C-to-V coarticulation in horizontal and vertical dimensions and its implications for phonology

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ABSTRACT

In this paper, I investigate the acoustic correlates of a vowel's coarticulatory dynamics manifested in preceding and following consonants along two dimensions of the vocal tract: place of articulation and degree of constriction. Two dimensional coarticulation is not necessarily executed either concomitantly or proportionally, and the modification induced by coarticulation with a vowel in CVC structures is merely restricted to the CV portion; that is, the prevocalic consonant is modified solely in its constriction location. This is consistent with the observation that C-to-V place assimilation does not accompany consonant lenition in phonology, which suggests that phonetic nature is effectively reflected in phonological patterns.

Keywords: C-to-V coarticulation, assimilation, horizontal dimension, vertical dimension

1. Introduction

This paper reports on experiments conducted to measure a vowel's coarticulatory effects on a consonant (hereafter, C-to-V coarticulation) in CV and VC structures. In addition, the anticipatory and carry-over effects of a vowel are acoustically examined in two dimensions: (1) place of articulation and (2) degree of constriction. Taking the view of Articulatory Phonology (Browman & Goldstein 1986, 1989, 1990) that a vowel gesture is characterized by constriction location and degree, it should be the case that the coarticulatory effects of the vowel on a consonant are implemented along the front-back (horizontal) dimension as well as the open-close (vertical) dimension during the consonant articulation. Consequently, a consonant will be coarticulatorily modified in such a way that its tongue body configuration is horizontally similar to the vowel's and that its constriction degree decreases due to the vowel's relatively great opening gesture. The aim of this paper is to investigate the interrelationship of the C-to-V

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coarticulation manifested in the horizontal place of articulation and the vertical degree of constriction by way of a comparison of its magnitudes in the mirror-image positions.

Although there are numerous studies-articulatory, acoustic, and perceptual-on coarticulation between a vowel and a consonant, very few phonetic studies have compared a vowel's effects on the preceding and following consonants in CVC sequences and compared horizontal and vertical influences of the tongue body gesture during consonant articulation. Much of the articulatory and acoustic literature has focused on coarticulation in a single direction or in a single dimension (Amerman & Daniloff 1977; Carney & Moll 1971; Farnetani & Recasens 1993; Fowler, Rubin, Remez & Turvey 1980; Gay 1974; House & Fairbanks 1953; Kiritani, Itoh, Hirose & Sawashima 1977; Öhman 1966; Perkell & Nelson 1985; Recasens 1991). None of these studies compare the coarticulatory effects of the vocalic gestures in mirror-image positions or in horizontal and vertical dimensions.

In this paper, I explore the extent to which a vowel's acoustic structures extend into the consonant region in CV and VC structures and then interpret the results in terms of the bi-directional tongue body dynamics. I assume in this experiment that C-to-V coarticulation arises due to gestural overlap and will be acoustically indicated in the formant transition into and out of the vowel. If gestural overlap is symmetric in CV and VC structures, I expect to find acoustic parallels.

It might be plausible that consonant and vowel mutually affect each other in their gestural sequences, but I assume that the vowel gesture will invoke dominant coarticulatory effects over a consonant, based on Recasens' claim (1991:178):

> *Vowels are resistant to coarticulation because they are produced by means of global vocal tract shapes which require articulatory control upon the entire tongue body configuration whereas consonants involve only local constrictions which have other articulatory regions free to coarticulate.*

In sections 2 and 3, I present two acoustic experiments, each of which explores horizontal and vertical dimensional coarticulation and then compares each dimension in CV and VC structures. In section 4, I attempt to relate the vowel's coarticulatory effects on a consonant's place of articulation with that of a consonant's constriction degree and then discuss some implications for phonological patterns of C-to-V place assimilation and lenition.

