussed in section 4.2.1.1.

4.2.1.1. Rate and Duration of F2 Transition

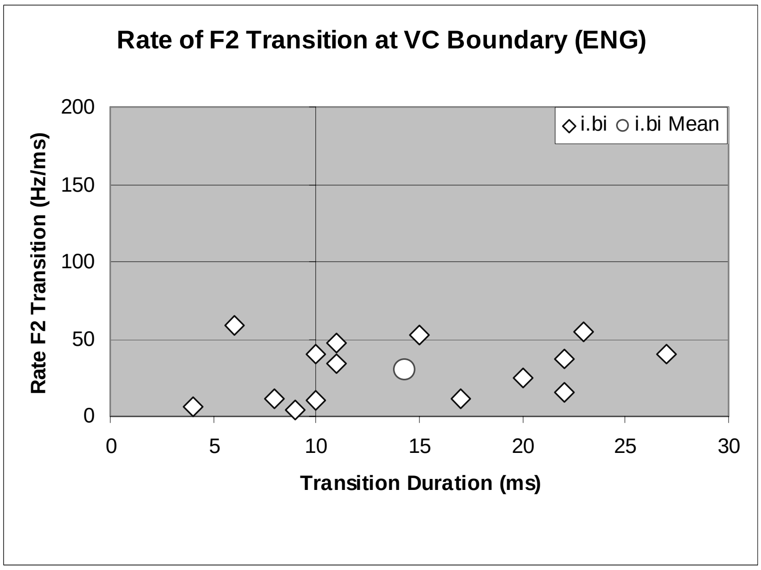
Rate of F2 transition was defined as the amount of change in vowel second formant frequency at VC and CV boundaries over time (ms). The procedures for measuring rate of F2 transition were described in section 2.1.4.2. In short, rate of transition was determined by measuring the amount or extent of F2 frequency change at VC and CV boundaries and then dividing the extent of F2 transition by the duration of F2 transition at each boundary.

Symmetrical [i.Ci] utterances where the intervocalic consonant was either a voiced or a voiceless aspirated bilabial stop were investigated. The total number of tokens investigated were 30 (1V*2C*5SUB*3REP) for English speakers and 12 for Persian speakers (1V*2C*2SUB*3REP). In some utterances no transitions were present at VC or CV boundaries. Thus no results are reported for these cases.

Rate and duration of F2 transition at the VC and CV boundaries of [i.bi] utterances produced by English speakers are given in table 4-1 and shown in figure 4-4. In this figure and other figures in this section, rate of F2 transition is plotted on the *y* axis and duration of F2 transition on the *x* axis. Each individual data point is represented by a diamond. Average values of all the data points are also plotted and represented by circles. The critical line of 10 milliseconds is marked in the scatterplots.

In the discussion of the results average duration and rate of F2 transition are taken into consideration. However, since considerable variability was observed between the speakers, duration and rate of F2 transition values for individual utterances produced by English and Persian speakers are also given in tables and discussed when necessary. Each table includes duration and rate of F2 transition at the VC and CV boundaries of the intended tokens. In each table, blank boxes indicate cases where no F2 transitions were observed at the relevant boundary. F2 transitions that lasted more than 10 ms and thus showed evidence of troughs are shaded in the tables. Transitions that lasted between 11-14 ms are shaded in a lighter color, suggesting that the results represented by the relevant tokens must be interpreted in conjunction with information on the rate of F2 transition.

As figure 4-4 shows, two very different transition patterns were observed at the VC and the CV boundaries of [i.bi] utterances produced by English speakers. While at the VC boundary rate of F2 transition showed relatively small variation (sd = 19 Hz/ms), considerable amount of variation was seen in the duration of F2 transition (sd = 7 ms). At the CV boundary, on the other hand, less variation was seen in the duration of F2 transition (sd = 3 ms), while rate of F2 transition varied considerably (sd =56 Hz/ms). On average, F2 transition of [i] into the closure for [b] at the VC boundary lasted 14 ms. Considering that rate of F2 transition was on average 30 Hz/ms and relatively slow, it can be concluded that changes at the VC boundary of [i.bi] utterances were due to tongue body as well as lip movement at this boundary. F2 transitions from the [b] release to [i] lasted 10 ms. Considering that rate of F2 transition was on average 73 Hz/ms and relatively fast, it can be concluded that changes at the CV boundary of [i.bi] utterances were mainly due to lip movement only.



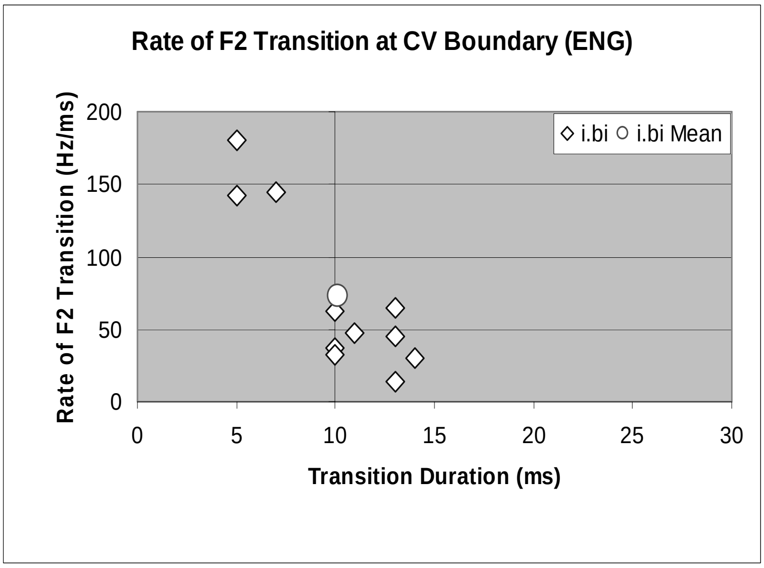


Figure 4-4. Duration and rate of F2 transition at the VC (top) and CV (bottom) boundaries of [i.bi] utterances produced by English speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds show actual data points. Circles show average values of individual data points.

	Duration (ms) & Rate (Hz/ms) of F2 Transition				
Speaker	**ib (n=15)**			**bi (n=11)**	
	ms	*Hz/ms*		*ms*	*Hz/ms*
E#1	17	12		5	143
	23	54		13	64
	22	37		-	-
E#2	20	25		13	14
	22	16		13	45
	27	40		-	-
E#3	11	34		-	-
	11	48		5	180
	6	58		7	145
E#4	10	40		10	63
	4	6		10	38
	10	10		11	48
E#5	15	53		14	30
	8	11		-	-
	9	4		10	33
M	**14**	**30**		**10**	**73**
SD	**7**	**19**		**3**	**56**

Table 4-1. Duration and rate of F2 transition at the VC and CV boundaries of [i.bi] utterances produced by English speakers.

Rate and duration of F2 transition at the VC and CV boundaries of [i.p^{h}i] utterances produced by English speakers are given in table 4-2 and shown in figure 4-5. Again, two very different transition patterns were observed at the VC and the CV boundaries of these utterances. In the VC boundary, rate of F2 transition showed relatively small variability (sd = 17 Hz/ms). Duration of F2 transition also showed little variation (sd = 3 ms). At the CV boundary, on the other hand, duration of F2 transition showed more variability (sd = 7ms) as did rate of F2 transition (sd = 34 Hz/ms). On average, F2 transition at the VC boundary lasted 10 ms. F2 transition at the CV boundary lasted 14 ms. Rate of F2 transition remained relatively slow at both boundaries. These results indicate that lip movement only was responsible for changes in F2 frequency at the VC boundary of the [i.p^{h}i] utterances produced by English speakers. On the other hand, tongue body as well as lip movement were responsible for changes in F2 frequency at the CV boundary of these utterances.

These results indicate that the voicing properties of the intervocalic consonant have an effect on the duration and rate of F2 transition at the VC and CV boundaries of [V.CV] utterances. Tongue body movement effects were observed at the VC, but not at the CV boundary of [i.bi] utterances. Conversely, tongue body movement effects were observed at the CV, but not at the VC boundary of [i.p^{h}i] utterances.

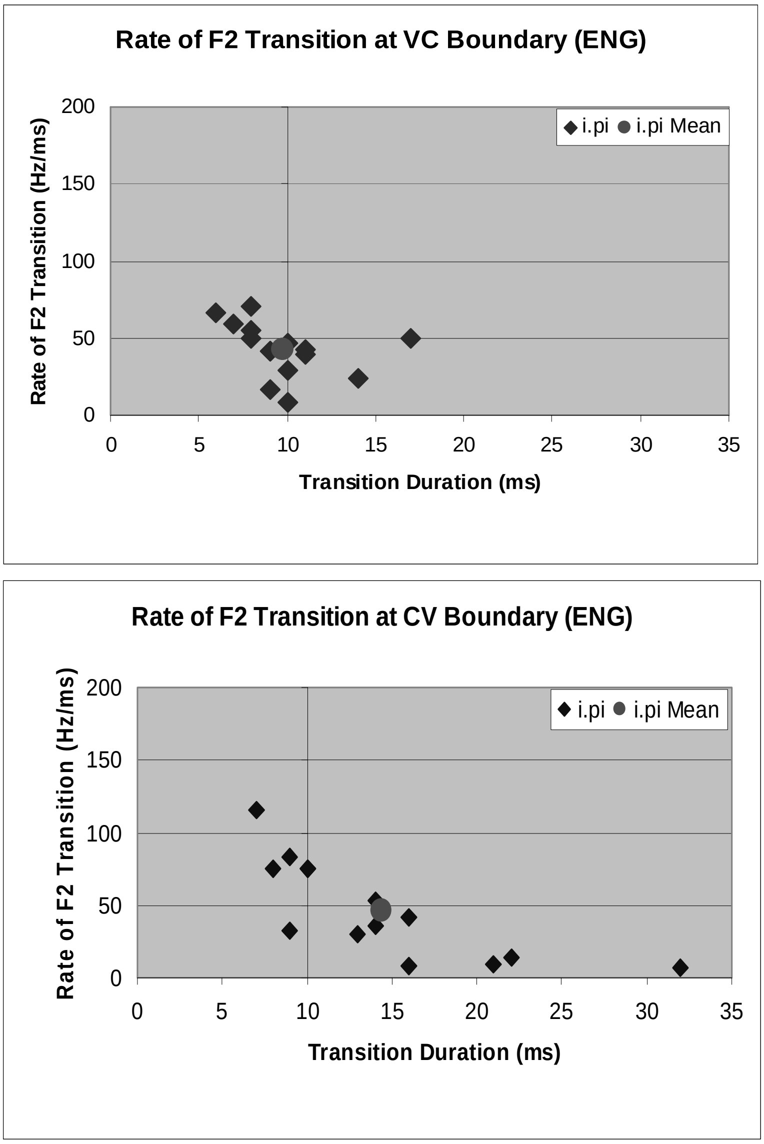


Figure 4-5. Duration and rate of F2 transition at the VC (top) and CV (bottom) boundaries of [i.p^{h}i] utterances produced by English speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds show actual data points. Circles show average values of individual data points.

	Duration (ms) & Rate (Hz/ms) of F2 Transition				
Speaker	**ip (n=15)**			**pi (n=14)**	
	ms	*Hz/ms*		*ms*	*Hz/ms*
E#1	17	49		14	54
	8	55		9	83
	6	67		8	75
E#2	10	46		16	41
	11	40		10	75
	14	24		22	14
E#3	9	42		13	30
	11	42		10	75
	7	59		7	116
E#4	9	42		32	7
	8	70		14	36
	9	17		16	8
E#5	10	9		21	10
	10	29		-	-
	8	50		9	32
M	**10**	**43**		**14**	**47**
SD	**3**	**17**		**7**	**34**

Table 4-2. Duration and Rate of F2 transition at the VC and CV boundaries of [i.p^{h}i] utterances produced by English speakers.

Rate and duration of F2 transition at the VC and CV boundaries of [i.bi] utterances produced by Persian speakers are given in table 4-3 and shown in figure 4-6. At the VC boundary of these tokens, duration of F2 transition showed considerable variability (sd = 9 ms), while rate of F2 transition showed relatively small variation (sd = 22 Hz/ms). At the CV boundary, on the other hand, duration of F2 transition showed little variation (sd =5 ms), while rate of F2 transition showed considerable amount of variation (sd = 62 Hz/ms). On average, F2 transition at the VC boundary lasted 14 ms. Considering that rate of F2 transition was on average 34 Hz/ms and relatively slow, it can be concluded that changes at the VC boundary of [i.bi] utterances were due to tongue body as well as lip movement at this boundary. On average, F2 transition lasted 10 ms at the CV boundary. Considering that rate of F2 transition was on average 93 Hz/ms and relatively fast, it can be concluded that changes at the CV boundary of [i.bi] utterances produced by Persian speakers were due to lip movement only. These results were similar to those obtained from English speakers.

The inter-speaker differences have to be taken into account in interpreting the data obtained from Persian speakers. In both VC and CV boundaries of the [i.bi] utterances produced by the Persian speakers, speaker P#2 showed transitions that lasted more than 10 ms. Speaker P#1, on the other hand, showed F2 transitions that lasted less than 10 ms at both boundaries. Thus, while the data from speaker P#2 suggests tongue body movement at both boundaries in [i.bi] utterances, the data from speaker P#1 suggests no tongue body movement. Although the average duration of F2 transition at the CV boundary of [i.bi] utterances is less than 10 ms and despite the fact that the transition durations of the utterances produced by speaker P#2 were close to 10 ms and had to be interpreted with caution, the relatively slow rate of transition associated with these utterances suggests the possibility of tongue body movement at the CV boundary of the [i.bi] utterances produced by this speaker.

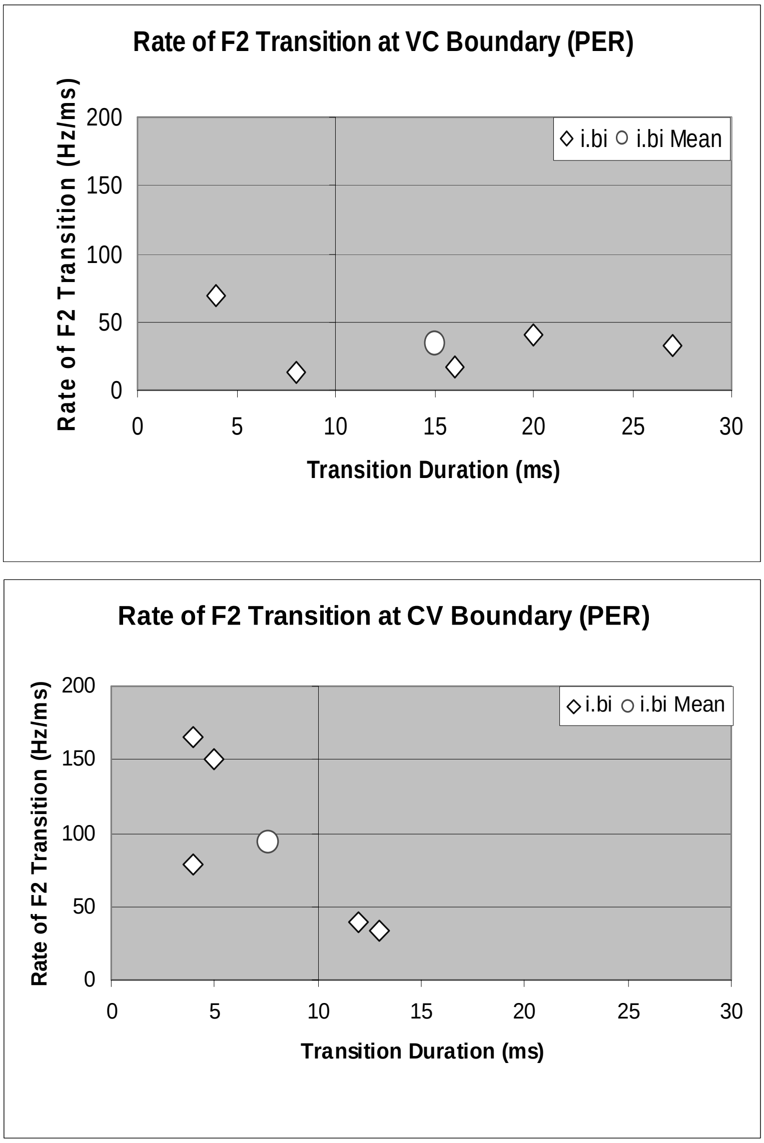


Figure 4-6. Duration and rate of F2 transition at the VC (top) and CV (bottom) boundaries of [i.bi] utterances produced by Persian speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds show actual data points. Circles show average values of individual data points.

	Duration (ms) & Rate (Hz/ms) of F2 Transition				
Speaker	**ib (n=5)**			**bi (n=5)**	
	ms	*Hz/ms*		*ms*	*Hz/ms*
P#1	8	13		4	166
	-	-		5	150
	4	69		4	78
P#2	16	17		13	34
	27	32		12	40
	20	41		-	-
M	**15**	**34**		**8**	**93**
SD	**9**	**22**		**5**	**62**

Table 4-3. Duration and rate of F2 transition at the VC and CV boundaries of [i.bi] utterances produced by Persian speakers.

Rate and duration of F2 transition at the VC and CV boundaries of [i.p^{h}i] utterances produced by Persian speakers are given in table 4-4 and shown in figure 4-7. Speaker P#1 did not show any transitions at the VC boundary of [i.p^{h}i] utterances. Speaker P#2 did not show any transitions at the CV boundary of these utterances. Thus, the top graph of figure 4-4 shows duration and rate of F2 transition at the VC boundary of the [i.p^{h}i] utterances produced by speaker P#2. The bottom graph in this figure shows duration and rate of F2 transition at the CV boundary of these utterances as produced by speaker P#1. The shorter transition durations and faster rates of transition observed with speaker P#1 indicated lip movement effects only. If the absence of transitions at the CV boundary of the [i.p^{h}i] utterances produced by speaker P#2 is taken to indicate no tongue body movement at this boundary, the results obtained from this speaker indicates tongue body movement at the VC boundary, but not at the CV boundary of [i.p^hi] sequences. This pattern was the reverse of what was in general observed with English speakers.

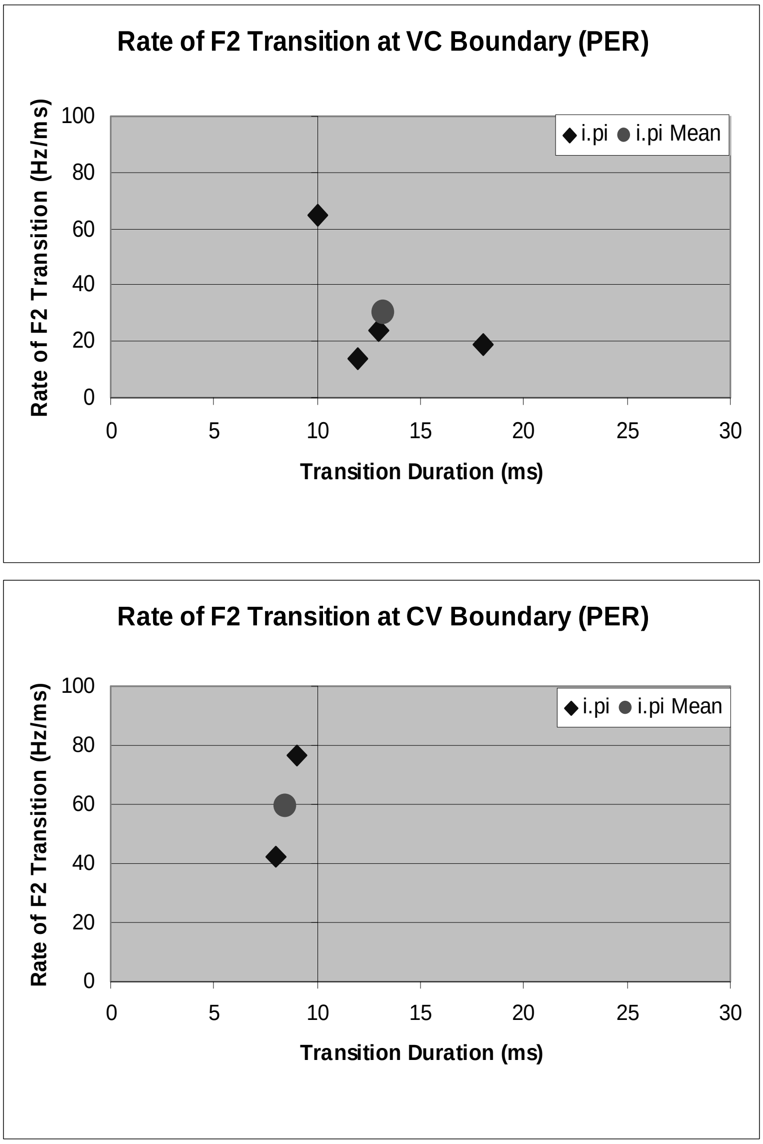


Figure 4-7. Duration and rate of F2 transition at the VC (top) and CV (bottom) boundaries of [i.p^{h}i] utterances produced by Persian speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds show actual data points. Circles show average values of individual data points.

	Duration (ms) & Rate (Hz/ms) of F2 Transition				
Speaker	**ip (n=4)**			**pi (n=2)**	
	ms	*Hz/ms*		*ms*	*Hz/ms*
P#1	-	-		9	76
	-	-		-	-
	10	65		8	42
P#2	13	24		-	-
	12	14		-	-
	18	19		-	-
M	**13**	**30**		**8.5**	**59**
SD	**3**	**23**		**.7**	**24**

Table 4-4. Duration and rate of F2 transition at the VC and CV boundary of utterances produced by Persian speakers.

The voicing properties of the intervocalic stop did not result in major differences in the duration and rate of F2 transition in the [i.bi] and [i.p^{h}i] utterances produced by speaker P#1. In the same utterances produced by speaker P#2, duration of F2 transition at the VC boundary of [i.bi] utterances was on average 7 ms longer than in [i.p^{h}i] utterances, indicating more tongue body involvement in the former compared to the latter. No evidence of tongue body movement was found at the CV boundary of the [i.p^{h}i] utterances produced by this speaker. The CV boundary of [i.bi] utterances, however, showed evidence of tongue body movement. In general, more evidence of tongue body movement was found in the [i.bi] than in the [i.p^{h}i] utterances produced by speaker P#2.

4.2.1.2. The Effect of Syllable Boundary on Rate and Duration of F2 Transition

If, according to the superimposition model, the tongue maintains its position throughout symmetrical [iCi] sequences, no changes are expected to be observed in the duration and rate of F2 transition as a function of the syllabic affiliation of the intervocalic stop. On the other hand, if the tongue body goes through continuous phases of deactivation and reactivation as maintained by a phoneme-by-phoneme view of segmental organization, changes are expected to occur in the duration and rate of F2 transition as a function of the syllabic affiliation of the intervocalic stop.

In the closed [iC.i] utterances of this study the two vowels were separated by a syllable boundary as well as a pause period between the release of the intervocalic stop and V_2. Since the temporal distance between V_1 and V_2 gestures is relatively longer in closed [iC.i] compared to open [i.Ci] utterances, the tongue body is expected to have more time to deactivate from its position for [i] into a neutral position and as a result slower F2 transitions during longer periods of time are expected to be observed at the VC boundary of closed syllable forms compared to their open counterparts. Since a period of pause intervened between C and V_2, rate and duration of F2 transition were meaningless in distinguishing between the effects of lip versus lip and tongue body movement at the CV boundary of closed utterances.

In order to investigate the effects of syllable boundary on the duration and rate of F2 transition at the VC boundary of [iCi] utterances, F2 transitions of symmetrical open [i.Ci] utterances were compared with those of closed [iC.i] utterances where the intervocalic consonant was a bilabial stop.

In this section, rate of F2 transition for open [i.Ci] sequences are repeated again in the graphs for comparison. In total, the number of closed syllable forms investigated for rate of transition was 30 (1V*2C*5SUB*3REP) for English and 12 (1V*2C*2SUB*3REP) for Persian speakers. Not all tokens showed changes in F2 frequency at the VC boundary and thus no values are reported for those cases. In each graph, diamonds represent open and triangles represent closed syllable forms. Circles represent average values for open syllables and plus signs represent average values for closed syllable forms.

Figure 4-8 shows a comparison of rate and duration of F2 transition at the VC boundary of [i.bi] and [ib.i] utterances produced by English speakers. Rate and duration of F2 transition at the VC boundary of [ib.i] utterances produced by English speakers are given in the left column of table 4-5 below. These values have to be considered in conjunction with the values of open syllable forms reported in the left column of table 4-1.

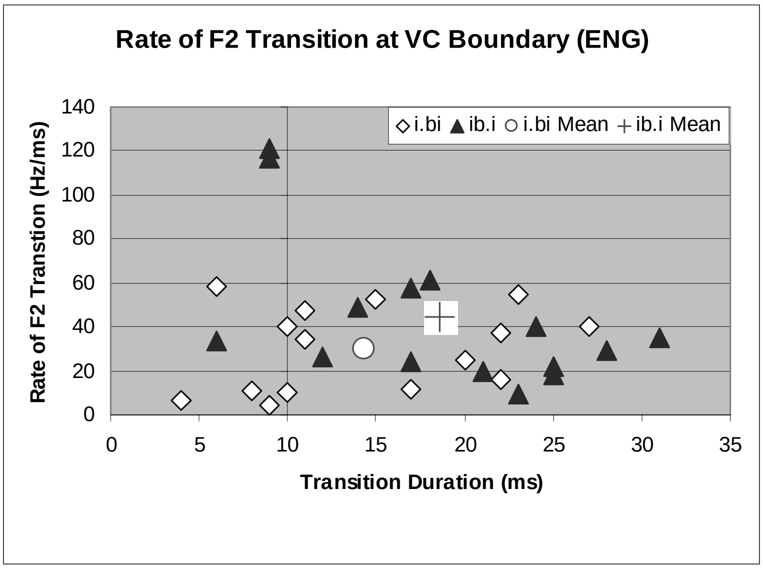


Figure 4-8. Rate of F2 transition at VC boundary in [i.bi] and [ib.i] utterances produced by English speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds and triangles show actual data points. The circle and plus signs show average values of individual data points.

As figure 4-8 shows, changing the syllabic affiliation of the intervocalic voiced bilabial stop resulted in generally longer F2 transition durations and slightly faster transition rates in closed versus open syllable forms. On average, F2 transitions lasted 5 ms longer in closed versus open [ibi] sequences. Although rate of F2 transition was only 14 Hz/ms faster in closed syllable forms, the average rate of F2 transition remained relatively slow in these tokens. In general, changing the syllabic affiliation of the intervocalic voiced bilabial stop resulted in the enhancement of tongue body movement effects at the VC boundary of [ibi] sequences produced by English speakers.

	Duration (ms) & Rate (Hz/ms) of VC F2 Transition				
Subject	**ib.**			**ip.**	
	ms	*Hz/ms*		*ms*	*Hz/ms*
E#1	9	117		-	-
	18	61		-	-
	9	121		-	-
E#2	28	29		16	37
	24	40		20	42
	25	22		25	34
E#3	17	57		14	45
	14	49		13	85
	31	35		12	73
E#4	12	26		8	39
	6	33		12	44
	17	24		12	21
E#5	23	9		13	10
	25	19		7	18
	21	20		8	31
M	**19**	**44**		**13**	**40**
SD	**8**	**34**		**5**	**21**

Table 4-5. Duration and Rate of F2 transition at the VC boundary of [ib.i] and [ip.i] utterances produced by English speakers.

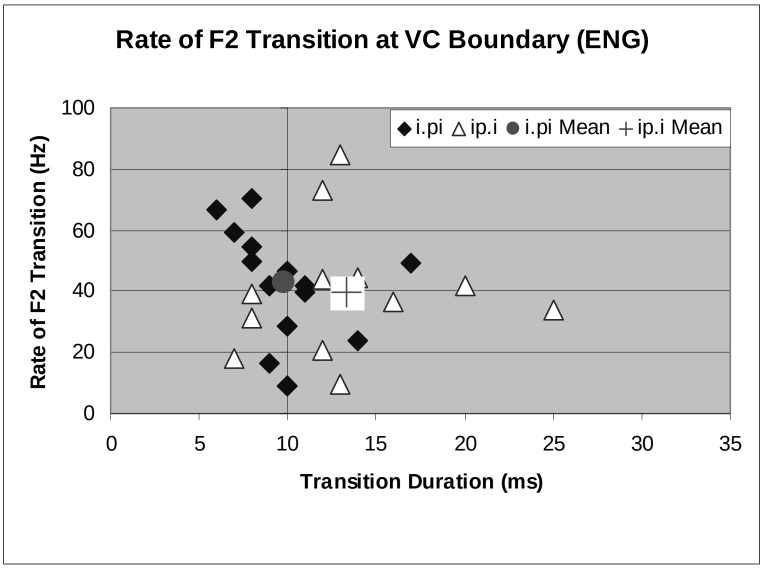


Figure 4-9. Rate of F2 transition at VC boundary in [i.p^{h}i] and [ip.i] utterances produced by English speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds and triangles show actual data points. The circle and plus signs show average values of individual data points.

Figure 4-9 shows a comparison of rate and duration of F2 transition at the VC boundary of [i.p^{h}i] and [ip.i] utterances produced by English speakers. Rate and duration of F2 transition at the VC boundary of [ip.i] utterances produced by English speakers are given in the right column of table 4-5 below. These values have to be considered in conjunction with the values of open syllable forms reported in the left column of table 4-2.

As figure 4-9 shows, changing the syllabic affiliation of the intervocalic voiceless bilabial stop in [ipi] sequences resulted in slightly longer F2 transition durations and slower transition rates in closed versus open syllable forms. On average, F2 transitions were 3 ms longer in closed compared to open [ipi] utterances. Rate of F2 transition remained relatively slow in closed forms and only 3 Hz/ms faster than in open forms. While no evidence of tongue body movement was found in the VC transitions of open [i.p^{h}i] utterances, the greater transition durations and slower rates of F2 transition observed with closed [ip.i] syllables indicated tongue body movements at the VC boundary of these utterances.

In both [ibi] and [ipi] utterances produced by English speakers, the F2 transition at the VC boundary lasted longer when the intervocalic stop was syllabified with V_1 than when it was syllabified with V_2.

The results also indicate that the voicing properties of the intervocalic consonant have an effect on the duration of the F2 transition at the VC boundary of closed syllables. On average, F2 transitions at the VC boundary of [ib.i] utterances were 6 ms longer than those of [ip.i] sequences indicating more tongue body involvement in the former compared to the latter. Rate of F2 transition was slow in both token types. These results are comparable to the results obtained from open [i.Ci] utterances where evidence of tongue body displacement was found at the VC boundary of [i.bi] utterances but not at the VC boundary of [i.p^{h}i] sequences.

Figure 4-10 shows a comparison of rate and duration of F2 transition in open [i.bi] and closed [ib.i] utterances produced by Persian speakers. Rate and duration of F2 transition at the VC boundary of closed [ib.i] utterances produced by Persian speakers are given in the left hand column of table 4-6. These values have to be considered in conjunction with the values of open syllable forms reported in the left column of table 4-3.

As figure 4-10 shows, changing the syllabic affiliation of the intervocalic voiced bilabial stop resulted in slightly shorter F2 transition durations and slower transition rates in closed versus open syllable forms. On average, F2 transitions were 3 ms shorter in closed versus open [ibi] sequences. Rate of F2 transition remained relatively slow in closed syllables. In general, changing the syllabic affiliation of the intervocalic voiced bilabial stop did not result in the enhancement of tongue body movement effects at the VC boundary of the utterances produced by Persian speakers.

The short F2 transition durations of closed [ib.i] utterances produced by speaker P#1 indicated that lip movement only was responsible for changes in F2 frequency at the VC boundary. On the other hand, the relatively longer F2 transition durations of these utterances as produced by speaker P#2 indicated that lip as well as tongue body movement were responsible for F2 frequency changes at this boundary.

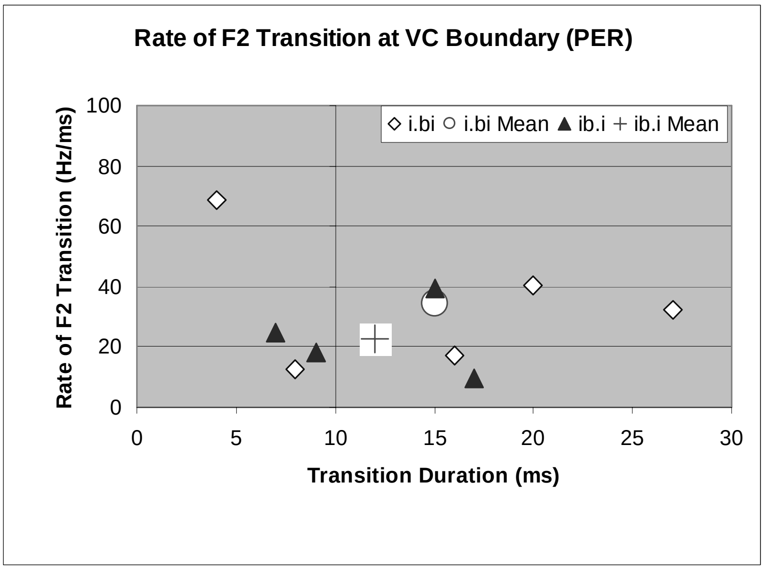


Figure 4-10. Rate of F2 transition at VC boundary in [i.bi] and [ib.i] utterances produced by Persian speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds and triangles show actual data points. The circle and plus signs show average values of individual data points.

	Duration (ms) & Rate (Hz/ms) of VC F2 Transition				
Subject	**ib.**			**ip.**	
	ms	*Hz/ms*		*ms*	*Hz/ms*
P#1	-	-		-	-
	9	18		-	-
	-	-		-	-
P#2	7	25		16	37
	15	39		8	8
	17	10		7	14
M	**12**	**23**		**10**	**20**
SD	**5**	**13**		**5**	**15**

Table 4-6. Duration and rate of F2 transition at the VC boundary of [ib.i] and [ip.i] utterances produced by Persian speakers.

Figure 4-11 compares rate and duration of F2 transition in [i.p^hi] and [ip.i] utterances produced by Persian speakers. Rate and duration of F2 transition at the VC boundary of closed [ip.i] utterances produced by Persian speakers are given in the right hand column of table 4-6. These values have to be considered in conjunction with the values of open syllable forms reported in the left column of table 4-4. Since none of the closed syllable forms produced by speaker P#1 showed transitions at the VC boundary of closed [ip.i] utterances, they were not included in the results. Comparing rate and duration of F2 transition in the closed and open syllable forms in figure 4-11, F2 transitions were on average 3 ms shorter in closed [ip.i] compared to open [i.p^hi] forms. Rate of F2 transition did not show any changes as a function of the syllabic affiliation of the intervocalic voiceless stop. In general, changing syllable boundaries resulted in shorter F2 transition durations. Rate of F2 transition did not show major changes.

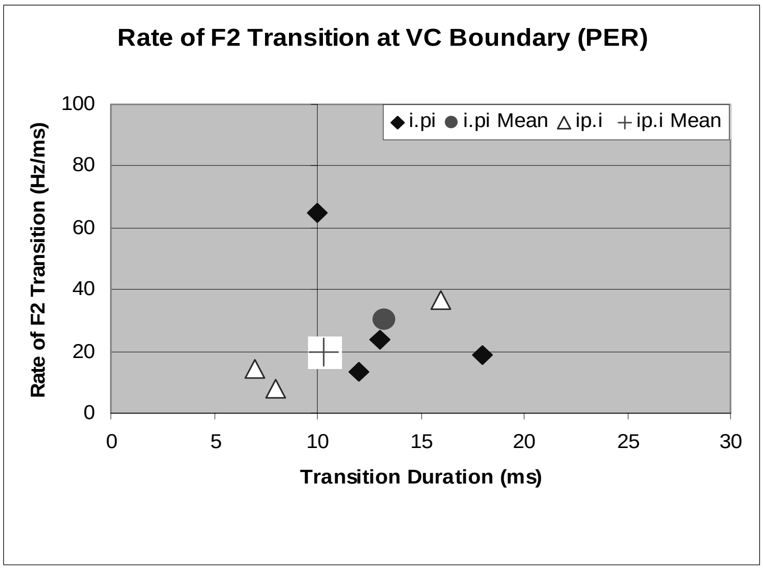


Figure 4-11. Rate of F2 transition at VC boundary in [i.p^{h}i] and [ip.i] utterances produced by Persian speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds and triangles show actual data points. The circle and plus signs show average values of individual data points.

As no data was available for speaker P#1 at the VC boundary of closed [ip.i] utterances, the effects of voicing on the rate and duration of F2 transition at this boundary is discussed only for speaker P#2. F2 transition lasted 3 ms longer in [ib.i] versus [ip.i] utterances for this speaker. Rate of F2 transition remained relatively slow. Evidence of tongue body movement was found in [ib.i] tokens produced by speaker P#2, but not in [ip.i] utterances. These results were similar to those observed in the utterances produced by English speakers where more evidence of tongue body movement was found at the VC boundary of [ibi] versus [ipi] sequences.

Since it was not possible to determine the rate of F2 transition at CV boundary when the intervocalic bilabial stop was syllabified with V_1 in closed [ib.i] and [ip.i] utterances, average F2 traces were made to compare F2 movement in these utterances compared to their open counterparts.

In figures 4-12 and 4-13 below, average F2 frequencies at V_1 mid point, V_1 offset, V_2 onset and V_2 mid point are plotted for English and Persian speakers respectively. Points 1-4 on the *x* axis of each plot indicate average F2 values at these four points. Solid lines show average F2 traces of open [i.bi] and [i.p^{h}i] utterances. Average F2 traces of closed [ib.i] and [ip.i] utterances are shown by dashed lines in each graph. It must be noted that the line connecting points 2 and 3 in open and closed syllable traces are interpolations between V_1 offset and V_2 onset and do not represent actual observed F2 frequencies during consonantal closure. Likewise, the lines connecting points 3 and 4 in closed syllable traces are interpolations between V_2 onset and V_2 mid point and do not represent actual observed F2 frequencies during the pause period that intervened between C release and V_2.

In figure 4-12, each trace represents an average of 15 utterances (1V*1C*5SUB*3REP) produced by English speakers. In figure 4-13, each trace represents an average of 6 (1V*1C*2SUB*3 REP) utterances for open syllable forms and 5 for closed syllable forms produced by Persian speakers.

As figure 4-12 shows, F2 decreased considerably in frequency at V_2 onset in closed versus open utterances produced by English speakers, although V_1 and V_2 mid point values were on average higher in frequency in the former versus the latter. On average, F2 onset was 348 Hz lower in [ib.i] compared to [i.bi] utterances. F2 onset was 333 Hz lower in [ip.i] compared to [i.p^{h}i] utterances produced by English speakers.

As figure 4-13 shows, F2 onset was considerably lower in closed compared to open [ibi] and [ipi] utterances produced by Persian speakers as well. On average, F2 onset was 434 Hz lower in [ib.i] compared to [i.bi] utterances. F2 onset was 521 Hz lower in [ip.i] compared to [i.p^{h}i] utterances.

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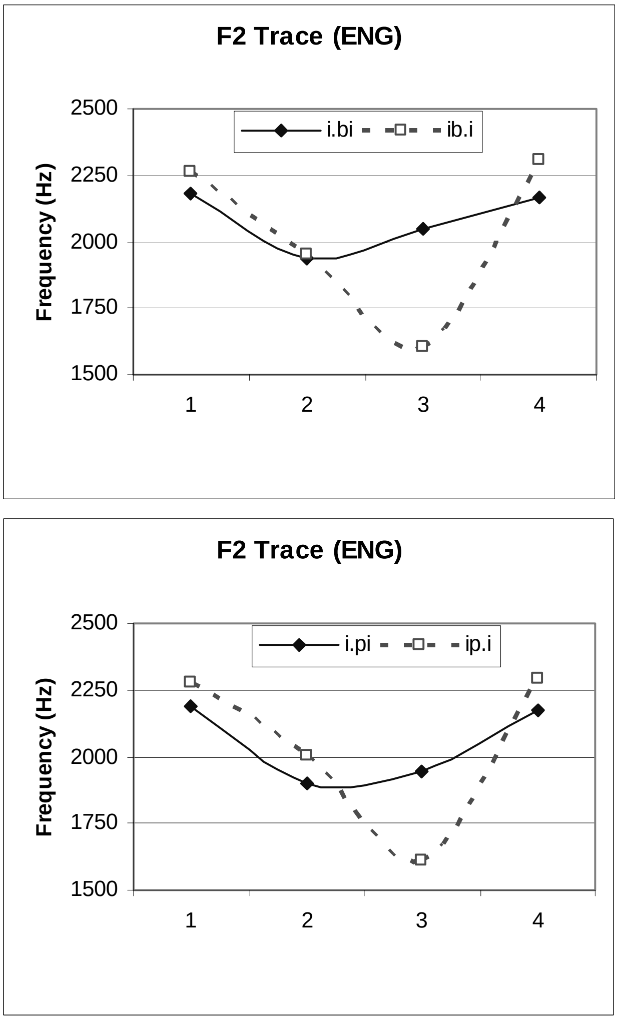
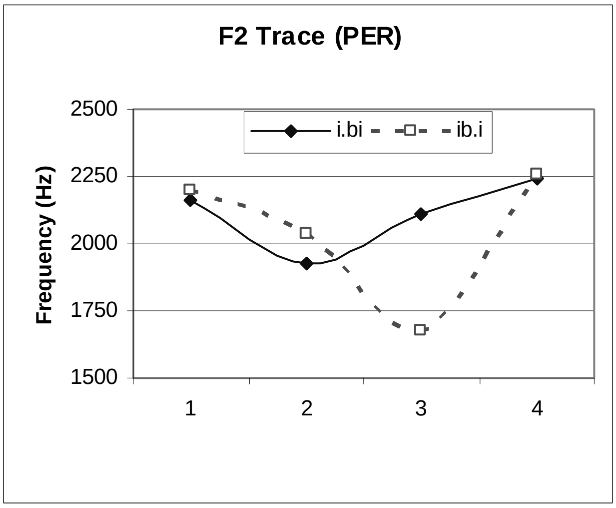


Figure 4-12. Average F2 traces of symmetrical open and closed syllables with intervocalic bilabial stops in **i-i** context (English). Points 1-4 in the above graphs represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closures. The traces between points 3 and 4 in closed forms are interpolations during the pause period.



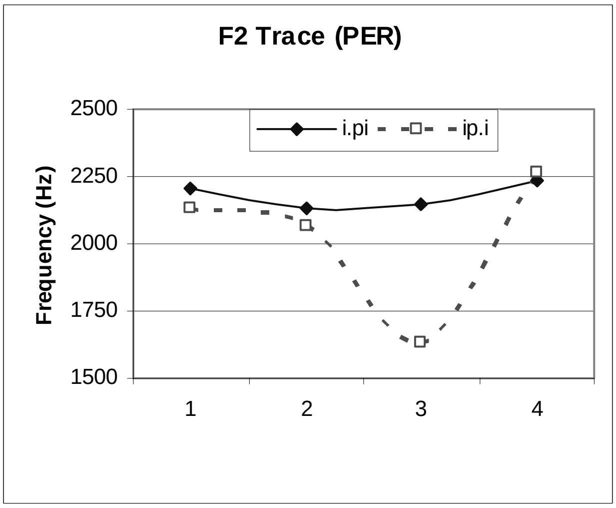


Figure 4-13. Average F2 traces of symmetrical open and closed syllables with intervocalic bilabial stops in **i-i** context (Persian). Points 1-4 in the above graphs represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closures. The traces between points 3 and 4 in closed forms are interpolations during the pause period.

As mentioned in section 2.1.4.1, F2 onset of open syllables was measured at the first pitch period of V_2 if the intervocalic consonant was a voiced stop and at the first F2 resonance after the release of stop closure if the intervocalic consonant was a voiceless aspirated stop. In closed syllables, F2 onset was measured at the release of the syllable-final stop irrespective of its voicing properties. Thus, F2 onset of open syllables was measured at a point closer to V_2 compared to closed syllables where a period of pause intervened between the release of the stop and the acoustic onset of V_2. As a result, the F2 onset of open syllable forms was closer in frequency to V_2 F2 mid vowel frequency compared to the F2 onset of closed syllable forms. The relatively low F2 onset frequency of closed syllable forms can have different explanations. Average F2 onset frequency was 1603 Hz for /b/ and 1614 Hz for /p/ at the release of the syllable-final stop in closed syllable forms produced by English speakers. Average F2 onset frequency was 1679 Hz for /b/ and 1629 Hz for /p/ at the release of the syllable-final stop in closed syllable forms produced by Persian speakers. An average F2 of 1600 Hz can emerge as a result of lip closing/opening movements only as discussed above. It can also emerge as a result of tongue body movement into a neutral position for the vowel [i]. Duration and rate of F2 transitions at the VC boundary of closed syllables produced by English speakers showed that the tongue body was in movement at this boundary. Assuming that the tongue body has been in movement during the bilabial stop closure as well, the value of F2 at the release of the syllable-final stop in closed syllable forms reflects the effects of lip closing/opening as well as tongue position at that point.

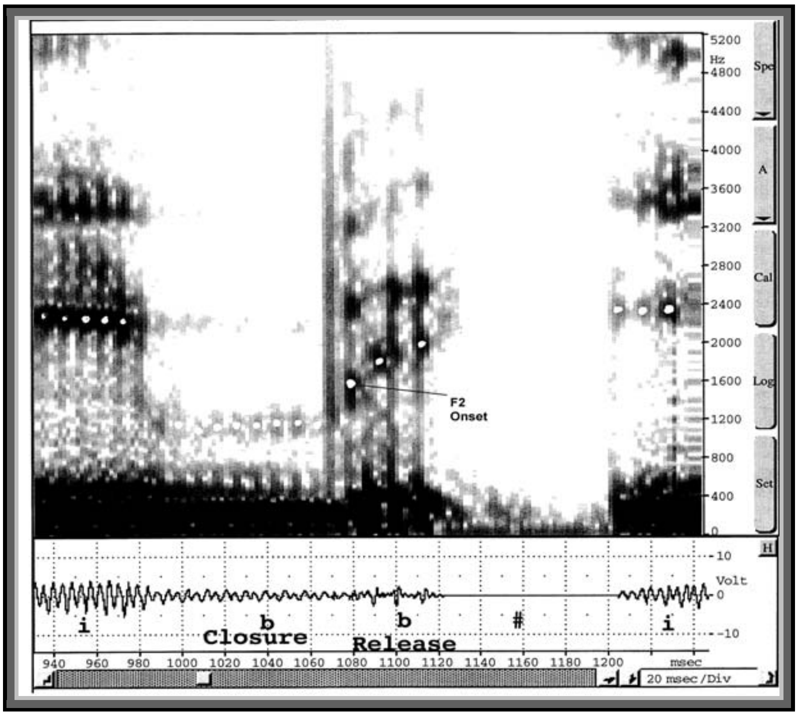


Figure 4-14. Second formant trace of an [ib.i] utterance produced by speaker E#1. A sharp fall in F2 frequency is seen at the VC boundary followed by a low frequency F2 resonance during stop closure and a gradual increase in F2 value after the release of the syllable-final stop towards the second vowel.

Figure 4-14 shows a spectrographic display of an [ib.i] utterance produced by speaker #E1. The second formant is traced during V_1, during bilabial closure, after the release of [b], and during V_2. Note the presence of resonances during the stop closure. In this particular utterance, F2 transition at the VC boundary lasted 9 ms which indicates lip movement effects only. Mere lip closure has the effect of decreasing F2 frequency to a considerable degree. The resonance frequency of the front cavity vocal tract configuration for an [i] is 1250 Hz ($c/4l_f$) when the length of the front cavity is 7 cm and the lips are closed. The resonance that shows up during the closure duration in the above figure is around 1250 Hz. Thus, the low frequency resonance during the stop closure can well be the resonance frequency of the front cavity while the tongue body is in place for an up coming [i]. Nevertheless, the gradual increase in F2 frequency as seen in the few striations after the labial release indicates gradual tongue body recovery from a neutral position towards the position for [i]. Had the tongue body stayed in position for [i] all throughout the utterance, formant transitions after the release of the stop would have been much faster and steeper. Thus, the F2 onset frequency at the release of syllable-final stops in closed syllable forms can indicate tongue body position at this point.

To summarize, evidence of tongue body movement was found at the VC boundary of closed syllables although in general more evidence of tongue body movement was found at the VC boundary when the consonant was [b] compared to [p]. F2 traces showed evidence of troughs at the CV boundary of these utterances in the utterances produced by English and Persian speakers.

4.2.1.3. The Effects of Stop Closure Duration on Rate and Duration of F2 Transition

If according to the superimposition model, the tongue maintains its position throughout a symmetrical [iCi] sequence, no changes are expected to be observed in the duration and rate of the F2 transition of the vowel [i] as a function of intervocalic stop consonant closure duration. On the other hand, if the tongue body goes through continuous phases of deactivation and reactivation, it is predicted to have more time to deactivate from its position for [i] into a neutral position when the intervocalic consonant is a geminate compared to a singleton and thus slower VC F2 transitions during longer periods of time are expected to be observed. Since the tongue has more time to reach a neutral position in geminate compared to singleton forms, it will take a longer time for the tongue body to go back to the position for [i] in V_2 position and the effects of recovering from the neutral position are expected to be observable at the CV boundary of geminate versus singleton forms. Again slower CV F2 transition rates during longer periods of time are expected to be observed in geminate compared to singleton utterances.

In order to investigate the effects of stop closure duration on the production of troughs, F2 transitions of symmetrical singleton [i.Ci] and geminate [iC.Ci] utterances were compared. As before, the intervocalic consonant was a bilabial stop.

In this section, rate and duration of F2 transition of singleton [i.Ci] utterances are repeated in the graphs for comparison. In total, the number of geminate utterances investigated was 30 (1V*2C*5SUB*3REP) for English and 12 (1V*2C*2SUB*3REP) for Persian speakers. Not all tokens showed changes in F2 frequency and thus no values are reported for those cases.

Rate and duration of F2 transition of [ib.bi] utterances at the VC and CV boundaries are given in table 4-7. The values in this table should be compared with those of the singleton [i.bi] utterances reported in table 4-1. Rate and duration of F2 transition at the VC and CV boundaries of [i.bi] and [ib.bi] utterances produced by English speakers are compared in figure 4-15. In this figure and the rest of the figures in this section, diamonds represent values obtained in singleton forms and stars represent values obtained in geminate utterances. Circles represent average values for singleton and crosses represent average values for geminate utterances.

As the top graph of figure 4-15 shows, evidence of tongue body movement was found at the VC boundary of geminate forms, although increasing the duration of the intervocalic stop resulted in a minimal increase in the duration and rate of F2 transition at the VC boundary of geminate forms. On average, the F2 transition was only 2 ms longer in [ib.bi] utterances than in [i.bi] utterances. Rate of F2 transition was relatively slow and only 26 Hz/ms faster in geminate versus singleton forms.

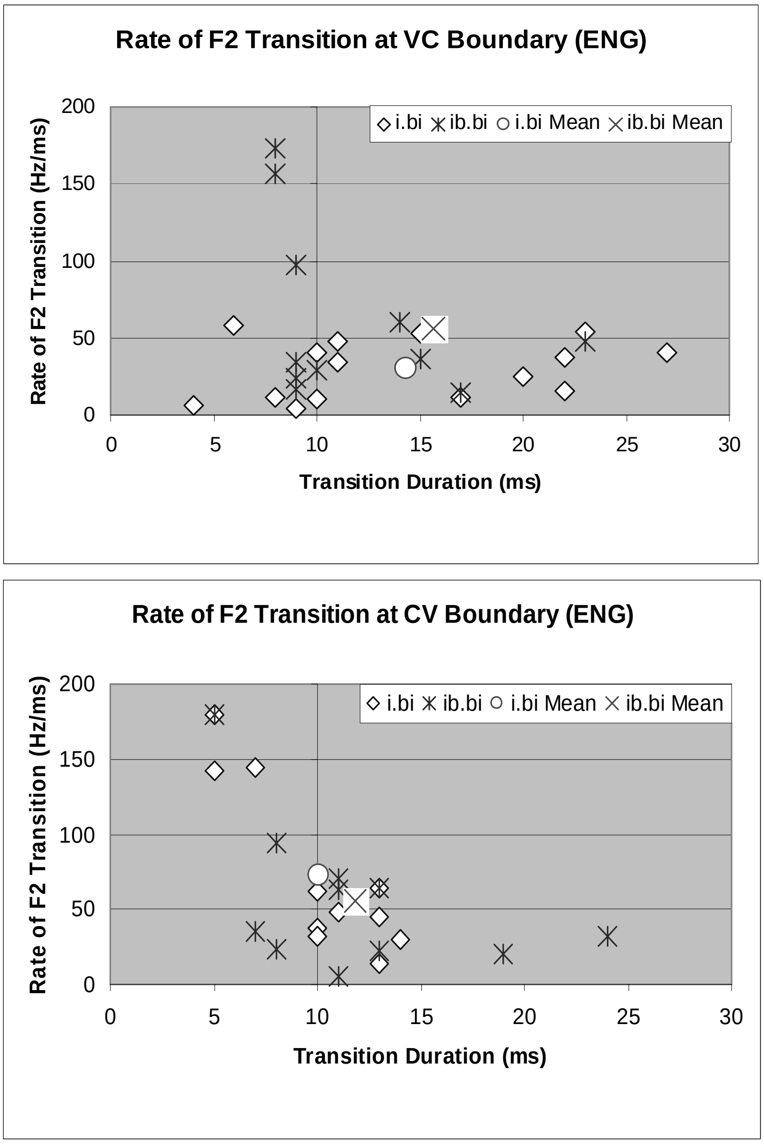


Figure 4-15. Rate of F2 transition at VC and CV boundaries of [i.bi] and [ib.bi] utterances produced by English speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds and stars show actual data points. Circles and cross signs show average values of individual data points.

	Duration (ms) & Rate (Hz/ms) of F2 Transition				
Speaker	**ib.b (n=13)**			**b.bi (n=11)**	
	ms	*Hz/ms*		*ms*	*Hz/ms*
E#1	9	97		-	-
	8	156		-	-
	8	173		5	180
E#2	36	15		11	6
	37	27		24	32
	23	48		13	64
E#3	15	36		11	64
	14	60		7	36
	9	24		11	70
E#4				19	20
	9	17		8	24
	9	35		8	94
E#5	10	29		13	22
	17	15		-	-
	-	-		-	-
M	**16**	**56**		**12**	**56**
SD	**10**	**53**		**6**	**49**

Table 4-7. Duration and rate of F2 transition at the VC and CV boundaries of [ib.bi] utterances produced by English speakers.

Increasing the duration of the intervocalic stop resulted in a minimal increase in the duration and a decrease in the rate of F2 transition at the CV boundary of [ib.bi] compared to [i.bi] utterances as shown the bottom graph of figure 4-15. The difference between the duration of F2 transition of singleton and geminate utterances was only 2 ms. Rate of F2 transition remained relatively slow in geminate forms and only 17 Hz/ms slower than those of their singleton counterparts. In general, more geminate tokens showed evidence of tongue body movement compared to the singleton forms at the CV boundary.

Rate and duration of the F2 transition at the VC and CV boundaries of [ip.p^{h}i] utterances produced by English speakers are given in table 4-8. The values in this table should be compared with those of the singleton [i.p^{h}i] utterances reported in table 4-2. Rate and duration of the F2 transition at the VC and CV boundaries of [i.p^{h}i] and [ip.p^{h}i] utterances are compared in figure 4-16. As the top graph in this figure shows, increasing the duration of the intervocalic stop in [ip.p^{h}i] utterances resulted in a minimal increase in the duration and a decrease in the rate of F2 transition at the VC boundary. On average, VC F2 transitions were only 2 ms longer in [ip.p^{h}i] than in [i.p^{h}i] utterances. Rate of F2 transition remained relatively slow at 33 Hz/ms in geminate forms. In general, more evidence of tongue body movement was found at the VC boundary of [ip.p^{h}i] compared to the [i.p^{h}i] utterances produced by English speakers.

As the bottom graph in figure 4-16 shows, increasing the duration of the intervocalic stop in [ip.p^{h}i] utterances resulted in a decrease in the duration and an increase in the rate of F2 transition at the CV boundary. On average, CV F2 transition was 3 ms shorter in [ip.p^{h}i] relative to [i.p^{h}i] utterances. Rate of transition remained relatively slow at 59 Hz/ms in geminate forms. In general, although evidence of tongue body movement was found at the CV boundary of [ip.p^{h}i] utterances produced by English speakers, increasing the duration of the intervocalic stop did not result in more extensive tongue body movement effects at this boundary.

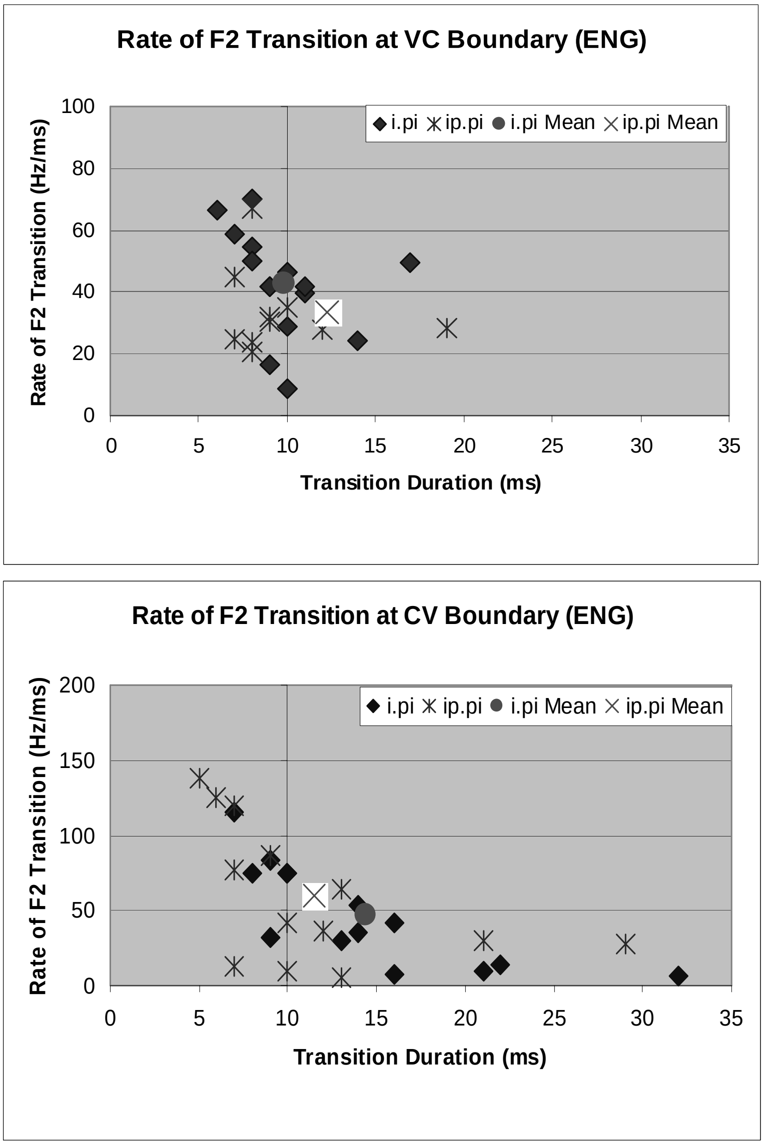


Figure 4-16. Rate of F2 transition at VC boundary in [i.p^{h}i] and [ip.p^{h}i] utterances produced by English speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds and stars show actual data points. Circles and cross signs show average values of individual data points.

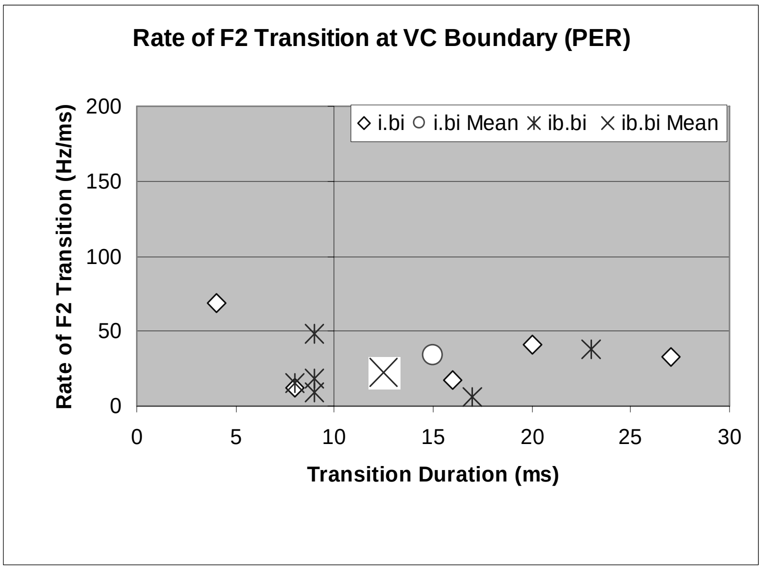
	Duration (ms) & Rate (Hz/ms) of F2 Transition				
Subject	**ip.p (n=11)**			**p.pi (n=13)**	
	ms	*Hz/ms*		*ms*	*Hz/ms*
E#1	8	67		6	125
	-	-		5	138
	-	-		7	13
E#2	19	28		7	77
	12	28		9	86
	38	31		29	28
E#3	9	31		21	30
	8	24		13	64
	8	20		7	120
E#4	7	44		12	36
	7	25		13	5
	-	-		10	41
E#5	9	32		10	10
	10	35		-	-
	-	-		-	-
M	**12**	**33**		**11**	**59**
SD	**9**	**13**		**7**	**46**

Table 4-8. Duration and rate of F2 transition at the VC and CV boundaries of [ip.p^{h}i] utterances produced by English speakers.

The voicing properties of the intervocalic stop had a minimal effect on the duration of F2 transitions at the VC boundary of geminate utterances. On average, duration of F2 transitions at the VC boundary was 4 ms longer in [ib.bi] compared to [ip.p^{h}i] utterances produced by English speakers. These results was compatible with earlier observations where more evidence of tongue body movement was observed at the VC boundary of open singleton and closed syllables when C was [b] rather than [p]. No major differences were observed between the rate and duration of F2 transition at the CV boundary of [ib.bi] and [ip.p^{h}i] utterances produced by English speakers. These results were not compatible with earlier observations where more evidence of tongue body movement was observed at the CV boundary of open singleton utterances when C was [p^h] rather than [b].

Rate and duration of F2 transition at the VC and CV boundaries of geminate [ib.bi] utterances produced by Persian speakers are given in table 4-9. The values in this table should be compared with those of the singleton [i.bi] utterances reported in table 4-3. Rate and duration of F2 transition at VC and CV boundaries of [i.bi] and [ib.bi] utterances produced by Persian speakers are compared in figure 4-17. As the top graph of this figure shows, although evidence of tongue body movement was found at the VC boundary of [ib.bi] utterances produced by Persian speakers, increasing the duration of the intervocalic stop resulted in a minimal decrease in the average duration and rate of F2 transition at the VC boundary of [ib.bi] utterances compared to their singleton counterparts. On average, VC F2 transitions were only 2 ms shorter in [ib.bi] utterances than in [i.bi] utterances. Rate of F2 remained relatively slow at 23 Hz/ms in geminate utterances.

As the bottom graph of figure 4-17 shows, increasing the duration of the intervocalic stop in geminate forms resulted in an increase in the average duration and a decrease in rate of F2 transition at the CV boundary of [ib.bi] versus [i.bi] utterances. On average, CV F2 transitions were 3 ms longer in [ib.bi] utterances than in [i.bi] utterances. Rate of transition was on average 53 Hz/ms slower in geminate versus singleton forms.



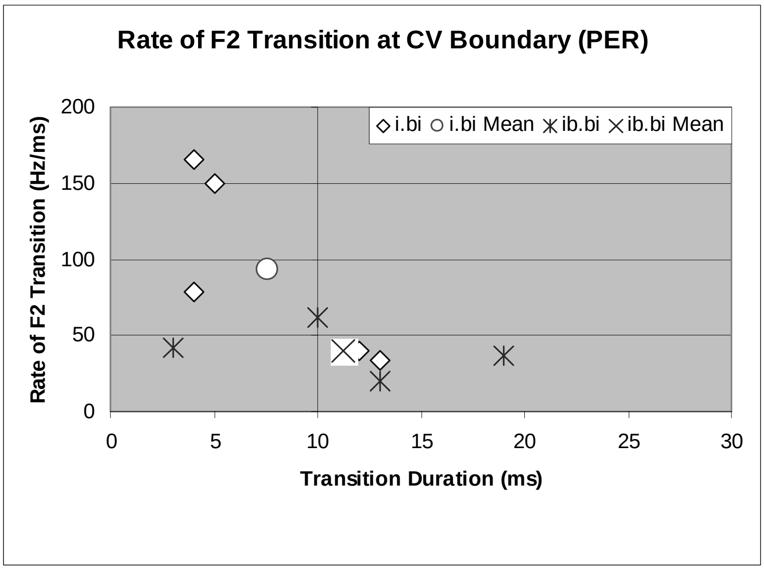


Figure 4-17. Rate of F2 transition at the VC and CV boundaries of [i.bi] and [ib.bi] utterances produced by Persian speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds and stars show actual data points. Circles and cross signs show average values of individual data points.

	Duration (ms) & Rate (Hz/ms) of F2 Transition				
Speaker	**ib.b (n=6)**			**b.bi (n=4)**	
	ms	*Hz/ms*		*ms*	*Hz/ms*
P#1	9	49		10	61
	8	16		3	42
	9	18		-	-
P#2	9	10		19	36
	23	37		13	20
	17	6		-	-
M	**13**	**23**		**11**	**40**
SD	**6**	**17**		**7**	**17**

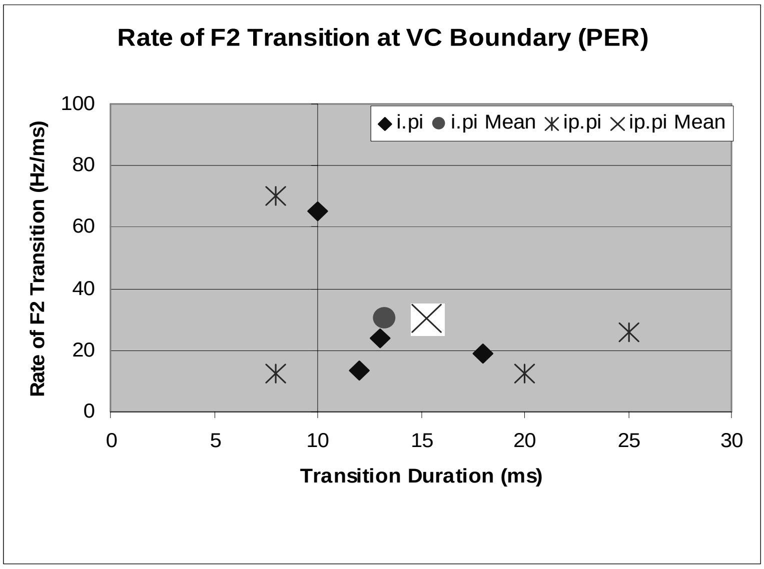
Table 4-9. Duration and rate of F2 transition at the VC boundary of [ib.bi] utterances produced by Persian speakers.

Rate and duration of F2 transitions at the VC and CV boundaries of geminate [ip.p^{h}i] utterances produced by Persian speakers are given in table 4-10. The values in this table should be compared with those of the singleton [i.p^{h}i] utterances reported in table 4-4. Rate and duration of F2 transition at the VC and CV boundaries of [i.p^{h}i] and [ip.p^{h}i] utterances produced by Persian speakers are compared in figure 4-18. As the top graph in this figure shows, increasing the duration of the intervocalic stop resulted in a minimal increase in the average duration of F2 transition at the VC boundary of [ip.p^{h}i] utterances compared to their singleton counterparts. On average, VC F2 transitions were only 2ms longer in [ip.p^{h}i] than in [i.p^{h}i] utterances. Rate of F2 transition remained constant at 30 Hz/ms.

As the bottom graph in figure 4-18 shows, increasing the duration of the intervocalic stop resulted in a minimal increase in the average duration of the F2 transition and a decrease in the rate of the F2 transition at the CV boundary of [ip.p^{h}i] utterances compared to their singleton counterparts. On average, CV F2 transitions were only 2.5 ms longer in [ip.p^{h}i] than in [i.p^{h}i] utterances. Rate of transition was on average 41 Hz/ms slower in geminate than in their singleton forms.

The voicing properties of the intervocalic stop minimally affected duration of F2 transition at the VC boundary of [ib.bi] and [ip.p^{h}i] utterances produced by Persian speakers. On average, F2 transitions were 2 ms longer in [ip.p^{h}i] compared to [ib.bi] utterances. Rate of F2 transition remained slow at 23 Hz/ms and 30 Hz/ms at the VC boundary of [ib.bi] and [ip.p^{h}i] utterances respectively. In general, contrary to the previously observed patterns more evidence of tongue body movement was found at the VC boundary of geminate utterances produced by Persian speakers when C was [p] rather than [b].

At the CV boundary, duration of F2 transition did not show any changes as a function of the voicing properties of the intervocalic geminate stop in [ib.bi] and [ip.p^{h}i] utterances produced by Persian speakers. Rate of F2 transition remained slow at 40 Hz/ms and 18 Hz/ms at the CV boundary of [ib.bi] and [ip.p^{h}i] utterances respectively. In general, little evidence of tongue body movement was found at the CV boundary of [ib.bi] and [ip.p^{h}i] utterances produced by Persian speakers.



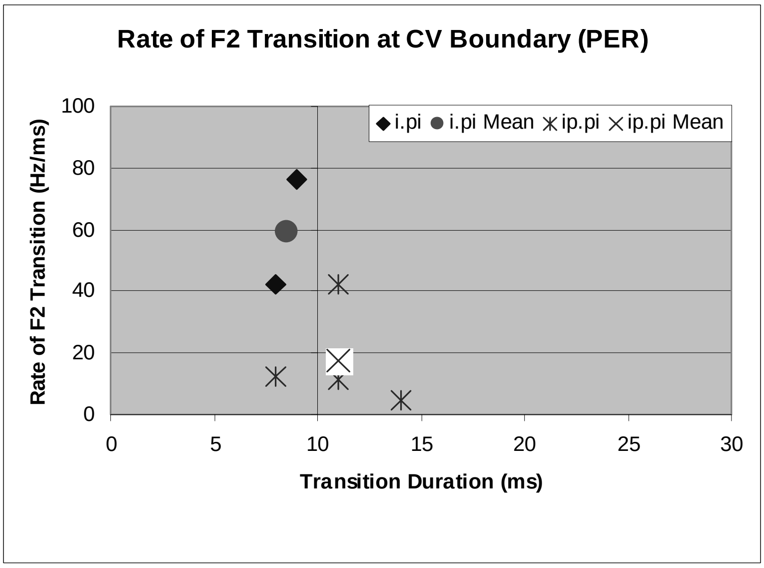


Figure 4-18. Rate of F2 transition at VC boundary in [i.p^{h}i] and [ip.p^{h}i] utterances produced by Persian speakers. Transitions lasting more than 10 ms indicate tongue body as well as lip movement effects. Diamonds and stars show actual data points. Circles and cross signs show average values of individual data points.

	Duration (ms) & Rate (Hz/ms) of F2 Transition				
Speaker	**ip.p (n=4)**			**p.pi (n=4)**	
	ms	*Hz/ms*		*ms*	*Hz/ms*
P#1	-	-		-	-
	-	-		-	-
	8	13		8	13
P#2	20	13		14	4
	25	26		11	11
	8	70		11	42
M	**15**	**30**		**11**	**18**
SD	**9**	**27**		**2**	**17**

Table 4-10. Duration and rate of F2 transition at the VC boundary of [ip.p^hi] utterances produced by Persian speakers.

To summarize, evidence of tongue body movement was found at the VC and CV boundaries of the majority of geminate utterances produced by English and Persian speakers. Nevertheless, germination did not result in considerably longer F2 transitions or considerably slower rates of F2 transition as predicted under a deactivation-reactivation scenario.

4.2.1.4. Summary and Discussion

Taking duration and rate of F2 transition as measures of tongue and lip versus lip movement in [iC(C)i] sequences, evidence of tongue body movement was found at the VC boundary of [i.bi] utterances produced by English speakers, but not at the VC boundary of [i.p^hi] utterances. Conversely, evidence of tongue body movement was found at the CV boundary of [i.p^hi] utterances, but not at the CV boundary of [i.bi] tokens produced by English speakers.

These patterns can be explained by considering the aerodynamic requirements for voicing and aspiration. Voiced stops require a transglottal pressure difference to maintain glottal vibration. This requirement is fulfilled either actively by enlarging the supraglottal vocal tract (Rothenberg, 1968; Kent and Moll, 1969; McGowan et al., 1995) or passively by relaxing the supraglottal muscles (Perkell, 1969). Svirsky et al. (1997) showed that this requirement is fulfilled by an active relaxation of tongue muscles during /b/ in /aba/ sequences which was absent during /p/ in /apa/ sequences. Thus, the requirements for voicing might be responsible for tongue body movement at the VC boundary of [b] as observed in the present study.

The requirements for aspiration can be responsible for the differences observed between [b] and [p^h] at the CV boundary. Gay (1979) showed that the activity of the muscles involved in the production of the vowel started earlier when the consonant was a voiced bilabial stop as opposed to its voiceless counterpart. According to Engstrand et al. (1997), the perceptual demands on the production of aspirated stops might be responsible for lesser degrees of V_2 anticipation at the release of /p^h/. The vocalic gesture is delayed relative to the release of an aspirated voiceless versus a voiced stop, because in the production of the former the vocal tract has to be wide enough to produce aspiration instead of frication (Molis, 1994).

Acoustic theory can also account for the differences observed between the F2 transition patterns of voiced and voiceless aspirated stops in this section. The formant frequencies of vowels are not only determined by the shape and dimensions of the supraglottal but also by those of the subglottal cavity. The opening of the glottis associated with voicelessness affects resonance frequencies of the vocal tract (Fant, 1970: 169; Ohala, 1974: 259). The more extensive F2 transition patterns observed in the context of [p] versus [b] at the CV boundaries of the utterances studied here might be due to the changes in the resonance properties of the vocal tract due to glottal opening rather than tongue body displacement effects necessitated by aspiration.

In closed syllable forms produced by English speakers, evidence of tongue body movement was found at the VC and CV boundaries of [ib.i] and [ip.i] utterances. Increasing the temporal distance between V_1 and V_2 resulted in an increase in the duration of F2 transition at both boundaries. CV F2 transitions of closed syllables provided the strongest evidence of tongue body movement towards a neutral position.

In geminate forms produced by English speakers, evidence of tongue body movement was found at the VC and CV boundaries of [ib.bi] utterances and at the VC boundary of [ip.p^{h}i] utterances. Increasing the temporal distance between the two vowels resulted in more extensive tongue body displacement effects at the VC boundary of [ib.bi] versus [i.bi] utterances. In general, however, increasing V-to-V temporal distance in geminate forms did not result in more prominent tongue body movement effects.

The data obtained from Persian speakers had to be interpreted individually due to inter-speaker differences. While speaker P#1 showed no evidence of tongue body movement at all, speaker P#2 showed evidence of tongue body movement under all conditions.

4.2.2. The Acoustic Correlates of Troughs in [ɔCɔ] and [ɒCɒ] Utterances

In order to determine whether changes in second formant frequencies at the VC and CV boundaries of [ɔCɔ] or [ɒCɒ] utterances (where C was a bilabial stop) were due to lip movement only or due to lip and tongue body movement, it is necessary to know the significance of F2 for the back vowels such as [ɔ] and [ɒ]. When the tongue body is in a non-high and back position, the vocal tract resonances are similar to the resonances of a two-tube model as shown in figure 4-19. The vocal tract is divided into two tubes/cavities when the tongue is in a non-high back position. Each of the two tubes has its own resonances. The lowest resonance of a front cavity with an assumed length of 10 cm is 875 Hz. This is the first formant of the back vowel under consideration. The lowest resonance of a back cavity with an assumed length of 7 cm is 1250 Hz. This is the second formant of the back vowel under consideration. Thus, the second formant of a back vowel is the lowest resonance of the back cavity.

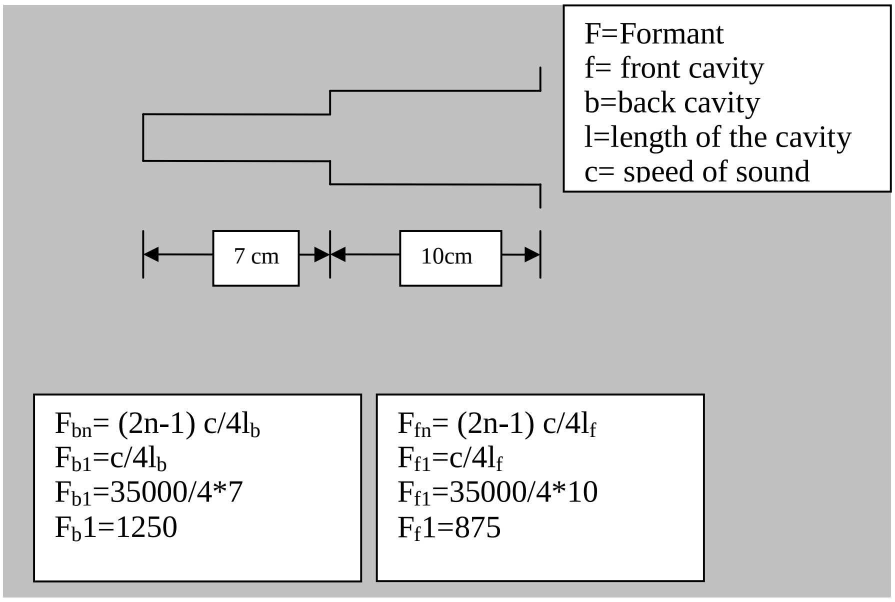


Figure 4-19. A two-tube resonator modeling vocal tract configuration for a non-high back vowel. The lowest resonance of the back and front cavities are calculated.

Back cavity resonances are minimally affected by changes in the front cavity including lip movement (Stevens, 1998: 342). These minimal changes are in the form of a small decrease in F2 frequency at the VC boundary and a small increase in F2 frequency at the CV boundary. Thus, if the tongue body remains in position during the production of [ɔCɔ] or [ɒCɒ] sequences with bilabial intervocalic stops, lip movement associated with the production of an intervocalic bilabial stop is expected to result in minimal changes in F2 frequency as described.

The study of Lindblom and Sussman (2002) showed that the tongue body moves to a lower and more forward position during bilabial closure in the context of [a]. The movement of the tongue towards a more forward position during stop closure results in relatively higher F2 values compared to the vocalic context. Thus, if the tongue does not maintain a back position during the production of [ɔCɔ] or [ɒCɒ] utterances, but rather starts moving into a neutral position at the VC boundary and recovers from the neutral position at the CV boundary, F2 is expected to show an increase in frequency at the VC boundary and a decrease at the CV boundary relative to the vocalic context.

Thus, two factors must be considered in the acoustic signal to determine whether the tongue body remains in position during the production of [ɔCɔ] or [ɒCɒ] utterances or goes through phases of deactivation and reactivation: (a) the extent and (b) the direction of F2 frequency change. If lip movement is the only factor involved in F2 frequency change at the VC and CV boundaries, the extent of F2 transition is expected to be minimal with F2 transition pattern being falling-rising. On the other hand, if the tongue body displaces from its position at the VC and CV boundary of [ɔCɔ] or [ɒCɒ] utterances, F2 transition is expected to show a rising-falling pattern. If the forward movement is considerable, the extent of frequency change at consonantal boundaries will be likewise considerable. If the forward movement is minimal the extent of frequency change will be likewise minimal.

To summarize, a maintained tongue position is expected to result in falling-rising F2 transition patterns in [ɔCɔ] and [ɒCɒ] utterances with minimal frequency changes at VC and CV boundaries. On the other hand, tongue body movement during the production of these utterances is expected to result in a reverse F2 transition pattern, i.e. a rising-falling pattern with variable extents of frequency change at VC and CV boundaries of these utterances.

4.2.2.1. Direction and Extent of F2 Transition

F2 transitions of the back vowels [ɔ] and [ɒ] into and from a bilabial closure were investigated to determine whether troughs or plateaus occurred in the speech samples of this study.

In order to achieve this goal, symmetrical VCV tokens where the intervocalic C was a voiced or voiceless aspirated bilabial stop and the flanking vowels were [ɔ] and [ɒ] for English and Persian speakers respectively were investigated. The extent of F2 transition was determined at VC and CV boundaries. The extent of F2 transition was defined as the difference between F2 offset and V_1 F2 mid point frequency (Offset-V_1 Mid) at the VC boundary and between V_2 F2 vowel mid point and F2 onset (V_2 Mid-Onset) at the CV boundary. The values thus obtained were positive, negative, or zero. Zero F2 transitions corresponded to cases where F2 vowel mid point frequency value was equal to F2 offset or F2 onset frequency. Negative F2 transition values represented falling F2 transitions, i.e. cases where V_1 F2 offset < V_1 F2 mid point at the V_1C boundary or where V_2 F2 onset > V_2 F2 mid point at the CV_2 boundary. Positive F2 transition values represented rising F2 transitions, i.e. cases where V_1 F2 offset > V_1 F2 mid point at the V_1C boundary or where V_2 F2 onset < V_2 F2 mid point at the CV_2 boundary. F2 transitions at VC and CV boundaries can show falling-falling, rising-rising, falling-rising, rising-falling, straight-

straight, straight-falling, straight-rising, falling-straight, or rising-straight patterns. These transition patterns, except for the patterns involving straight transitions, are shown in figure 4-20 below. Falling-falling transitions reflect lip movement effects at the VC boundary and tongue body as well as lip movement effects at the CV boundary. Rising-falling transitions are due to tongue body and lip movement at both boundaries. Rising-rising patterns reflect tongue body and lip movement effects at the VC and lip movement effects at the CV boundary. Falling-rising transitions are only due to lip movement at both boundaries.

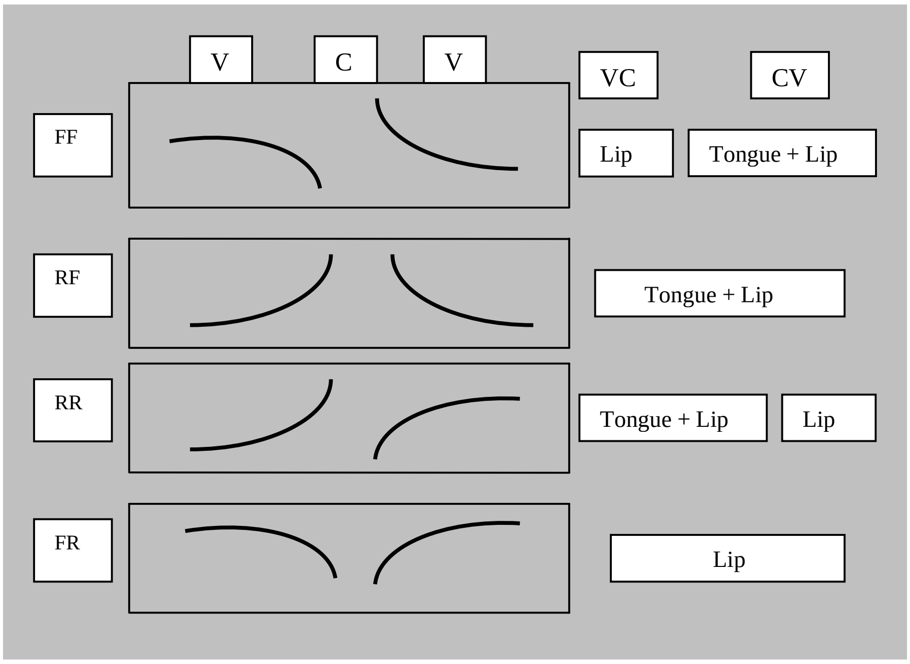


Figure 4-20. Schematic representation of Falling-Falling (FF), Rising-Falling (RF), Rising-Rising (RR), and Falling-Rising (FR) F2 transition patterns in [ɔCɔ] and [ɒCɒ] sequences with intervocalic bilabial stop.

The extent and direction of the F2 transition in [ɔ.bɔ] utterances produced by English speakers are presented in figures 4-21 and 4-22 below. In each graph and other graphs in this section, the extent of F2 transition at the VC boundary is plotted on the *x* axis and the extent of F2 transition at the CV boundary is plotted on the *y* axis. Each plot is divided into four sections each marked for the F2 transition pattern they signify. Points that fall on the *x* axis zero line show straight-falling or straight-rising F2 transition patterns depending on whether the point falls below or above the *y* axis zero line. Points that fall on the *y* axis zero line show falling-straight or rising-straight F2 transition patterns depending on whether the point falls below or above the *x* axis zero line. Points that fall on the intersection of the two zero lines indicate straight-straight F2 transition patterns. Actual data points are shown using diamonds. Average of all data points are shown using circles. The vowels [ɔ] and [ɒ] are represented as [aw] and [a] respectively in the figures.

Figure 4-21 shows the extent and direction of F2 transition in [ɔ.bɔ] sequences produced by English speakers. In total, 15 utterances were investigated (1V*1C*5SUB*3REP). On average, F2 fell by 50 Hz at the VC boundary and rose by 45 Hz at the CV boundary. The minimal fall and rise in F2 frequency at consonantal boundaries indicated that the tongue body was in position for the vowels at these boundaries and lip movement was the only factor responsible for minimal changes in F2 frequency.

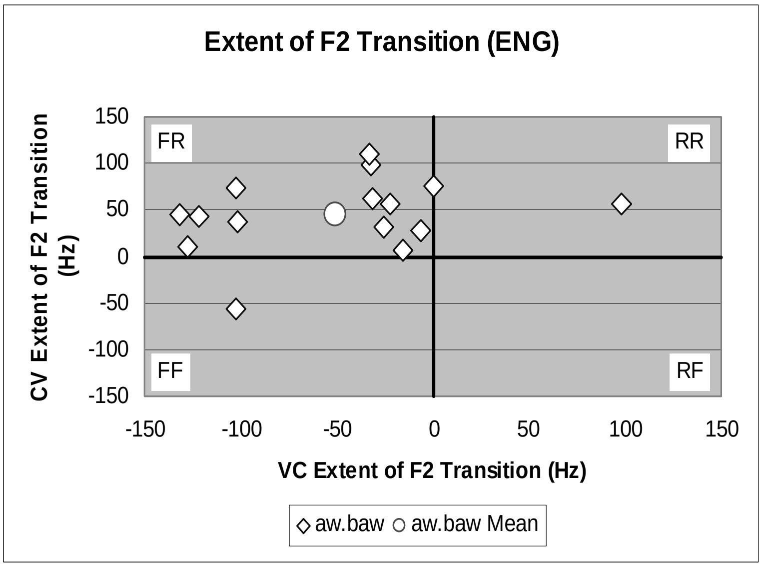


Figure 4-21. Extent of F2 transition at VC and CV boundaries in [ɔ.bɔ] utterances produced by English speakers. Diamonds show actual data points. The circle shows average values of individual data points.

Figure 4-22 shows the extent of F2 transition in [ɔ.pʰɔ] utterances produced by English speakers. In total, 15 utterances were investigated (1V*1C*5SUB*3REP). Although all F2 transition patterns except for a rising-rising pattern were observed with [i.pʰi] sequences, on average F2 transitions showed a falling-falling pattern. F2 fell by 24 Hz at the VC and by 67 Hz at the CV boundary. While the minimal fall in F2 frequency at the VC boundary reflects lip movement effects only with a maintained tongue position, the fall in F2 frequency at the CV boundary reflects tongue body as well as lip movement effects at this boundary.

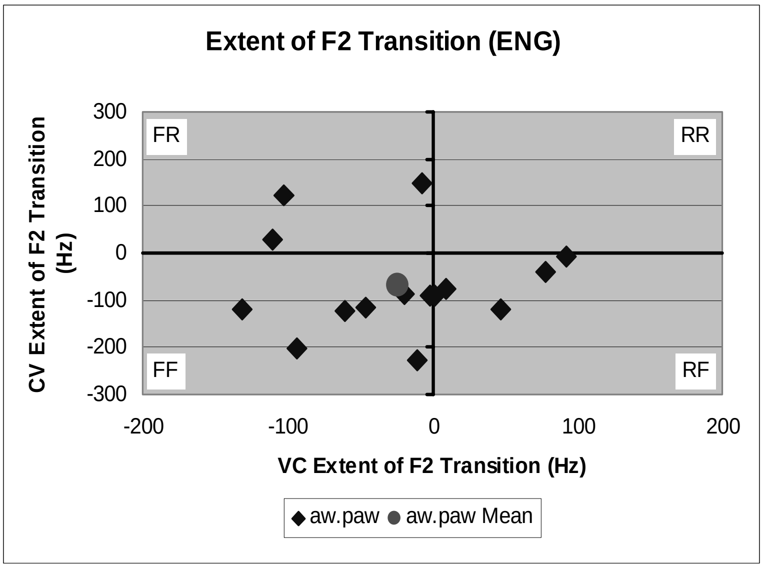


Figure 4-22. Extent of F2 transition at VC and CV boundaries in [ɔ.pʰɔ] utterances produced by English speakers. Diamonds show actual data points. The circle shows average values of individual data points.

Voiced and voiceless aspirated bilabial stops showed different F2 transition patterns in [ɔCɔ] sequences produced by English speakers. While the data from [ɔ.bɔ] utterances indicated vowel-to-vowel movement with maintained low back tongue position, the data from [ɔ.pʰɔ] utterances showed some effects of tongue body recovery from a neutral position at the CV boundary. The difference in F2 transition patterns of voiced and voiceless aspirated bilabial stops are shown in figure 4-23. In this figure, average F2 frequencies at V_1 mid point, V_1 offset, V_2 onset and V_2 mid point are plotted for English speakers and connected to create F2 traces. Points 1-4 on the *x* axis indicate average F2 values at these four points. The solid line shows average F2 trace of [ɔ.bɔ] utterances.

Average F2 trace of [ɔ.pʰɔ] utterances is shown by the dashed line. The line connecting points 2 and 3 in this graph are interpolations between V_1 offset and V_2 onset and do not represent actual observed F2 frequencies during consonantal closure. In figure 4-23, each trace represents an average of 15 utterances (1V*1C*5SUB*3REP). On average, V_1 F2 offset was minimally higher in frequency (20 Hz) in [ɔ.pʰɔ] compared to [ɔ.bɔ] utterances. V_2 F2 onset was, on the other hand, considerably higher in frequency (108 Hz) in [ɔ.pʰɔ] compared to [ɔ.bɔ] utterances. This is while V_1 and V_2 mid points were respectively only 5 and 7 Hz different. Note that shape of the F2 trace of [ɔ.pʰɔ] utterances produced by English speakers is the reverse of an acoustic trough.

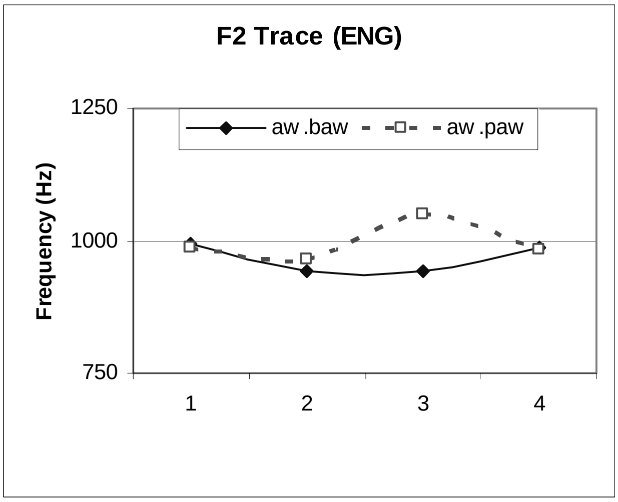


Figure 4-23. Average F2 traces of voiced and voiceless aspirated singleton and geminate stop consonants in ɔ-ɔ context produced by English speakers. Points 1-4 represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closure.

Figure 4-24 shows, the extent of F2 transition in [ɒ.bɒ] sequences produced by Persian speakers. In total, 6 utterances were investigated (1V*1C*2SUB*3REP). As with the English data, all data points fell in the falling-rising category in the [ɒ.bɒ] utterances produced by Persian speakers. On average, F2 decreased by 112 Hz at the VC boundary and increased by 77 Hz at the CV boundary. The falling-rising F2 transition pattern observed with Persian utterances indicate that the changes in F2 frequency at consonantal boundaries were only due to lip movement. However, lip movement is not expected to result in considerable F2 frequency change as seen at the VC boundary of [ɒ.bɒ] utterances produced by Persian speakers. The extensive fall in F2 transition at the VC boundary of these utterances indicates a backward tongue body movement relative to the vocalic context. As [ɒ] is a low vowel in Persian, one speculation is that the gradual jaw elevation towards lip closure at the VC boundary of [ɒ.bɒ] utterances is accompanied by a gradual backward movement of the tongue body resulting in lower F2 frequencies at V_1 offset relative to vowel mid point.

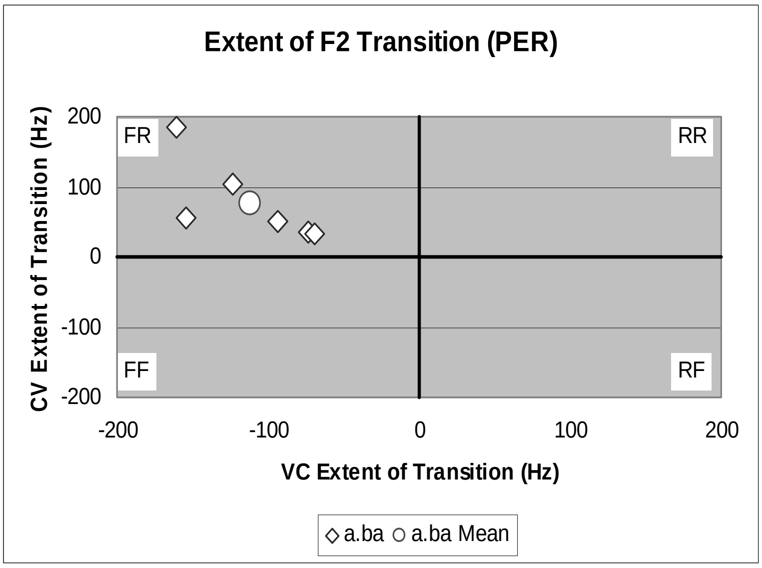


Figure 4-24. Extent of F2 transition at VC and CV boundaries in [ɒ.bɒ] utterances produced by Persian speakers. Diamonds show actual data points. The circle shows average values of individual data points.