2. C-to-V coarticulation in the horizontal dimension

2.1 Assumption & Hypothesis

Kewley-Port (1982) examines the acoustic correlates of the consonant place of articulation in the vowel formant transitions in stop-vowel sequences. Contrary to the traditional view that formant transitions serve as the primary cues of stop place articulation (through the effects of stop locus, Liberman et al. 1967), she concludes that *transition measurements show little evidence of invariant acoustic correlates of consonant place*. This conclusion derives from the observation that the F2 formant transition values are variable across various vowel contexts in stop-vowel sequences. Based on Kewley-Port's conclusion, I assume that the F2 variability reflects a vowel's coarticulatory effects on a consonant manifested in the CV transition region. Therefore, I hypothesize that the more variant the F2 values are, the greater the coarticulatory effect of a vowel on a consonant is; the less variance (or possibly invariance) of F2 values during the transition would indicate that the stop is being articulated in a manner independent of the vowel.

2.2 Data and methods

Nonsense CiVCi syllables with /b, d, g/ and /i, e, a, o, u/ were produced 12 times by three English native speakers, and the order of the tokens were randomized. The CiVCi tokens were recorded in 16-bit and 8 KHz onto a Sparc station by a Sony F-VX30 microphone. Among formant trajectories, F2 was calculated using the Entropics Waves program at 5 different points: at the steady state of the vowels, at the onset and offset of the transitions, and at the pre- and postvocalic stop bursts.[1] The F2 frequencies that were obtained from the F2 trajectory measurements were confirmed by the LPC spectra display. The frequencies at the spectral peak corresponding to the vowel's second peak were taken as data from the spectra. The 25ms spectrum windows were created for the F2 measurements at the onset and offsets; the left edge of the window was positioned at the beginning of the vowels for the onset spectrum and the right edge of the window was positioned at the end of vowels for the offset spectrum as in Keating (1993). The burst spectrum (half a window, 13ms) was computed by centering the window at the burst onset, following Keating (1993) and Blumstein & Stevens (1979). F2 variations over the 5 vowel contexts were compared at two different pairs of acoustic points: at the onset and offset of the transitions and at the CV and VC bursts, and all results were statistically analyzed.

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1) The speakers were asked to release the postvocalic stops.

2.3 Results

Figures 1 and 2 show the results acquired from the /bVb/ sequences for speaker1: F2 mean frequencies at five different acoustic timings and the variation ranges over the five vowels at the mirror-image positions. Though F2 frequencies go down toward the labial locus at both the onset and offset of transitions, the slope is much steeper at the offset, converging far more to the locus value as shown in Figure 1. Consequently, the variance over the five vowels is greater at the onset than at the offset. Moreover, F2 frequencies are more dispersed at the prevocalic burst than at the postvocalic burst; the F2 burst frequencies converge to 1500 Hz. Figure 2 shows that all the F2 values are overlaid from the five vowels in CV and VC bursts in (a) and at F2 onset and offset in (b). Figure (a) illustrates that the range of F2 values in the CV burst is greater than that in the VC burst, and the difference is statistically significant ($F = 111.313$, $p < 0.0005$). Moreover, the onset F2 transition values are significantly more variable than the offset values ($F = 45.990$, $p < 0.0005$). The results for speakers 2 and 3 are almost the same as speaker 1, and their statistics are presented in Table 1.