Figure 4-25 shows the extent of F2 transition in [ɒ.pʰɒ] sequences produced by Persian speakers. In total, 6 utterances were investigated (1V*1C*2SUB*3REP). Although all F2 transition patterns were observed with the [ɒ.pʰɒ] utterances, the average value showed a falling-rising F2 transition pattern. On average, F2 decreased by 57 Hz at the VC boundary and increased by 40 Hz at the CV boundary. The average value was misleading due to the effects of the single utterance that showed a falling-rising F2 transition pattern. No general patterns were obvious.

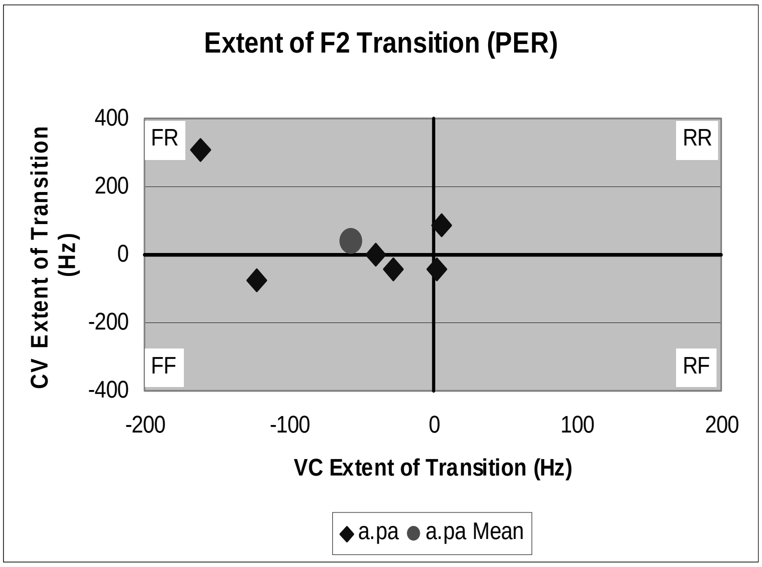


Figure 4-25. Extent of F2 transition at VC and CV boundaries in [ɒ.pʰɒ] utterances produced by Persian speakers. Diamonds show actual data points. The circle shows average values of individual data points.

Figure 4-26 shows F2 traces of [ɒ.bɒ] and [ɒ.pʰɒ] utterances produced by Persian speakers. Each trace is an average of 6 tokens (1V*1C*2SUB*3REP). The only difference between utterances containing voiced and voiceless aspirated bilabial stops was that F2 was on average higher in [ɒ.pʰɒ] than in [ɒ.bɒ] utterances at all measurement points. Both utterance types showed falling-rising patterns as shown previously in figures 4-24 and 4-25. No evidence of tongue body movement was evident from the transition patterns of the utterances produced by Persian speakers. Nevertheless, the extensive fall observed in F2 transition at the VC boundary of [ɒ.bɒ] utterances was not expected if the lips were the only factor involved. The fall in F2 transition at the VC boundary of these utterances indicates backward tongue body movement relative to the vocalic context.

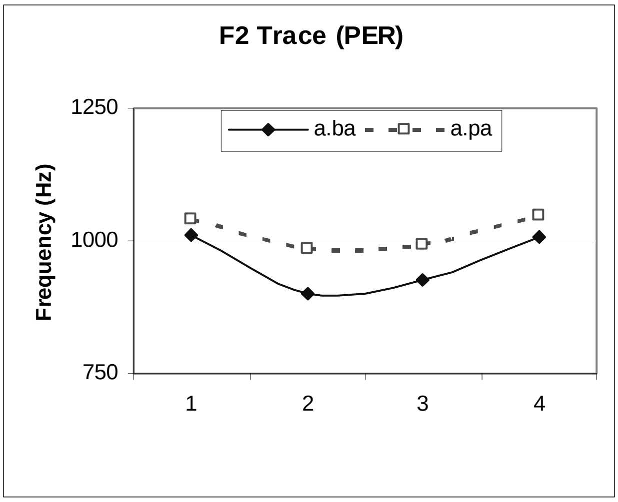


Figure 4-26. Average F2 traces of voiced and voiceless aspirated singleton and geminate stop consonants in ɒ-ɒ context produced by Persian speakers. Points 1-4 represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closure.

In general no evidence of tongue body movement was found in F2 transitions of [ɔ.bɔ] and [ɒ.pʰɒ] utterances produced by English and Persian speakers. Only [ɔ.pʰɔ] utterances produced by English speakers showed evidence of tongue body movement at the CV boundary. Only [ɒ.bɒ] utterances produced by Persian speakers showed evidence of tongue body movement at the VC boundary. The lack of evidence in favor of tongue body movement at the VC and CV boundaries of [ɔ.bɔ] and [ɒ.pʰɒ] utterances does not totally rule out the prossibility of tongue body displacement during consonantal closure. Moreover, since the closure duration of the intervocalic stops was relatively small in these utterances, any tongue body displacements that might have happened at the VC and CV boundaries might have been too subtle to show up in the acoustic signal.

A phoneme-by-phoneme view predicts greater tongue body deactivation patterns as the temporal distance between the two vocalic gestures is increased. This hypothesis was tested by comparing open [V_1.CV_2] with closed [V_1C.V_2] and geminate [V_1C.CV_2] utterances where the temporal distance between V_1 and V_2 was greater in the latter two compared to the former utterance type.

In both open [V_1.CV_2] and closed [V_1C.V_2] utterances, V_1 and V_2 belonged to different syllables, but in closed tokens an additional period of pause intervened between the release of the syllable-final stop and the acoustic beginning of V_2. This period of pause caused the two tongue body gestures to be temporally more apart than in open syllables and as a result make tongue body deactivation more prominent. Consequently, tongue body deactivation effects should be more evident in the acoustic signal. The results of investigating the effects of syllable boundary on the extent and direction of F2 transition of back vowels are presented in section 4.4.1.

In geminate [V_1C.CV_2] utterances, the distance between the two vowels is greater than in singleton [V_1.CV_2] utterances due to longer intervocalic stop closure durations. Again, as the temporal distance between the two tongue body gestures for the two vowels increases, the tongue body will have more time to deviate from its position for V_1 and the effects of this greater deactivation should be more detectable in the acoustic signal. The results of investigating the effects of stop consonant closure duration on the extent and direction of F2 transition of low back vowels are presented in section 4.4.2.

4.2.2.2. The Effects of Syllable Boundary on the Direction and Extent of F2 Transition

In order to investigate the effects of syllable boundary on the extent and direction of F2 transition of back vowels, symmetrical open [$V_{1.}CV_2$] utterances where the intervocalic bilabial consonant was syllabified with V_2 were compared with closed [$V_1C.V_2$] utterances where the intervocalic bilabial stop was syllabified with V_1.

The extent and direction of F2 transition was determined at VC and CV boundaries in [ɔb.ɔ] and [ɔp.ɔ] utterances produced by English speakers. A total of 15 tokens (1V*1C*5SUB*3REP) were investigated for each utterance type. For the sake of comparison, figures 4-27 and 4-28 below repeat the data for open syllable forms previously presented in figures 4-21 and 4-22. In the figures included in this section, data points showing the extent of F2 transition of open syllables are shown using diamonds. Average of these data points are shown using circles. Data points showing the extent and direction of F2 transition of closed syllables are shown using cross signs. Averages of these data points are shown using plus signs.

As figure 4-27 shows, closed [ɔb.ɔ] forms on average showed a falling-falling (straight-falling) pattern as opposed to open forms which showed a falling-rising pattern. F2 fell by 8 Hz at the VC and by 122 Hz at the CV boundary in closed syllables. Minimal changes in F2 frequency at the VC boundary were only due to the effects of lip closure gestures, while the considerable fall in F2 frequency at the CV boundary were due to tongue body movement effects.

Although the average value showing the extent and direction of F2 transition of closed syllable forms showed a falling-falling (straight-falling) pattern, the majority of the cases showed a rising-falling pattern as initially predicted. It can be inferred indirectly from F2 transition patterns that greater temporal distance between V_1 and V_2 in closed syllable forms resulted in greater extents of deactivation and reactivation of the tongue body gestures. In tokens that showed a rising-falling pattern, greater F2 offset frequencies relative to V_1 midpoint and greater F2 onset frequencies relative to V_2 midpoint indicate more advanced tongue body position at the VC and CV boundaries relative to vowel mid points.

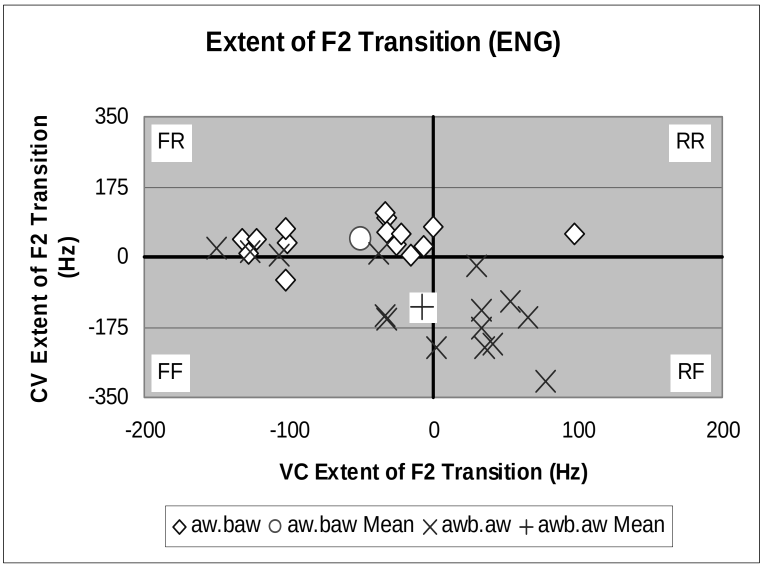


Figure 4-27. Extent of F2 transition at VC and CV boundaries in [ɔ.bɔ] and [ɔb.ɔ] utterances produced by English speakers. Diamonds and crosses show actual data points. The circle and plus signs show average values of individual data points.

As figure 4-28 shows, closed [ɔp.ɔ] forms on average showed a rising-falling pattern as opposed to open [ɔ.pʰɔ] forms which showed a falling-falling pattern. F2 increased by 17 Hz at the VC boundary and fell by 146 Hz at the CV boundary in [ɔp.ɔ] utterances. The increase in F2 frequency at the VC boundary is minimal and does not indicate tongue body movement effects. The fall in F2 frequency at the CV boundary of [ɔp.ɔ] utterances, nevertheless indicates tongue body movement effects at this boundary.

No major differences were detected in the general F2 transition patterns of closed [ɔp.ɔ] and open [ɔ.pʰɔ] utterances produced by English speakers. In both cases, F2 transition patterns indicate maintained tongue body position at the VC and tongue body movement at the CV boundaries. As with [ɔb.ɔ] utterances, greater F2 onset frequencies relative to V_2 midpoint indicate more advanced tongue body position at the CV boundary relative to vowel mid point.

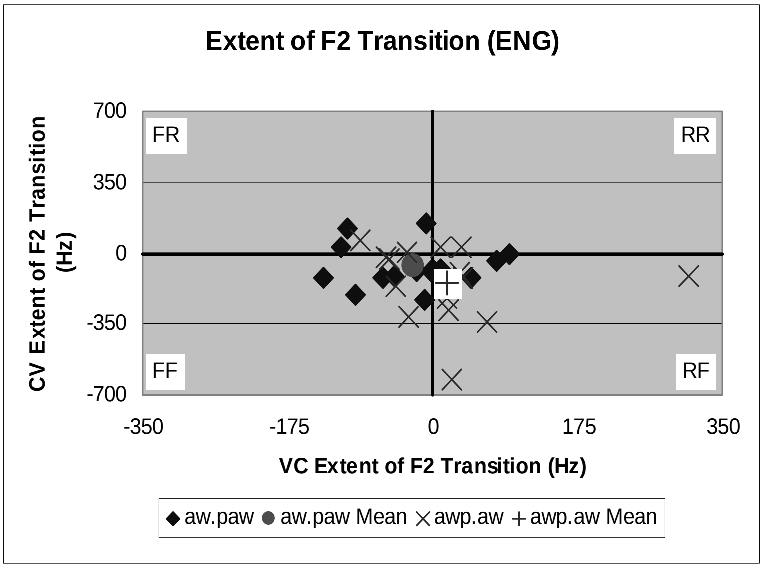


Figure 4-28. Extent of F2 transition at VC and CV boundaries in [ɔ.pʰɔ] and [ɔp.ɔ] utterances produced by English speakers. Diamonds and crosses show actual data points. The circle and plus signs show average values of individual data points.

The difference in the transition patterns of [ɔ.bɔ] versus [ɔb.ɔ] and [ɔ.pʰɔ] versus [ɔp.ɔ] sequences are captured in figures 4-29 and 4-30 respectively. In these graphs, F2 frequencies at V_1 mid point, V_1 offset, V_2 onset and V_2 mid point of the respective utterances are plotted along the *x* axis, with points 1-4 indicating averages of these for points. Solid lines show average F2 trace of open [ɔ.bɔ] and [ɔ.pʰɔ] utterances. Average F2 traces of closed [ɔb.ɔ] and [ɔp.ɔ] utterances are shown by dashed lines in each graph. The line connecting points 2 and 3 in open and closed syllable traces are interpolations between V_1 F2 offset and V_2 F2 onset and do not represent actual observed F2 frequencies during consonantal closure. Likewise, the lines connecting points 3 and 4 in closed syllable traces are interpolations between V_2 F2 onset and V_2 F2 mid point respectively and do not represent actual observed F2 frequencies during the pause period that intervened between F2 onset and F2 mid point. Each trace represents an average of 15 utterances (1V*1C*5SUB*3REP).

As figures 4-29 and 4-30 show, F2 onset was considerably higher in frequency in closed versus open syllable forms produced by English speakers. On average, F2 onset was 175 Hz higher in [ɔb.ɔ] compared to [ɔ.bɔ] utterances. F2 onset was 63 Hz higher in [ɔp.ɔ] compared to [ɔ.p^{h}ɔ] utterances. The falling-falling transition pattern of closed [ɔb.ɔ] utterances compared to the falling-rising pattern of their open counterparts is evident in figure 4-29. The more exaggerated F2 transition pattern of closed [ɔp.ɔ] utterances compared to their open counterparts is also apparent in figure 4-30.

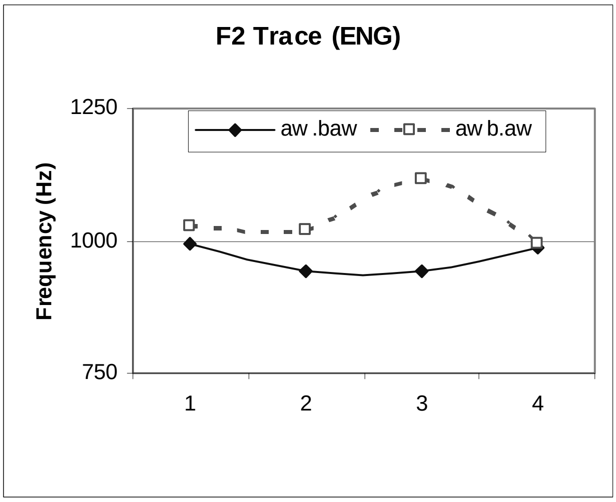


Figure 4-29. Average F2 traces of symmetrical open and closed syllables with intervocalic voiced bilabial stops in ɔ-ɔ context (English). Points 1-4 represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closure. The traces between points 3 and 4 in the closed form are interpolations during the pause period.

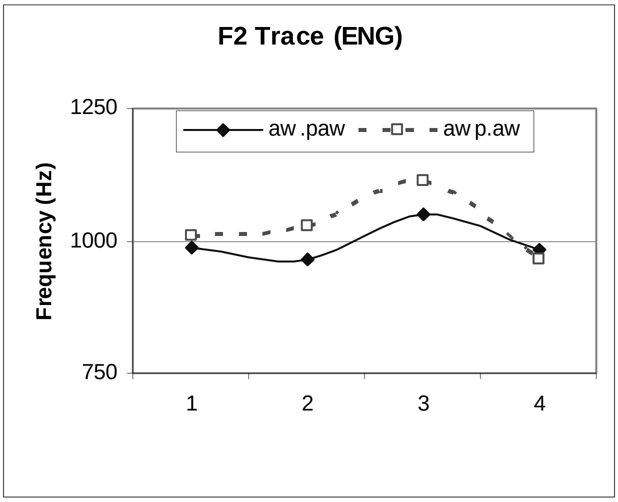


Figure 4-30. Average F2 traces of symmetrical open and closed syllables with intervocalic voiceless bilabial stops in ɔ-ɔ context (English). Points 1-4 represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closure. The traces between points 3 and 4 in the closed form are interpolations during the pause period.

Thus, when the temporal distance between V_1 and V_2 was increased in closed [ɔb.ɔ] utterances produced by English speakers, tongue body displacement effects were observed at the CV boundary these utterances. Increasing the temporal distance between V_1 and V_2 in [ɔp.ɔ] utterances resulted in more exaggerated patterns.

Figure 4-31 shows a comparison of F2 traces of closed [ɔb.ɔ] and [ɔp.ɔ] previously presented in figures 4-29 and 4-29 for English speakers. No differences were detected in the F2 transition patterns of closed syllable as a function of the voicing properties of the intervocalic bilabial stops.

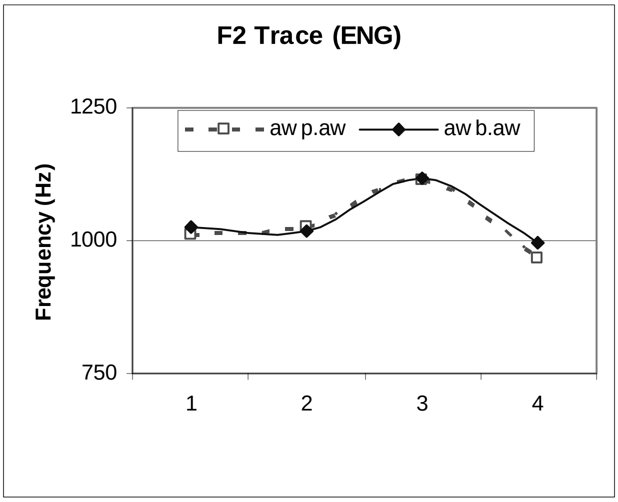


Figure 4-31. Average F2 traces of symmetrical closed syllables with intervocalic voiced and voiceless bilabial stops in ɔ-ɔ context (English). Points 1-4 represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closure. The traces between points 3 and 4 are interpolations during the pause period.

The extent and duration of F2 transition was determined in the VC and CV boundaries of [ɒb.ɒ] and [ɒp.ɒ] utterance produced by Persian speakers. A total of 5 tokens (1V*1C*2SUB*3REP) were investigated for closed syllable forms. For the sake of comparison, figures 4-32 and 4-33 below repeat F2 transition values for open syllable forms previously presented in figures 4-24 and 4-25. Data points showing the extent of F2 transition of open syllables are shown by diamonds in figures 4-32 and 4-33. Average of these data points are shown using circles. Data points showing the extent and direction of F2 transition of closed syllables are shown using cross signs in each graph. Averages of these data points are shown using plus signs.

From the total of 5 [ɒb.ɒ] utterances produced by Persian speakers only one token showed a rising-falling F2 transition pattern as originally predicted. The rest of the tokens showed a falling-straight pattern. On average, F2 fell by 126 Hz at VC and increased only 2 Hz at the CV boundary. The falling-straight transition pattern observed with closed [ɒb.ɒ] utterances produced by Persian speakers indicates no tongue body movement effects at the CV boundary of these utterances. Nevertheless, the extensive decrease in F2 transition at the VC boundary of these utterances is unexpected if lips are the only factors involved. The considerably lower F2 frequency at the VC boundary of closed [ɒb.ɒ] utterances relative to V_1 mid point indicates tongue body retraction associated with jaw elevation towards bilabial closure at this boundary.

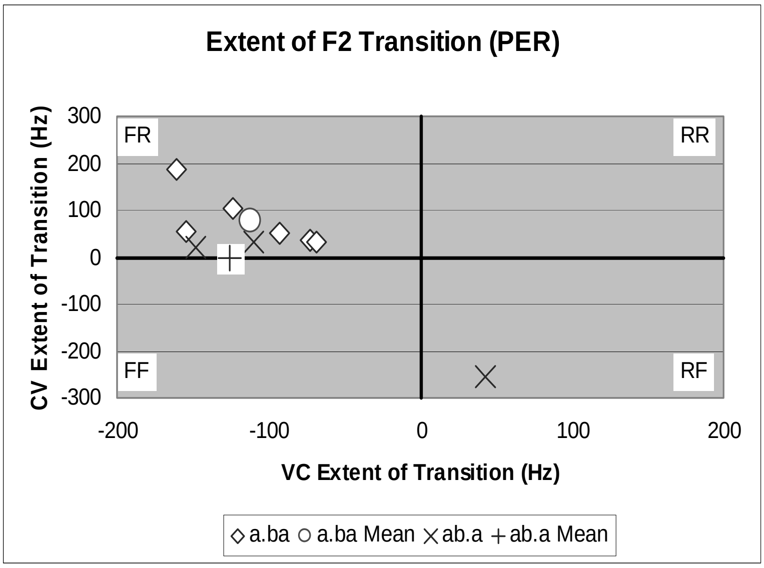


Figure 4-32. Extent of F2 transition at VC and CV boundaries in [ɒ.bɒ] and [ɒb.ɒ] utterances produced by Persian speakers. Diamonds and crosses show actual data points. The circle and plus signs show average values of individual data points.

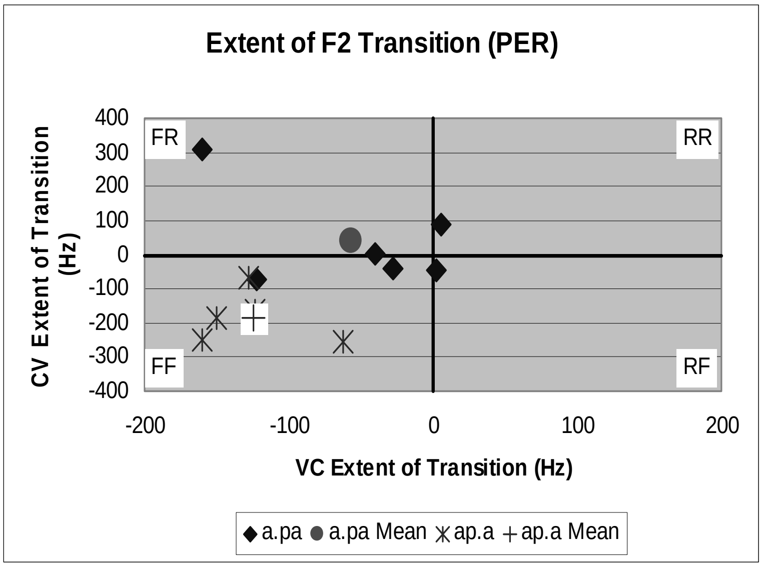


Figure 4-33. Extent of F2 transition at VC and CV boundaries in [ɒ.pʰɒ] and [ɒp.ɒ] utterances produced by Persian speakers. Diamonds and crosses show actual data points. The circle and plus signs show average values of individual data points.

As figure 4-33 shows, all data points representing F2 transitions of closed [ɒp.ɒ] utterances produced by Persian speakers had a falling-falling pattern. On average, F2 fell by 125 Hz at the VC and by 184 Hz at the CV boundary. The considerable decrease in F2 frequency at the VC boundary is observed again in these tokens indicating tongue body retraction due to jaw elevation towards bilabial closure. The relatively higher F2 onset frequency compared to V_2 F2 midpoint, on the other hand, indicates a more advanced tongue body position at F2 onset compared to vowel midpoint.

The transition patterns of closed syllable forms produced by Persian speakers are compared with their open counterparts in figures 4-34 and 4-35 below. Each trace represents an average of 6 (1V*1C*2SUB*3 REP) utterances for open syllable forms and 5 for closed syllable forms. The falling-straight transition pattern of closed [ɒb.ɒ] compared to the falling-falling transition pattern of open [ɒ.bɒ] utterances is shown in figure 4-34. Likewise, the falling-falling pattern of closed [ɒp.ɒ] utterances compared to the falling-falling transition pattern of open [ɒ.pʰɒ] utterances is shown in figure 4-35.

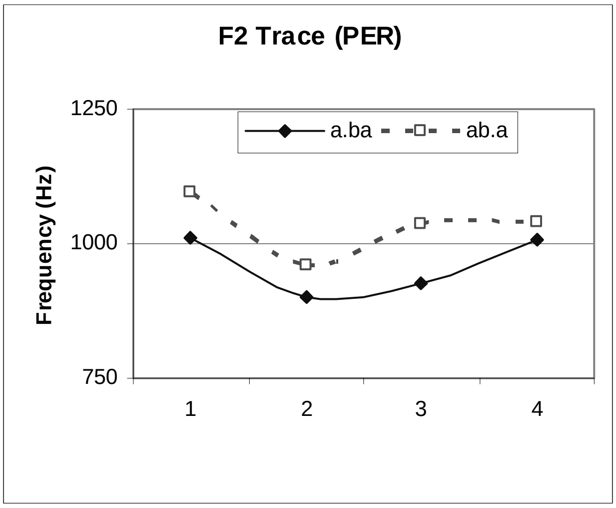


Figure 4-34. Average F2 traces of symmetrical open and closed syllables with intervocalic voiced bilabial stops in ɒ-ɒ context (Persian). Points 1-4 represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closure. The traces between points 3 and 4 in the closed form are interpolations during the pause period.

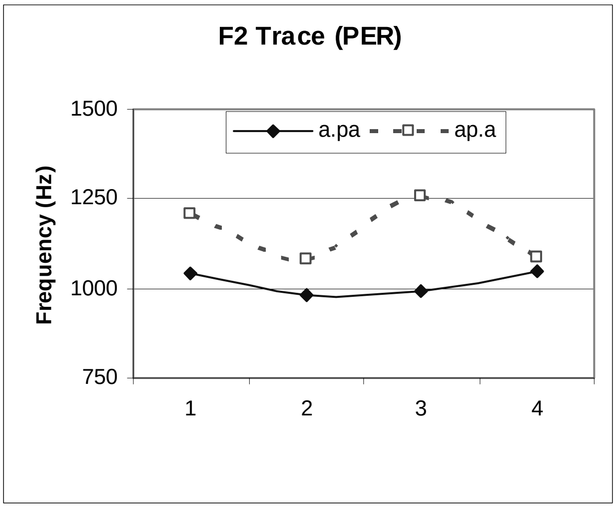


Figure 4-35. Average F2 traces of symmetrical open and closed syllables with intervocalic voiceless bilabial stops in ɒ-ɒ context (Persian). Points 1-4 represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closure. The traces between points 3 and 4 in the closed form are interpolations during the pause period.

Thus, when the temporal distance between V_1 and V_2 was increased in closed [ɒb.ɒ] utterances produced by Persian speakers, no major differences in F2 transition patterns were observed. Increasing the temporal distance between V_1 and V_2 in [ɒp.ɒ] utterances, however, resulted in the emergence of tongue body displacement effects at the CV boundary of these utterances.

Figure 4-36 shows a comparison of F2 traces of closed [ɔb.ɔ] and [ɔp.ɔ] previously presented in figures 4-34 and 4-35 for Persian speakers. Both cases showed a falling F2 transition pattern at the VC boundary. F2 transition was straight from the release of [b] to the following vowel. F2 transition had a falling pattern from the release of [p] to the following vowel. The results indicate that the tongue body had been in position for V_2 at the release of [b], but had been in a more advanced position at the release of [p] relative to V_2 midpoint.

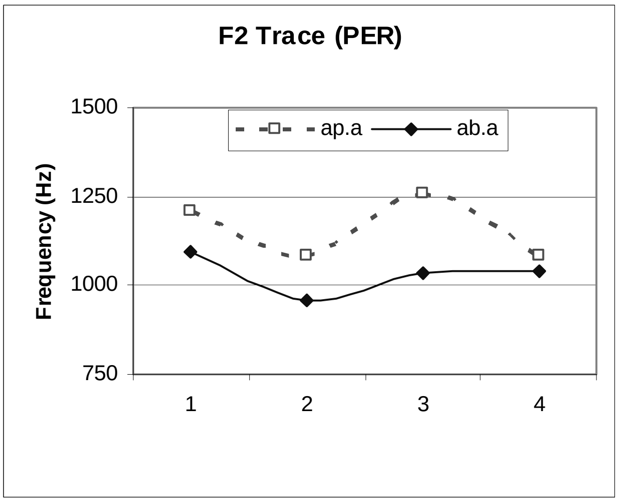


Figure 4-36. Average F2 traces of symmetrical closed syllables with intervocalic bilabial stops in ɒ-ɒ context (Persian). Points 1-4 represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closure. The traces between points 3 and 4 are interpolations during the pause period.

To summarize, greater temporal distance between the tongue body gestures for V_1 and V_2 in closed syllable forms resulted in changes in F2 transition patterns previously observed with open syllables. The closed [ɔb.ɔ] utterances produced by English speakers showed a falling-falling pattern as opposed to their open counterparts that showed a falling-rising F2 transition pattern. The closed [ɒp.ɒ] utterances produced by Persian speakers also showed a falling-falling transition pattern. These results reflected tongue body movement effects at the CV boundary in these utterances. The closed [ɔp.ɔ] utterances produced by English speakers showed a rising-falling pattern which also indicated tongue body involvement at the VC as well as the CV boundary. The closed [ɒb.ɒ] utterances produced by Persian speakers showed a falling-straight pattern which did not reflect any tongue body movement at all.

Figure 4-37 below shows a spectrographic display of an [ɔb.ɔ] utterance produced by speaker #E1 with a rising-falling F2 transition pattern. The second formant is traced during V_1, during bilabial closure, at the release of [b], and during V_2. Note the presence of resonances during the stop closure. The increase in F2 frequency at V_1 mid point compared to V_1 offset is only 35 Hz in this utterance. The F2 resonance that shows up during the closure duration gradually increases in frequency towards the release of the intervocalic stop. V_2 F2 onset measured at the marked point on the spectrogram has a frequency of 1187 Hz, which is 237 Hz higher than V_1 F2 midpoint and 226 Hz higher that V_2 F2 mid point in this utterance. The increase in F2 frequency observed during stop closure and at V_2 F2 onset indicates tongue body advancement during and at the release of the bilabial stop relative to V_1 and V_2 midpoint. Had the tongue body remained in the low back position required for the vocalic context, the frequency of F2 onset would have been closer to the F2 frequency of the vocalic context.

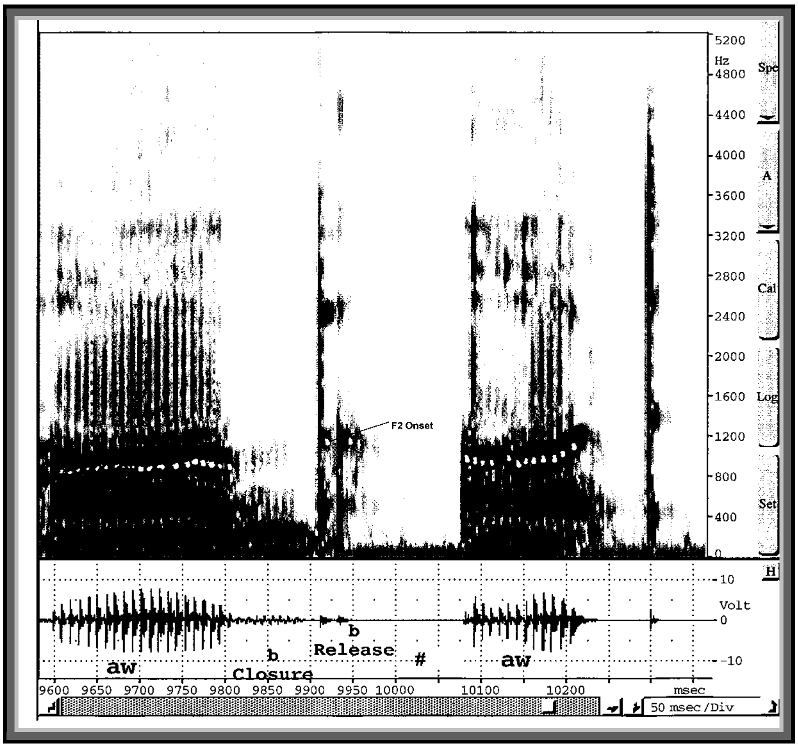


Figure 4-37. Spectrogram of one [ɔb.ɔ] utterance produced by speaker E#1. F2 onset measurement point at the release of the syllable-final stop is marked.

4.2.2.3. The Effects of Stop Closure Duration on the Direction and Extent of F2 Transition

In order to investigate the effects of bilabial stop consonant closure duration on the extent and direction of the F2 transition of back vowels, the extent and direction of F2 transition was compared in symmetrical singleton open [V.CV] and geminate [VC.CV] utterances.

The extent and direction of F2 transition was determined in VC and CV boundaries [ɔb.bɔ] and [ɔp.pʰɔ] utterances produced by English speakers. A total of 15 tokens (1V*1C*5SUB*3REP) were investigated for each utterance type. For the sake of comparison, figures 4-38 and 4-39 below repeat data for singleton forms previously presented in figures 4-27 and 4-28. Data points showing the extent of F2 transition of singleton forms are shown using diamonds. Average of these data points are shown using circles. Data points showing the extent of F2 transition in geminate forms are shown using cross signs. Averages of these data points are shown using plus signs.

As figure 4-38 shows, F2 transition patterns were in general the same in singleton [ɔ.bɔ] and geminate [ɔb.bɔ] utterances. Both cases showed a falling-rising pattern. In the geminate forms, F2 fell by 37 Hz at the VC (vis-à-vis 50 Hz for singletons) and increased by 34 Hz at the CV boundary (vis-à-vis 45 Hz for singletons). These results indicate that lip movement only was responsible for the minor changes in F2 frequency at VC and CV boundaries of both token types and that increasing the duration of the intervocalic stop consonant did not result in greater tongue body displacement effects and consequently in a change in F2 transition patterns.

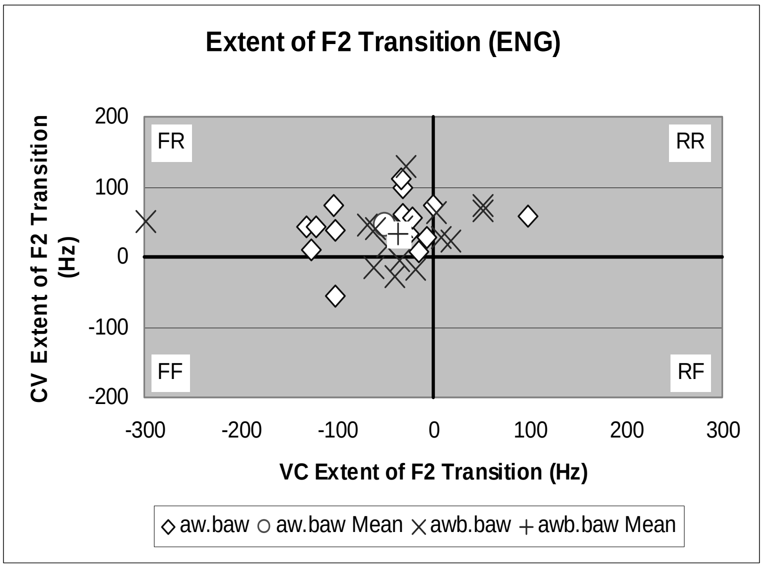


Figure 4-38. Extent of F2 transition at VC and CV boundaries in [ɔ.bɔ] and [ɔb.bɔ] utterances produced by English speakers. Diamonds and crosses show actual data points. The circle and plus signs show average values of individual data points.

Figure 4-39 shows the extent of F2 transition in [ɔ.pʰɔ] and [ɔp.pʰɔ] utterances produced by English speakers. On average, geminate forms showed a falling-falling transition pattern similar to their singleton counterparts. On average, in geminate forms F2 fell by 33 Hz at the VC (vis-à-vis 24 Hz for singletons) and by 117 Hz at the CV boundary (vis-à-vis 67 Hz for singletons). These results indicate that in both singleton and geminate forms, lip movement only was responsible for the minimal F2 frequency change at the VC boundary. However, the relatively considerable decrease in F2 frequency at the CV boundary of singleton and geminate utterances reflects tongue body movement effects at this boundary.

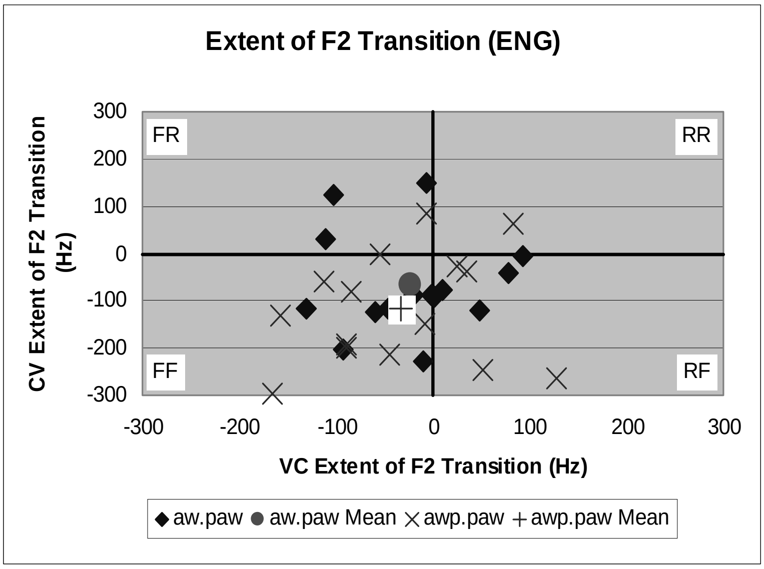


Figure 4-39. Extent of F2 transition at VC and CV boundaries in [ɔ.pʰɔ] and [ɔp.pʰɔ] utterances produced by English speakers. Diamonds and crosses show actual data points. The circle and plus signs show average values of individual data points.

Figure 4-40 below compares F2 transition patterns of voiced and voiceless aspirated stops in geminate forms produced by English speakers. The figure shows that F2 transition patterns are sensitive to the voicing properties of the intervocalic geminate consonant. While voiced geminate bilabials showed a falling-rising pattern, voiceless aspirated geminate stops showed a falling-falling pattern. F2 frequency at V_1 mid point, V_1 offset, and V_2 mid points of the two utterance types were respectively only 26, 27, and 7 Hz different in the two categories and relatively stable. On the other hand, V_2 F2 onset was on average 144 Hz higher in [ɔp.pʰɔ] compared to [ɔb.bɔ] utterances. The considerably higher F2 frequency at V_2 onset of voiceless aspirated bilabial stops relative to V_2 mid point indicates active tongue body movement associated with these consonants at the CV boundary.

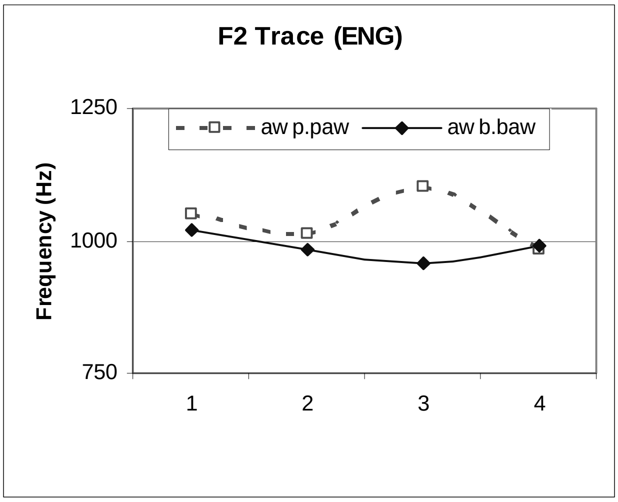


Figure 4-40. Average F2 traces of voiced and voiceless aspirated geminate stop consonants in ɔ-ɔ context produced by English speakers. Points 1-4 represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closure.

The extent of F2 transition was determined at the VC and CV boundaries in [ɒb.bɒ] and [ɒp.pʰɒ] utterance produced by Persian speakers. A total of 6 (1V*1C*2SUB*3REP) geminate tokens were investigated. The values for corresponding singleton forms are repeated in figures 4-41 and 4-42 for comparison. Data points showing the extent of F2 transition of singleton forms are shown using diamonds in these figures. Average of these data points are shown using circles. Data points showing the extent and direction of F2 transition of geminate syllables are shown using cross signs. Averages of these data points are shown using plus signs.

As figure 4-41 shows, all geminate [ɒb.bɒ] utterances produced by Persian speakers had a falling-rising pattern as did the singleton [ɒ.bɒ] utterances. On average, in geminate forms F2 fell by 178 Hz at the VC (vis-à-vis 112 Hz for singletons) and increased by 61 Hz at the CV boundary (vis-à-vis 77 Hz for singletons). No evidence of tongue body movement was found at the CV boundary of the [ɒb.bɒ] utterances produced by Persian speakers. The considerable drop in F2 frequency at the VC boundary of geminate utterances was not expected if the lips were the only articulators responsible for F2 frequency changes. Again, the extent of F2 transition at the VC boundary of [ɒb.bɒ] utterances produced by Persian speakers indicates tongue body retraction associated with jaw elevation towards bilabial closure at the VC boundary of these utterances.

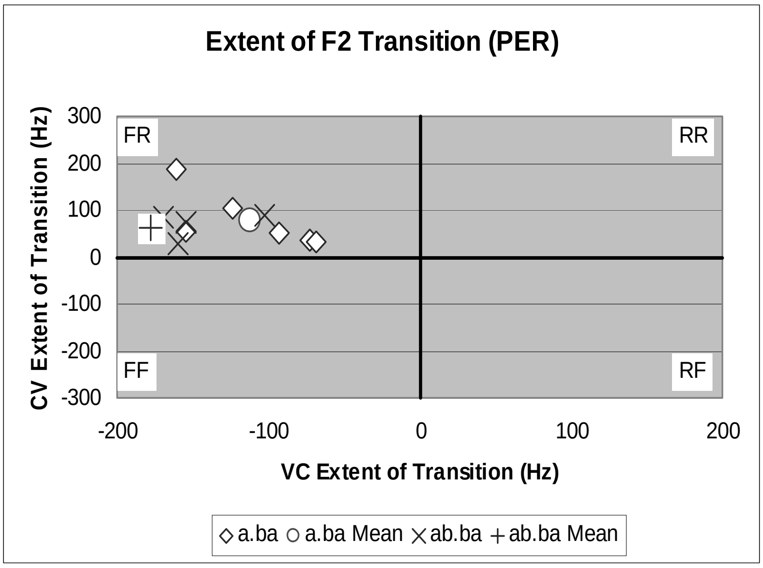


Figure 4-41. Extent of F2 transition at VC and CV boundaries in [ɒ.bɒ] and [ɒb.bɒ] utterances produced by Persian speakers. Diamonds and crosses show actual data points. The circle and plus signs show average values of individual data points.

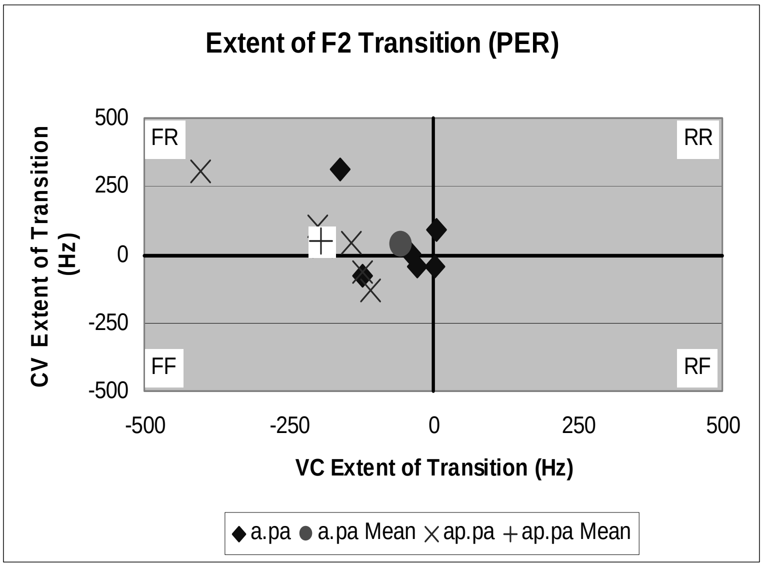


Figure 4-42. Extent of F2 transition at VC and CV boundaries in [ɒ.pʰɒ] and [ɒp.pʰɒ] utterances produced by Persian speakers. Diamonds and crosses show actual data points. The circle and plus signs show average values of individual data points.

As figure 4-42 shows, the geminate [ɒp.pʰɒ] utterances produced by Persian speakers showed a falling-rising transition pattern similar to their singleton counterparts. On average, in geminate forms F2 fell by 194 Hz at the VC (vis-à-vis 57 Hz for singletons) and increased by 47 Hz at the CV boundary (vis-à-vis 40 Hz for singletons). The relatively small change in F2 frequency at the CV boundary of geminate [ɒp.pʰɒ] utterances indicates lip movement effects while the tongue body is in position for V_2. The relatively considerable F2 frequency change at the VC boundary of geminate forms reflects the effects of jaw elevation on the position of the tongue in the vocal tract.

Figure 4-43 below compares F2 transition patterns of voiced and voiceless aspirated stops in geminate forms produced by Persian speakers. The figure shows no differences in the F2 transition patterns of voiced versus voiceless aspirated stops in geminate forms, except that F2 was on average higher in frequency at all measurement points in [ɒp.p^hɒ] compared to [ɒb.bɒ] utterances.

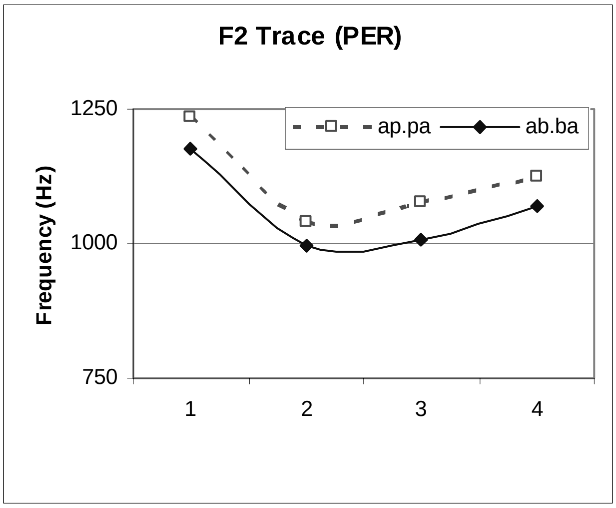


Figure 4-43. Average F2 traces of voiced and voiceless aspirated geminate stop consonants in ɒ-ɒ context produced by Persian speakers. Points 1-4 represent V_1 mid point, V_1 offset, V_2 onset and V_2 mid point respectively. The traces between points 2 and 3 are interpolations during C closure.

4.2.2.4. Summary and Discussion

A diphthongal vowel-to-vowel movement in symmetrical VCV utterances, where V is a back vowel and the intervocalic consonant is a bilabial stop, results in a falling-rising (lip-lip) F2 transition pattern with the extent of F2 transition being minimal at the consonantal boundaries. On the other hand, a tongue body deactivation-reactivation movement pattern in the same utterances was expected to result in a rising-falling (tongue+lip-tongue+lip) F2 transition pattern with the extent of F2 transition being variable.

Open singleton [V.CV] utterances produced by English and Persian speakers showed a falling-rising (lip-lip) F2 transition pattern with the extent of F2 transition being minimal. An exception to this general pattern was seen with [ɔ.pʰɔ] utterances produced by English speakers where a falling-falling (lip-tongue+lip) transition pattern was observed. The falling pattern of the CV transition of these utterances is not predicted under a superimposition scenario. Rather, it indicates that the tongue body is in a more forward position at the release of C relative to the position required for the production of the following back vowel.

When the temporal distance between the two vowels was increased in geminate forms, no changes in the above patterns were observed. The geminate utterances produced by English and Persian speakers showed a falling-rising (lip-lip) F2 transition pattern with the extent of F2 transition being minimal. Again, F2 transition of the geminate [ɔp.pʰɔ] utterances produced by English speakers showed an exception to this general pattern. They showed a falling-falling (lip-tongue+lip) F2 transition pattern with the extent of F2 transition at the CV boundary being considerable. The extent of F2 transition at the CV boundary was considerably higher in [ɔp.p^{h}ɔ] versus singleton [ɔ.p^{h}ɔ] forms, indicating more extensive tongue body displacement effects in the former compared to the latter.

The frequently observed falling-rising (lip-lip) F2 transition pattern of open/singleton and geminate utterances containing a voiced bilabial stop does not, however, eliminate the possibility of the occurrence of troughs during the stop closure period. In other words, although F2 transitions did not show evidence of tongue body movement at the VC and CV boundaries in these utterances, there is a possibility for tongue body displacement to have started and ended during stop consonant closure duration, making it impossible to detect any tongue body displacement effects.

The extent and direction of F2 transition were affected by the syllabic affiliation of the intervocalic stop in VCV sequences produced by English speakers. Closed [ɔb.ɔ] and [ɔp.ɔ] utterances showed a straight-falling (lip-tongue+lip) F2 transition pattern compared to their open counterparts where a falling-falling (lip-lip) F2 transition pattern was observed. Thus, increasing the temporal distance between the two vowels in closed versus open syllable forms resulted in more prominent tongue body displacement effects at the CV boundary of the former compared to the latter. These results were not replicated in the closed syllables produced by Persian speakers. No evidence of tongue body displacement effects was found in the [ɒb.ɒ] utterances produced by Persian speakers. Evidence of tongue body displacement was only found at the CV boundary of the [ɒp.ɒ] utterances produced by Persian speakers showing a falling-falling (lip-tongue+lip) pattern.

4.3. CONCLUSIONS

According to Perkell (1986) troughs are subtle articulatory events with no acoustic consequences. It was shown in this chapter that troughs have acoustic consequences despite their subtlety. Evidence of tongue body movement was found in the transitions of symmetrical VCV sequences produced by English and Persian speakers. Tongue body displacement effects emerged as ‘trough-like’ F2 transition patterns in the acoustic signal in the context of [i]. In the context of back vowels, tongue body displacement effects emerged as F2 transition patterns that were the reverse of a trough. In both cases, F2 transition patterns indicated more central tongue body positions relative to the vocalic context.

Although the data considered in this chapter was relatively small and evidence of tongue body movement was not found in all cases and under all conditions, the fact that tongue body movement was seen at the VC and CV boundaries of certain the utterances produced by certain speakers provides evidence in favor of a phoneme-by-phoneme view of segmental organization.

English and Persian speakers showed different patterns in many cases. Since the number of Persian speakers was relatively small and since the number of the utterances studied here was also small, the differences observed with the two groups of speakers should not be interpreted as reflecting differences between the two languages.

The strongest evidence of tongue body movement in symmetrical utterances produced by English and Persian speakers was found at the CV boundary of closed syllable forms. That was because the release of the syllable-final stop provided a window to tongue body position between the two vocalic gestures. Such a window was not available in open/singleton and geminate utterances, making tongue body movement effects more elusive and difficult to detect in these utterances.

Interesting differences were detected between the F2 transition patterns of [b] and [p]. Evidence of tongue body movement was found at the VC boundary of [iCi] sequences when the intervocalic stop was [b]. Evidence of tongue body movement was found at the CV boundary of these sequences when the consonant was [p]. In the context of back vowels, no evidence of tongue body movement effects was observed at the VC boundary when the intervocalic consonant was [b]. Tongue body movement effects were more prominent at the CV boundary when the intervocalic consonant was [p].

If F2 transition patterns observed in this chapter reflect tongue body displacement effects, other vocalic and consonantal environments should show these effects as well. In chapter 5, tongue body displacement is investigated at the CV boundary of closed versus open and singleton versus geminate syllable forms in all vocalic, consonantal, and voicing contexts using the locus equation paradigm to test this hypothesis.

Chapter 5: The Effects of Syllable Boundary, Stop Closure Duration, and VOT on CV_2 Coarticulation

In chapter 4, evidence of tongue body movement was found at the VC and CV boundaries of selected [V.CV] utterances. F2 transitions were affected by the voicing properties of the intervocalic stops. Evidence of tongue body movement was mainly found at the CV boundary of [V.p^hV] and at the VC boundary of [V.bV] utterances. Gemination did not result in more extensive F2 transitions indicative of more extensive tongue body movement. The strongest evidence of tongue body displacement was found in the F2 transitions at the CV boundary of closed syllable forms.

In this chapter, tongue body displacement effects are investigated on a broader scale considering all consonantal and vocalic contexts. The discussion is mainly limited to tongue body displacement at the CV boundary. The main goal of this broader investigation is to determine whether the general patterns observed in chapter 4 hold true in all consonantal and vocalic contexts considered in this study.

CV_2 coarticulation is investigated under the conditions of varying syllable boundary, stop consonant closure duration, and VOT using the locus equation paradigm. Section 5.1 includes an introduction to CV_2 coarticulation as indicated by locus equation slopes. The effects of syllable boundary on CV_2 coarticulation are discussed in section 5.2. Section 5.3 deals with the effects of stop consonant closure duration on CV_2 coarticulation. The effects of VOT on CV_2 coarticulation are discussed in section 5.4. A summary and discussion of the results obtained in this chapter appears in section 5.5.

5.1. INTRODUCTION

The locus equation (LE) paradigm is used to investigate tongue body displacement at the CV boundary of open/singleton, closed, and geminate utterances. The procedures for developing locus equation scatterplots and obtaining LE slopes were described in section 2.2.2. In short, locus equation scatterplots are derived by plotting F2 onset frequency values of a given stop consonant in CV combinations on the *y*-axis and F2 vowel frequency values of the following vowels on the *x*-axis. Regression lines are fitted to the data points thus plotted and the slope of the regression line is calculated. The slope of locus equation regression function reflects the degree of CV coarticulation. Relatively flat LE slopes indicate lower degrees of CV coarticulation. These are cases where F2 onset has a relatively fixed and less variable frequency than that of the following vocalic context. On the other hand, relatively steep LE slopes indicate higher degrees of CV coarticulation. These are cases where F2 onset varies with the following vowel.

Troughs are expected to result in relatively flatter LE slopes. That is because F2 onset values are expected to be more removed from F2 vowel frequency when the tongue is in a neutral position. According to the results obtained in chapter 4, LE slopes are expected to be lower in closed versus open, and for voiceless aspirated versus voiced stops. LE slopes are expected to remain stable irrespective of consonantal closure duration. These expectations are investigated below.

5.2. THE EFFECT OF SYLLABLE BOUNDARY ON CV_2 COARTICULATION

It was shown in chapter 4 that in closed syllable forms F2 onset frequency measured at the release of the syllable-final stop was considerably lower than F2 frequency of the surrounding front vowels. Taking F2 onset to reflect tongue body position at the release of the syllable-final stop, the relatively lower F2 frequency in front vowel contexts indicated more retracted tongue body position relative to the front position required for the vocalic context.

In back vowel contexts, F2 onset frequency measured at the release of the syllable-final stop was higher than F2 frequency of the surrounding back vowels. Relatively higher F2 frequency at the release of the syllable-final stop in these cases indicated relatively more forward tongue body position.

Both cases showed a tendency towards a more central tongue body position. This central place was taken to reflect maximum tongue body displacement. If the tongue body had remained in position for the surrounding vowels, F2 frequency at the release of the syllable-final stop would have been much closer to F2 frequency values of the surrounding vowels.

If F2 onset measured at the release of syllable-final stop in closed syllables indicates maximum tongue body displacement, it should be independent of vocalic and consonantal context. Differences in F2 frequency at the release of the syllable-final stop are expected to be observed as a function of the consonantal context due to the different effects that place of articulation has on F2 frequency. Nevertheless, F2 onset frequencies more removed from the frequency of the following vocalic context are expected to be observed at the release of the syllable-final stops irrespective of consonantal place of articulation.

In order to investigate this hypothesis, F2 onset values obtained at the release of the syllable-final stops were compared with the F2 values of the following vowels in closed syllables using the locus equation paradigm. Closed and open syllables were compared. LE slopes were expected to be lower in closed compared to open syllables, as F2 onset measured at the release of the syllable-final stop was expected to be more removed in frequency from F2 mid vowel than F2 onset measured after the release of the syllable-initial stop in open syllable forms.

Section 5.2.1 describes the procedures followed to produce locus equation scatterplots and obtain LE slope values for the two syllable forms. Results are discussed in sections 5.2.2 and 5.2.3 for English and Persian speakers respectively. Section 5.2.4 includes a summary and a discussion of the results obtained in this section.

5.2.1. Procedures

For any given stop consonant in CV_2 combination in open and closed syllable forms, locus equation scatterplots were obtained by plotting the F2 onset against F2 vowel values. A regression line was fit to the data points on the scatterplots and slope and y-intercept of the regression line were determined.

Each scatterplot included 75 data points ($5V_1$*1C*$5V_2$*3REP.) per English speaker. LE scatterplots of open and closed syllable forms produced by speaker P#2 included 108 ($6V_1$*1C*$6V_2$*3REP.) data points. Since one repetition of the closed syllable forms produced by speaker P#1 was discarded, the LE scatterplots of closed and open syllable forms produced by this speaker included 72 ($6V_1$*1C*$6V_2$*2REP.) and 108 data points respectively.

In the results sections, LE parameters obtained from CV_2 combinations in open and closed syllable forms are presented in tables. Individual scatterplots are not included.

5.2.2. English

Tables 5-1 to 5-6 contain locus equation slope (k) and y-intercept (c) values, as well as the coefficient of determination (R^2) and standard error (SE) values of the correlation between F2 onset of stop consonants and F2 vowel of V_2 in open versus closed syllables produced by English speakers. Locus equation slope values are an index of CV_2 coarticulation. R^2 and SE values indicate the linearity and tightness of clustering of data points. More linear and tighter data clustering along a regression line are characterized by greater R^2 and smaller SE values.

Speaker		**V.bV**					**Vb.V**		
	k	*c*	R^2	SE		*K*	*c*	R^2	SE
E#1	.76	256	.93	104		.31	848	.57	161
E#2	.83	182	.97	77		.27	896	.65	121
E#3	.81	234	.94	101		.22	1034	.48	128
E#4	.84	181	.96	92		.08	1224	.10	136
E#5	.78	240	.94	78		.22	993	.35	139
M	**.80**	**219**	**.95**	**90**		**.22**	**999**	**.43**	**137**
SD	**.03**	**35**	**.016**	**13**		**.09**	**146**	**.22**	**15**

Table 5-1. /bV/ locus equation statistics in open and closed syllable forms produced by English speakers.

Speaker		**V.pV**					**Vp.V**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.63	499	.92	98		.46	611	.75	157
E#2	.62	449	.91	97		.23	985	.64	102
E#3	.59	590	.83	123		.19	1088	.41	115
E#4	.63	540	.85	134		.09	1249	.09	172
E#5	.73	373	.90	101		.15	1143	.17	166
M	**.64**	**490**	**.88**	**111**		**.22**	**1015**	**.41**	**142**
SD	**.05**	**84**	**.04**	**17**		**14**	**245**	**.29**	**32**

Table 5-2. /pV/ locus equation statistics in open and closed syllable forms produced by English speakers.

Speaker		V.dV					Vd.V		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.38	1140	.69	126		.24	1313	.44	167
E#2	.47	999	.78	110		.10	1608	.40	76
E#3	.32	1322	.62	103		.15	1556	.28	128
E#4	.42	1122	.81	93		.04	1629	.03	138
E#5	.48	924	.76	89		.08	1564	.14	92
M	**.41**	**1101**	**.73**	**104**		**.12**	**1534**	**.26**	**120**
SD	**.07**	**152**	**.08**	**15**		**.77**	**127**	**.17**	**36**

Table 5-3. /dV/ locus equation statistics in open and closed syllable forms produced by English speakers.

Speaker		V.tV					Vt.V		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.18	1484	.45	97		.24	1289	.49	146
E#2	.27	1339	.59	93		.09	1582	.32	83
E#3	.23	1557	.54	92		.10	1709	.19	102
E#4	.20	1523	.53	90		.04	1606	.05	105
E#5	.29	1291	.55	90		.08	1554	.14	96
M	**.23**	**1439**	**.53**	**92**		**.11**	**1548**	**.24**	**106**
SD	**.05**	**117**	**.05**	**3**		**.08**	**156**	**.17**	**24**

Table 5-4. /tV/ locus equation statistics in open and closed syllable forms produced by English speakers.

Speaker		V.gV					Vg.V		
	k	*c*	R^2	SE		*K*	*c*	R^2	SE
E#1	.88	356	.92	135		.68	701	.82	192
E#2	.96	234	.87	183		.36	1215	.39	270
E#3	.78	566	.86	132		.47	1154	.58	198
E#4	1.01	93	.93	162		.33	1303	.21	372
E#5	.81	468	.86	133		.28	1344	.31	208
M	**.89**	**343**	**.89**	**149**		**.42**	**1143**	**.46**	**248**
SD	**.10**	**187**	**.03**	**23**		**.16**	**258**	**.24**	**76**

Table 5-5. /gV/ locus equation statistics in open and closed syllable forms produced by English speakers.

Speaker		V.kV					Vk.V		
	k	*c*	R^2	SE		*K*	*c*	R^2	SE
E#1	.75	531	.91	133		.72	582	.87	163
E#2	.97	185	.83	219		.44	1017	.48	271
E#3	1.04	309	.87	181		.39	1382	.45	221
E#4	1.05	131	.91	182		.31	1271	.23	335
E#5	.83	443	.84	152		.50	898	.56	224
M	**.93**	**320**	**.87**	**173**		**.47**	**1030**	**.52**	**243**
SD	**.13**	**169**	**.04**	**33**		**.16**	**316**	**.23**	**64**

Table 5-6. /kV/ locus equation statistics in open and closed syllable forms produced by English speakers.

Locus equation slope values of all stops were lower in closed syllable forms compared to open syllables, indicating that in closed syllables F2 onset was more removed in frequency from F2 vowel frequency than in open syllables. Averaging across all places of articulation and voicing conditions, the difference between slope values in open versus closed syllable forms was 0.39. An ANOVA run across all five English speakers showed that the difference in the slope values of closed and open syllable forms was statistically significant ($p<.0001$).

Locus equation y-intercept values were consistently higher in closed syllables compared to open syllables for all places of articulation and voicing conditions. On average, y-intercept values were 560 Hz greater in closed versus open syllables. This pattern was expected as a reverse relationship exists between slopes and y-intercepts.

R^2 values were consistently higher in open syllable forms (average R^2 = 0.81) compared to closed syllables (average R^2 = 0.39), indicating that F2 onset and F2 vowel were more correlated in open versus closed syllables. SE values were on average higher in closed syllables (average SE = 166 Hz) compared to open syllable forms (average SE = 120 Hz). In general, the correlation between F2 onset and F2 vowel was weaker in closed syllables compared to open syllable forms.

5.2.3. Persian

Tables 5-7 to 5-12 contain LE slope (k) and y-intercept (c) values, as well as the coefficient of determination (R^2) and standard error (SE) values of the correlation between F2 onset of each stop consonant and F2 vowel of V_2 in open versus closed syllables produced by Persian speakers.

Speaker		V.bV					Vb.V		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.88	118	.96	102		.30	758	.65	139
P#2	.86	73	.96	89		.39	669	.59	143
M	**.87**	**96**	**.96**	**96**		**.35**	**714**	**.62**	**141**
SD	**.01**	**32**	**0**	**9**		**.06**	**63**	**.04**	**3**

Table 5-7. /bV/ locus equation statistics in open and closed syllable forms produced by Persian speakers.

Speaker		V.pV					Vp.V		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.65	527	.91	119		.28	931	.61	132
P#2	.73	318	.85	144		.20	987	.22	167
M	**.69**	**443**	**.88**	**131**		**.24**	**959**	**.42**	**150**
SD	**.06**	**148**	**.04**	**17**		**.06**	**40**	**.28**	**25**

Table 5-8. /pV/ locus equation statistics in open and closed syllable forms produced by Persian speakers.

Speaker		V.dV					Vd.V		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.52	1013	.83	125		.19	1486	.50	114
P#2	.43	1008	.75	103		.20	1260	.48	91
M	**.48**	**1011**	**.79**	**114**		**.20**	**1373**	**.49**	**103**
SD	**.06**	**4**	**.06**	**16**		**.007**	**160**	**.01**	**16**

Table 5-9. /dV/ locus equation statistics in open and closed syllable forms produced by Persian speakers.

Speaker		V.tV					Vt.V		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.24	1541	.60	107		.07	1740	.19	85
P#2	.29	1257	.53	110		.08	1463	.08	135
M	**.27**	**1399**	**.57**	**109**		**.08**	**1602**	**.14**	**110**
SD	**.04**	**201**	**.05**	**2**		**.007**	**196**	**.08**	**35**

Table 5-10. /tV/ locus equation statistics in open and closed syllable forms produced by Persian speakers.

Speaker		V.gV					Vg.V		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.95	208	.94	141		.56	1108	.52	321
P#2	1.10	-57	.91	161		.64	766	.47	325
M	**1.03**	**76**	**.93**	**151**		**.60**	**937**	**.50**	**323**
SD	**.11**	**187**	**.02**	**14**		**.06**	**241**	**.04**	**3**

Table 5-11. /gV/ locus equation statistics in open and closed syllable forms produced by Persian speakers.

Speaker		V.kV					Vk.V		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.85	468	.86	187		.58	1145	.52	328
P#2	1.07	14	.84	207		.44	1010	.24	364
M	**.96**	**241**	**.85**	**197**		**.51**	**1078**	**.38**	**346**
SD	**.16**	**321**	**.01**	**14**		**.10**	**95**	**.20**	**25**

Table 5-12. /kV/ locus equation statistics in open and closed syllable forms produced by Persian speakers.

Locus equation slope values were uniformly lower in closed syllables compared to open syllables produced by Persian speakers, indicating that in closed syllables F2 onset was more removed in frequency than in open syllables. The difference in slope values of open versus closed syllable was 0.39. Since the number of subjects was limited to two, no separate statistical analysis was performed for Persian speakers.

On average, locus equation y-intercept values were expectedly higher in closed syllables compared to open syllables with a difference of 566 Hz. R^2 values were greater in open (R^2 = 0.83) versus closed (R^2 = 0.43) syllables, indicating greater correlation between F2 onset and F2 vowel in open syllables. SE values were on average greater in closed syllables (SE = 196 Hz) versus open syllable forms (SE = 133 Hz). In general, the correlation between F2 onset and F2 vowel was weaker in closed syllables compared to open syllable forms.

5.2.4. Summary and Discussion

Locus equation slope values obtained from English and Persian speakers were uniformly lower in closed versus open syllables for all places of articulation as originally predicted. An ANOVA run across all seven speakers of this study showed that the difference in LE slopes of close and open syllable forms produced by English and Persian speakers is statistically significant ($p<.0001$).

Flatter regression slopes in closed versus open syllables indicate a reduction in CV_2 coarticulation in the former compared to the latter. In other words, F2 onset measured at the release of the syllable-final stop in closed syllable forms was relatively stable despite changes in the F2 frequency of the following vowel. In comparison, F2 onset measured after the release of the syllable-initial stop in open syllable forms varied as the following vowel changed.

In articulatory terms, the flatter LE slopes of closed syllables indicated tongue body displacement from the position required for the following vowel. The steeper LE slopes of open syllables indicated that the tongue body was more or less in position for the following vowel at the release of the syllable-initial stop.

The flat LE slopes of closed syllable forms indicate that the tongue body is not in position for the following vowel at the release of the syllable-final stop. The tongue body can be either in a neutral position as assumed under a deactivation-reactivation scenario or still in position for the first vowel in closed [VC.V] sequences.

Since V_1 context included all vowels in this study, F2 onset of closed syllables might have reflected tongue body position for V_1 rather than a neutral position. In order to investigate this possibility, locus equation scatterplots of F2 onset and V_1 mid vowel were developed. A regression line was fit to data points and slope, y-intercept, R^2, and standard error values were obtained. Tables 5-13 to 5-18 provide locus equation parameters and other statistical information for consonants in closed syllables when their F2 onset values were plotted against V_1 F2 vowel. The LE parameters presented previously in tables 5-1 to 5-12 are presented again for comparison. English (E) and Persian (P) data are presented together.

$V_1b.V_2$	**V1mid * F2 onset**					**V2mid * F2 Onset**			
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.14	1116	.10	231		.31	848	.57	161
E#2	.11	1161	.07	196		.27	896	.65	121
E#3	.17	1111	.22	156		.22	1034	.48	128
E#4	.20	1038	.63	87		.08	1224	.10	136
E#5	.15	1089	.12	163		.22	993	.35	139
P#1	.16	966	.11	220		.30	758	.65	139
P#2	.21	898	.14	207		.39	669	.59	143
M	**.16**	**1054**	**.20**	**180**		**.26**	**917**	**.48**	**138**
SD	**.03**	**93**	**.20**	**49**		**.10**	**185**	**.20**	**13**

Table 5-13. Locus equation parameters of /b/ F2 onset in closed syllable forms plotted against V_1 mid point (left) and V_2 mid point (right).

$V_1p.V_2$	**V1mid * F2 onset**					**V2mid * F2 Onset**			
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.12	1146	.42	307		.46	611	.75	157
E#2	.01	1327	.002	171		.23	985	.64	102
E#3	.14	1161	.16	137		.19	1088	.41	115
E#4	.25	1007	.53	123		.09	1249	.09	172
E#5	.19	1089	.18	165		.15	1143	.17	166
P#1	.18	1067	.12	199		.28	931	.61	132
P#2	.20	967	.17	172		.20	987	.22	167
M	**.16**	**1109**	**.23**	**182**		**.23**	**999**	**.41**	**144**
SD	**.08**	**119**	**.18**	**60**		**.12**	**203**	**.26**	**28**

Table 5-14. Locus equation parameters of /p/ F2 onset in closed syllable forms plotted against V_1 mid point (left) and V_2 mid point (right).

$V_1d.V_2$	**V1mid * F2 onset**					**V2mid * F2 Onset**			
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.19	1394	.20	200		.24	1313	.44	167
E#2	.11	1590	.35	79		.10	1608	.40	76
E#3	.22	1429	.41	115		.15	1556	.28	128
E#4	.22	1352	.77	68		.04	1629	.03	138
E#5	.12	1496	.23	87		.08	1564	.14	92
P#1	.16	1517	.23	141		.19	1486	.50	114
P#2	.14	1338	.15	117		.20	1260	.48	91
M	**.17**	**1445**	**.33**	**115**		**.14**	**1488**	**.32**	**115**
SD	**.05**	**93**	**.21**	**45**		**.07**	**146**	**.18**	**32**

Table 5-15. Locus equation parameters of /d/ F2 onset in closed syllable forms plotted against V_1 mid point (left) and V_2 mid point (right).

$V_1t.V_2$	**V1mid * F2 onset**					**V2mid * F2 Onset**			
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.21	1335	.26	175		.24	1289	.49	146
E#2	.11	1557	.29	84		.09	1582	.32	83
E#3	.18	1552	.48	82		.10	1709	.19	102
E#4	.14	1446	.45	80		.04	1606	.05	105
E#5	.13	1457	.25	90		.08	1554	.14	96
P#1	.09	1697	.21	84		.07	1740	.19	85
P#2	.19	1298	.24	122		.08	1463	.08	135
M	**.15**	**1477**	**.31**	**102**		**.10**	**1563**	**.21**	**107**
SD	**.04**	**138**	**.11**	**35**		**.06**	**153**	**.15**	**24**

Table 5-16. Locus equation parameters of /t/ F2 onset in closed syllable forms plotted against V_1 mid point (left) and V_2 mid point (right).

$V_1g.V_2$	**V1mid * F2 onset**					**V2mid * F2 Onset**			
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.22	1418	.06	440		.68	701	.82	192
E#2	.43	1090	.42	264		.36	1215	.39	270
E#3	.15	1690	.05	298		.47	1154	.58	198
E#4	.63	841	.64	250		.33	1303	.21	372
E#5	.39	1166	.40	193		.28	1344	.31	208
P#1	.38	1338	.17	420		.56	1108	.52	321
P#2	.55	829	.27	382		.64	766	.47	325
M	**.39**	**1196**	**.29**	**321**		**.47**	**1084**	**.47**	**269**
SD	**.17**	**313**	**.21**	**94**		**.16**	**254**	**.20**	**72**

Table 5-17. Locus equation parameters of /g/ F2 onset in closed syllable forms plotted against V_1 mid point (left) and V_2 mid point (right).

$V_1k.V_2$	**V1mid * F2 onset**					**V2mid * F2 Onset**			
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.16	1482	.03	452		.72	58	.87	163
E#2	.41	1074	.30	316		.44	1017	.48	271
E#3	.26	1600	.12	289		.39	1382	.45	221
E#4	.60	820	.61	237		.31	1271	.23	335
E#5	.19	1374	.06	327		.50	898	.56	224
P#1	.36	1410	.12	442		.58	1145	.52	328
P#2	.75	517	.51	291		.44	1010	.24	364
M	**.39**	**1182**	**.25**	**336**		**.48**	**969**	**.48**	**272**
SD	**.22**	**395**	**.23**	**81**		**.13**	**434**	**.22**	**73**

Table 5-18. Locus equation parameters of /k/ F2 onset in closed syllable forms plotted against V_1 mid point (left) and V_2 mid point (right).

On average, slope values remained stable across the two conditions with the CV_2 slopes being merely .04 points greater than V_1C slopes. ANOVA run across all seven speakers showed that this difference was not statistically significant (p=.0840).

LE y-intercept values were on average 235 Hz greater when F2 onset was plotted against V_1 F2 vowel versus V_2 F2 vowel. R^2 was on average greater in V_2 condition ($R^2 = 0.40$) compared to the V_1 condition ($R^2 = 0.27$). On average, SE values were greater when F2 onset was plotted against V_1 F2 vowel (SE = 206 Hz) compared to when it was plotted against V_2 F2 vowel (SE = 174 Hz).

The stability of LE slopes across the two conditions indicates that F2 onset measured at the release of the syllable-final stops in closed syllables was affected equally by V_1 and V_2. The relatively flat LE slopes observed in both cases indicate that F2 onset value was relatively fixed and unaffected by F2 frequency values of either V_1 or V_2. In other words, V_1 and V_2 had equally minimal effects on F2 frequency at the release of the intervocalic stop. In articulatory terms, this means that the tongue body was in a neutral position minimally affected by the surrounding vowels.

It was mentioned earlier in section 4.1 that the neutral position for the tongue body is not fixed, but is sensitive to the surrounding vowel context. The effect of the surrounding vowel context is seen in the normal distribution of F2 onset of closed syllables as shown in figures 5-1 and 5-2 for English and Persian speakers respectively. These figures show histograms of F2 onset of closed syllable forms with superimposed frequency curves. As the figures show, F2 onset frequency at the release of the syllable-final stop had a normal distribution for all places of articulation. In other words, the neutral position for the tongue body was not fixed, but was affected (minimally) by the vocalic context.

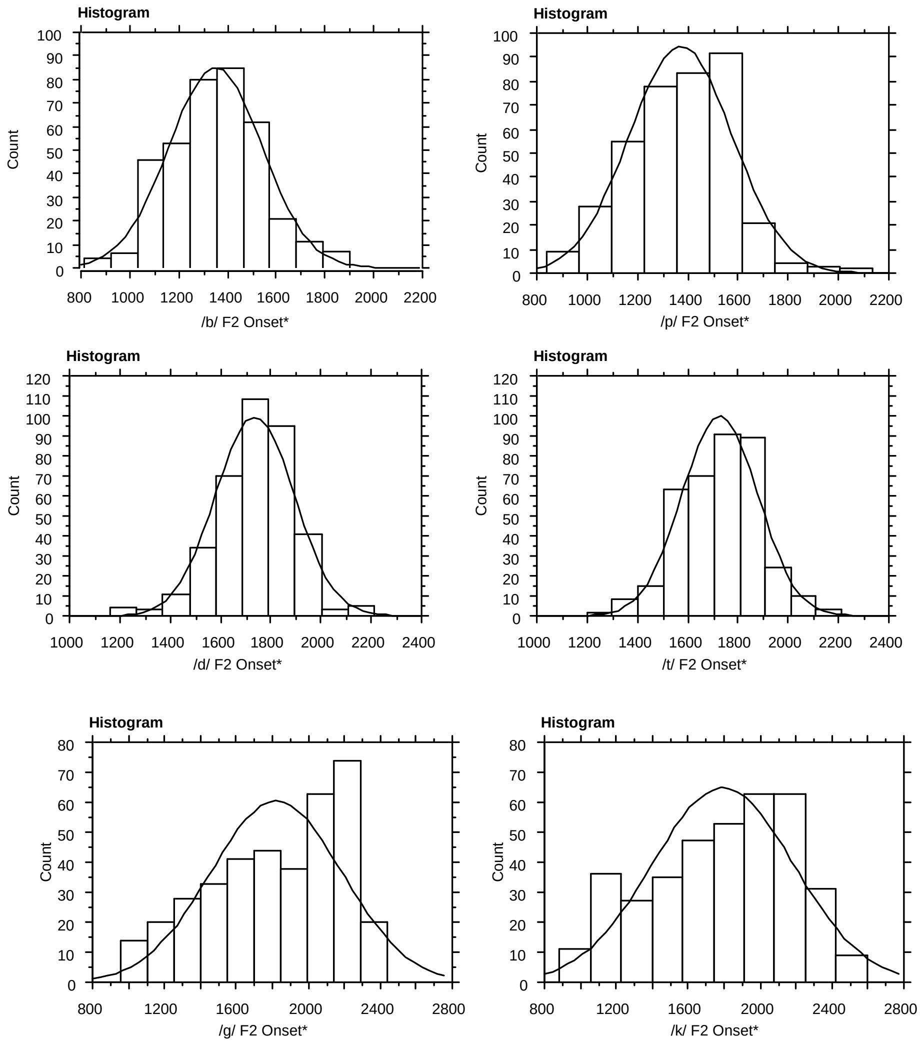


Figure 5-1 Histograms and frequency curves showing normal distribution of F2 onset values measured at the release of syllable-final bilabial (top), alveolar (middle), and velar (bottom) stops in closed syllable forms produced by English speakers.

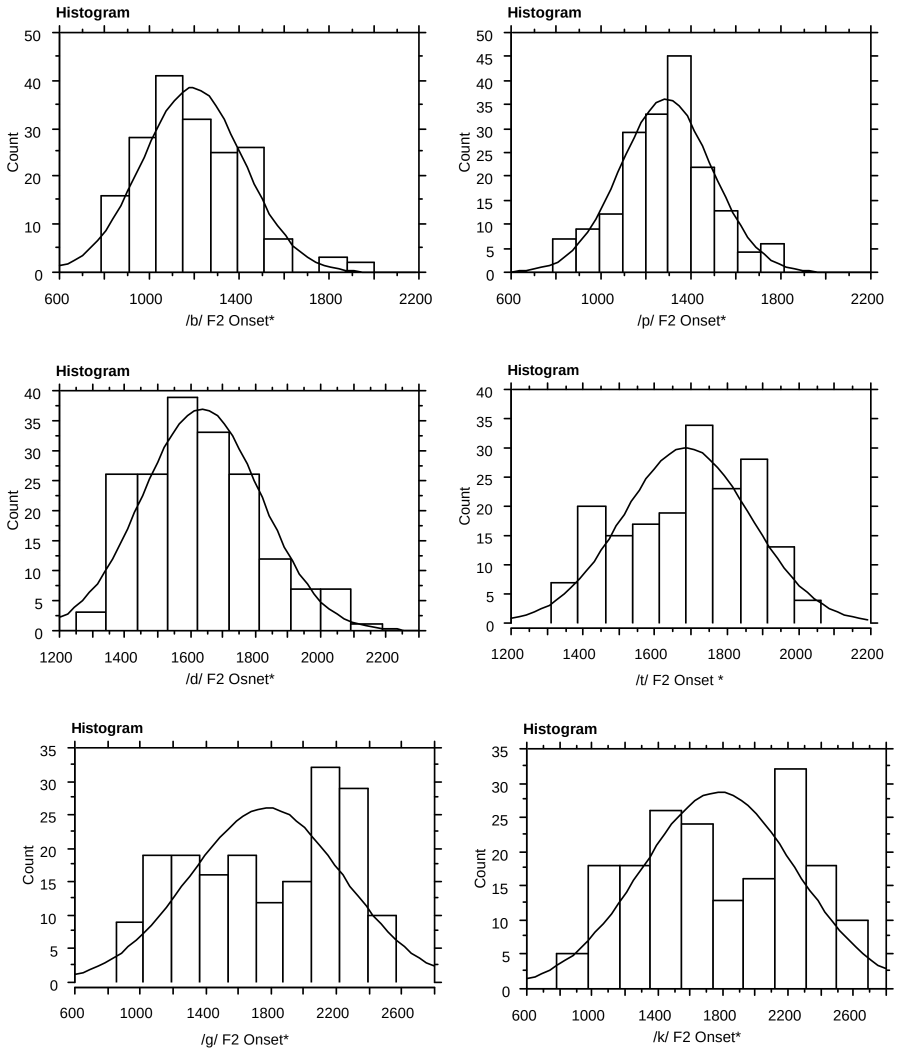


Figure 5-2 Histograms and frequency curves showing normal distribution of F2 onset values measured at the release of syllable-final bilabial (top), dental (middle), and velar (bottom) stops in closed syllable forms produced by Persian speakers.

To summarize, tongue body displacement was investigated in closed versus open syllable forms in a variety of vocalic and consonantal contexts using LE parameters. Significantly lower LE slopes were observed at the CV_2 boundary of closed versus open syllables. LE slopes were also flat when F2 onset of closed syllable forms was plotted against V_1 F2 mid point. Relatively flatter LE slopes of closed syllables indicated that F2 onset of closed syllable forms was stable and minimally affected by the surrounding vocalic context. In articulatory terms, this meant that the tongue body was in a neutral position minimally affected by the surrounding context. Thus, the results obtained in chapter 4 was replicated here for all vocalic and consonantal contexts in that changing the syllabic affiliation of the intervocalic stop resulted in maximum tongue body displacement effects in closed versus open syllables.

5.3. THE EFFECT OF STOP CLOSURE DURATION ON CV_2 COARTICULATION

It was shown in chapter 4 that an increase in the closure duration of the intervocalic stop does not result in more extensive F2 transition indicative of more extensive tongue body movement. One explanation is that longer closure durations not only give the tongue body more time to relax, but at the same time provide more time for the tongue body to recover from neutral position and assume the position required for the following vowel. Unlike the closed syllable forms in which the release of the intervocalic stop provided a window to tongue body position between the two vocalic gestures, such a window was not available in geminate forms. Although more extensive troughs might have occurred during the closure duration of geminate stops, they could not be detected in the VC and CV F2 transitions due to the fact that stop closures are associated with silence in the acoustic signal.

In this section, F2 transitions at the CV boundary of geminate [$V_1C.CV_2$] forms are compared with those of singleton [V.CV] forms in all consonantal and vocalic contexts using the locus equation paradigm. If the pattern observed with the selected symmetrical utterances in chapter 4 holds true for all contexts, LE slopes are expected to show no major differences as a function of consonantal closure duration. Section 5.3.1 describes the procedures followed to produce locus equation (LE) scatterplots and obtain LE slope values for the two utterance types. Results are presented in section 5.3.2 for English and in section 5.3.3 for Persian speakers. Section 5.3.4 includes a summary and a discussion of the results.

5.3.1. Procedures

LE scatterplots were made for CV_2 sequences in singleton and geminate forms across all V_1 contexts for each stop consonant. Each scatterplot included 75 data points ($5V_1$*1C*$5V_2$*3REP.) per English speaker and 108 ($6V_1$*1C*$6V_2$*3REP.) data points per Persian speaker. The results sections are limited to presenting LE statistics and actual scatterplots are not included.

5.3.2. English

Tables 5-19 to 5-24 contain LE slope (k), y-intercept (c), coefficient of determination (R^2), and standard error (SE) values of each stop consonant plus vowel combination in singleton versus geminate forms produced by English speakers.

Speaker		**V.bV**					**Vb.bV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.76	256	.93	104		.83	167	.96	93
E#2	.83	182	.97	77		.83	172	.98	172
E#3	.81	234	.94	101		.83	198	.94	93
E#4	.84	181	.96	92		.88	121	.98	76
E#5	.78	240	.94	78		.82	227	.97	58
M	**.80**	**219**	**.95**	**90**		**.84**	**177**	**.97**	**98**
SD	**.03**	**35**	**.016**	**13**		**.02**	**39**	**.02**	**44**

Table 5-19. /bV/ locus equation statistics in singleton and geminate utterances produced by English speakers.

Speaker		**V.pV**					**Vp.pV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.63	499	.92	98		.60	573	.88	123
E#2	.62	449	.91	97		.56	562	.89	110
E#3	.59	590	.83	123		.55	680	.84	112
E#4	.63	540	.85	134		.68	491	.92	106
E#5	.73	373	.90	101		.70	461	.89	116
M	**.64**	**490**	**.88**	**111**		**.62**	**553**	**.88**	**113**
SD	**.05**	**84**	**.04**	**17**		**.07**	**85**	**.03**	**6**

Table 5-20. /pV/ locus equation statistics in singleton and geminate utterances produced by English speakers.

Speaker		**V.dV**					**Vd.dV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.38	1140	.69	126		.48	975	.92	66
E#2	.47	999	.78	110		.51	936	.82	113
E#3	.32	1322	.62	103		.37	1295	.73	88
E#4	.42	1122	.81	93		.55	874	.92	81
E#5	.48	924	.76	89		.49	928	.86	77
M	**.41**	**1101**	**.73**	**104**		**.48**	**1002**	**.85**	**85**
SD	**.07**	**152**	**.08**	**15**		**.07**	**168**	**.08**	**18**

Table 5-21. /dV/ locus equation statistics in singleton and geminate utterances produced by English speakers.

Speaker		**V.tV**					**Vt.tV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.18	1484	.45	97		.25	1336	.63	99
E#2	.27	1339	.59	93		.33	1238	.71	105
E#3	.23	1557	.54	92		.28	1487	.62	92
E#4	.20	1523	.53	90		.33	1255	.83	79
E#5	.29	1291	.55	90		.31	1265	.49	119
M	**.23**	**1439**	**.53**	**92**		**.30**	**1316**	**.66**	**99**
SD	**.05**	**117**	**.05**	**3**		**.03**	**103**	**.13**	**15**

Table 5-22. /tV/ locus equation statistics in singleton and geminate utterances produced by English speakers.

Speaker		**V.gV**					**Vg.gV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.88	356	.92	135		.84	350	.91	140
E#2	.96	234	.87	183		.93	169	.95	108
E#3	.78	566	.86	132		.68	751	.89	89
E#4	1.01	93	.93	162		.99	63	.96	123
E#5	.81	468	.86	133		.78	470	.88	124
M	**.89**	**343**	**.89**	**149**		**.84**	**361**	**.92**	**117**
SD	**.10**	**187**	**.03**	**23**		**.12**	**269**	**.04**	**19**

Table 5-23. /gV/ locus equation statistics in singleton and geminate utterances produced by English speakers.

Speaker		**V.kV**					**Vk.kV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.75	531	.91	133		.81	406	.88	166
E#2	.97	185	.83	219		.91	236	.92	139
E#3	1.04	309	.87	181		.96	303	.78	211
E#4	1.05	131	.91	182		1.04	92	.90	198
E#5	.83	443	.84	152		.80	490	.80	173
M	**.93**	**320**	**.87**	**173**		**.90**	**305**	**.86**	**177**
SD	**.13**	**169**	**.04**	**33**		**.10**	**154**	**.06**	**28**

Table 5-24. /kV/ locus equation statistics in singleton and geminate utterances produced by English speakers.

On average, the slope values of geminate stops of all places of articulation were only 0.01 points greater than the slope values of singleton stops. An ANOVA run across all five English speakers showed that the difference between the slope values of singleton and geminate forms was not statistically significant (p= .6072). In other words, locus equation slopes remained stable despite changes in consonantal closure duration as expected.

The y-intercept values of geminate stops were only 33 Hz lower than those of singleton stops. R^2 values of geminate stops were on average 0.05 points higher for geminate stops compared to singletons and SE values were on average only 5 Hz lower in the former compared to the latter.

To summarize, no differences were observed between locus equation parameters of singleton and geminate stops as expected. No differences were detected either between singleton and geminates in the correlation between F2 onset and V_2 F2vowel.

5.3.3. Persian

Tables 5-25 to 5-30 contain LE slope (k), y-intercept (c), coefficient of determination (R^2), and standard error (SE) values for each stop consonant plus vowel combinations in singleton versus geminate forms produced by Persian speakers.

Speaker		**V.bV**					**Vb.bV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.88	118	.96	102		.92	61	.99	60
P#2	.86	73	.96	89		.98	-45	.98	63
M	**.87**	**96**	**.96**	**96**		**.95**	**8**	**.99**	**62**
SD	**.01**	**32**	**0**	**9**		**.04**	**75**	**.007**	**2**

Table 5-25. /bV/ locus equation statistics in singleton and geminate utterances produced by Persian speakers.

Speaker		V.pV					Vp.pV		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.65	527	.91	119		.70	436	.92	98
P#2	.73	318	.85	144		.85	186	.87	123
M	**.69**	**443**	**.88**	**131**		**.78**	**311**	**.90**	**111**
SD	**.06**	**148**	**.04**	**17**		**.11**	**177**	**.04**	**18**

Table 5-26. /pV/ locus equation statistics in singleton and geminate utterances produced by Persian speakers.

Speaker		V.dV					Vd.dV		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.52	1013	.83	125		.57	907	.83	118
P#2	.43	1008	.75	103		.64	681	.82	98
M	**.48**	**1011**	**.79**	**114**		**.61**	**794**	**.83**	**108**
SD	**.06**	**4**	**.06**	**16**		**.05**	**160**	**.007**	**14**

Table 5-27. /dV/ locus equation statistics in singleton and geminate utterances produced by Persian speakers.

Speaker		V.tV					Vt.tV		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.24	1541	.60	107		.25	1486	.60	92
P#2	.29	1257	.53	110		.42	1071	.64	96
M	**.27**	**1399**	**.57**	**109**		**.34**	**1279**	**.62**	**94**
SD	**.04**	**201**	**.05**	**2**		**.12**	**293**	**.03**	**3**

Table 5-28. /tV/ locus equation statistics in singleton and geminate utterances produced by Persian speakers.

Speaker		V.gV					Vg.gV		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.95	208	.94	141		1.01	93	.94	131
P#2	1.10	-57	.91	161		1.15	-138	.89	151
M	**1.03**	**76**	**.93**	**151**		**1.08**	**-23**	**.92**	**141**
SD	**.11**	**187**	**.02**	**14**		**.10**	**163**	**.04**	**14**

Table 5-29. /gV/ locus equation statistics in singleton and geminate utterances produced by Persian speakers.

Speaker		V.kV					Vk.kV		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.85	468	.86	187		.96	305	.85	187
P#2	1.07	14	.84	207		1.20	-206	.85	181
M	**.96**	**241**	**.85**	**197**		**1.08**	**50**	**.85**	**184**
SD	**.16**	**321**	**.01**	**14**		**.17**	**361**	**0**	**4**

Table 5-30. /kV/ locus equation statistics in singleton and geminate utterances produced by Persian speakers.

In utterances produced by Persian speakers, LE slope values were on average only .09 points higher in geminate compared to singleton forms for all places of articulation. Since the number of speakers was limited to two, no separate statistical test was performed for Persian.

Locus equation y-intercept values of geminate stops were on average 173 Hz lower than those of singleton stops. R^2 values of geminate stops were on average only 0.02 points higher than those of singletons. SE values were on average only 16 Hz lower in the former compared to the latter. In general, LE parameters remained stable despite changes in the closure duration of the intervocalic stop.

5.3.4. Summary and Discussion

Locus equation slope values remained stable across changes in consonantal closure duration in singleton and geminate utterances produced by English and Persian speakers. An ANOVA run across all seven speakers showed that the difference in slope values of singleton and geminate consonants produced by English and Persian speakers was not statistically significant ($p=.1186$).

The results obtained in this section were consistent with those in chapter 4 in that changes in the closure duration of the intervocalic stop did not result in more extensive F2 transitions at the CV boundary of geminate versus singleton utterances. The stability of LE slopes indicates that a high correlation exists between C and V_2 when they form a syllable together and that this correlation is unaffected by the closure duration of the stop consonant.

It has been hypothesized that in a VCV sequence the gesture for V_2 is coordinated with the release of a syllable-initial intervocalic stop consonant (Smith, 1995). A study of tongue body movement in C_nV sequences by Gay (1979) also showed that articulatory movements towards a vowel target were linked to the time of the consonantal release rather than to the consonantal closure. The results obtained in this section also indicate a tight bonding between a syllable-initial consonant and the following vowel. Although more extensive tongue body displacement might have occurred during the closure period of geminate stops, the effects of this displacement are not actualized at the CV boundary due to the overriding requirement for vowel synchronization with consonantal release.

CV bonding is not only independent of consonantal closure duration, but is unaffected by V_1 context in [$V_1.CV_2$] utterances. Gay (1977b) also showed that in VCV sequences the articulators are in the same position at the release of the intervocalic stop into the second vowel across all V_1 contexts. Gay (1977b) maintained that this finding strengthens the suggestion that the CV component of a VCV string forms a basic integral unit as postulated by Kozhevnikov and Chistovich (1965).