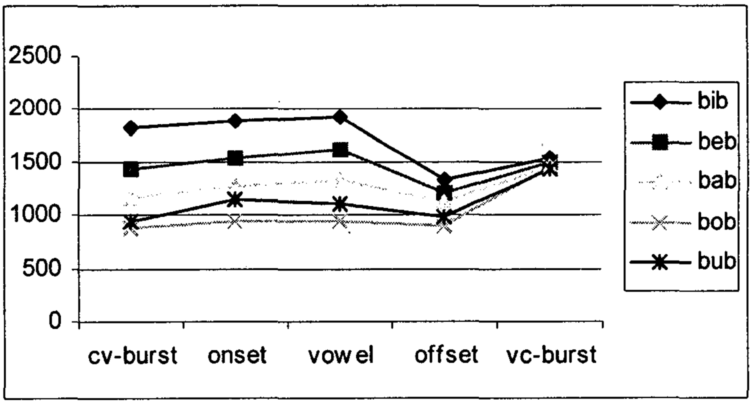
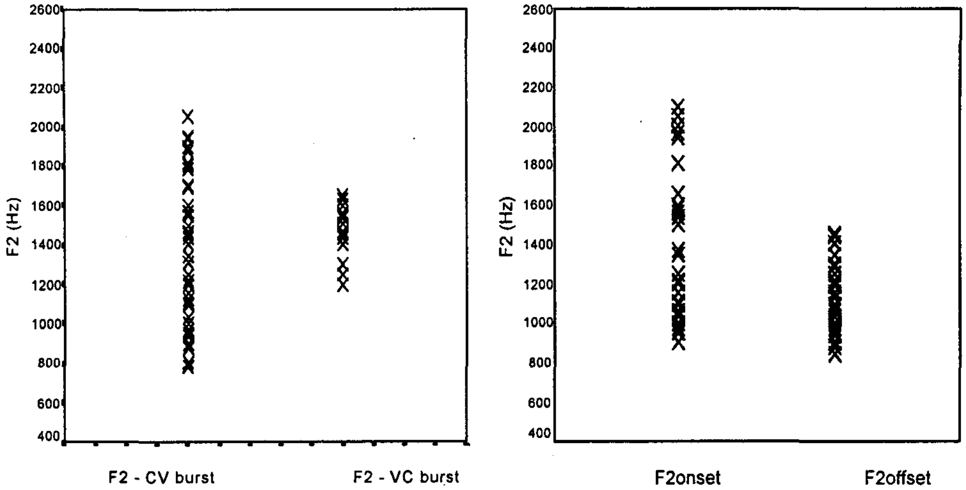


Figure 1. F2 mean frequencies at the prevocalic stop burst, at the onset and offset of transitions, at the steady state of a vowel, and at the postvocalic stop burst in the labial stop context (speaker 1)



(a) F2 variance: CV burst vs. VC burst (b) F2 variance: onset vs. offset

Figure 2. F2 variance in CVC structures in the labial stop contexts (speaker 1)

Table 1. F-values for speakers 2 & 3 (labial)

	CV vs. VC bursts	onset vs. offset
speaker 2	51.459 *	15.072 *
speaker 3	52.098 *	39.203 *

* Variances are significantly different at $p<0.0005$

Figures 3 and 4 show the results obtained from the /dVd/ sequences for speaker 1. As displayed in Figure 3, F2 variation over the five vowels seems to be much smaller than in the labial stop context, and the frequencies all converge to approximately 1800Hz at the CV and VC bursts and at the onset and offset of transitions. Similarly to the labial stop, the degree of convergence is, however, much greater in VC structures, that is, at the offset and at the VC burst. All the repeated F2 frequencies are overlaid in Figure 4. F2 frequencies are more variably distributed in the CV burst than in the VC burst as shown in (a). F2 onset values are also more widely dispersed than F2 offset values in (b). F2 frequencies both in the VC burst and at the offset of transitions are more converged, although the range seems to be smaller in the VC burst than at the offset of transitions. The test of equality of variances show that the range of dispersion in the CV burst is significantly different from that of the VC burst ($F = 14.071$, $p < 0.005$) and that F2 onset frequencies are significantly more variant than F2 offset frequencies ($F = 13.176$, $p < 0.005$). The other speakers show almost the same results as shown in Table 2.