In the present investigation, the bonding between C and V captured by LE slopes is also unaffected by V_1 context. LE scatterplots were developed for CV_2 sequences produced by English and Persian speakers for each V_1 context. Tables 5-31 to 5-33 provide LE slope values of CV_2 sequences produced by English speakers as a function of V_1 context.

	i.bV	e.bV	æ.bV	u.bV	ɔ.bV		i.pV	e.pV	æ.pV	u.pV	ɔ.pV
E#1	.79	.80	.73	.74	.73		.69	.57	.59	.62	.66
E#2	.85	.89	.78	.85	.77		.65	.70	.64	.54	.59
E#3	.87	.86	.79	.69	.80		.66	.61	.59	.45	.64
E#4	.83	.86	.85	.83	.79		.57	.71	.64	.48	.71
E#5	.74	.79	.83	.68	.89		.91	.69	.68	.77	.64
Mean	**.82**	**.84**	**.80**	**.76**	**.80**		**.70**	**.66**	**.63**	**.57**	**.65**
SD	**.05**	**.04**	**.05**	**.08**	**.06**		**.13**	**.06**	**.04**	**.13**	**.04**

Table 5-31. Locus equation slope values of singleton bilabial stops as a function of V_1 context (English).

	i.dV	e.dV	æ.dV	u.dV	ɔ.dV		i.tV	e.tV	æ.tV	u.tV	ɔ.tV
E#1	.33	.37	.31	.48	.41		.19	.23	.15	.17	.13
E#2	.38	.56	.45	.53	.47		.29	.29	.31	.21	.23
E#3	.31	.23	.31	.30	.48		.27	.22	.26	.19	.19
E#4	.29	.36	.45	.51	.44		.15	.20	.21	.26	.19
E#5	.43	.38	.44	.54	.59		.21	.22	.33	.30	.35
Mean	**.35**	**.38**	**.39**	**.47**	**.48**		**.22**	**.23**	**.25**	**.23**	**.22**
SD	**.06**	**.12**	**.07**	**.10**	**.07**		**.06**	**.03**	**.07**	**.05**	**.08**

Table 5-32. Locus equation slope values of singleton alveolar stops as a function of V_1 context (English).

	i.gV	e.gV	æ.gV	u.gV	ɔ.gV		i.kV	e.kV	æ.kV	u.kV	ɔ.kV
E#1	.76	.90	.82	.97	.95		.70	.61	.65	.89	.86
E#2	1.0	1.0	.94	.96	.92		1.04	.98	.89	.98	.97
E#3	.63	.69	.84	.83	.86		1.04	.95	.95	1.06	1.19
E#4	.92	1.07	1.05	1.05	1.13		.95	1.0	1.1	1.06	1.12
E#5	.77	.75	.86	.88	.77		.78	.78	.87	.98	.77
Mean	**.82**	**.88**	**.90**	**.94**	**.93**		**.90**	**.86**	**.89**	**.99**	**.98**
SD	**.15**	**.16**	**.09**	**.09**	**.13**		**.15**	**.17**	**.16**	**.07**	**.17**

Table 5-33. Locus equation slope values of singleton velar stops as a function of V_1 context (English).

The difference between the mean slope value of each V_1 context and the overall slope value for each stop was calculated. This difference was .02 for /b/, .032 for /p/, .048 for /d/, .008 for /t/, .036 for /g/, and .048 for /k/. On average, the variation in slope values across all stops as a function of V_1 context was .032. Repeated-measures ANOVA run across all V_1 contexts showed no significant effects (p=.5331).

Tables 5-34 to 5-36 show LE slope values of CV_2 sequences produced by Persian speakers as a function of V_1 context.

	i.bV	**e.bV**	**æ.bV**	**u.bV**	**o.bV**	**a.bV**		**i.pV**	**e.pV**	**æ.pV**	**u.pV**	**o.pV**	**a.pV**
P#1	.90	.91	.91	.83	.80	.89		.69	.64	.62	.65	.62	.68
P#2	.89	.89	.87	.90	.78	.83		.77	.73	.67	.74	.66	.79
Mean	**.90**	**.90**	**.89**	**.87**	**.79**	**.86**		**.73**	**.69**	**.65**	**.70**	**.64**	**.74**
SD	**.01**	**.01**	**.03**	**.05**	**.01**	**.04**		**.06**	**.06**	**.04**	**.06**	**.03**	**.08**

Table 5-34. Locus equation slope values of singleton bilabial stops as a function of V_1 context (Persian).

	i.dV	**e.dV**	**æ.dV**	**u.dV**	**o.dV**	**a.dV**		**i.tV**	**e.tV**	**æ.tV**	**u.tV**	**o.tV**	**a.tV**
P#1	.48	.43	.51	.53	.61	.57		.19	.22	.26	.25	.24	.27
P#2	.39	.38	.36	.45	.52	.48		.17	.24	.27	.25	.41	.35
Mean	**.44**	**.41**	**.44**	**.49**	**.57**	**.53**		**.18**	**.23**	**.27**	**.25**	**.33**	**.31**
SD	**.06**	**.04**	**.11**	**.06**	**.06**	**.06**		**.01**	**.01**	**.01**	**0**	**.12**	**.06**

Table 5-35. Locus equation slope values of singleton dental stops as a function of V_1 context (Persian).

	i.gV	e.gV	æ.gV	u.gV	o.gV	a.gV		i.kV	e.kV	æ.kV	u.kV	o.kV	a.kV
P#1	.94	.93	.91	.99	.99	.92		.86	.83	.81	.91	.93	.77
P#2	.99	1.1	1.1	1.1	1.2	1.1		1.1	1.0	1.1	.98	1.1	1.1
Mean	**.97**	**1.0**	**1.0**	**1.1**	**1.1**	**1.0**		**.97**	**.92**	**.95**	**.95**	**1.0**	**.93**
SD	**.03**	**.11**	**.14**	**.08**	**.11**	**.16**		**.15**	**.12**	**.20**	**.05**	**.15**	**.23**

Table 5-36. Locus equation slope values of singleton velar stops as a function of V_1 context (Persian).

The difference between the mean slope value of each V_1 context and the overall slope value for each stop was calculated. This difference was .028 for /b/, .032 for /p/, .05 for /d/, .038 for /t/, .038 for /g/, and .02 for /k/. On average, the variation in slope values across all stops as a function of V_1 context was .034. Since the number of Persian speakers was limited to two, it was not possible to perform an ANOVA test to determine the statistical significance of the difference in slope values of each CV_2 sequence as a function of V_1 context in Persian.

Tables 5-37 to 5-39 provide CV_2 locus equation slope values in geminate forms as a function of V_1 context as produced by English speakers.

	ib.bV	eb.bV	æb.bV	ub.bV	ɔb.bV		ip.pV	ep.pV	æp.pV	up.pV	ɔp.pV
E#1	.86	.86	.86	.76	.82		.65	.60	.53	.55	.67
E#2	.86	.83	.87	.79	.79		.53	.55	.60	.50	.61
E#3	.88	.85	.85	.83	.75		.66	.51	.55	.50	.54
E#4	.79	.89	.92	.91	.90		.69	.65	.63	.68	.74
E#5	.85	.84	.79	.80	.83		.69	.73	.60	.75	.78
Mean	**.85**	**.85**	**.86**	**.82**	**.82**		**.64**	**.61**	**.58**	**.60**	**.67**
SD	**.03**	**.02**	**.05**	**.06**	**.06**		**.07**	**.09**	**.04**	**.11**	**.10**

Table 5-37. Locus equation slope values of geminate bilabial stops as a function of V_1 context (English).

	id.dV	ed.dV	æd.dV	ud.dV	ɔd.dV		it.tV	et.tV	æt.tV	ut.tV	ɔt.tV
E#1	.44	.50	.50	.48	.46		.26	.22	.24	.27	.27
E#2	.52	.49	.49	.54	.51		.35	.29	.29	.27	.43
E#3	.25	.37	.39	.39	.47		.28	.27	.31	.23	.31
E#4	.50	.50	.60	.55	.57		.31	.34	.36	.31	.31
E#5	.42	.50	.44	.50	.58		.26	.20	.23	.31	.56
Mean	**.43**	**.47**	**.48**	**.49**	**.52**		**.29**	**.26**	**.29**	**.28**	**.38**
SD	**.11**	**.06**	**.08**	**.06**	**.06**		**.04**	**.06**	**.05**	**.03**	**.12**

Table 5-38. Locus equation slope values of geminate alveolar stops as a function of V_1 context (English).

	ig.gV	eg.gV	æg.gV	ug.gV	ɔg.gV		ik.kV	ek.kV	æk.kV	uk.kV	ɔk.kV
E#1	.74	.86	.87	.86	.87		.72	.82	.79	.85	.87
E#2	.93	.94	.91	.94	.96		.95	.90	.84	.99	.89
E#3	.46	.73	.77	.67	.75		1.1	.89	1.03	.86	.95
E#4	.97	1.0	1.0	.97	1.0		1.0	1.1	1.02	1.1	1.04
E#5	.74	.79	.82	.81	.73		.83	.76	.70	.86	.86
Mean	**.77**	**.86**	**.87**	**.85**	**.86**		**.92**	**.89**	**.88**	**.93**	**.92**
SD	**.20**	**.11**	**.09**	**.12**	**.12**		**.15**	**.13**	**.15**	**.11**	**.07**

Table 5-39. Locus equation slope values of geminate velar stops as a function of V_1 context (English).

The difference between the mean slope value of each V_1 context and the overall slope value for each stop was calculated. This difference was .016 for /b/, .028 for /p/, .034 for /d/, .032 for /t/, .03 for /g/, and .018 for /k/. On average, the variation in slope values across all stops as a function of V_1 context was .026. Repeated-measures ANOVA run across all V_1contexts showed no significant effects (p=.4197).

Tables 5-40 to 5-42 show CV_2 locus equation slope values in geminate sequences as a function of V_1 context as produced by Persian speakers.

	ib.bV	eb.bV	æb.bV	ub.bV	ob.bV	ab.bV	ip.pV	ep.pV	æp.pV	up.pV	op.pV	ap.pV
P#1	.90	.88	.92	.95	.96	.94	.73	.71	.68	.73	.61	.73
P#2	.94	1.02	1.02	.94	.97	.97	.84	.75	.85	.79	.96	.93
M	**.92**	**.95**	**.97**	**.95**	**.97**	**.96**	**.79**	**.73**	**.77**	**.76**	**.79**	**.83**
SD	**.03**	**.10**	**.07**	**.01**	**.01**	**.02**	**.08**	**.03**	**.12**	**.04**	**.25**	**.14**

Table 5-40. Locus equation slope values of geminate bilabial stops as a function of V_1 context (Persian).

	id.dV	ed.dV	æd.dV	ud.dV	od.dV	ad.dV	it.tV	et.tV	æt.tV	ut.tV	ot.tV	at.tV
P#1	.49	.53	.64	.63	.55	.58	.19	.20	.23	.30	.36	.27
P#2	.67	.58	.58	.61	.67	.72	.34	.40	.40	.41	.43	.52
Mean	**.58**	**.56**	**.61**	**.62**	**.61**	**.65**	**.27**	**.30**	**.32**	**.36**	**.40**	**.40**
SD	**.13**	**.04**	**.04**	**.01**	**.08**	**.10**	**.11**	**.14**	**.12**	**.08**	**.05**	**.18**

Table 5-41. Locus equation slope values of geminate dental stops as a function of V_1 context (Persian).

	ig.gV	eg.gV	æg.gV	ug.gV	og.gV	ag.gV	ik.kV	ek.kV	æk.kV	uk.kV	ok.kV	ak.kV
P#1	.99	1.03	1.04	.99	1.01	1.03	.80	.92	.98	.99	1.09	1.01
P#2	1.1	1.13	1.18	1.16	1.18	1.18	1.14	1.13	1.15	1.33	1.24	1.21
Mean	**1.0**	**1.08**	**1.11**	**1.08**	**1.10**	**1.11**	**.97**	**1.03**	**1.07**	**1.16**	**1.17**	**1.11**
SD	**.05**	**.07**	**.10**	**.12**	**.12**	**.11**	**.24**	**.15**	**.12**	**.24**	**.11**	**.14**

Table 5-42. Locus equation slope values of geminate velar stops as a function of V_1 context (Persian).

The difference between the mean slope value of each V_1 context and the overall slope value for each stop was calculated. This difference was .01 for /b/, .03 for /p/, .02 for /d/, .05 for /t/, .02 for /g/ and .07 for /k/. On average, the variation in slope values across all stops as a function of V_1 context was .033. Since the number of Persian speakers was limited to two, it was not possible to perform an ANOVA test to determine the statistical significance of the difference in slope values as a function of V_1 context.

The results obtained from English and Persian speakers indicate that CV_2 coarticulation captured by locus equation slopes is unaffected by changes in the closure duration of the intervocalic stop and by changes in the V_1 context. These results provide more evidence in favor of the tight bonding between a syllable-initial C and the following vowel. The gesture for V_2 is timed relative to the release of the syllable-initial C and this timing is insensitive to the length of the consonantal closure and V_1 context.

As mentioned in section 2.2.2, LE slopes have been established as 'relational invariants' capable of signaling stop place of articulation. An ANOVA run across the seven speakers of this study showed that place (bilabial, alveolar/dental, and velar) was a significant factor ($p<.0001$) in distinguishing LE slopes in open/singleton and geminate utterances.

5.4. THE EFFECTS OF VOT ON CV_2 COARTICULATION

The results in chapter 4 showed that voiced and voiceless aspirated stops had different F2 transition patterns especially at the CV_2 boundary of open/singleton and geminate utterances. More evidence of tongue body displacement was generally observed at the CV boundary of open/singleton and geminate utterances when C was a voiceless aspirated bilabial stop. In this section, the effects of aspiration on tongue body displacement at the CV boundary of open/singleton and geminate stops are investigated using the locus equation paradigm. All consonantal and vocalic contexts are investigated. LE slopes are expected to be lower for voiceless aspirated stops compared to their voiced counterparts. That is because the tongue body is expected to be more in place for the production of the vowel after the release of a voiced consonant than at the release of a voiceless aspirated consonant (Gay, 1979).

The data presented in this section are repeated from previous sections in this chapter; they are presented again to investigate the effects of aspiration on tongue body displacement. Section 5.4.1 describes the procedures followed to produce locus equation scatterplots and obtain LE slope values. Results are discussed in sections 5.4.2 and 5.4.3 for English and Persian speakers respectively. Section 5.4.4 includes a summary and a discussion of the results.

5.4.1. Procedures

LE scatterplots were made for voiced and voiceless aspirated CV_2 sequences in singleton [V.CV] and geminate [VC.CV] forms across all V_1 contexts. Each scatterplot included 75 data points ($5V_1$*1C*$5V_2$*3REP.) per English speaker and 108 ($6V_1$*1C*$6V_2$*3REP.) data points per Persian speaker. The results sections are limited to presenting LE statistics and actual scatterplots are not included.

5.4.2. English

Tables 5-43 to 5-48 contain LE slope (k) and y-intercept (c) values as well as the coefficient of determination (R^2) and standard error (SE) values of the correlation between F2 onset and F2 vowel of voiced and voiceless aspirated stops in singleton and geminate syllables produced by English speakers.

Speaker		**V.bV**					**V.pV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.76	256	.93	104		.63	499	.92	98
E#2	.83	182	.97	77		.62	449	.91	97
E#3	.81	234	.94	101		.59	590	.83	123
E#4	.84	181	.96	92		.63	540	.85	134
E#5	.78	240	.94	78		.73	373	.90	101
M	**.80**	**219**	**.95**	**90**		**.64**	**490**	**.88**	**111**
SD	**.03**	**35**	**.016**	**13**		**.05**	**84**	**.04**	**17**

Table 5-43. Locus equation parameters of singleton bilabial consonants produced by English speakers.

Speaker		**Vb.bV**					**Vp.pV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.83	167	.96	93		.60	573	.88	123
E#2	.83	172	.98	172		.56	562	.89	110
E#3	.83	198	.94	93		.55	680	.84	112
E#4	.88	121	.98	76		.68	491	.92	106
E#5	.82	227	.97	58		.70	461	.89	116
M	**.84**	**177**	**.97**	**98**		**.62**	**553**	**.88**	**113**
SD	**.02**	**39**	**.02**	**44**		**.07**	**85**	**.03**	**6**

Table 5-44. Locus equation parameters of geminate bilabial consonants produced by English speakers.

Speaker		**V.dV**				**V.tV**		
	k	*c*	R^2	SE	*k*	*c*	R^2	SE
E#1	.38	1140	.69	126	.18	1484	.45	97
E#2	.47	999	.78	110	.27	1339	.59	93
E#3	.32	1322	.62	103	.23	1557	.54	92
E#4	.42	1122	.81	93	.20	1523	.53	90
E#5	.48	924	.76	89	.29	1291	.55	90
M	**.41**	**1101**	**.73**	**104**	**.23**	**1439**	**.53**	**92**
SD	**.07**	**152**	**.08**	**15**	**.05**	**117**	**.05**	**3**

Table 5-45. Locus equation parameters of singleton alveolar consonants produced by English speakers.

Speaker		**Vd.dV**					**Vt.tV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.48	975	.92	66		.25	1336	.63	99
E#2	.51	936	.82	113		.33	1238	.71	105
E#3	.37	1295	.73	88		.28	1487	.62	92
E#4	.55	874	.92	81		.33	1255	.83	79
E#5	.49	928	.86	77		.31	1265	.49	119
M	**.48**	**1002**	**.85**	**85**		**.30**	**1316**	**.66**	**99**
SD	**.07**	**168**	**.08**	**18**		**.03**	**103**	**.13**	**15**

Table 5-46. Locus equation parameters of geminate alveolar consonants produced by English speakers.

Speaker		**V.gV**					**V.kV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.88	356	.92	135		.75	531	.91	133
E#2	.96	234	.87	183		.97	185	.83	219
E#3	.78	566	.86	132		1.04	309	.87	181
E#4	1.01	93	.93	162		1.05	131	.91	182
E#5	.81	468	.86	133		.83	443	.84	152
M	**.89**	**343**	**.89**	**149**		**.93**	**320**	**.87**	**173**
SD	**.10**	**187**	**.03**	**23**		**.13**	**169**	**.04**	**33**

Table 5-47. Locus equation parameters of singleton velar consonants produced by English speakers.

Speaker		**Vg.gV**					**Vk.kV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
E#1	.84	350	.91	140		.81	406	.88	166
E#2	.93	169	.95	108		.91	236	.92	139
E#3	.68	751	.89	89		.96	303	.78	211
E#4	.99	63	.96	123		1.04	92	.90	198
E#5	.78	470	.88	124		.80	490	.80	173
M	**.84**	**361**	**.92**	**117**		**.90**	**305**	**.86**	**177**
SD	**.12**	**269**	**.04**	**19**		**.10**	**154**	**.06**	**28**

Table 5-48. Locus equation parameters of geminate velar consonants produced by English speakers.

LE slope values were higher for bilabial and alveolar voiced stops compared to their voiceless counterparts in both singleton and geminate forms. The reverse pattern was observed when C was a velar stop. Averaging across place and utterance type, the slope values for voiced stops were 0.11 points higher than those of voiceless aspirated stops. An ANOVA performed across voicing conditions showed significant effects for this variable ($p<.01$). Taking LE slope values as a measure of CV_2 coarticulation, higher slope values associated with voiced bilabial and alveolar stops indicated that they coarticulate more with V_2 compared to their voiceless aspirated counterparts.

Averaging across singleton and geminate utterances, locus equation y-intercept values were on average 203 Hz lower for voiced versus voiceless aspirated stops. R^2 values were on average 0.11 points higher for voiced versus voiceless stops, while SE values were 20 Hz lower in the former versus the latter. To summarize, LE parameters of voiced stops indicated higher degrees of correlation between F2 onset and V_2 F2 vowel compared to voiceless aspirated stops.

5.4.3. Persian

Tables 5-49 to 5-54 contain LE slope (k) and y-intercept (c) values as well as the coefficient of determination (R^2) and standard error (SE) values of the correlation between F2 onset and F2 vowel of voiced and voiceless aspirated stops in singleton and geminate utterances produced by Persian speakers.

Speaker		**V.bV**					**V.pV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.88	118	.96	102		.65	527	.91	119
P#2	.86	73	.96	89		.73	318	.85	144
M	**.87**	**96**	**.96**	**96**		**.69**	**443**	**.88**	**131**
SD	**.01**	**32**	**0**	**9**		**.06**	**148**	**.04**	**17**

Table 5-49. Locus equation parameters of singleton bilabial consonants produced by Persian speakers.

Speaker		**Vb.bV**					**Vp.pV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.92	61	.99	60		.70	436	.92	98
P#2	.98	-45	.98	63		.85	186	.87	123
M	**.95**	**8**	**.99**	**63**		**.78**	**311**	**.90**	**111**
SD	**.04**	**75**	**.007**	**2**		**.11**	**177**	**.04**	**18**

Table 5-50. Locus equation parameters of geminate bilabial consonants produced by Persian speakers.

Speaker		V.dV					V.tV		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.52	1013	.83	125		.24	1541	.60	107
P#2	.43	1008	.75	103		.29	1257	.53	110
M	**.48**	**1011**	**.79**	**114**		**.27**	**1399**	**.57**	**109**
SD	**.06**	**4**	**.06**	**16**		**.04**	**201**	**.05**	**2**

Table 5-51. Locus equation parameters of singleton dental consonants produced by Persian speakers.

Speaker		Vd.dV					Vt.tV		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.57	907	.83	118		.25	1486	.60	92
P#2	.64	681	.82	98		.42	1071	.64	96
M	**.61**	**794**	**.83**	**108**		**.34**	**1279**	**.62**	**94**
SD	**.05**	**160**	**.007**	**14**		**.12**	**293**	**.03**	**3**

Table 5-52. Locus equation parameters of geminate dental consonants produced by Persian speakers.

Speaker		V.gV					V.kV		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	.95	208	.94	141		.85	468	.86	187
P#2	1.10	-57	.91	161		1.07	14	.84	207
M	**1.03**	**76**	**.93**	**151**		**.96**	**241**	**.85**	**197**
SD	**.11**	**187**	**.02**	**14**		**.16**	**321**	**.01**	**14**

Table 5-53. Locus equation parameters of singleton velar consonants produced by Persian speakers.

Speaker		**Vg.gV**					**Vk.kV**		
	k	*c*	R^2	SE		*k*	*c*	R^2	SE
P#1	1.01	93	.94	131		.96	305	.85	187
P#2	1.15	-138	.89	151		1.20	-206	.85	181
M	**1.08**	**-23**	**.92**	**141**		**1.08**	**50**	**.85**	**184**
SD	**.10**	**163**	**.04**	**14**		**.17**	**361**	**0**	**4**

Table 5-54. Locus equation parameters of geminate velar consonants produced by Persian speakers.

In the singleton utterances produced by Persian speakers, LE slope values were uniformly lower for voiceless stops compared to their voiced counterparts. In geminate utterances, LE slopes were lower for voiceless aspirated bilabial and dental stops compared to their voiced cognates. LE slopes remained constant when C was a geminate velar stop. Averaging across place and utterance type, locus equation slopes of voiced stops were 0.15 points greater than those of voiceless aspirated stops. Since the number of Persian speakers was limited to two, it was not possible to determine the statistical significance of the differences in slope values as a function of voicing.

On average, y-intercept values were 294 Hz lower for voiced compared to voiceless aspirated stops in singleton and geminate utterances. R^2 values of voiced stops were on average 0.13 points higher than those of voiceless aspirated stops, while SE values were on average 26 Hz lower for the former versus the latter. In general, higher degrees of correlation were observed between F2 onset and F2 vowel when C was voiced compared to when it was voiceless aspirated.

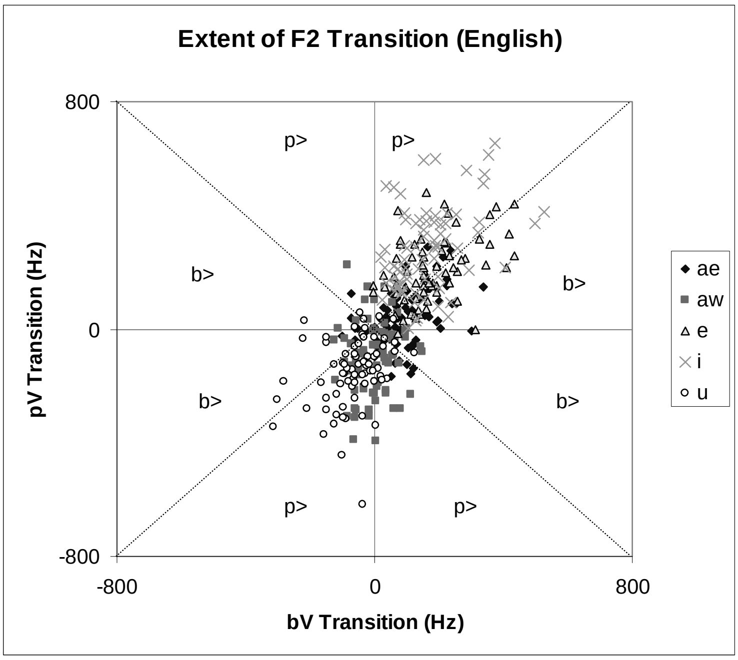
5.4.4. Summary and Discussion

LE slopes were in general higher for voiced versus voiceless aspirated stops in singleton and geminate utterances produced by English and Persian speakers. An ANOVA run across all seven speakers of the present study showed a highly significant effect for voicing ($p<.0001$). This result was especially true for bilabial and alveolar/dental stops. Velars did not show a particular pattern. The results obtained here replicated those reported in previous studies. Sussman and Shore (1996) reported lower slopes for voiceless aspirated alveolar stops compared to their voiced counterparts produced by English speakers. Molis (1994) also observed lower slope values for /p/ compared to /b/ in VCV utterances produced by Swedish and English speakers. Engstrand et al. (1997) also reported similar results for bilabial and dental voiceless aspirated stops in Swedish where a reverse relationship between VOT and LE slope values were observed. Labial slope values tended to decrease VOT increased. Similar but considerably weaker effects were observed with dental stops. Velars, however, did not show a consistent pattern.

Locus equation scatterplots are produced by plotting F2 vowel against F2 onset of CV_2 combinations. Considering that V_2 F2 vowel values remain relatively constant in different contexts, the difference in LE slopes of voiced and voiceless aspirated stops must be attributed to their difference in F2 onset values. Lower slope values associated with bilabial and alveolar/dental aspirated stops compared to their voiced counterparts indicate that F2 onset values of the former are more removed in frequency from V_2 F2 vowel compared to the latter. In other words, the extent of F2 transition at CV_2 boundary is greater for voiceless aspirated versus voiced stops.

In order to determine the extent of F2 transition at the CV boundary of singleton and geminate utterances with voiced and voiceless aspirated stops, a series of plots were generated. Figures 5-3 to 5-5 and 5-6 to 5-8 show the extent of F2 transition (F2 vowel – F2 onset) for voiced versus voiceless aspirated stops produced by English and Persian speakers respectively. In each figure, the top graph shows CV_2 transitions in singleton utterances and the bottom graph shows CV_2 transitions in geminate utterances. In these graphs, the extent of F2 transition (Hz) is plotted on the *x* axis for voiced stops and on the *y* axis for voiceless aspirated stops. Each V_2 context is shown by a separate symbol. The number of data points is 375 (5V1*5V2*5SUB*3REP) per plot for English and 216 per plot for Persian (6V1*6V2*2SUB*3REP) speakers. Data points below and to the left of the zero lines represent falling transitions, i.e. cases where F2 vowel was lower than F2 onset. Data points above and to the right of the zero lines represent rising transitions, i.e. cases where F2 vowel was higher than F2 onset. Data points falling exactly on the rising diagonal line are cases where the F2 transition of voiced consonants was identical to the F2 transition of the voiceless aspirated stops in combination with the same vowel.

As figures 5-3 to 5-8 show, data points tended to cluster around the rising diagonal line instead of falling exactly on the line. This pattern indicated that F2 transitions were not the same for voiced and voiceless aspirated stops, rather they were in some cases greater and in others smaller for voiceless stops compared to their voiced counterparts. In order to facilitate reading the graphs, each graph was divided into eight triangles and each triangle was marked for the consonant whose transitions were greater in frequency in that triangle than that of the other consonant plotted.



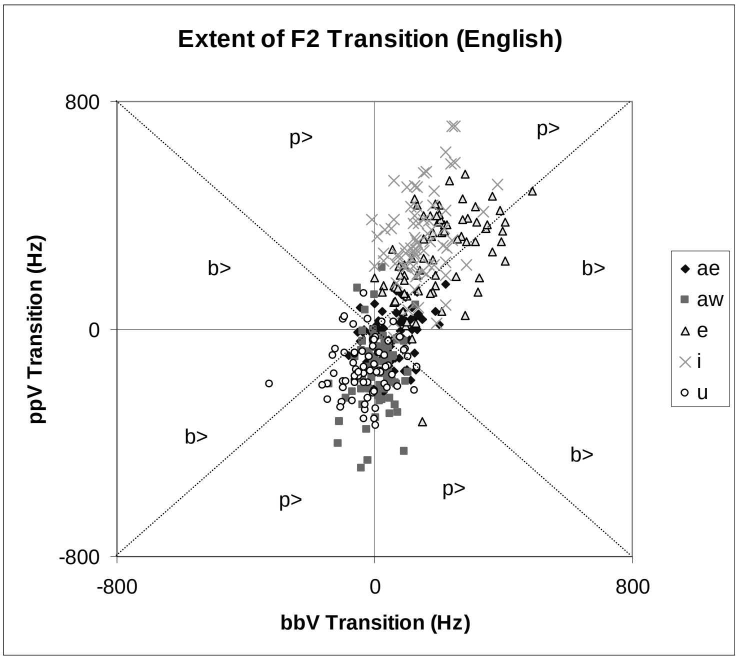


Figure 5-3. Extent of F2 transition of singleton (top) and geminate (bottom) voiced and voiceless aspirated bilabial stops (English).

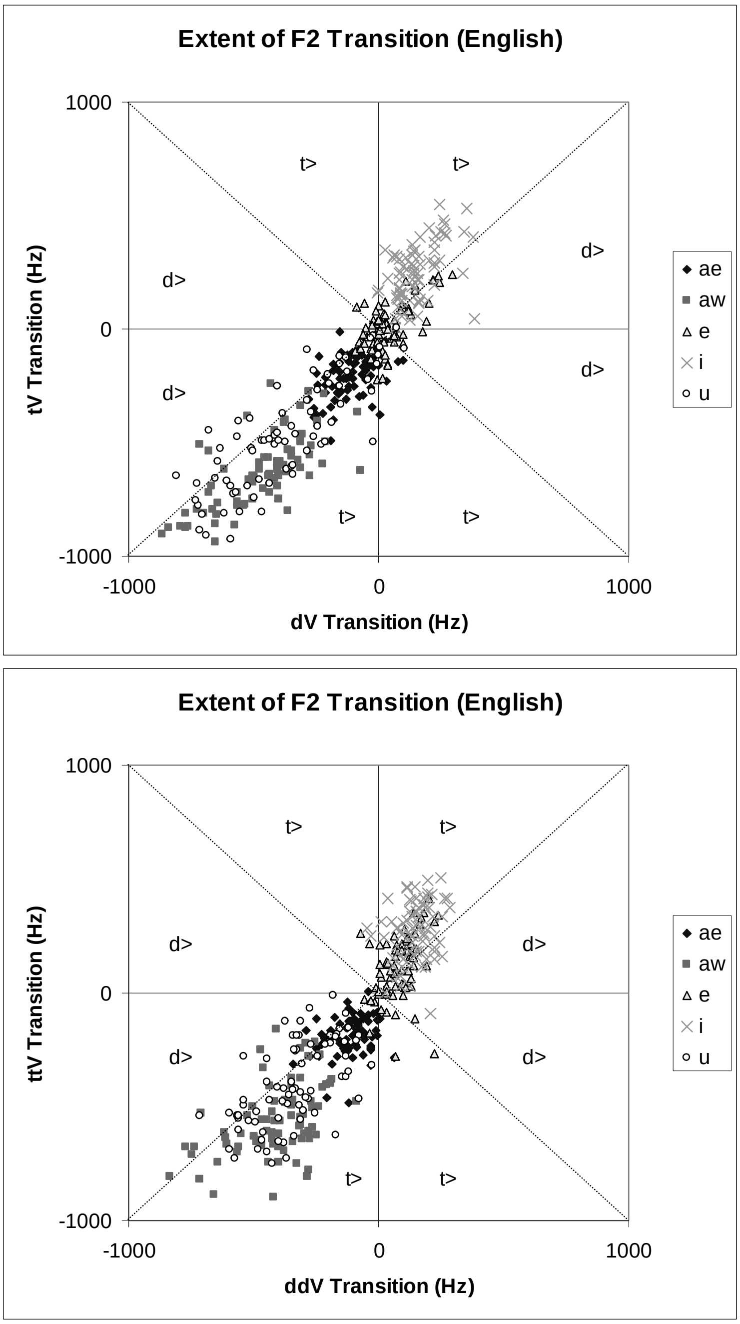


Figure 5-4. Extent of F2 transition of singleton (top) and geminate (bottom) voiced and voiceless aspirated alveolar stops (English).

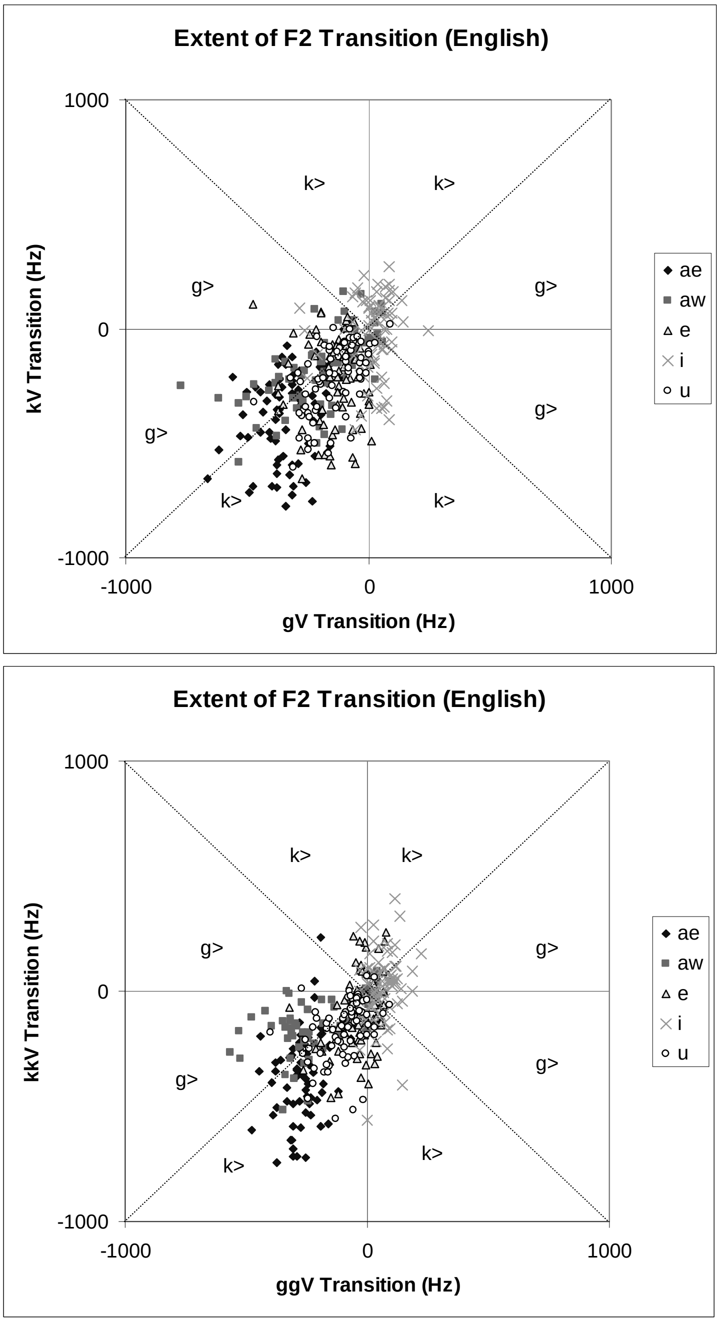
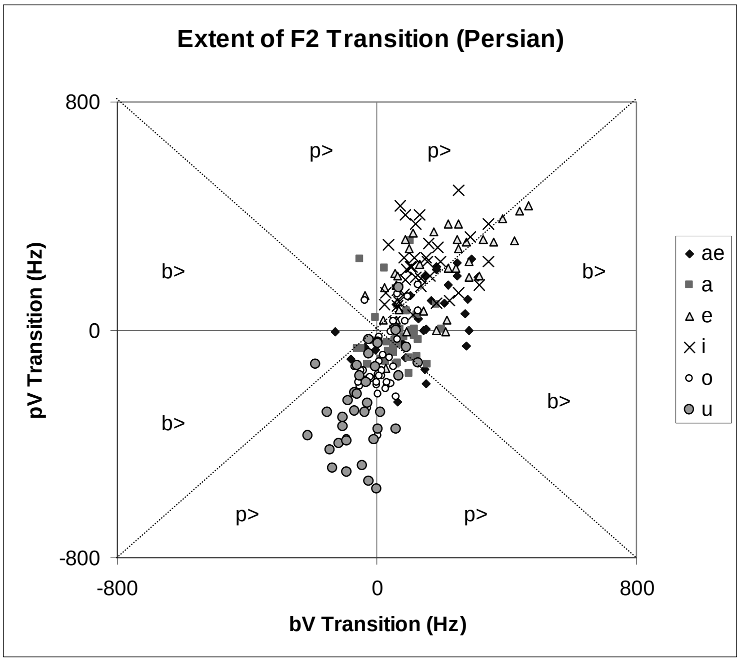


Figure 5-5. Extent of F2 transition of singleton (top) and geminate (bottom) voiced and voiceless aspirated velar stops (English).



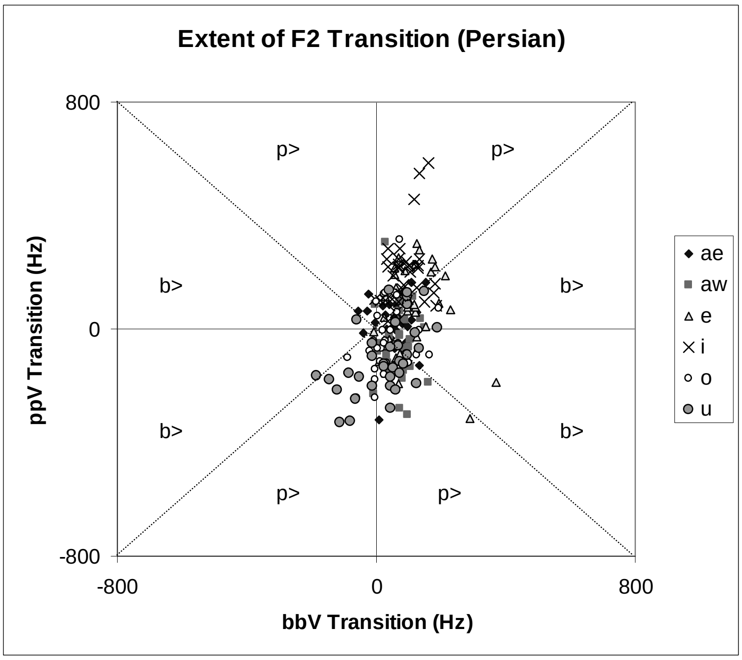
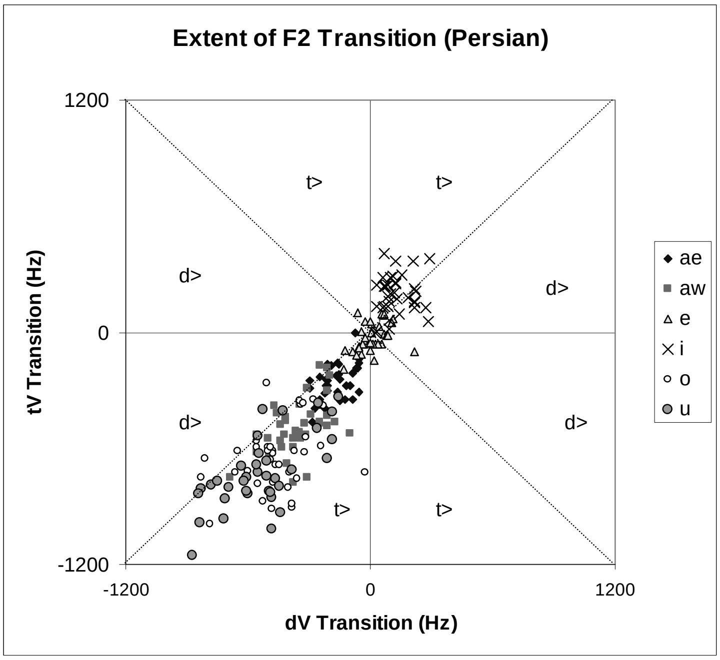


Figure 5-6. Extent of F2 transition of singleton (top) and geminate (bottom) voiced and voiceless aspirated bilabial stops (Persian).



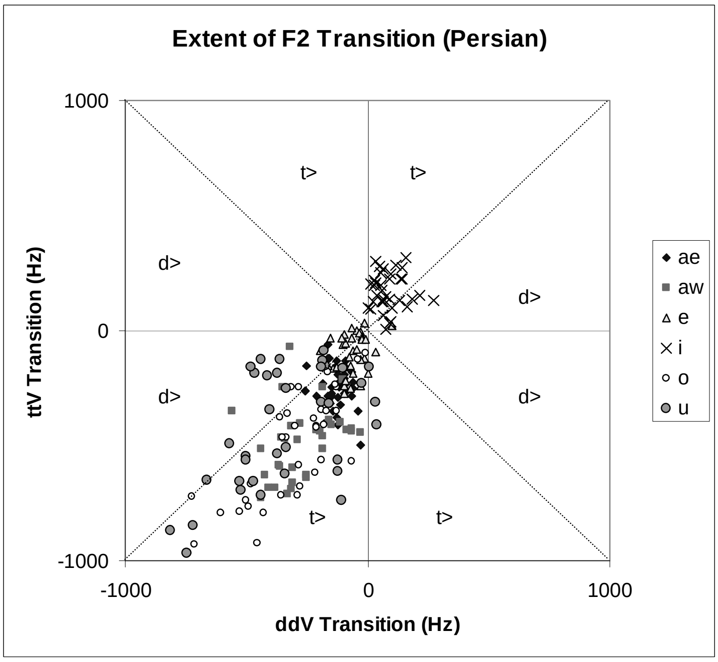
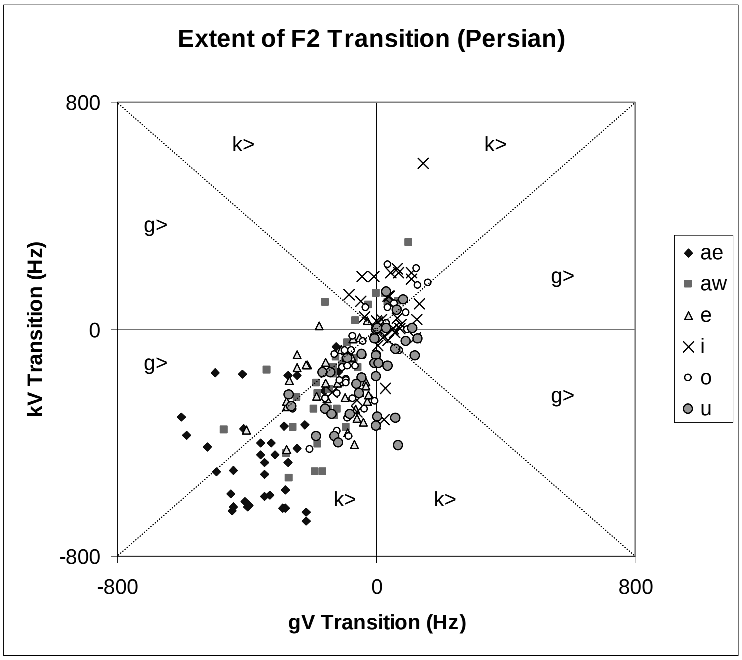


Figure 5-7. Extent of F2 transition of singleton (top) and geminate (bottom) voiced and voiceless aspirated dental stops (Persian).



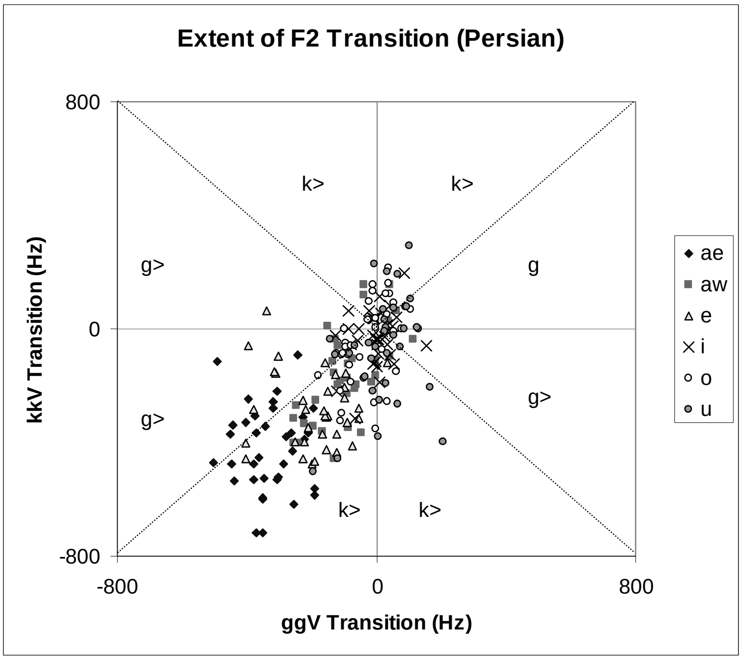


Figure 5-8. Extent of F2 transition of singleton (top) and geminate (bottom) voiced and voiceless aspirated velar stops (Persian).

In figure 5-3 showing F2 transitions of singleton and geminate bilabial stops in English, the majority of data points for the back vowels /u, ɔ/ fall in /p/ and /pp/ triangles. As for front vowels /i, e, æ/, the data points are split between voiced and voiceless bilabials, although the /pp/ triangle seems to contain more data points than /bb/. The same pattern is observed in figure 5-6 where F2 transitions of singleton and geminate bilabial stops in Persian are given.

The majority of alveolar data points in figure 5-4 fell in the triangles for /t, tt/. The same pattern was seen with dental stops produced by Persian speakers in figure 5-7.

In figure 5-5 showing F2 transitions for singleton and geminate velar stops in English, the majority of data points fell in /k/ and /kk/ triangles, although a considerable number of the data points for the low vowels /æ, ɔ/ fell in the /g/ and /gg/ triangles. F2 transitions of velar stops for Persian speakers in figure 5-8 showed a similar pattern. The majority of data points fell in /k/ and /kk/ triangles, although a few data points for the vowel /æ/ fell in the /g/ and /gg/ triangles.

In general, F2 transitions for voiceless aspirated stops were greater compared to their voiced counterparts. Larger transitions indicate larger frequency differences between F2 onset and F2 vowel. The greater the frequency difference between the two measurement points, the flatter the regression line becomes. Lower slope values and consequently lesser degrees of CV_2 coarticulation observed with voiceless aspirated compared to voiced stops can be due to differences in the timing of V_2 relative to C as a function of the voicing properties of the consonant. The tongue body has been shown to be more in place for the production of a vowel after the release of a voiced consonant than at the release of a voiceless aspirated consonant (Gay, 1979). It was mentioned in section 4.2.1.4 above that aerodynamic and/or acoustic reasons might be responsible for the differences observed in the F2 transition patterns of voiced versus voiceless aspirated stops.