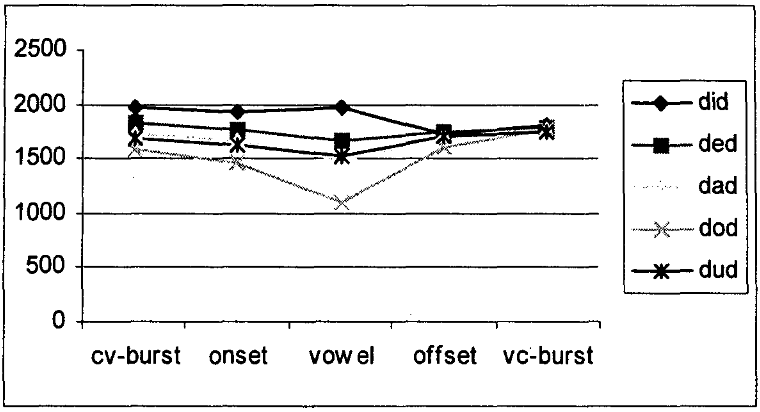
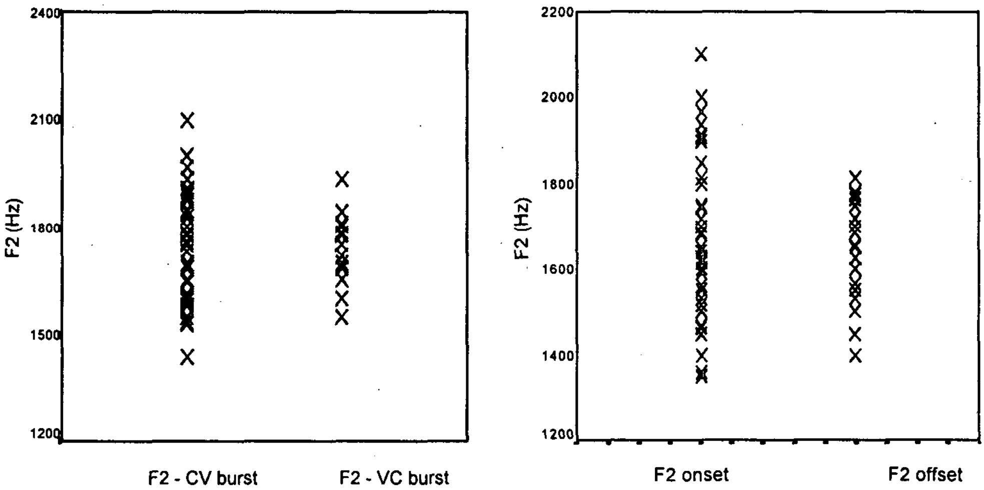


Figure 3. F2 mean frequencies at the prevocalic stop burst, at the onset and offset of transitions, at the steady state of a vowel, and at the postvocalic stop burst in the alveolar stop context (speaker 1)



(a) F2 variance: CV burst vs. VC burst (b) F2 variance: onset vs. offset

Figure 4. F2 variance in CVC structures in the alveolar stop contexts (sp. 1)

Table 2. F-values for speakers 2 & 3 (alveolar)

	CV vs. VC bursts	onset vs. offset
speaker 2	56.116 *	26.638 *
speaker 3	14.473 *	44.087 *

* Variances are significantly different at $p<0.0005$

Figures 5 and 6 show the results acquired from the /gVg/ sequences. As illustrated in Figure 5, in comparison to labial and alveolar stops, the F2 frequencies at the offset are considerably more variable; the offset frequencies are more likely to converge on the loci values in labial and alveolar stop contexts.