The difference in the slope values of voiced versus voiceless aspirated stops can also be attributed to the different methods employed in measuring F2 onset of voiceless versus voiced stops. The aspiration noise made it possible to measure F2 onset of voiceless aspirated stops at a point closer to the release of the consonant compared to voiced stops whose F2 onset was measured at the first pitch period of V_2, i.e. at a point closer to the vowel rather than to the consonantal release. In other words, F2 onset of voiceless aspirated stops was more 'locus-like' or relatively more stable than the F2 onset of their voiced counterparts. Coefficient of variation (sd/mean) was used to determine the degree of F2 onset stability/variability as a function of voicing. Table 5-55 shows coefficient of variation for F2 onset of voiced and voiceless singleton and geminate stops for both groups of speakers. On average, the coefficient of variation was significantly smaller for voiceless stops compared to their voiced counterparts ($p<.01$) indicating more stable F2 onset for the latter compared to the former.

	b	bb	p	pp	d	dd	t	tt	g	gg	k	kk
E	.279	.286	.225	.223	.121	.140	.087	.106	.269	.266	.290	.283
P	.383	.345	.283	.246	.160	.156	.112	.098	.339	.304	.316	.286
M	**.331**	**.316**	**.254**	**.235**	**.141**	**.148**	**.099**	**.102**	**.304**	**.285**	**.303**	**.285**

Table 5-55. Coefficient of variation of F2 onset of singleton and geminate voiced and voiceless aspirated stops in English (E) and Persian (P).

Looking at individual consonants, the coefficient of variation was lower for voiceless aspirated stops compared to their voiced counterparts when the consonant was a bilabial or an alveolar/dental stop. Coefficient of variation remained stable for voiced versus voiceless aspirated velar stops. Lesser variation of F2 onset of voiceless bilabial and alveolar/dental stops compared to their voiced counterparts is responsible for flatter slopes of the former versus the latter. LE slopes for velar stops showed less variability as a function of voicing compared to other places of articulation as F2 onset of voiced and voiceless velar stops showed similar amounts of variability.

In order to determine whether the difference between LE slope values of voiced and voiceless stops was due to actual motor programming differences between the two groups or due to methodological differences, F2 onset of voiced stops was also measured at a point comparable to that of a voiceless aspirated stop, that is at the first F2 resonance after the stop burst. This measurement point was called F2 onset @burst. Tables 5-56 and 5-57 provide slope values of voiced stops measured at burst compared to slope values of their voiceless aspirated counterparts in singleton and geminate utterances produced as by English speakers. It must be noted that it was not always possible to obtain an @burst measurement for all voiced stop plus vowel combinations as no F2 resonances were observable between the first pitch period of V_2 and the release of the stop. Thus, in cases where an F2 onset @burst measurement was not possible, the default F2 onset measurement at the first pitch period of V_2 was taken instead. On average, F2 onset @burst measurement was possible for 38, 83, and 78 percent of cases for /b/, /d/, and /g/ respectively in the English data set. F2 onset @burst measurement was possible for 46, 94, and 77 percent of cases for /bb/, /dd/, and /gg/ respectively. F2 onset @burst measurements of bilabial and alveolar stops were not available for speaker E#3 and thus it was not possible to derive @burst locus equations for this speaker for the two stop categories mentioned.

	b@ burst	**p**		**d@ burst**	**t**		**g@ burst**	**k**
E#1	.67	.63		.25	.18		.86	.75
E#2	.76	.62		.32	.27		.94	.97
E#3	N/A	.59		N/A	.23		.76	1.04
E#4	.78	.63		.31	.20		1.09	1.05
E#5	.68	.73		.30	.29		.96	.83
M	**.72**	**.64**		**.30**	**.23**		**.92**	**.93**
SD	**.06**	**.05**		**.03**	**.05**		**.12**	**.13**

Table 5-56. LE slope values of voiced stops measured @ burst compared to the slope values of voiceless aspirated stops in singleton forms (English).

	bb@ burst	pp		dd@ burst	tt		gg@ burst	kk
E#1	.72	.60		.26	.25		.82	.81
E#2	.75	.56		.33	.33		.97	.91
E#3	N/A	.55		N/A	.28		.71	.96
E#4	.77	.68		.37	.33		1.11	1.04
E#5	.60	.70		.33	.31		.85	.80
M	**.71**	**.62**		**.32**	**.30**		**.89**	**.90**
SD	**.08**	**.07**		**.05**	**.03**		**.15**	**.10**

Table 5-57. LE slope values of voiced stops measured @ burst compared to the slope values of voiceless aspirated stops in geminate forms (English).

Although in both singleton and geminate forms the slope values of voiceless aspirated bilabial and alveolar stops were lower compared to their voiced counterparts when F2 onset was measured at burst, this difference was not statistically significant (p=.0998).

LE slope values remained stable across voicing conditions when F2 onset was measured at burst rather than at the first pitch period of V_2. The results obtained here replicated those reported in Sussman and Shore (1996) where no significant differences were detected between the average slope values of /t/ and /d/ @burst.

These results suggest that the differences observed earlier in this study between the slope values of voiced and voiceless aspirated stops were due to methodological reasons rather than actual motor programming reasons. In other words, when F2 onset of voiced stops was measured at a point comparable to that of voiceless stops, the significant differences observed between the slope values of voiced and voiceless stops were lost. However, considering that on average only 69% of F2 onset data points were measured at burst for voiced stops, it was not possible to make this conclusion with absolute certainty.

For singleton stops produced by Persian speakers, F2 onset @burst measurement was possible for 31, 63, and 47 percent of cases for /b/, /d/, and /g/ respectively. F2 onset @burst measurement was possible for 53, 80, and 59 percent of cases for /bb/, /dd/, and /gg/ respectively.

As tables 5-58 and 5-59 show, the slope values of voiceless aspirated stops produced by Persian speakers were on average smaller compared to their voiced counterparts irrespective of place of articulation and consonantal closure duration. The limited number of Persian subjects made it impossible to perform an ANOVA to detect any significant changes in slope values as a function of voicing.

	b@ burst	**p**		**d@ burst**	**t**		**g@ burst**	**k**
P#1	.78	.65		.29	.24		.88	.85
P#2	.82	.73		.31	.29		1.12	1.07
M	**.80**	**.69**		**.30**	**.27**		**1.0**	**.96**
SD	**.03**	**.06**		**.01**	**.04**		**.17**	**.16**

Table 5-58. LE slope values of voiced stops measured @ burst compared to the slope values of voiceless aspirated stops in singleton forms (Persian).

	bb@ burst	pp		dd@ burst	tt		gg@ burst	kk
P#1	.82	.70		.38	.25		.98	.96
P#2	.91	.85		.46	.42		1.19	1.2
M	**.87**	**.78**		**.42**	**.34**		**1.09**	**1.08**
SD	**.06**	**.11**		**.06**	**.12**		**.15**	**.17**

Table 5-59. LE slope values of voiced stops measured @ burst compared to the slope values of voiceless aspirated stops in geminate forms (Persian).

A repeated-measures ANOVA run across all seven speakers of this study showed an overall significant effect of voicing ($p<.05$). Pooling Persian and English subjects together resulted in differences between LE slopes of voiced and voiceless stops to become significant. Considering that on average only 56% of F2 onset data points were measured at burst for voiced stops produced by Persian speakers, pooling the two groups of subjects resulted in only 63% of F2 onset data points of voiced stops measured at burst. A decrease in the number of @burst F2 onsets resulted in voicing to become a significant factor. In other words, voicing became a significant factor when the number of default F2 onset measurement points increased. This suggests that the difference between LE slope values of voiced and voiceless aspirated stops can be due to methodological reasons. Only if all cases of F2 onset of voiced stops were measured at burst one could with certainty determine whether the difference between the slope values of voiced and voiceless stops was due to motor programming or methodological reasons.

5.5. CONCLUSIONS

The results obtained in this chapter confirmed the patterns observed in chapter 4 on a macro level. Locus equations were employed to uncover the acoustic correlates of troughs at the CV boundary of a broad variety of VCV sequences. Troughs were expected to lower the slope of locus equation regression function. Lower slopes (tongue body displacement effects) were observed in closed versus open syllables and with voiceless versus voiced stops although it was not clear whether the latter effects were real or due to methodological reasons. LE slopes remained stable across changes in the closure duration of C. This pattern was attributed to the tight bonding between the release of a syllable-initial stop and the following vowel.

Chapter 6: The Effects Syllable Boundary, Stop Closure Duration, and VOT on V-to-V Coarticulation

In this chapter, the effects of syllable boundary, stop consonant closure duration, and VOT on vowel-to-vowel coarticulation are investigated. The theoretical background and the goals of this investigation are discussed in section 6.1. The effects of syllable boundary on vowel-to-vowel coarticulation are investigated in section 6.2. Section 6.3 deals with the effects of stop consonant closure duration on V-to-V coarticulation. In section 6.4, the effects of VOT on vowel-to-vowel coarticulation are investigated. A summary and discussion of the results appears in section 6.5.

6.1. INTRODUCTION

Models of inter-segmental timing can be divided into two basic groups: (a) 'vowel-to-vowel timing' (Smith, 1995) or the superimposition models in which the vocalic gestures are timed with respect to one another irrespective of the intervocalic consonant and (b) "combined consonant-vowel timing" (Smith, 1995) or phoneme-by-phoneme models in which vocalic and consonantal gestures are timed with respect to one another irrespective of the phonetic qualities of the segments.

Considering vowel-to-vowel coarticulatory effects in VCV utterances, "vowel-to-vowel timing" models predict the same amount of vowel-to-vowel coarticulation irrespective of the duration of the intervocalic consonant, its intrinsic temporal characteristics, or its syllabic affiliation. On the other hand, “combined consonant-vowel timing” models, predict that the degree of vowel-to-vowel coarticulation will vary as a function of changes in the duration of the intervocalic consonant and its intrinsic temporal properties. In this chapter, the predictions of these two models are investigated by considering the effects of the syllabic affiliation of the intervocalic stop, its closure duration and voicing properties on vowel-to-vowel coarticulation in the VCV sequences produced by English and Persian speakers.

6.2. THE EFFECT OF SYLLABLE BOUNDARY ON V-TO-V COARTICULATION

The effects of the syllabic affiliation of an intervocalic stop on vowel-to-vowel coarticulation were investigated by comparing vowel-to-vowel effects in V.CV (open) versus VC.V (closed) syllable forms produced by American English and Persian speakers. Anticipatory as well as carry-over effects were investigated. The effects of syllable boundary on anticipatory coarticulation are discussed in section 6.2.1.1 for English speakers and in section 6.2.1.2 for Persian speakers. The effects of syllable boundary on carry-over coarticulation are investigated in section 6.2.2.1 for English speakers and in section 6.2.2.2 for Persian speakers. Summary and discussion of the results obtained in this subsection appear in section 6.2.3.

6.2.1. Anticipatory Coarticulation

In the investigation of anticipatory vowel-to-vowel coarticulation, the following procedures were followed for utterances produced by English and Persian speakers:

(a) In V_1CV_2 utterances, V_1 was taken as the fixed vowel and V_2 as the changing vowel alternating between /i/ and /ɔ/ in English and between /i/ and /ɒ/ in Persian tokens.

(b) The difference in V_1 F2 offset frequency as a function of the changing vowel was calculated and was taken as a measure of anticipatory vowel-to-vowel coarticulation.

(c) F2 offset delta values thus obtained for the same VCV sequence in open and closed syllable forms were compared using bar graphs.

For example, V_1 F2 offset frequency value of /e/ in /e.bi/ was subtracted from F2 offset frequency value of the same vowel in /e.bɔ/ to determine the amount of V_2 anticipation in frequency at V_1 offset. Then, V_1 F2 offset frequency value of /e/ in /eb.i/ was subtracted from V_1 F2 offset frequency value of the same vowel in /eb.ɔ/ to determine the amount of V_2 anticipation at V_1 offset in this sequence. The delta values obtained in each case were compared using bar graphs to detect any changes in the amount of anticipation of V_2 as a function of the syllabic affiliation of the intervocalic consonant. This procedure is shown in table 6-1.

Anticipatory Coarticulation		△=V_1 F2 offset Differences (Hz)	
Open Syllable	Closed Syllable	Open Syllable	Closed Syllable
$V_1.CV_2$	$V_1C.V_2$	**e.**Ci **e.**Cɔ ↘ ↙ △	**e**C.i **e**C.ɔ ↘ ↙ △

Table 6-1. Experimental conditions of investigating the amount of anticipatory co-articulation in open versus closed syllables.

In the bar graphs comparing F2 offset delta values in open and closed syllables, the dark bars show average V_1 F2 offset delta values in open syllable forms and light bars show average V_1 F2 offset delta values for the same vowel in closed syllable forms.

In order to determine the statistical significance of differences in F2 offset values between open and closed utterances, a series of t-tests were performed. The t-test results are shown by the use of asterisks in the graphs, where **** = $p \leq .0001$, *** = $p \leq .01$, **= $p \leq .05$, and * = $p \leq .10$.

6.2.1.1. English

Average F2 offset delta values of the fixed vowels /i, e, æ, u, ɔ/ in V_1 position as a function of the changing vowel /i/ versus /ɔ/ in V_2 position in open and closed syllable forms produced by American English speakers are plotted in figures 6-1 to 6-3. Each bar shows average V_1 F2 offset delta values for 15 pairs of tokens (5SUB*3REP). The vowel /ɔ/ is represented as /aw/ in the graphs. The token types used to calculate F2 offset delta values for each individual fixed vowel context are given in appendix A.

As the results in figures 6-1 to 6-3 show, F2 offset delta values were uniformly smaller in all vocalic and consonantal contexts in closed syllable forms compared to open syllables produced by English speakers.

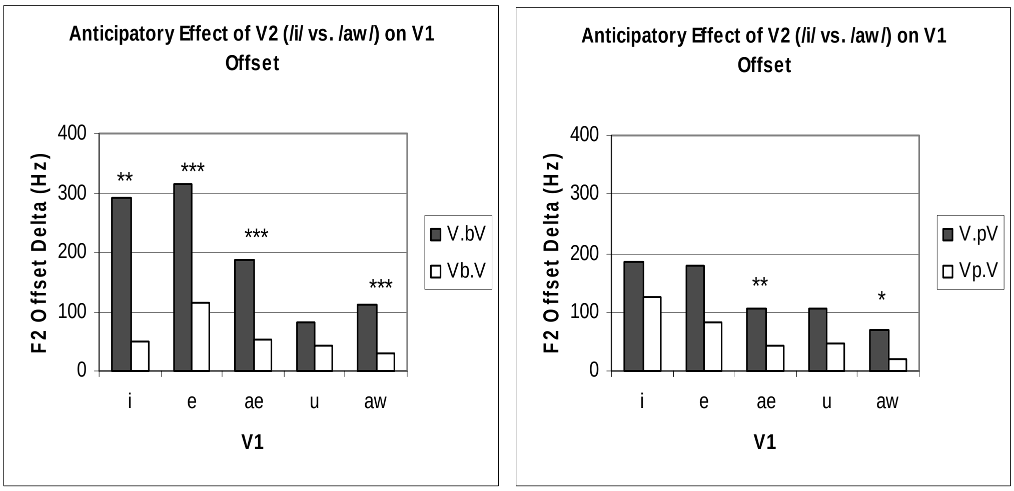


Figure 6-1. Average anticipatory effects of V_2 (/i/ versus /ɔ/) on V_1 F2 offset in open and closed syllables containing bilabial stops (English).

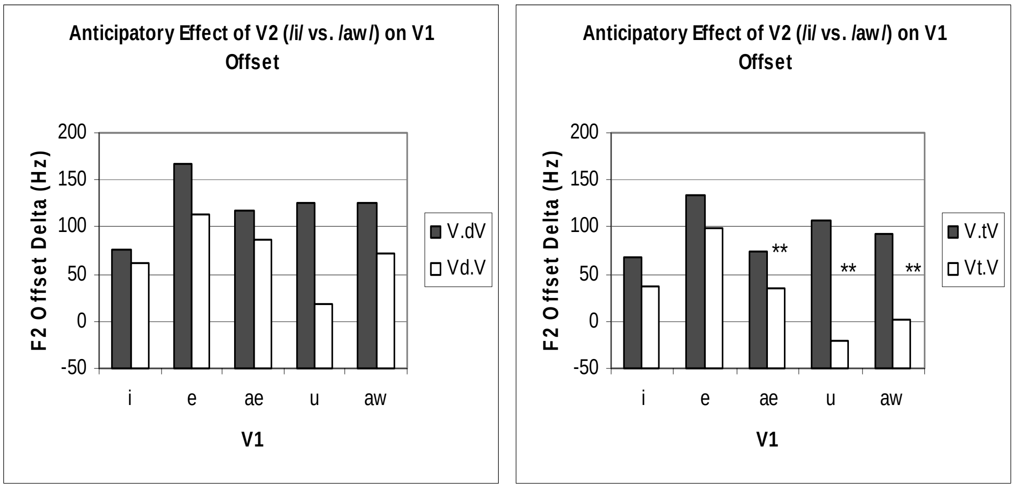


Figure 6-2. Average anticipatory effects of V_2 (/i/ versus /ɔ/) on V_1 F2 offset in open and closed syllables containing alveolar stops (English).

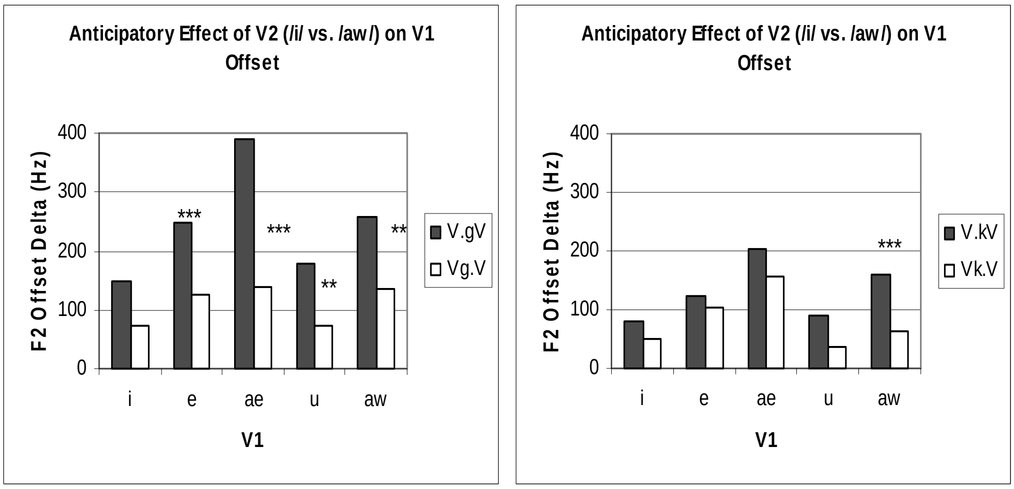


Figure 6-3. Average anticipatory effects of V_2 (/i/ versus /ɔ/) on V_1 F2 offset in open and closed syllables containing velar stops (English).

The decrease in F2 offset delta values in closed syllable forms was not, however, statistically significant in all cases. As the asterisks above the bars in figures 6-1 to 6-3 show, the reduction in F2 offset delta values in closed syllable forms compared to open syllables were significant for most V_1 contexts when the intervocalic consonant was a voiced bilabial or velar stop as well as a voiceless aspirated alveolar stop. The vowel contexts that did not show a significant decrease in F2 offset delta values in closed syllable forms involved high vowels in the context of /b/ and /g/ and front non-low vowels in the context of /t/. When the intervocalic consonant was /p/ and /k/, the only V_1 contexts that showed a significant reduction in F2 offset delta values in closed syllables were low vowels. None of the V_1 contexts showed a significant decrease in F2 offset delta values in closed syllable forms when the intervocalic consonant was /d/.

6.2.1.2. Persian

Average F2 offset delta values for the fixed vowels /i, ɛ, æ, u, o, ɒ/ in V_1 position as a function of the changing vowel /i/ versus /ɒ/ in V_2 position in open and closed syllable forms produced by Persian speakers are plotted in figures 6-4 to 6-6. F2 offset delta values for open syllable forms are averages of 6 pairs of tokens (2SUB*3REP). F2 offset delta values for closed syllable forms are averages of 5 pairs of tokens as one repetition of closed syllable forms had to be removed for speaker P#1. The vowel /ɒ/ is represented as /a/ in the graphs. The token types used to calculate F2 offset delta values for each individual fixed vowel context are given in appendix A.

The results obtained from Persian speakers were not as uniform as those obtained from English speakers. In general, the Persian data showed a decrease in anticipatory vowel-to-vowel coarticulation in closed syllable forms compared to open syllables. With /b, g/ five out of six, with /p, d, t/ four out of six, and with /k/ all cases showed this pattern. The vowels that did not follow the general pattern were front vowels. The exceptional vowel was /i/ in /b, g/, /i, e/ in /p, t/, and /i, æ/ in /d/ context.

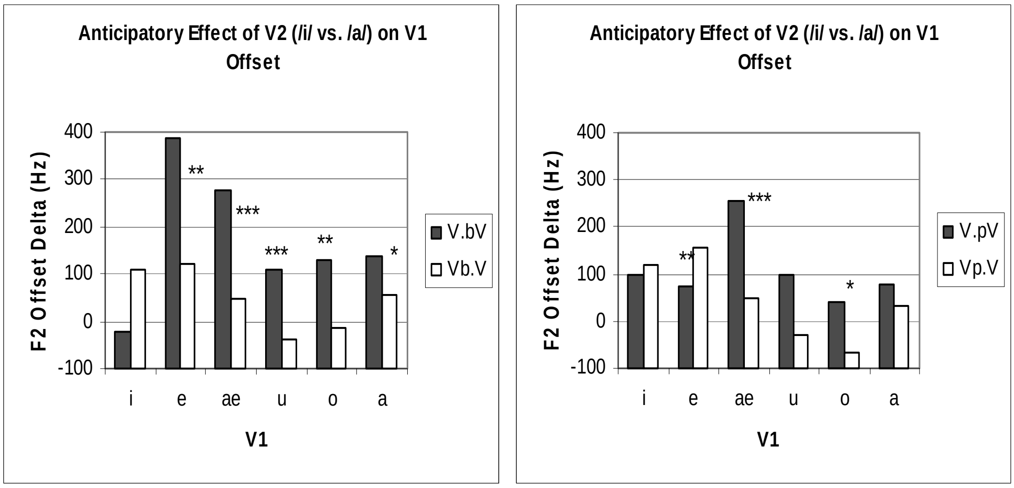


Figure 6-4. Average anticipatory effects of V_2 (/i/ versus /ɒ/) on V_1 F2 offset in open and closed syllables containing bilabial stops (Persian).

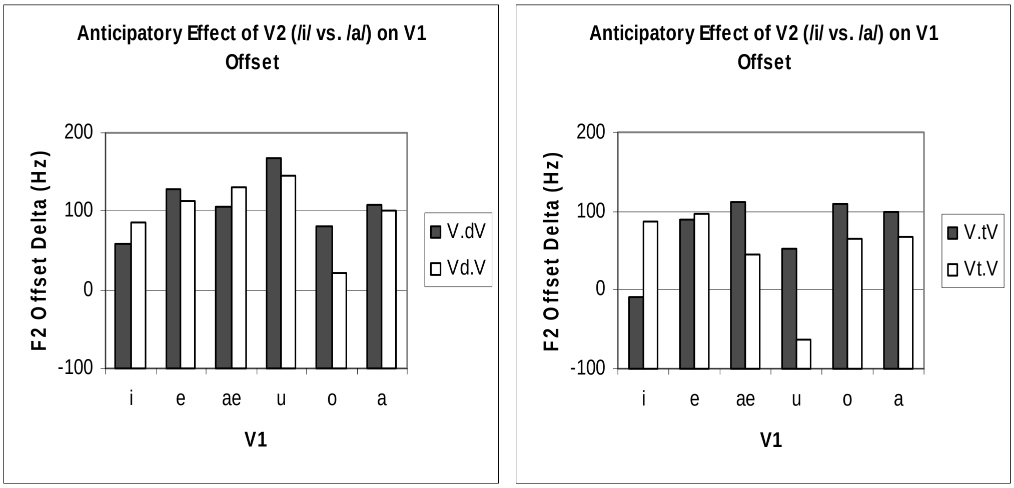


Figure 6-5. Average anticipatory effects of V_2 (/i/ versus /ɒ/) on V_1 F2 offset in open and closed syllables containing dental stops (Persian).

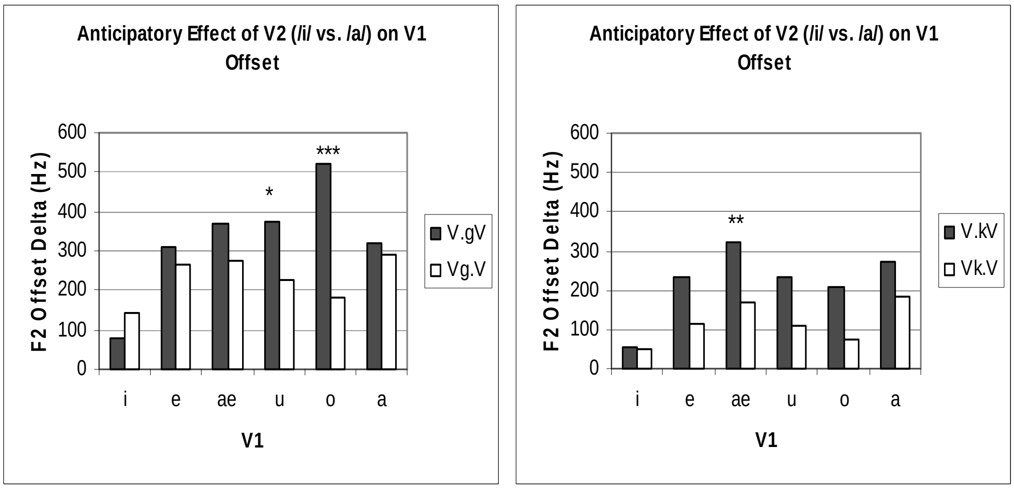


Figure 6-6. Average anticipatory effects of V2 (/i/ versus /ɒ/) on V1 F2 offset in open and closed syllables containing velar stops (Persian).

The difference in F2 offset delta values between closed and open syllable forms produced by Persian speakers was not statistically significant in all cases.

While most V_1 contexts showed a significant effects in /b/ context, the only V_1 contexts that showed a significant difference between closed and open syllable forms were non-high front vowels in the context of /p/ and /k/. The decrease in F2 offset delta values in closed syllables compared to open syllable forms observed with /g/ was only significant when V_1 was /o/. None of the differences in F2 offset delta values for dental stops were statistically significant.

6.2.2. Carryover Coarticulation

In the investigation of carry-over vowel-to-vowel coarticulation, the following procedures were followed for utterances produced by English and Persian speakers:

(d) In V_1CV_2 utterances, V_2 was taken as the fixed vowel and V_1 as the changing vowel alternating between /i/ and /ɔ/ in English and between /i/ and /ɒ/ in Persian tokens.

(e) The difference in frequency of V_2 F2 onset values as a function of the changing vowel was calculated and was taken as a measure of carry-over vowel-to-vowel coarticulation.

(f) F2 onset delta values thus obtained for the same VCV sequences in open and closed syllable forms were compared using bar graphs.

For example, V_2 F2 onset frequency value of /e/ in /i.be/ was subtracted from F2 onset frequency value of the same vowel in /ɔ.be/ to determine the amount of V_1 retention in frequency at V_2 onset. Then, V_2 F2 onset frequency value of /e/ in /ib.e/ was subtracted from V_2 F2 onset frequency value of the same vowel in /ɔb.e/ to determine the amount of V_1 retention at V_2 onset in this sequence. The F2 onset delta values thus obtained for each case were compared using bar graphs with the purpose of detecting changes in the amount of carry-over effects of V_1 on V_2 as a function of the syllabic affiliation of the intervocalic stop. This procedure is shown in table 6-2.

Carry-over Coarticulation		△=V_2 F2 onset Differences (Hz)	
Open Syllable	Closed Syllable	Open Syllable	Closed Syllable
V_1.CV_2	V_1C.V_2	i.C**e** ↘ △ ↙ ɔ.C**e**	iC.**e** ↘ △ ↙ ɔC.**e**

Table 6-2. Experimental conditions of investigating the amount of carryover co-articulation in open versus closed syllables.

6.2.2.1. English

Average F2 onset delta values for the fixed vowels /i, e, æ, u, ɔ/ in V_2 position as a function of the changing vowel /i/ versus /ɔ/ in V_1 position in open and closed syllable forms produced by English speakers are plotted in figures 6-7 to 6-9. Each bar shows average V_2 F2 onset delta values for 15 pairs of tokens (5SUB*3REP). The token types used to calculate F2 onset delta values for each individual fixed vowel context are given in appendix B.

In each graph, dark bars indicate V_2 F2 onset delta values in open syllable forms and light bars indicate the same values in closed syllable forms. The asterisks indicate statistical significance of the differences between F2 onset delta values between the two syllable forms as described in section 6.2.1 above.

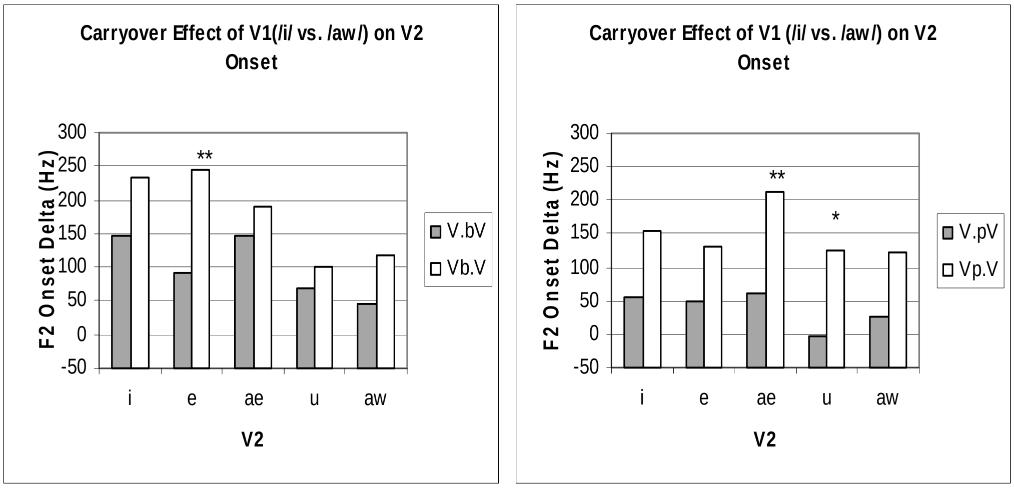


Figure 6-7. Average carry-over effects of V_1 (/i/ versus /ɔ/) on V_2 F2 onset in open and closed syllables containing bilabial stops (English).

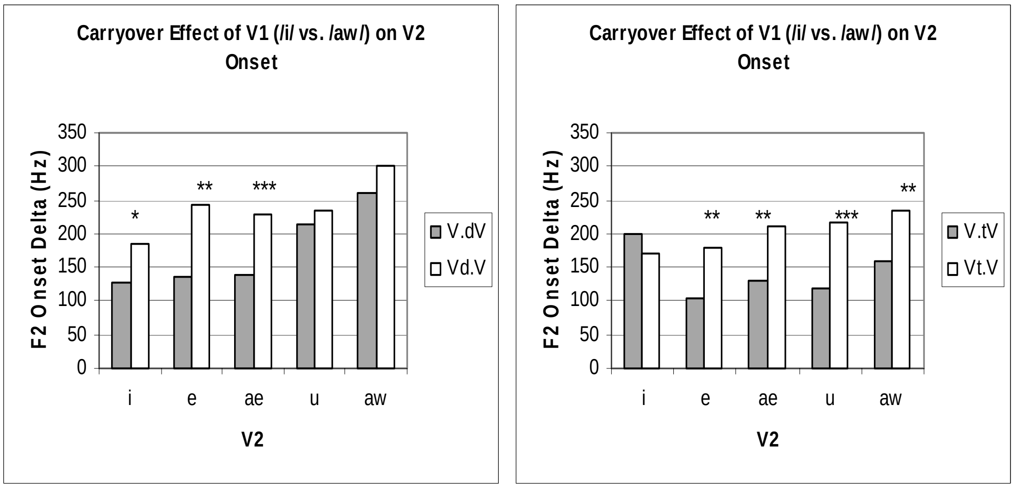


Figure 6-8. Average carry-over effects of V_1 (/i/ versus /ɔ/) on V_2 F2 onset in open and closed syllables containing alveolar stops (English).

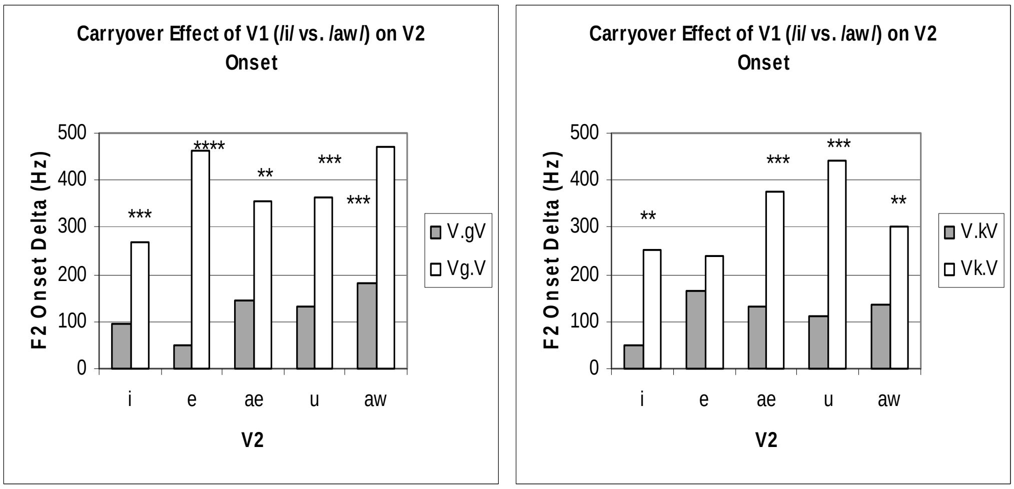


Figure 6-9. Average carry-over effects of V_1 (/i/ versus /ɔ/) on V_2 F2 onset in open and closed syllables containing velar stops (English).

As the graphs in figures 6-7 to 6-9 show, F2 onset delta values taken as a measure of carry-over vowel-to-vowel coarticulation were greater in closed syllables compared to open syllables in all vocalic and consonantal contexts except with the intervocalic /t/ followed by /i/. The difference between F2 onset delta values of open and closed syllable forms was not, however, statistically significant in all cases. The vowel contexts that showed significantly greater F2 onset delta values in closed compared to open syllables were front vowels when the intervocalic consonant was /b, p, d/. When the intervocalic consonant was /t, k/ the only V_2 contexts that did not show a significant increase in F2 onset delta values in closed syllables were front vowels. All V_2 contexts showed significantly greater F2 onset delta values in closed compared to open syllables when the intervocalic stop was /g/.

6.2.2.2. Persian

Average F2 onset delta values for the vowels /i, ɛ, æ, o, u, ɒ/ in V_2 position as a function of the changing vowel /i/ versus /ɒ/ in V_1 position in open and closed syllable forms produced by Persian speakers are plotted in figures 6-10 to 6-12. F2 onset delta values are averages of 6 pairs of tokens (2SUB*3REP) in open syllable forms. In closed syllable forms, F2 onset delta values are averages of 5 pairs of tokens. The token types used to calculate F2 onset delta values for each individual fixed vowel context are given in appendix B.

The Persian data on vowel-to-vowel carry-over effects did not show the uniform pattern observed with English speakers. Bilabial and dental stop consonants showed different results depending on V_2 context, while velar consonants uniformly showed an increase in F2 onset delta values in closed syllables compared to open syllables following the pattern observed with English speakers.

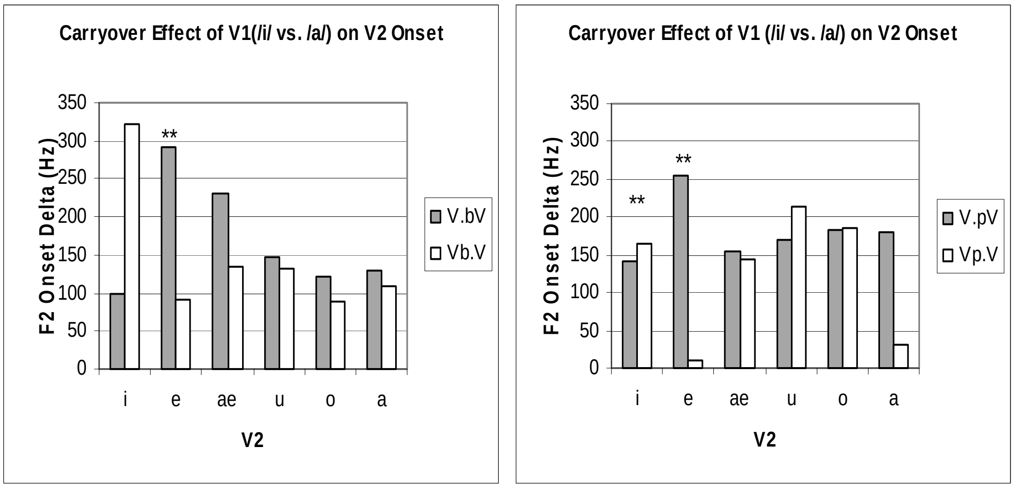


Figure 6-10. Average carry-over effects of V_1 (/i/ versus /ɒ/) on V_2 F2 onset in open and closed syllables containing bilabial stops (Persian).

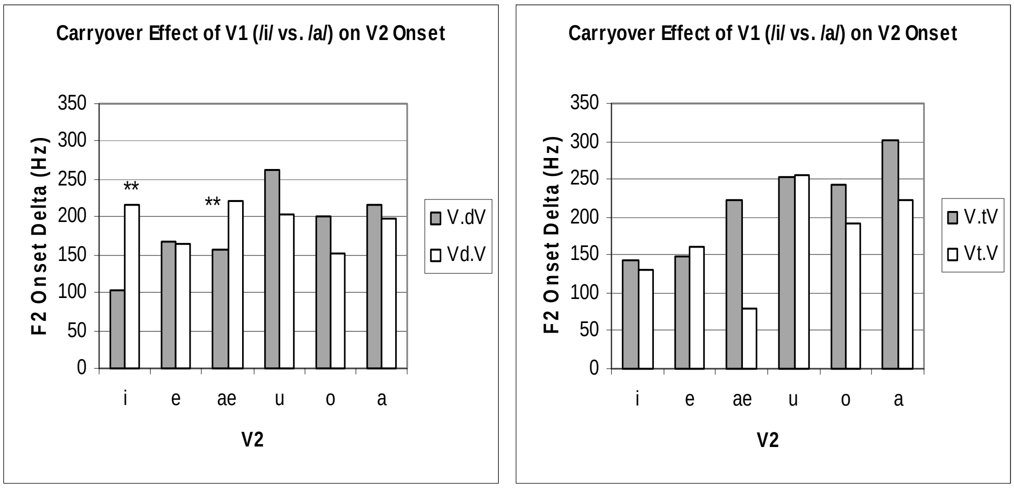


Figure 6-11. Average carry-over effects of V_1 (/i/ versus /ɒ/) on V_2 F2 onset in open and closed syllables containing dental stops (Persian).

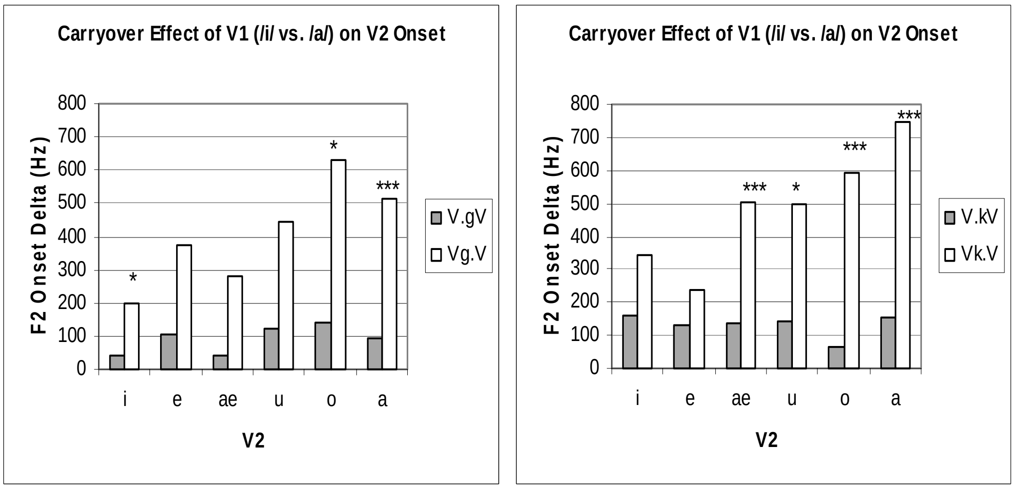


Figure 6-12. Average carry-over effects of V_1 (/i/ versus /ɒ/) on V_2 F2 onset in open and closed syllables containing velar stops (Persian).

No general pattern was observed with bilabial and dental stops except that the significant differences in F2 onset delta values between closed and open syllable forms always involved a front vowel. With bilabial stops, F2 onset delta was significantly smaller in closed versus open syllables when V_2 was /ɛ/. F2 onset delta was significantly greater in closed syllables compared to open syllables when V_2 was /i/ for /p/ and /i, æ/ for /d/. When the intervocalic consonant was a velar stop, significant effects were only observed in the context of non-high vowels.

6.2.3. Summary and Discussion

In the investigation of the effects of syllable boundary on anticipatory vowel-to-vowel coarticulation, the results obtained from English speakers showed that F2 offset delta values were consistently smaller in closed syllable forms compared to open syllables. The same general pattern was observed with utterances produced by Persian speakers. Taking F2 offset delta as a measure of anticipatory coarticulation, these results indicate that anticipatory coarticulation is affected by the syllabic affiliation of the intervocalic stop. In [V_1.CV_2] sequences, where V_2 forms a syllable with C, the anticipatory effects of V_2 on V_1 offset are greater than in [V_1C.V_2] sequences where V_2 does not form a syllable with C.

The results on carry-over coarticulation showed different results for the two groups of speakers. In the utterances produced by English speakers, F2 onset delta values were consistently smaller in open syllable forms compared to closed syllables. The same pattern was observed with Persian data, when the intervocalic consonant was a velar stop. Other stop places of articulation did not show a regular pattern. Taking F2 onset delta values as a measure of carry-over vowel-to-vowel coarticulation, the data of the present study showed that carry-over coarticulation is also affected by the syllabic affiliation of the intervocalic stop. In [$V_1C.V_2$] sequences, where V_1 forms a syllable with the intervocalic stop consonant, the carry-over effects of V_1 on V_2 F2 onset are greater than in [$V_1.CV_2$] utterances where V_1 does not form a syllable with C.

To summarize, the data obtained in this study indicates that the vowel that forms a syllable with the intervocalic stop in VCV sequences has greater effects on the trans-consonantal vowel than the other way round.

It is important to interpret these results considering vowel-to-vowel temporal distance in open and closed syllable forms. A phoneme-by-phoneme view of the serial organization of speech segments suggests that as the temporal distance between the two vowels increases the mutual effect of the two vowels on one another decreases. Under this view, differences in vowel-to-vowel temporal distance between closed and open syllables can be accountable for the differences in the degree of coarticulatory effects between these two syllable forms. In order to investigate this possibility it is necessary to define vowel-to-vowel temporal distance for each syllable form.

Since the onset of V_2 was measured at different points depending on the voicing properties of the intervocalic consonant, its syllabic affiliation, and the direction of influence, vowel-to-vowel temporal distance was likewise defined differently in each case. In open syllable forms, vowel-to-vowel temporal distance was defined differently for voiced versus voiceless aspirated intervocalic stops because the onset of V_2 was defined differently in each case. The temporal distance between V_1 offset and V_2 onset in open syllables containing a voiced stop consisted of stop closure duration and VOT, since the onset of V_2 was measured to be at the first pitch period of V_2 (see section 2.1.4.1). Figure 6-13 shows an example of vowel-to-vowel temporal distance in an open [V.CV] sequence containing a voiced stop, where V-to-V temporal distance consists of stop closure and VOT duration irrespective of the direction of influence.

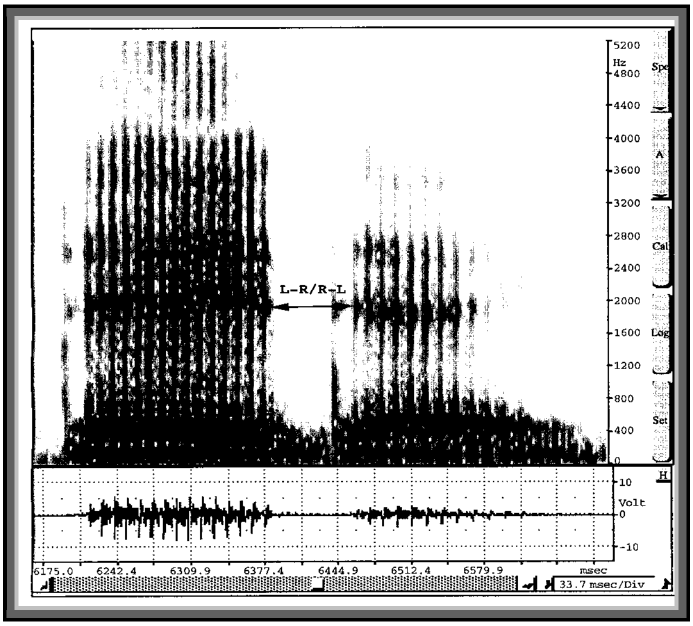


Figure 6-13. Vowel-to-vowel temporal distance in open syllable forms containing voiced stops consisted of stop closure duration and VOT considering both anticipatory (R-L) and carry-over (L-R) vowel-to-vowel effects.

In open syllable forms containing voiceless aspirated stops, the temporal distance between the two vowels as observed on the acoustic signal consisted of stop closure duration only, since the onset of V_2 was taken immediately after stop consonant release burst (see section 2.14.1). Figure 6-14 shows an example of vowel-to-vowel temporal distance in open [V.CV] sequences containing voiceless aspirated stops, where V-to-V temporal distance consists of stop consonant closure duration irrespective of the direction of influence.

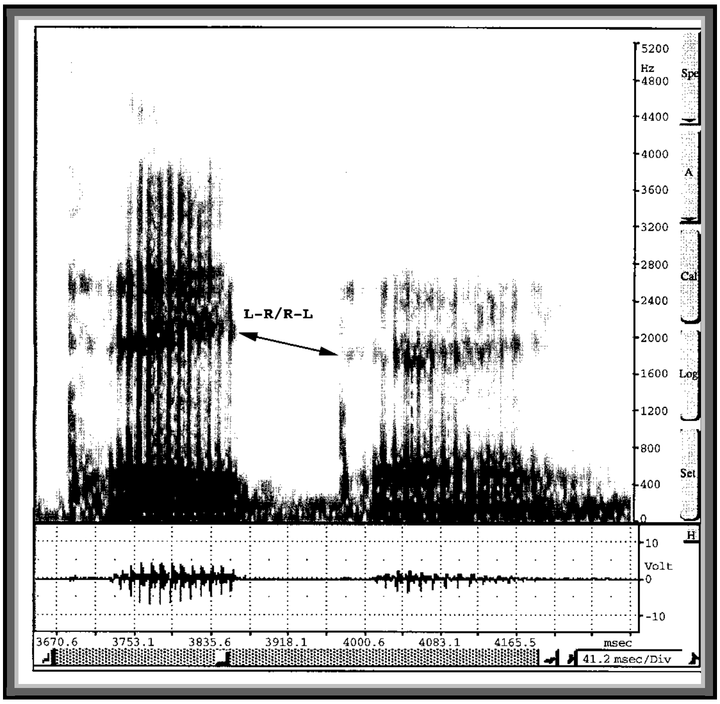


Figure 6-14. Vowel-to-vowel temporal distance in open syllable forms containing voiceless aspirated stops consisted of stop closure duration considering both anticipatory (R-L) and carry-over (L-R) vowel-to-vowel effects.

In closed syllable forms, vowel-to-vowel temporal distance was defined on the basis of the direction of influence rather than the voicing properties of the intervocalic consonant. When investigating anticipatory effects, the temporal distance between V_1 offset and V_2 consisted of stop closure and pause duration. That was because V_1 F2 offset and the acoustic beginning of V_2 were separated by stop closure and a period of pause. However, when investigating carry-over effects, vowel-to-vowel temporal distance consisted of stop closure duration only. That was because in the investigation of carry-over effects, the influences of V_1 on V_2 F2 onset were of interest and F2 onset was measured at the release of the intervocalic stop in closed syllable forms (see section 2.1.4.1) rather than at the actual beginning of V_2 on the acoustic signal. Figure 6-15 shows an example of vowel-to-vowel temporal distance in closed syllable forms when considering anticipatory (R-L) versus carry-over (L-R) influences.

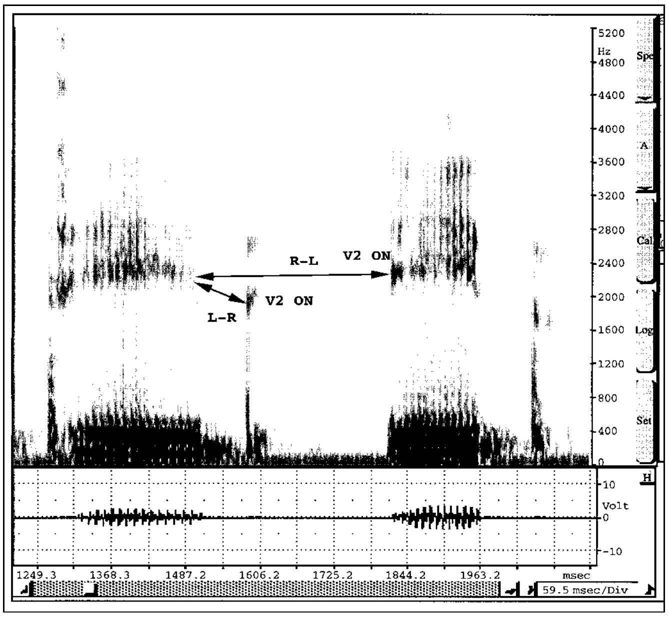


Figure 6-15. Vowel-to-vowel temporal distance in closed syllable forms consisted of stop closure and pause duration when considering anticipatory (R-L) coarticulation and of stop closure duration only when considering carry-over (L-R) effects.

Table 6-3 provides a summary of the definition of V-to-V temporal distance in each utterance type.

	V.C[+voice]V	**V.C[-voice]V**	**VC.V**
R-L Coarticulation	Stop Closure + VOT	Stop Closure	Stop Closure + Pause
L-R Coarticulation	Stop Closure + VOT	Stop Closure	Stop Closure

Table 6-3. Definition of vowel-to-vowel temporal distance as a function of the direction of influence and the voicing properties and syllabic affiliation of the intervocalic stop.

Figures 6-16 and 6-17 show vowel-to-vowel temporal distance in open and closed syllable forms produced by English and Persian speakers respectively when considering anticipatory coarticulation. In these graphs V-to-V temporal distance is shown in light color for open syllable forms and in dark color for closed syllable forms.

As the figures show, in the utterances produced by both groups of speakers, the temporal distance between V_2 onset and V_1 offset was on average 3.36 times greater in closed syllable forms compared to open syllables. A paired t-test showed that this difference was statistically highly significant ($p<.0001$) for both groups of speakers.

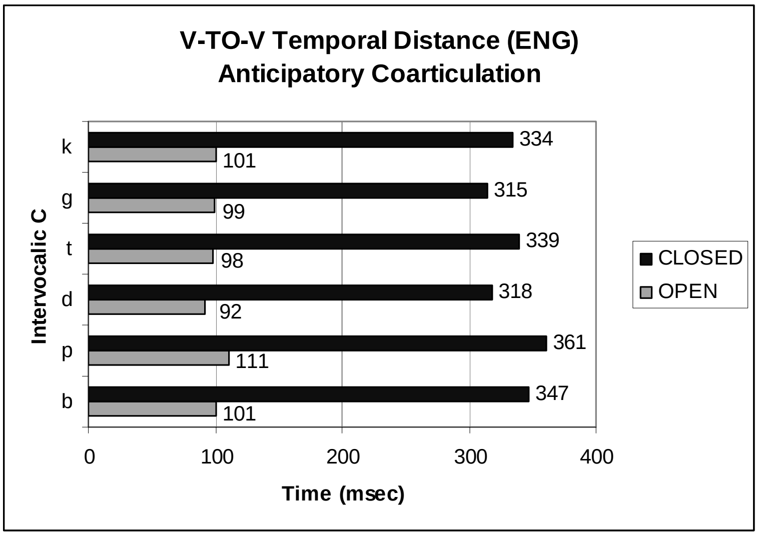


Figure 6-16. Vowel-to-vowel temporal distance in open versus closed syllable forms for all stop places of articulation produced by American English speakers considering anticipatory influences.

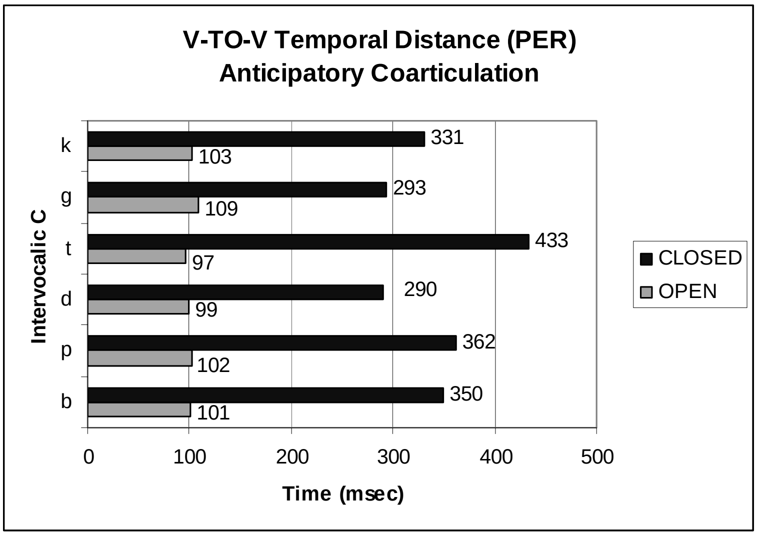


Figure 6-17. Vowel-to-vowel temporal distance in open versus closed syllable forms for all stop places of articulation produced by Persian speakers considering anticipatory influences.

Considering that anticipatory V-to-V effects were in general smaller in closed syllable forms compared to open syllables for both groups of speakers, and considering that vowel-to-vowel temporal distance between the two vowels were greater in all cases in closed syllables versus open syllables, it seems that a reverse relationship existed between vowel-to-vowel temporal distance and the amount of anticipatory coarticulation. Anticipatory vowel-to-vowel coarticulation decreased as V-to-V temporal distance increased. This observation makes it difficult to conclude whether the decrease in anticipatory vowel-to-vowel coarticulation in closed syllables is a function of the syllabic affiliation of the intervocalic stop or the result of an increase in the temporal distance between the two vowels.

Figures 6-18 and 6-19 show vowel-to-vowel temporal distance in open versus closed syllable forms produced by English and Persian speakers respectively when considering carry-over effects. In these graphs, dark bars show vowel-to-vowel temporal distance in closed syllable forms and light bars show vowel-to-vowel temporal distance in open syllable forms.

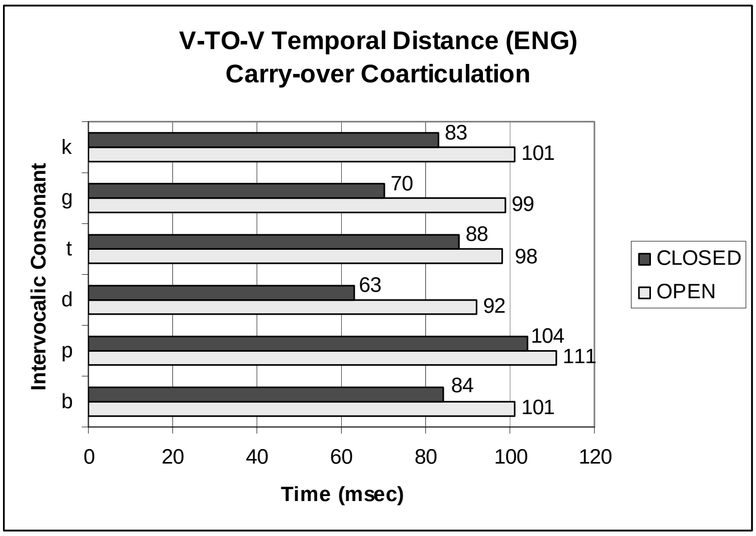


Figure 6-18. Vowel-to-vowel temporal distance in open versus closed syllable forms for all stop places of articulation produced by English speakers considering carry-over influences.

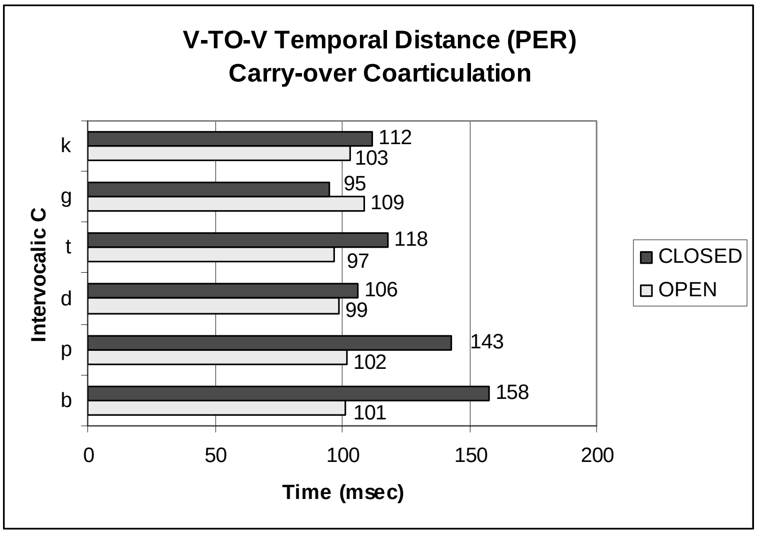


Figure 6-19. Vowel-to-vowel temporal distance in open versus closed syllable forms for all stop places of articulation produced by Persian speakers considering carry-over influences.

The data on vowel-to-vowel temporal distance summarized in figure 6-18 shows that the temporal distance between V_1 offset and V_2 onset is on average 18 milliseconds or 1.2 times longer in open versus closed syllable forms produced by English speakers when considering carry-over coarticulation. These results were expected considering that V-to-V temporal distance consisted of stop closure duration in closed syllables and of stop closure duration plus VOT in open syllable forms when considering carry-over effects. A paired t-test showed that the difference between open and closed syllables in terms of V-to-V temporal distance was statistically significant ($p<.0001$ for all places of articulation except for /p/ where $p<.05$). Thus, the results indicate that as the temporal distance between V_1 and V_2 increases, the carry-over effects of V_1 on V_2 F2 onset decreases.

As figure 6-19 shows, in the utterances produced by Persian speakers, V-to-V temporal distance was longer in closed versus open syllables for all stops, except for /g/ when considering carry-over effects. On average, the temporal distance between V_1 offset and V_2 onset was 20 milliseconds or 1.2 times longer in closed versus open syllable forms. A paired t-test showed that the difference between open and closed syllable forms in terms of V-to-V temporal distance was statistically significant ($p<.0001$) for /b, p, t, g/, but not for /d, k/.

Considering the temporal distance between the two vowels in the utterances produced by Persian speakers, greater carry-over effects were expected in open versus closed syllable except for when the intervocalic consonant was /g/ in which case a reverse pattern was expected. However, none of the consonantal contexts showed consistently greater carry-over effects in open versus closed syllable forms. Velar consonants showed uniformly smaller carry-over coarticulatory effects in open syllable forms. This pattern was expected as vowel-to-vowel temporal distance was significantly longer in open syllables when the intervocalic consonant was /g/. Smaller carry-over effects in closed syllables were not expected when the intervocalic consonant was /k/, as there was no significant difference in vowel-to-vowel temporal distance between closed and open syllables when the intervocalic consonant was /k/.

Thus, V-to-V temporal distance can account for certain V-to-V coarticulatory effects, but not all. It is difficult to determine whether the coarticulatory patterns observed in the two groups of utterances investigated in this section can best be described by temporal considerations or the syllabic affiliation of the intervocalic stop or both. Smaller carry-over effects of V_1 on V_2 onset across /k/ in open versus closed syllables produced by Persian speakers despite constant vowel-to-vowel temporal distance is the only case that can be explained only by syllabic affiliation considerations.

6.3. THE EFFECTS OF STOP CONSONANT CLOSURE DURATION ON V-TO-V COARTICULATION

It was shown in section 3.1 that the speakers of this study produced geminate stops with closure durations significantly longer than those of their singleton counterparts. The effects of stop consonant closure duration on vowel-to-vowel coarticulation were investigated in [V.CV] (singleton) and [VC.CV] (geminate) utterances produced by English and Persian speakers. Anticipatory as well as carry-over effects were studied. The effects of stop consonant closure duration on anticipatory vowel-to-vowel coarticulation are investigated in section 6.3.1.1 for English speakers and in section 6.3.1.2 for Persian speakers. Consonantal closure duration effects on carry-over vowel-to-vowel coarticulation are investigated in section 6.3.2.1 for English and in section 6.3.2.2 for Persian speakers. Summary and discussion of the results obtained in this section are provided in section 6.3.3.

It must be noted that singleton utterances are the same as the open utterances discussed in the previous section. Thus, the data for these utterances are repeated here in comparison with geminate utterances.

6.3.1. Anticipatory Coarticulation

The procedures followed to investigate the effects of intervocalic stop consonant duration on anticipatory vowel-to-vowel coarticulation were similar to those employed in the investigation of syllable boundary effects in section 6.2.1. F2 offset delta values indicating degree of anticipatory vowel-to-vowel coarticulation were compared in singleton versus geminate utterances to determine the effects of stop consonant closure duration on V-to-V coarticulation. For example, V_1 F2 offset frequency value of /e/ in /e.bi/ was subtracted from F2 offset frequency value of the same vowel in /e.bɔ/ to determine the amount of V_2 anticipation. Then, V_1 F2 offset frequency value of /e/ in /eb.bi/ was subtracted from V_1 F2 offset frequency value of the same vowel in /eb.bɔ/ to determine the amount of V_2 anticipation in this sequence. The third step was to compare the F2 offset delta values obtained in each case to detect any changes in the amount of anticipation of V_2 as a function of consonantal closure duration. This procedure is shown in table 6-4.

<table>
<tr><td colspan="2">Anticipatory Coarticulation</td><td>△=V_1 F2 offset Differences (Hz)</td></tr>
<tr><td>$V_1.CV_2$</td><td>$V_1C.CV_2$</td><td>V_1=Fixed Vowel V_2=Changing Vowel
eC(C)i eC(C)ɔ
↘ ↙
△</td></tr>
</table>

Table 6-4. Experimental conditions for assessing the magnitude of anticipatory coarticulation across singleton and geminate consonants.

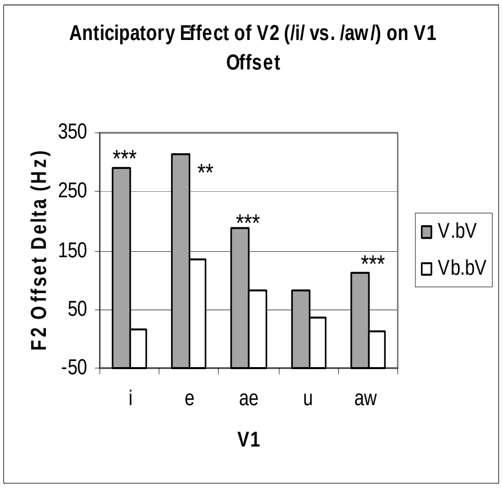
Bar graphs were used to compare F2 offset delta values in singleton versus geminate forms. In each graph, dark bars show average V_1 F2 offset delta values in singleton utterances and light bars show average V_1 F2 offset delta values for the same vowel in geminate tokens.

In order to determine the statistical significance of the difference in F2 offset delta values in singleton versus geminate forms, a series of paired t-tests was performed. The asterisks above bar graphs indicate the statistical significance of F2 offset delta differences between singleton and geminate utterances as mentioned in section 6.2.1.

6.3.1.1. English

Average F2 offset delta values for fixed vowels /i, e, æ, u, ɔ/ in V_1 position as a function of the changing vowel /i/ versus /ɔ/ in V_2 position in singleton and geminate utterances produced by English speakers are plotted in figures 6-20 to 6-22. Each bar shows average V_1 F2 offset delta values for 15 pairs of tokens (5SUB*3REP). The token types used to calculate F2 offset delta values for each individual fixed vowel context are given in appendix A.

As the graphs in figures 6-20 to 6-22 show, the F2 offset delta values were consistently smaller in geminate versus singleton forms. Smaller F2 offset delta values in geminate versus singleton forms indicate lesser degrees of V_2 anticipation as the closure duration of the intervocalic stop increases. The only exception to this general pattern was seen with /t/ when V_1 was /e/. In this case, F2 offset delta values remained the same despite an increase in the closure duration of the intervocalic consonant.



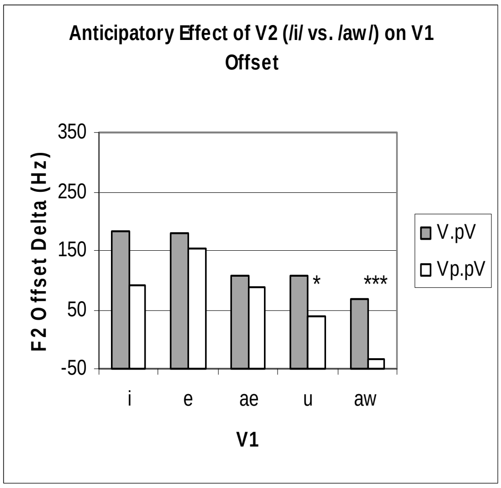


Figure 6-20. Average anticipatory effects of V_2 (/i/ versus /ɔ/) on V_1 F2 offset across intervocalic singleton and geminate bilabial stops (English).

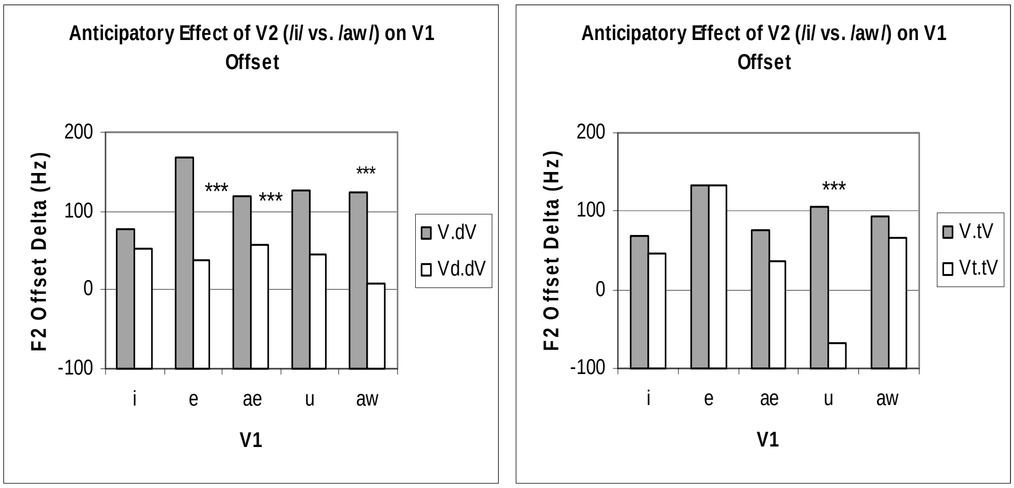


Figure 6-21. Average anticipatory effects of V_2 (/i/ versus /ɔ/) on V_1 F2 offset across intervocalic singleton and geminate alveolar stops (English).

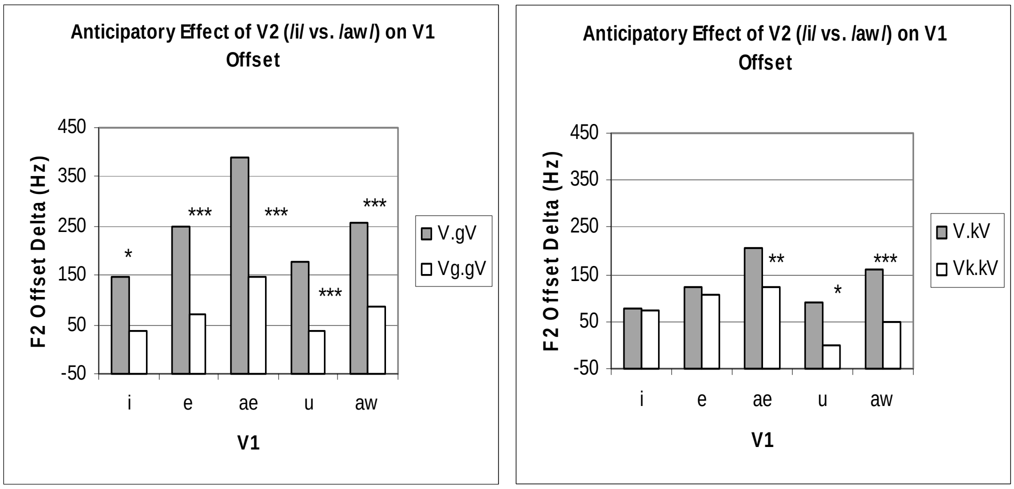


Figure 6-22. Average anticipatory effects of V_2 (/i/ versus /ɔ/) on V_1 F2 offset across intervocalic singleton and geminate velar stops (English).

The decrease in F2 offset delta values in geminate compared to singleton forms was not, however, statistically significant in all cases. When the intervocalic consonant was a voiced stop, most V_1 contexts showed a significant decrease in geminate versus singleton forms. Non-significant cases all involved a high vowel, i.e. /u/ for /b/, /i, u/ for /d/, and /i/ for /g/. When the intervocalic consonant was a voiceless aspirated stop, the only V_1 contexts that showed a significant decrease in F2 offset delta values in geminate forms were low vowels for /p/ and /k/ and /u/ for /t/.

6.3.1.2. Persian

Average F2 offset delta values for the fixed vowels /i, ɛ, æ, u, o, ɒ/ in V_1 position as a function of the changing vowel /i/ versus /ɒ/ in singleton and geminate utterances produced by Persian speakers are plotted in figures 6-23 to 6-25. Each bar shows average V_1 F2 offset delta values for 6 pairs of tokens (2SUB*3REP). The token types used to calculate F2 offset delta values for each individual fixed vowel context are given in appendix A.

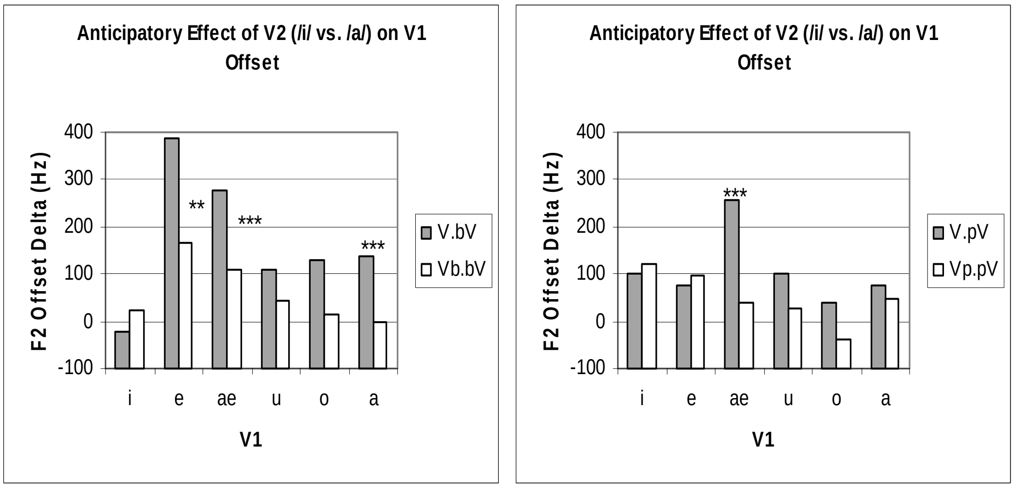


Figure 6-23. Average anticipatory effects of V_2 (/i/ versus /ɒ/) on V_1 F2 offset across intervocalic singleton and geminate bilabial stops (Persian).

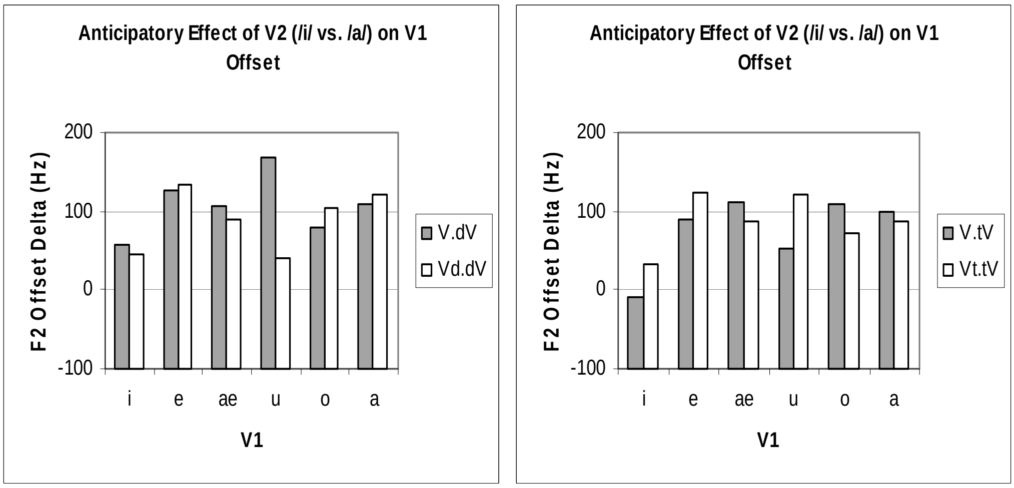


Figure 6-24. Average anticipatory effects of V_2 (/i/ versus /ɒ/) on V_1 F2 offset across intervocalic singleton and geminate dental stops (Persian).

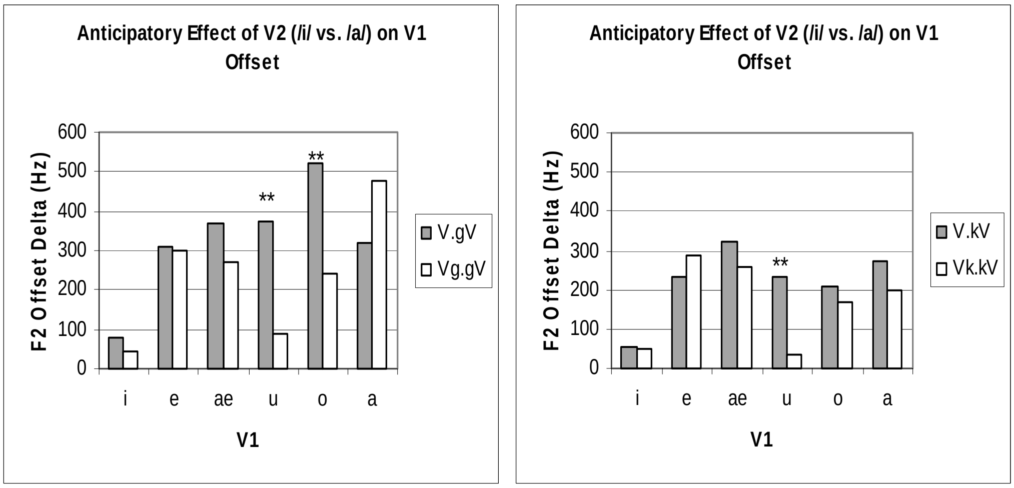


Figure 6-25. Average anticipatory effects of V_2 (/i/ versus /ɒ/) on V_1 F2 offset across intervocalic singleton and geminate velar stops (Persian).

As the data in figures 6-23 to 6-25 show, when the intervocalic consonant was a bilabial or a velar stop, F2 offset delta values were generally smaller in geminate versus singleton forms produced by Persian speakers. This pattern was not, however, as uniform for the Persian speakers as it was for the English speakers. With /b, g, k/ five out of six and with /p/ four out of six cases showed a decrease in F2 offset delta values in geminate forms. Significantly smaller F2 offset delta values in geminate forms occurred with non-high front vowels with bilabial stops and non-low back vowels with velar stops. When the intervocalic consonant was a dental stop, half of the cases showed an increase in F2 offset delta values in geminate forms compared to singleton forms and half showed a decrease. No general pattern was detected and none of the differences in F2 offset delta values between singleton and geminate forms containing dental stops were statistically significant.

6.3.2. Carry-over Coarticulation

The procedures followed to investigate the effects of intervocalic stop consonant duration on carry-over vowel-to-vowel coarticulation were similar to those employed in the investigation of the effects of syllable boundary in section 6.2.2. F2 onset delta values taken as a measure of carry-over vowel-to-vowel coarticulation were compared in singleton versus geminate utterances to determine the effect of consonantal closure duration on carry-over effects.

For example, V_2 F2 onset frequency value of /e/ in /i.be/ was subtracted from F2 onset frequency value of the same vowel in /ɔ.be/ to determine the amount of V_1 retention. Then, V_2 F2 onset frequency value of /e/ in /ib.be/ was subtracted from V_2 F2 onset frequency value of the same vowel in /ɔb.be/ to determine the amount of V_1 retention in this sequence. The third step was to compare the delta values obtained in each case to detect any changes in the amount of carry-over effects of V_1 of V_2 F2 onset as a function of consonantal closure duration. This procedure is illustrated in table 6-5.

Carryover Coarticulation		△=V_2 F2 onset Differences (Hz)
$V_1.CV_2$	$V_1C.CV_2$	V_2=Fixed Vowel V_1=Changing Vowel iC(C)**V2** ɔC(C)**V2** ↘ ↙ △

Table 6-5. Experimental conditions for assessing the magnitude of carry-over coarticulation across singleton and geminate consonants.

In the graphs comparing F2 onset delta values in singleton versus geminate forms, dark bars show average V_2 F2 onset delta values in singleton utterances and light bars show average V_2 F2 onset delta values for the same vowel in geminate tokens.

A series of paired t-tests were performed to determine the statistical significance of differences in F2 onset delta values observed between singleton and geminate forms. The statistical significance of the differences in F2 onset values of singleton and geminate forms is indicated by the use of asterisks above the graphs as mentioned in section 6.2.1 above.

6.3.2.1. English

Average F2 onset delta values for the fixed vowels /i, e, æ, u, ɔ/ in V_2 position as a function of the changing vowel /i/ versus /ɔ/ in V_1 position in singleton and geminate forms produced by English speakers are plotted in figures 6-26 to 6-28. Each bar in these graphs shows average V_2 F2 onset delta values for 15 pairs of tokens (5SUB*3REP). The token types used to calculate F2 onset delta values for each individual fixed vowel context are given in appendix B.

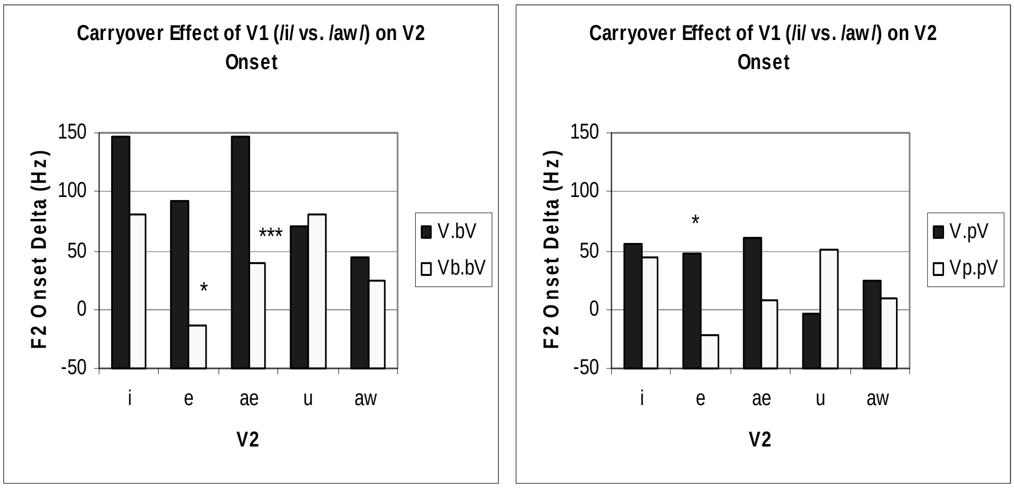


Figure 6-26. Average carry-over effects of V_1 (/i/ versus /ɔ/) on V_2 F2 onset across intervocalic singleton and geminate bilabial stops (English).

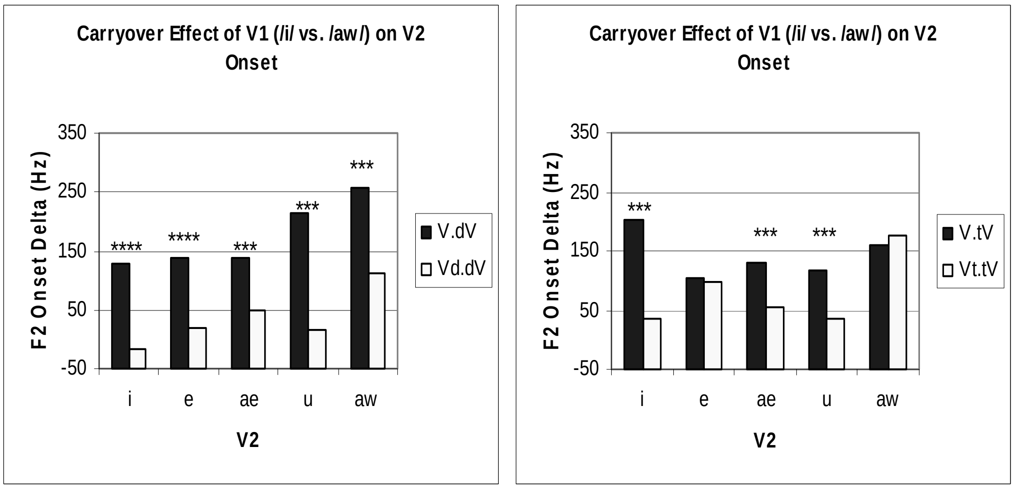


Figure 6-27. Average carry-over effects of V_1 (/i/ versus /ɔ/) on V_2 F2 onset across intervocalic singleton and geminate alveolar stops (English).

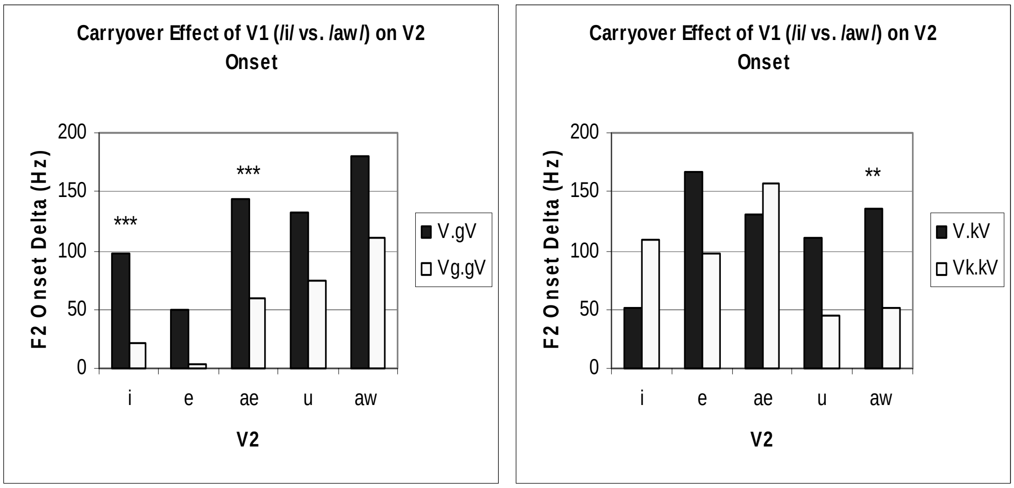


Figure 6-28. Average carry-over effects of V_1 (/i/ versus /ɔ/) on V_2 F2 onset across intervocalic singleton and geminate velar stops (English).

The general trend observed with English speakers was that the carry-over effects of V_1 on V_2 onset decreased as the duration of the intervocalic stop consonant increased. The intervocalic stop consonants /d/ and /g/ showed this pattern uniformly, while with /b, p, t/ four out of five cases and with /k/ three out of five cases followed this pattern.

With /b/ and /g/, the only cases that showed significantly smaller F2 onset delta values in geminate versus singleton forms involved a front vowel, i.e. /æ/ for /b/ and /i, æ/ for /g/. When the intervocalic consonant was /d/, all vowel contexts showed a significant decrease in F2 onset delta values in geminate forms compared to singleton forms. None of the differences in F2 onset delta values of singleton and geminate stops were statistically significant when the intervocalic consonant was /p/. In the context of /t/, the difference between the F2 onset delta values of singleton and geminate forms was highly significant when V_2 was /i, æ, u/. When the stop was /k/, the only V_2 context that showed a significant decrease in F2 onset delta value in geminate forms was /ɔ/.

6.3.2.2. Persian

Average F2 onset delta values for the fixed vowels /i, ɛ, æ, o, u, ɒ/ in V_2 position as a function of the changing vowel /i/ versus /ɒ/ in singleton and geminate forms produced by Persian speakers are plotted in figures 6-29 to 6-31. Each bar shows average V_2 F2 onset delta values for 6 pairs of tokens (2SUB*3REP). The token types used to calculate F2 onset delta values for each individual fixed vowel context are given in appendix B.

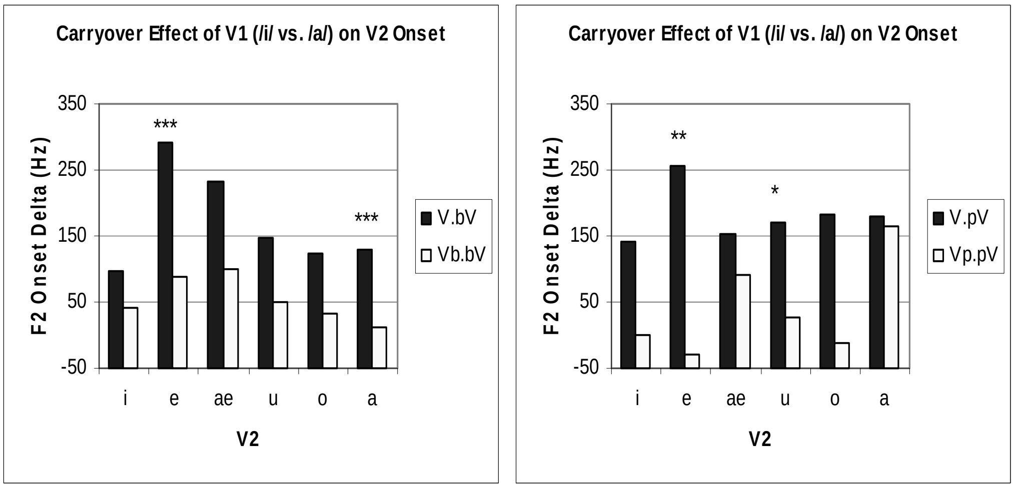


Figure 6-29. Average carry-over effects of V_1 (/i/ versus /ɒ/) on V_2 F2 onset across intervocalic singleton and geminate bilabial stops (Persian).

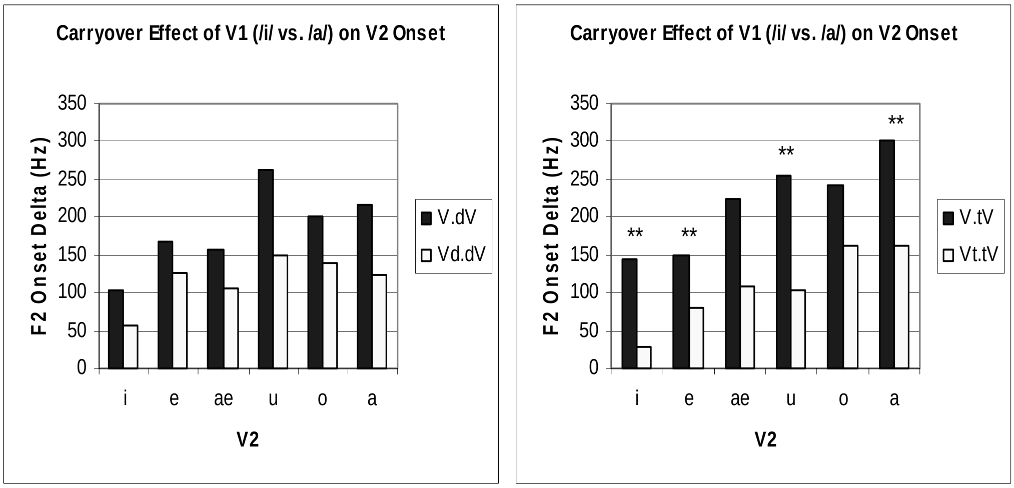


Figure 6-30. Average carry-over effects of V_1 (/i/ versus /ɒ/) on V_2 F2 onset across intervocalic singleton and geminate dental stops (Persian).

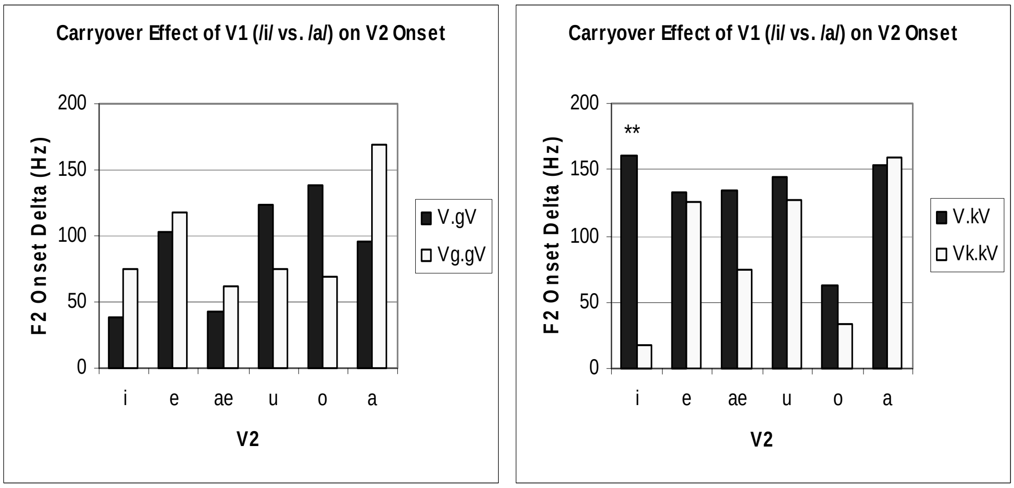


Figure 6-31. Average carry-over effects of V_1 (/i/ versus /ɒ/) on V_2 F2 onset across intervocalic singleton and geminate velar stops (Persian).

As the data in figures 6-29 to 6-31 show, F2 onset delta values decreased uniformly as the closure duration of the intervocalic bilabial and dental stop consonants increased. The decrease in F2 onset delta values in geminate forms containing bilabial and dental consonants was not, however, statistically significant in all V_2 contexts. When the intervocalic consonant was a bilabial stop, the only V_2 contexts that showed a significant decrease in F2 onset delta values in geminate forms involved a non-high vowel, i.e. /ɛ, ɒ/ for /b/ and /ɛ/ for /p/. As for dental stops, while none of the V_2 contexts showed significantly smaller F2 onset delta values in geminate versus singleton forms with /d/, most cases showed a significant decrease in F2 onset delta when the intervocalic consonant was /t/. Considering velar stops, /g/ showed a decrease in F2 onset delta values in geminate versus singleton forms only when V_2 was a non-low back vowel. None of the differences in F2 onset delta values were statistically significant. /k/ showed a decrease in F2 onset delta values in four out of five cases, although the only significant case was observed when V_2 was /i/.

6.3.3. Summary and Discussion

The results presented in the present section indicate that in VCV sequences vowel-to-vowel coarticulation is affected by the closure duration of the intervocalic stop. A reverse relationship was observed between the extent of vowel-to-vowel coarticulation and vowel-to-vowel temporal distance. As the temporal distance between the two vowels increased, the effects of the two vowels on one another decreased. This observation is best accounted for by a phoneme-by-phoneme view or a combined consonant-vowel timing model of the segmental organization of speech where consonantal and vocalic gestures overlap in time and are sensitive to the temporal aspects of other segments in a sequence.

6.4. THE EFFECTS OF VOT ON VOWEL-TO-VOWEL COARTICULATION

It was shown in section 3.2. that voiceless aspirated stops had significantly longer VOT durations compared to the voiced counterparts. In the investigation of the effects of VOT on vowel-to-vowel coarticulation, [V_1(C).CV_2] sequences (singleton as well as geminate forms) where the intervocalic consonant was a voiced stop were compared with similar sequences with a voiceless aspirated stop in the intervocalic position. The effects of VOT on anticipatory vowel-to-vowel coarticulation are discussed in section 6.4.1.1 for English speakers and in section 6.4.1.2 for Persian speakers. The effects of VOT on carry-over vowel-to-vowel coarticulation are presented in section 6.4.2.1 for English speakers and in section 6.4.2.2 for Persian speakers. Summary and discussion of the results appear in section 6.4.3.

It must be noted that the data presented in this section have been presented before in the previous sections, but they are reorganized and presented again in the discussion of the effects of VOT on vowel-to-vowel coarticulation.

6.4.1. Anticipatory Coarticulation

The same procedures employed in section 6.2.1 were followed to investigate the effects of VOT on anticipatory vowel-to-vowel coarticulation. In this case, F2 offset delta values in voiced sequences were compared with the same values in voiceless aspirated utterances. This comparison was made separately for singleton and geminate voiced versus voiceless aspirated consonants. For example, V_1 F2 offset frequency value of /e/ in /e.bi/ was subtracted from F2 offset frequency value of the same vowel in /e.bɔ/ to determine the amount of V_2 anticipation. Then, V_1 F2 offset frequency value of /e/ in /e.pʰi/ was subtracted from V_1 F2 offset frequency value of the same vowel in /e.pʰɔ/ to determine the amount of V_2 anticipation in this sequence. Finally the F2 offset delta values obtained in each case were plotted in bar graphs to visualize the amount of V_2 anticipation as a function of VOT.

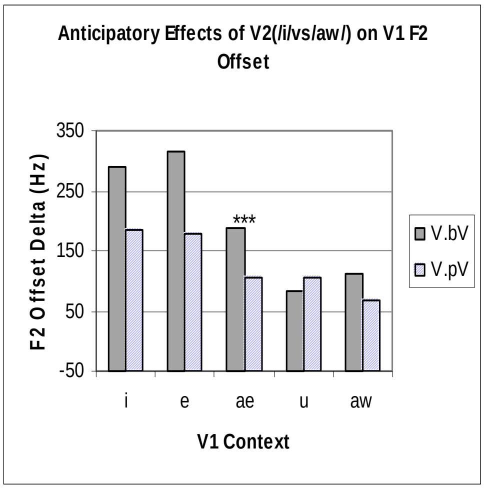
In the graphs comparing F2 offset delta values in voiced versus voiceless utterances, filled bars show average V_1 F2 offset delta values in the context of voiced stop consonants /b, d, g/ and striped bars show average V_1 F2 offset delta values for the same vowel in the context of voiceless aspirated stops /pʰ, tʰ, kʰ/.

In order to determine the statistical significance of the difference in V_1 F2 offset delta values in the context of voiced and voiceless aspirated stops a series of paired t-tests was performed. The asterisks above the bar graphs indicate the statistical significance of the difference between V_1 F2 offset delta values in the context of voiced and voiceless aspirated stops as mentioned in section 6.2.1 above.

6.4.1.1. English

Average F2 offset delta values for the fixed vowels /i, e, æ, u, ɔ/ in V_1 position as a function of the following changing vowel /i/ versus /ɔ/ in voiced versus voiceless aspirated singleton and geminate utterances as produced by English speakers are given in figures 6-32 to 6-34. F2 offset delta comparisons in singleton utterances are given on the left and F2 offset delta comparisons in geminate utterances are given on the right. Each bar shows average V_1 F2 offset delta values for 15 pairs of tokens (5SUB*3REP).

As the graphs of singleton stops in figures 6-32 to 6-34 show, F2 offset delta decreased when the intervocalic stop consonant was a voiceless aspirated stop compared to when it was a voiced stop in singleton forms. The only exception to this general pattern was seen with bilabial stops when V_1 was a /u/. Smaller F2 offset delta values in voiceless aspirated versus voiced contexts were only statistically significant in a few cases. The decrease in anticipatory vowel-to-vowel coarticulation was only significant when V_1 was /æ/ in bilabial and alveolar contexts and when V_1 was a non-high vowel in velar contexts.



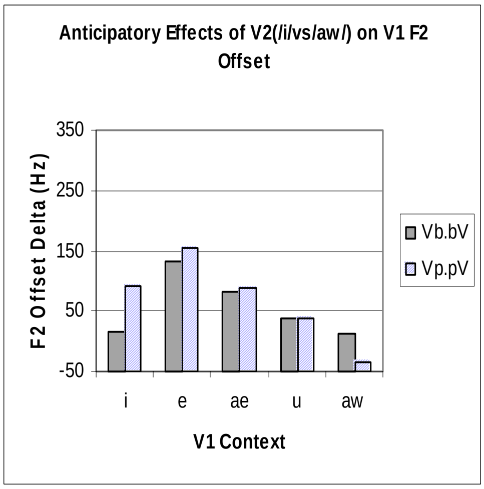
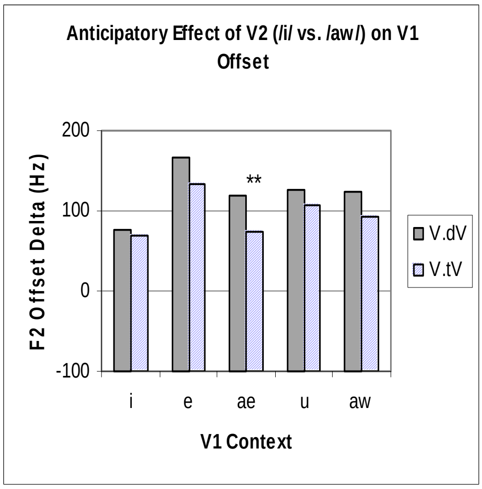


Figure 6-32. Average anticipatory effects of V_2 (/i/ versus /ɔ/) on V_1 F2 offset across singleton and geminate voiced and voiceless aspirated bilabial stops (English).



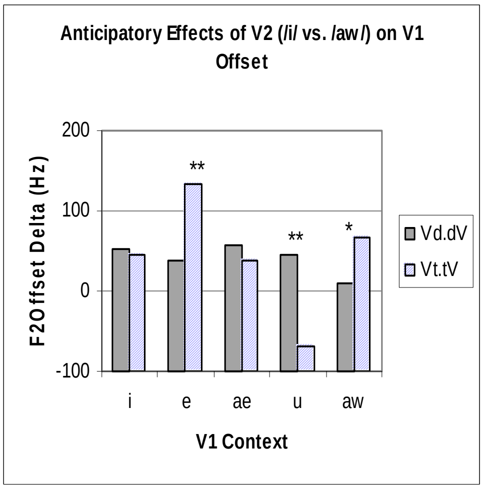


Figure 6-33. Average anticipatory effects of V_2 (/i/ versus /ɔ/) on V_1 F2 offset across singleton and geminate voiced and voiceless aspirated alveolar stops (English).

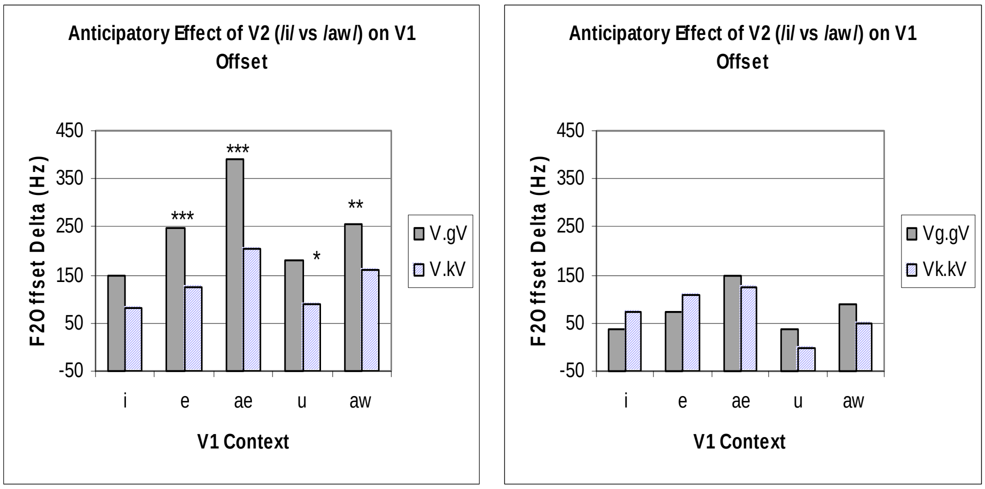


Figure 6-34. Average anticipatory effects of V_2 (/i/ versus /ɔ/) on V_1 F2 offset across singleton and geminate voiced and voiceless aspirated velar stops (English).

F2 offset delta comparisons in geminate utterances did not show the regular pattern observed with their singleton counterparts. Since V-to-V temporal distance was considerable in geminate forms, V-to-V coarticulatory effects across geminate voiced and voiceless aspirated stops were minimal and mainly non-significant. The only significant effects were observed in the context of geminate alveolar stops where /tt/ had significantly higher V_1 F2 offset delta values than /dd/ in the context of /e/ and significantly lower V_1 V2 offset delta values in the context of /u/.

6.4.1.2. Persian

Average F2 offset delta values for the fixed vowels /i, ɛ, æ, u, o, ɒ/ in V_1 position as a function of the following changing vowel /i/ versus /ɒ/ in voiced and voiceless singleton and geminate utterances produced by Persian speakers are given in figures 6-35 to 6-37. F2 offset delta values across singleton stops are given on the left and F2 offset delta values across geminate stops are given on the right. Each bar shows average V_1 F2 offset delta values for 6 pairs of tokens (2SUB*3REP).

As the graphs of singleton stops in figures 6-35 to 6-37 show, F2 offset delta values were in general smaller for voiceless aspirated compared to voiced stops. This pattern was observed in five out of six cases with bilabials, four out of six cases with dentals, and in all V_1 contexts with velar stops, although only a few cases were statistically significant. With bilabial and velars in intervocalic position, the only V_1 contexts that showed a significant decrease in F2 offset delta values in the context of voiceless aspirated stops were a mid vowel, i.e. /ɛ, o/ for bilabials and /o/ for velars. Singleton dental stops showed no significant differences in F2 offset delta as a function of VOT.

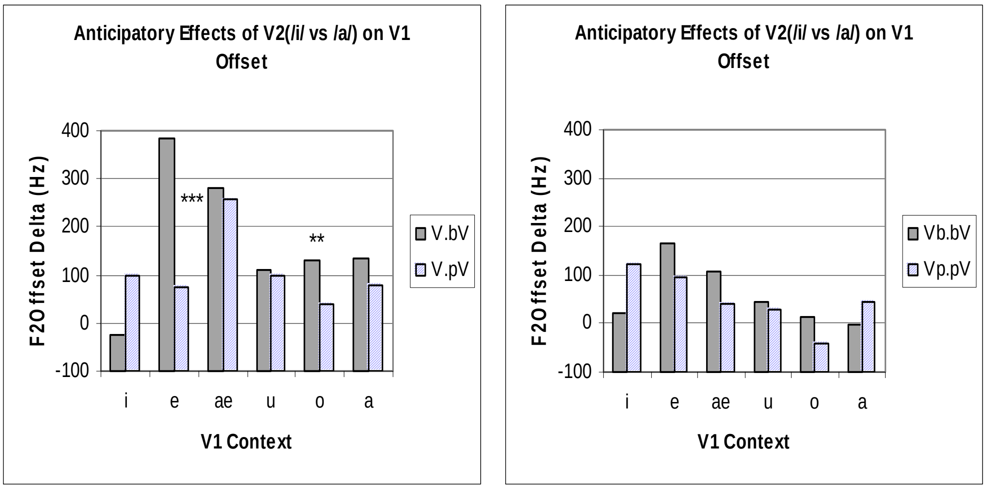


Figure 6-35. Average anticipatory effects of V_2 (/i/ versus /ɒ/) on V_1 F2 offset across singleton and geminate voiced and voiceless aspirated bilabial stops (Persian).

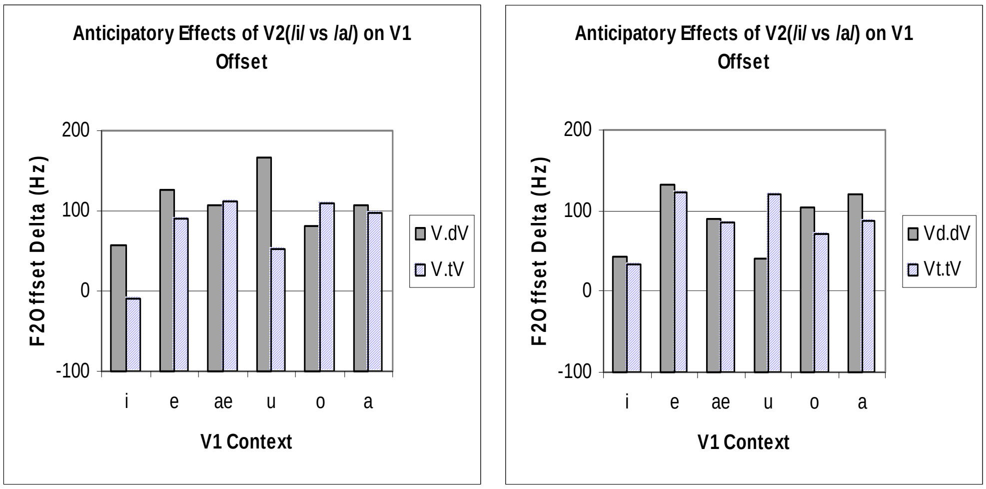


Figure 6-36. Average anticipatory effects of V_2 (/i/ versus /ɒ/) on V_1 F2 offset across singleton and geminate voiced and voiceless aspirated dental stops (Persian).

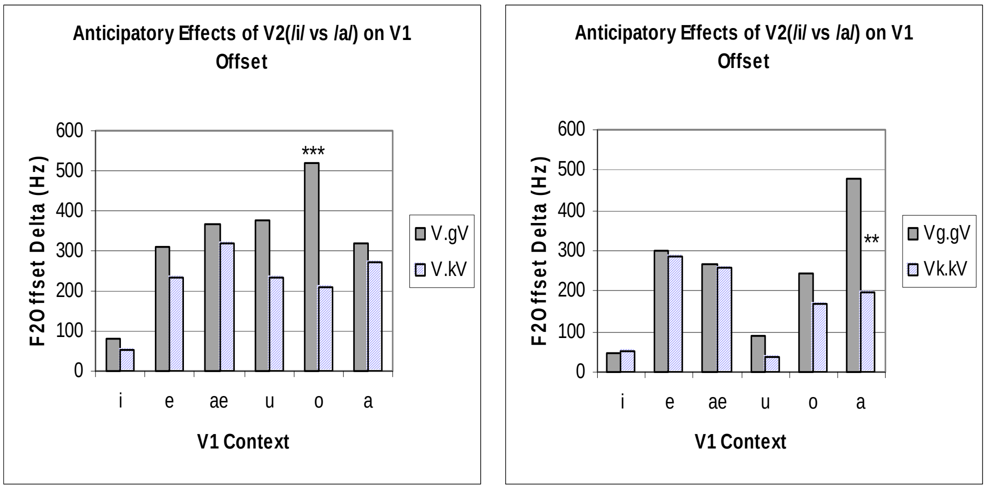


Figure 6-37. Average anticipatory effects of V_2 (/i/ versus /ɒ/) on V_1 F2 offset across singleton and geminate voiced and voiceless aspirated velar stops (Persian).

When the intervocalic stop was a geminate, F2 offset delta values showed different patterns depending on the place of articulation of the stop and V_1. As with English speakers, since V-to-V temporal distance was considerable in geminate forms, V-to-V coarticulatory effects across geminate voiced and voiceless aspirated stops were minimal and mainly non-significant. The only significant effect was seen with velar geminate stops, where a decrease in V_1 F2 offset was observed with /kk/ in the context of /ɒ/.

6.4.2. Carry-over Coarticulation

The same procedures employed in section 6.2.2 were followed to investigate the effects of VOT on carry-over vowel-to-vowel coarticulation. In this case, F2 onset delta values in voiced sequences were compared with the same values in voiceless aspirated utterances. This comparison was made separately for singleton and geminate consonants. For example, V_2 F2 onset frequency value of /e/ in /i.be/ was subtracted from F2 onset frequency value of the same vowel in /ɔ.be/ to determine the amount of V_1 retention. Then, V_2 F2 onset frequency value of /e/ in /i.pe/ was subtracted from V_2 F2 onset frequency value of the same vowel in /ɔ.pe/ to determine the amount of V_1 retention in this sequence. Finally, the F2 onset delta values obtained in each case were plotted in bar graphs to visualize the amount of V_1 retention as a function of VOT.

In the graphs comparing F2 onset delta values in voiced and voiceless aspirated stops, filled bars show average V_2 F2 onset delta values in the context of voiced stop consonants /b, d, g/ and striped bars show average V_2 F2 onset delta values for the same vowel in the context of voiceless aspirated stops /p^h, t^h, k^h/.

In order to determine the statistical significance of the differences in V_2 F2 onset delta values between voiced and voiceless aspirated stops a series of paired t-tests was performed. The asterisks above the bar graphs indicate the statistical significance of the differences in F2 onset delta values between voiced and voiceless aspirated sequences. The asterisks are to be interpreted as mention in section 6.2.1 above.

6.4.2.1. English

Average F2 onset delta values for fixed vowels /i, e, æ, u, ɔ/ in V_2 position as a function of the preceding changing vowel /i/ versus /ɔ/ in voiced and voiceless aspirated singleton and geminate utterances produced by English speakers are given in figures 6-38 to 6-40. F2 offset delta values across singleton stops are given on the left and F2 offset delta values across geminate stops are given on the right. Each bar shows average V_2 F2 onset delta values for 15 pairs of tokens (5SUB*3REP).

Considering singleton consonants in intervocalic position, the general pattern observed was that F2 onset delta values were smaller for voiceless aspirated stops compared to their voiced counterparts. Bilabials showed this pattern uniformly, while for alveolar and velar stops four out of five cases followed this general pattern. Exceptional cases involved a non-low front vowel, i.e. /i/ for alveolars and /e/ for velars. The decrease in F2 onset delta values in the context of voiceless aspirated stops was only significant in a few cases. Statistically significant cases involved the high front vowel /i/ for bilabials and back vowels for alveolars. The greater F2 offset delta observed with alveolar stops in the context of /i/ was also statistically significant. None of the cases of decrease in F2 offset delta values were statistically significant for velar stops.

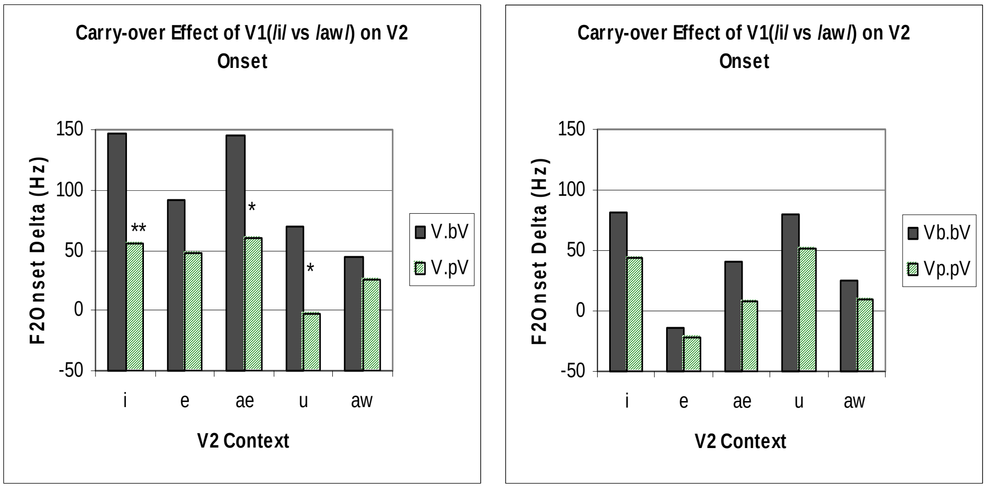


Figure 6-38. Average carry-over effects of V_1 (/i/ versus /ɔ/) on V_2 F2 onset across singleton and geminate voiced and voiceless aspirated bilabial stops (English).

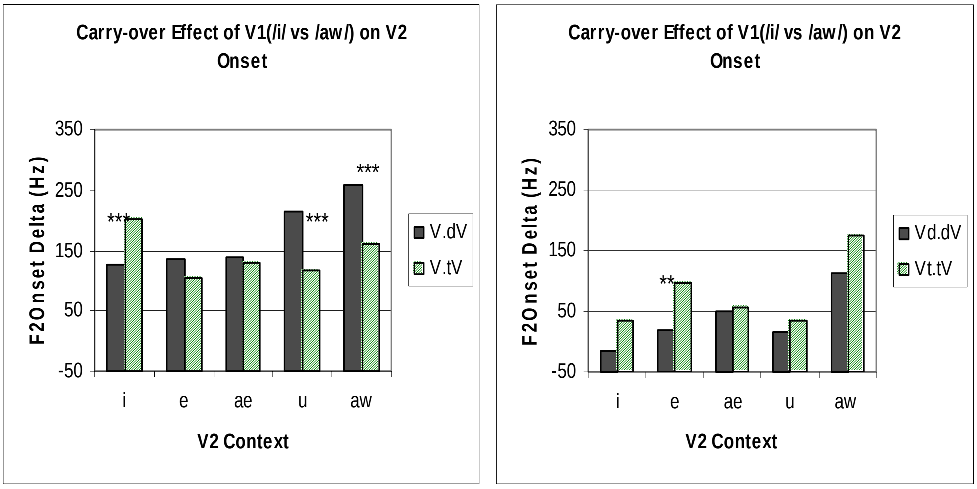


Figure 6-39. Average carry-over effects of V_1 (/i/ versus /ɔ/) on V_2 F2 onset across singleton and geminate voiced and voiceless aspirated alveolar stops (English).

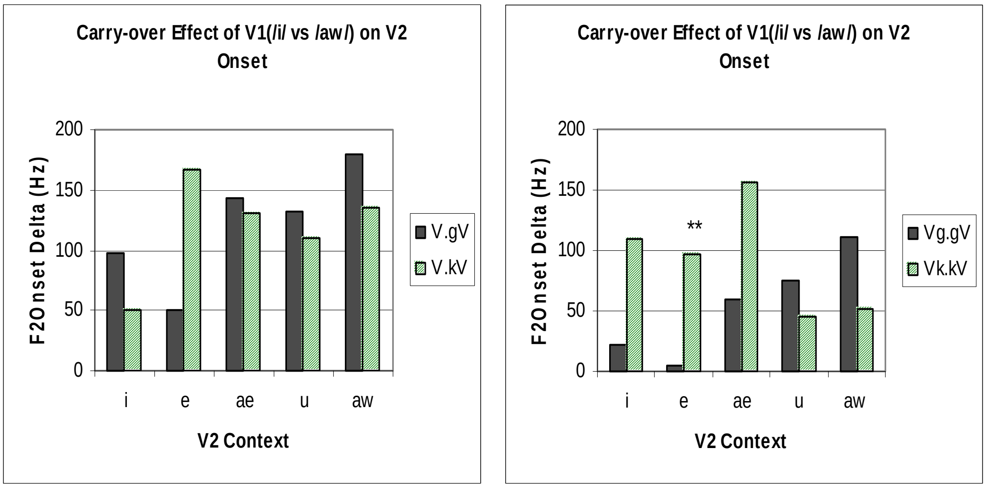


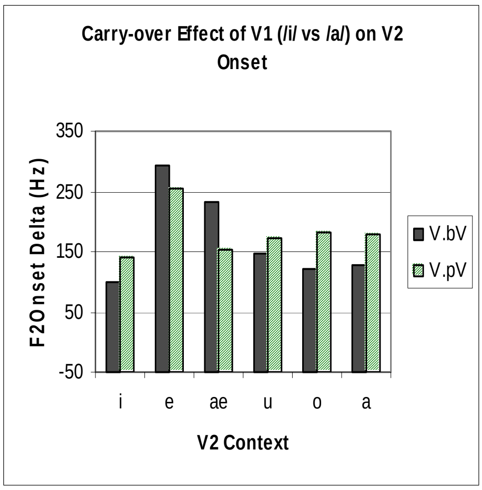
Figure 6-40. Average carry-over effects of V_1 (/i/ versus /ɔ/) on V_2 F2 onset across singleton and geminate voiced and voiceless aspirated velar stops (English).

Geminate stops showed different patterns depending on their place of articulation. While bilabials showed uniformly smaller F2 onset delta values in the context of voiceless aspirated versus voiced stops, alveolars showed a reverse pattern in all vocalic contexts. Voiceless aspirated velars showed an increase in F2 onset delta values when V_2 was a front vowel and the reverse pattern when V_2 was a back vowel. The only significant cases were observed with the vowel /e/ in the context of alveolar and velar stops where an increase in F2 offset delta values was observed with voiceless aspirated versus voiced stops.

6.4.2.2. Persian

Average F2 onset delta values for fixed vowels /i, ɛ, æ, u, o, ɒ/ in V_2 position as a function of the preceding changing vowel /i/ versus /ɒ/ in voiced and voiceless aspirated singleton and geminate utterances produced by Persian speakers are given in the graphs in figures 6-41 to 6-43. F2 offset delta values across singleton stops are given on the left and F2 offset delta values across geminate stops are given on the right. Each bar shows average V_2 F2 onset delta values for 6 pairs of tokens (2SUB*3REP).

Considering singleton stops, F2 onset delta values were in general greater for voiceless aspirated versus voiced stops. This pattern was observed in four out of six cases for bilabials and dentals and in five out of six cases for velar stops. Exceptional cases involved non-high front vowels for bilabials, /ɛ, u/ for dentals, and /o/ for velars. The only statistically significant case was seen with velars in the context of /æ/.



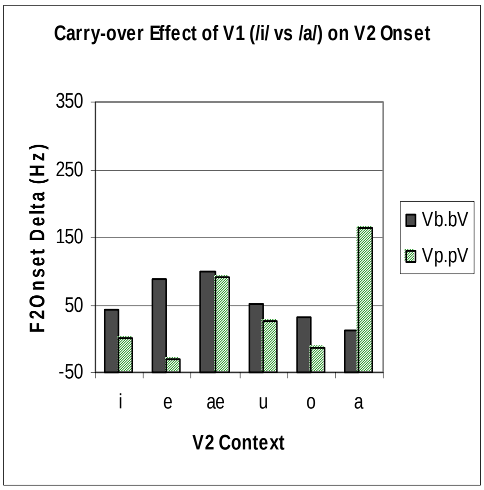


Figure 6-41. Average carry-over effects of V_1 (/i/ versus /ɒ/) on V_2 F2 onset across singleton and geminate voiced and voiceless aspirated bilabial stops (Persian).

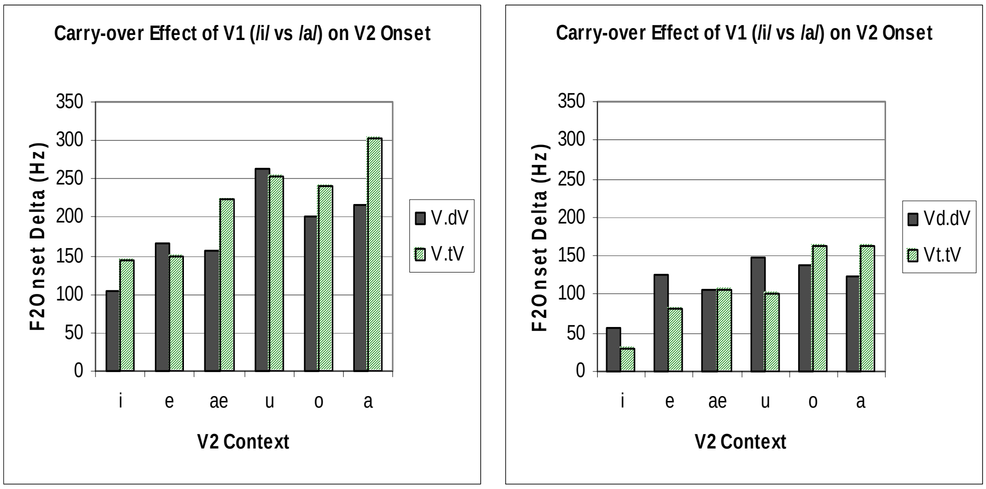


Figure 6-42. Average carry-over effects of V_1 (/i/ versus /ɒ/) on V_2 F2 onset across singleton and geminate voiced and voiceless aspirated dental stops (Persian).

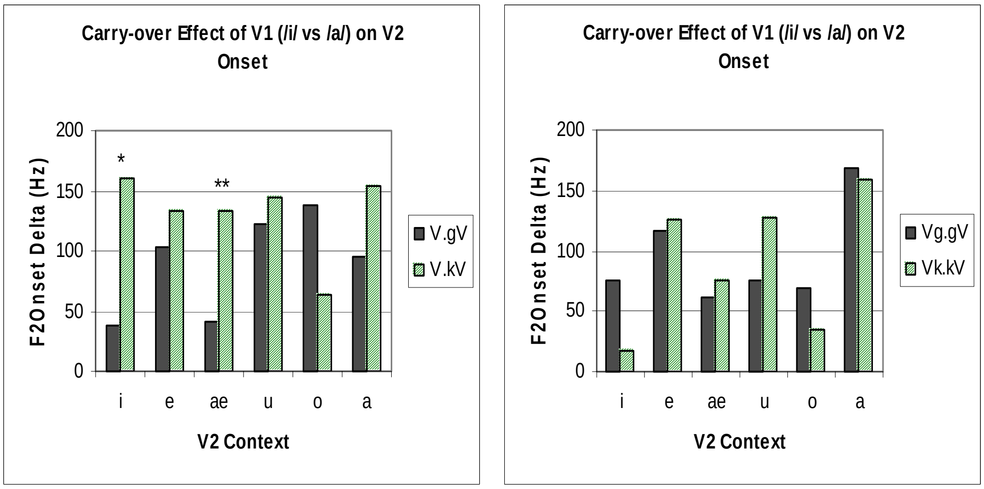


Figure 6-43. Average carry-over effects of V_1 (/i/ versus /ɒ/) on V_2 F2 onset across singleton and geminate voiced and voiceless aspirated velar stops (Persian).

Considering geminate consonants, the F2 onset delta values were generally smaller for voiceless aspirated versus voiced bilabial and dental stops. Exceptional cases involved non-high back vowels, i.e. /ɒ/ for bilabials and /o, ɒ/ for dentals. Geminate velar stops showed different patterns depending on the vocalic context. None of the differences observed between F2 onset delta values of voiced and voiceless aspirated geminate stops were statistically significant.

6.4.3. Summary and Discussion

The results presented in sections 6.4.1 and 6.4.2 above indicate that vowel-to-vowel coarticulation is affected by the voicing properties of the intervocalic stop. In the singleton utterances produced by English speakers, the anticipatory effects of V_2 on V_1 offset were generally smaller when the intervocalic stop was voiceless aspirated versus voiced. Anticipatory effects were likewise generally smaller across voiceless versus voiced singleton stops in the utterances produced by Persian speakers. The difference between the anticipatory effects of V_2 on V_1 as a function of voicing was, however, significant only in a few cases. Also, in the geminate utterances produced by English and Persian speakers only a few cases showed significant differences in anticipatory V-to-V coarticulatory effects as a function of the voicing properties of the intervocalic stop. No general anticipatory patterns were observed.

The data on carry-over coarticulation showed different patterns for the two groups of speakers. In the singleton utterances produced by English speakers, the carry-over effects of V_1 on V_2 onset were generally smaller across voiceless stops compared to their voiced counterparts. The reverse pattern was observed with Persian speakers where the carry-over effects of V_1 on V_2 onset were generally greater across voiceless versus voiced singleton stops. The difference between the carry-over effects of V_1 on V_2 across voiced and voiceless aspirated stop was, however, significant only in a few cases.

When the intervocalic consonant was a geminate stop, English speakers showed different carry-over effects depending on consonantal place of articulation and V_1 context. For bilabial stops, carry-over coarticulation was smaller across /p^h/ versus /b/. The reverse pattern was seen with alveolar stops. /k/ showed greater carry-over effects than /g/ when V_2 was a front vowel and smaller carry-over effects when V_2 was a back vowel. The difference between the carry-over effects of V_2 on V_1 across voiced and voiceless aspirated geminate stops produced by English speakers was, however, significant only in a few cases.

In the singleton and geminate utterances produced by Persian speakers, only one case showed a significant difference in the carry-over effects of V_1 on V_2 onset as a function of the voicing properties of the intervocalic consonant. A relatively pattern was observed with singleton velar stops where the carry-over effects of V_1 on V_2 was generally greater across /k/ versus /g/.

Although the patterns observed in this section are scattered and non-significant in the majority of the cases, the fact that V-to-V coarticulation is affected by the voicing properties of the intervocalic stop in some cases should receive consideration in devising models of coarticulation.

6.5. CONCLUSIONS

In this chapter, the effects of the syllabic affiliation of the intervocalic stop, its closure duration and voicing properties on anticipatory and carry-over vowel-to-vowel coarticulation were investigated. Results showed a general decrease in anticipatory V-to-V effects in closed versus open and in singleton versus geminate utterances. The voicing properties of the intervocalic consonant had a less consistent effect on anticipatory coarticulation compared to the other cases. The same general patterns were observed with Persian speakers, although with less consistency.

The decrease in the anticipatory effects of V_2 on V_1 offset in closed versus open and in geminate versus singleton utterances was attributed to greater V-to-V temporal distance in closed versus open and geminate versus singleton forms.

Greater anticipatory V-to-V effects observed with singleton voiced stops compared to voiceless aspirated counterparts is compatible with Gay's (1979) observation that tongue movement towards V_2 starts earlier when the intervocalic consonant is a voiced rather than a voiceless aspirated bilabial stop. Earlier tongue body movement towards V_2 results in greater anticipatory effects of this vowel on V_1 offset when the intervocalic consonant is a voiced stop. The results obtained in this study indicated generally earlier tongue body movements for all voiced places of articulation.

Carry-over effects showed an increase in closed versus open syllable forms produced by English speakers. Persian speakers showed this pattern uniformly only with velar stops. The increase in the carry-over effects of V_1 on V_2

onset in closed syllable forms compared to open syllables was attributed to smaller temporal distance between the two vowels in closed versus open syllables produced by English speakers. Temporal distance could not, however, account for increased carry-over V-to-V coarticulation for the intervocalic consonant /k/ in the Persian utterances. In this case, the syllabic affiliation of the consonant accounted for the observed patterns.

A general decrease in carry-over V-to-V coarticulation was observed in geminate versus singleton forms produced by English speakers. Persian speakers showed this pattern consistently when the intervocalic consonant was a bilabial or a dental stop. Greater temporal distance between the two vowels in geminate versus singleton forms also accounted for lesser degrees of carry-over effects in the former compared to the latter.

Carry-over V-to-V coarticulation was also affected by the voicing properties of the intervocalic stop. English and Persian speakers showed different patterns. While English speakers showed generally reduced carry-over effects across voiced versus voiceless aspirated stops, Persian speakers showed a reverse pattern.

Although the patterns observed in this chapter were not statistically significant in all cases, the fact that V-to-V coarticulation can be affected by the syllabic affiliation of the intervocalic stop, its closure duration, and voicing properties provides evidence in favor of a phoneme-by-phoneme or a ‘combined consonant-vowel timing’ model in which vocalic and consonantal gestures are timed with respect to one another irrespective of the phonetic qualities of the segments.

Chapter 7: Summary and Conclusions

This chapter includes a summary of the results obtained in the present investigation and a conclusion based on those results. The summary appears in section 7.1 and the conclusion in section 7.2.

7.1. SUMMARY: RESEARCH QUESTIONS AND ANSWERS

According to the superimposition model of coarticulation the vocalic gestures in VCV sequences are produced with a single diphthongal movement and the consonantal gesture is superimposed on it. On the other hand, according to a phoneme-by-phoneme model of coarticulation, the consonantal and vocalic gestures in such sequences are distinct events that overlap in time. This investigation sought to determine whether the two vocalic gestures in VCV sequences are produced as a single diphthongal gesture or as separate events. The answer to this question was sought in the acoustic signal.

Articulatory 'troughs' or discontinuities in anticipatory vowel-to-vowel coarticulation during the closure period of bilabial stops in symmetrical VCV sequences have provided evidence in favor of a phoneme-by-phoneme view. This investigation sought to uncover the acoustic correlates of troughs in VCV utterances produced by five English and two Persian speakers. More specifically, the following questions were asked:

(a) Is it possible to detect the effects articulatory troughs in the acoustic signal?

(b) Since troughs represent kinematic discontinuities in anticipatory coarticulation, are their acoustic correlates enhanced when V_2 in V_1CV_2 sequences is temporally removed from V_1, as in geminate [VC.CV] sequences and in voiceless aspirated contexts?

(c) Can troughs be more easily observed in the acoustic signal if the syllable boundary is altered as in closed [VC.V] utterances?

It was shown that trough-like movement patterns can be detected in F2 transitions into and out of bilabial stop closures. Rate and duration of F2 transitions were taken as a measure of tongue body displacement (indicating the trough) at the VC and CV boundaries of symmetrical [i.Ci] sequences where C was a bilabial stop. F2 transitions exceeding 10 ms in duration were interpreted as indicating tongue body displacement as well as lip closing/opening gestures at these boundaries. Results showed evidence of tongue body movement at the VC boundary when C was /b/ and at the CV boundary when C was /p/. These patterns were explained by considering the aerodynamic/acoustic requirements for voicing and aspiration.

The extent and direction of F2 transitions were taken as measures of tongue body displacement at the VC and CV boundaries of symmetrical [V.CV] sequences where V was a back vowel and C was a bilabial stop. Rising-falling F2 transition patterns showing greater extents of F2 transition were taken as indicating tongue body movement at both boundaries. Evidence of tongue body movement was found mainly at the CV boundary when C was a voiceless aspirated bilabial stop. This pattern was again accounted for by considering the aerodynamic requirements for aspiration.

More extensive tongue body displacement patterns are predicted by a phoneme-by-phoneme view under conditions of varying syllable boundary and consonantal closure duration. Although instances of tongue body movement were found at the VC and CV boundaries of geminate [VC.CV] utterances, no evidence of more extensive tongue body displacement effects were found in these utterances compared to their singleton counterparts. More pronounced tongue body displacements are not ruled out, though, as they could have occurred during the stop closure period where no information is available in the acoustic signal.

The strongest evidence of tongue body movement and hence troughs was found at the CV boundary of closed syllable forms. In [iC.i] utterances, F2 onset measured at the release of the syllable-final stop was considerably lower in frequency than the surrounding environment. In back vowel contexts, F2 onset was considerably higher in frequency than the surrounding vowel context. The frequency shifts in both cases strongly suggested tongue body movement to a more central position relative to the position for the surrounding vowels. These F2 onset loci strongly suggest trough-like movement patterns occurring between V_1 and V_2.

The release of the syllable-final stop in closed syllables provided a window to detect tongue body position in the time period between the two vowels. Such a window was not available in other utterance types where extensive tongue body displacement (if any) could not be detected in the time period between the two vowels. Though somewhat unnatural for speakers, the closed syllable forms provided acoustic access to articulatory events usually masked by consonantal occlusions.

Locus equations (LE) were employed as a second methodology to uncover the acoustic correlates of troughs in a variety of consonantal and vocalic contexts. LE slopes capture CV coarticulation. Troughs were expected to lower the slopes of locus equation regression functions. LE results confirmed the earlier observations at a more macro level. Strongest evidence for tongue body movement (trough) was found at the CV boundary of closed syllables, where LE slopes were considerably lower compared to open syllables indicating maximum tongue body displacement at the release of the intervocalic stop in the former compared to the latter. LE slopes were also lower in CV combinations where C was a voiceless aspirated versus a voiced stop, indicating more tongue body displacement effects in the former compared to the latter. Locus equation slopes remained stable in singleton and geminate forms indicating that CV coarticulation is independent of consonantal closure duration. The stability of LE slopes in singleton and geminate utterances despite changes in consonantal closure duration and V_1 context indicated a tight bonding between C in syllable-initial position and a following vowel.

The superimposition model predicts no changes in vowel-to-vowel coarticulatory effects as a function of the syllabic affiliation and temporal properties of an intervocalic stop consonant. On the other hand, a phoneme-by-phoneme view predicts changes in V-to-V coarticulation under such conditions. Anticipatory as well as carry-over coarticulatory effects were investigated under the conditions of varying syllable boundary, consonantal closure duration, and VOT. Results showed a general decrease in anticipatory V-to-V effects in closed versus open, singleton versus geminate, and voiceless versus voiced conditions in the utterances produced by English speakers. The same general patterns were observed with Persian speakers, although with less consistency.

The decrease in the anticipatory effects of V_2 on V_1 offset in closed syllable forms compared to open syllables was attributed to greater temporal distance between the two vowels in closed versus open syllables. Greater temporal distance between the two vowels in geminate versus singleton forms also accounted for lesser degrees of anticipatory effects in the former compared to the latter. Greater anticipatory V-to-V effects observed with singleton voiced stops compared to their voiceless aspirated counterparts is compatible with Gay's (1979) observation that tongue movement towards V_2 starts earlier when the intervocalic consonant is a voiced compared to when it is a voiceless aspirated bilabial stop. Earlier tongue body movement towards V_2 results in greater anticipatory effects of this vowel on V_1 offset when the intervocalic consonant is a voiced stop. The results obtained in this study indicated generally earlier tongue body movements for all voiced places of articulation.

Carry-over effects showed an increase in closed versus open syllable forms produced by English speakers. Persian speakers showed this pattern uniformly only with velar stops. The increase in the carry-over effects of V_1 on V_2 onset in closed syllable forms compared to open syllables was attributed to smaller temporal distance between the two vowels in closed versus open syllables produced by English speakers. Temporal distance could not, however, account for increased carry-over V-to-V coarticulation for the intervocalic consonant /k/ in the Persian utterances. In this case, the syllabic affiliation of the consonant accounted for the observed patterns.

A general decrease in carry-over V-to-V coarticulation was observed in geminate versus singleton forms produced by English speakers. Persian speakers showed this pattern consistently when the intervocalic consonant was a bilabial or a dental stop. Greater temporal distance between the two vowels in geminate versus singleton forms also accounted for lesser degrees of carry-over effects in the former compared to the latter.

Carry-over V-to-V coarticulation was also affected by the voicing properties of the intervocalic stop. English and Persian speakers showed different patterns. While English speakers showed generally reduced carry-over effects across voiced versus voiceless aspirated stops, Persian speakers showed a reverse pattern.

Although V-to-V coarticulatory effects were not statistically significant in all cases, the fact that V-to-V coarticulation can be affected by the syllabic affiliation of the intervocalic stop, its closure duration, and voicing properties provides evidence in favor of a phoneme-by-phoneme or a ‘combined consonant-vowel timing’ model in which vocalic and consonantal gestures are timed with respect to one another irrespective of the phonetic qualities of the segments.

7.2. CONCLUSIONS

Troughs are subtle articulatory events with subtle acoustic consequences. The results obtained in the present investigation indicated that the syllabic affiliation of the intervocalic stop and its voicing properties have the most considerable effect on tongue body displacement patterns.

In a phoneme-by-phoneme view of speech organization where the gestures for consonants and vowels overlap and their effects on the articulators wax and wane smoothly over time, troughs represent the deactivation and reactivation phases of vocalic gestures as consonants are being produced.

In the closed syllable forms of this study, the release of the syllable-final stop into a neutral context-dependent ‘vowel’ configuration as opposed to the configuration for the following vowel indicates strategies to mark the syllabic affiliation of the intervocalic stop. In other words, the distinction between a syllable-final and a syllable-initial consonant is whether it is released to a neutral vocal tract configuration or to the position configuration for the following vowel.

The sensitivity of F2 transition to the voicing properties of the intervocalic stop consonant suggests that troughs might have an aerodynamic explanation as well. This suggestion is reinforced considering that troughs have not been observed in languages such as French where voiceless consonants are not aspirated.

Whether troughs represent the deactivation and reactivation phases of vocalic gestures or the aerodynamic requirements for the intervocalic consonant production or whether they are seen as markers of syllable boundary, they have to be considered and incorporated into models of segmental organization. These considerations together with the fact that vowel-to-vowel coarticulation is interrupted by the voicing properties and closure durations of intervocalic stops as well as their syllabic affiliation calls for a revision of superimposition models of coarticulation.

Appendix A

TOKEN TYPES USED TO CALCULATE F2 OFFSET DELTA VALUES AS A MEASURE OF ANTICIPATORY COARTICULATION

1. English

	V_1=/i/	V_1=/e/	V_1=/æ/	V_1=/u/	V_1=/ɔ/
V_1.CV_2	i.Ci - i.Cɔ	e.Ci - e.Cɔ	æ.Ci - æ.Cɔ	u.Ci - u.Cɔ	ɔ.Ci - ɔ.Cɔ
V_1C.V_2	iC.i - iC.ɔ	eC.i - eC.ɔ	æC.i - æC.ɔ	uC.i - uC.ɔ	ɔC.i - ɔC.ɔ
V_1C.CV_2	iC.Ci - iC.Cɔ	eC.Ci - eC.Cɔ	æC.Ci - æC.Cɔ	uC.Ci - uC.Cɔ	ɔC.Ci - ɔC.Cɔ

2. Persian

	V_1=/i/	V_1=/ɛ/	V_1=/æ/	V_1=/u/	V_1=/o/	V_1=/ɒ/
V_1.CV_2	i.Ci - i.Cɒ	ɛ.Ci- ɛ.Cɒ	æ.Ci - æ.Cɒ	u.Ci - u.Cɒ	o.Ci - o.Cɒ	ɒ.Ci - ɒ.Cɒ
V_1C.V_2	iC.i - iC.ɒ	ɛC.i-ɛC. ɒ	æC.i - æC.ɒ	uC.i - uC.ɒ	oC.i - oC. ɒ	ɒC.i - ɒC.ɒ
V_1C.CV_2	iC.Ci - iC.Cɒ	ɛC.Ci-ɛC.Cɒ	æC.Ci- æC.Cɒ	uC.Ci - uC.Cɒ	oC.Ci - oC.Cɒ	ɒC.Ci - ɒC.Cɒ

Appendix B

TOKEN TYPES USED TO CALCULATE F2 ONSET DELTA VALUES AS A MEASURE OF CARRY-OVER COARTICULATION

1. English

	V_2=/i/	V_2=/e/	V_2=/æ/	V_2=/u/	V_2=/ɔ/
V_1.CV_2	i.Ci - ɔ.Ci	i.Ce - ɔ.Ce	i.Cæ – ɔ.Cæ	i.Cu – ɔ.Cu	i.Cɔ - ɔ.Cɔ
V_1C.V_2	iC.i - ɔC.i	iC.e - ɔC.e	iC.æ – ɔC.æ	iC.u – ɔC.u	iC. ɔ - ɔC.ɔ
V_1C.CV_2	iC.Ci - ɔC.Ci	iC.Ce - ɔC.Ce	iC.Cæ - ɔC.Cæ	iC.Cu - ɔC.Cu	iC.Cɔ - ɔC.Cɔ

2. Persian

	V_2=/i/	V_2=/ɛ/	V_2=/æ/	V_2=/u/	V_2=/o/	V_2=/ɒ/
V_1.CV_2	i.Ci - ɒ.Ci	i.Cɛ - ɒ.Cɛ	i.Cæ - ɒ.Cæ	i.Cu - ɒ.Cu	i.Co - ɒ.Co	i.Cɒ - ɒ.Cɒ
V_1C.V_2	iC.i - ɒC.i	iC.ɛ - ɒC.ɛ	iC.æ - ɒC.æ	iC.u - ɒC.u	iC.o - ɒC.o	iC.ɒ- ɒC.ɒ
V_1C.CV_2	iC.Ci- ɒC.Ci	iC.Cɛ- ɒC.Cɛ	iC.Cæ- ɒC.Cæ	iC.Cu- ɒC.Cu	iC.Co- ɒC.Co	iC.Cɒ-ɒC.Cɒ

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