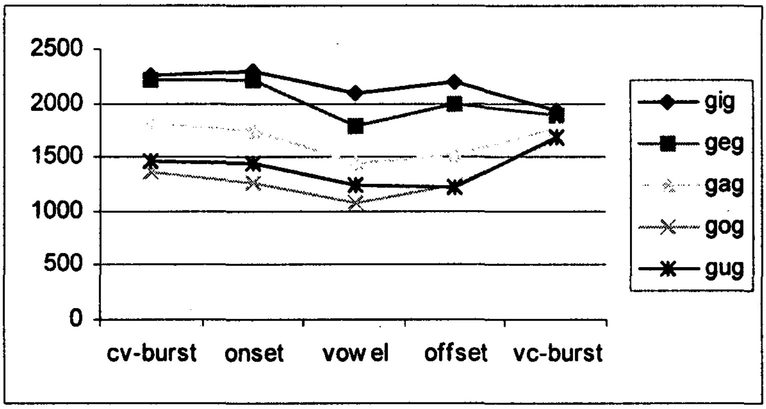
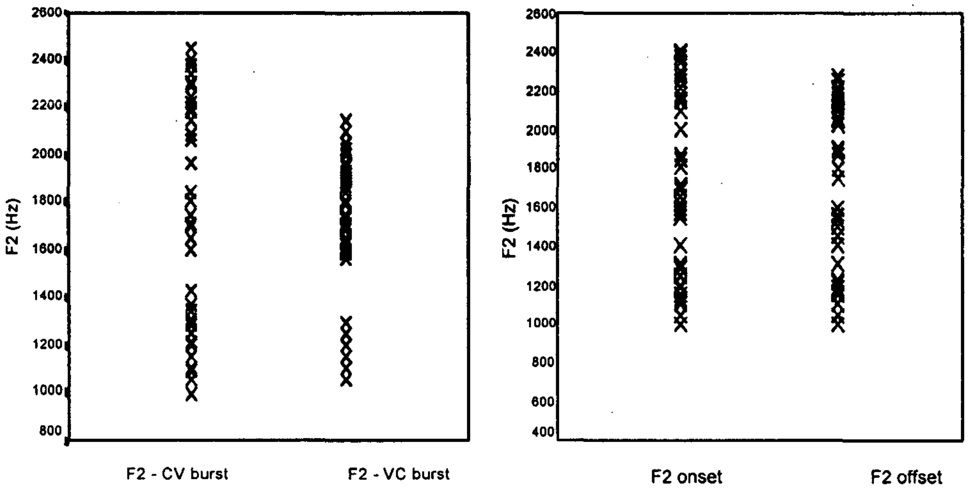


Figure 5. F2 mean frequencies at the prevocalic stop burst, at the onset and offset of transitions, at the steady state of a vowel, and at the postvocalic stop burst in the velar stop context (speaker 1)



(a) F2 variance: CV burst vs. VC burst (b) F2 variance: onset vs. offset

Figure 6. F2 variance in CVC structures in the velar stop contexts (speaker 1)

The F2 frequencies at the VC-burst, however, converge as shown in labial and alveolar stops. As shown in Figure 6, graphical illustrations of differences in variance are not immediately recognizable as much as in the cases of labial and alveolar stops. Although the variance between the onset and offset distributions is not significantly different ($p = 0.5$), the variation of F2 values in the CV burst is greater than that in the VC burst, and the difference in F2 variance is more statistically significant in the CV burst than in the VC burst ($F = 19.240$, $p < 0.005$). Speakers 2 and 3 show the same tendency as speaker 1; the F2 variations are not significantly different at the onset and offset, but the variations are statistically greater at the prevocalic stop bursts than at the corresponding postvocalic stop bursts. This is shown in Table 3.

Table 3. F-values for speakers 2 & 3 (velar)

	CV vs. VC bursts	onset vs. offset
speaker 2	51.765 *	0.095
speaker 3	5.618 *	0.885

* Variances are significantly different at p<0.0005

2.4 Discussion

Results in the contexts of the three stop places of articulation consistently show that F2 frequencies in CV structures are more likely to correspond to the F2 values of vowels and that F2 variances are significantly greater within CV structures than VC structures, although this does not seem to be the case at the onset and the offset of transitions of the velar stop. This can be interpreted as saying that CV structures exhibit substantially greater coarticulation than VC structures and suggests that a vowel's tongue body gesture is more readily anticipated in the preceding consonant, but its carry-over effects on the following consonant is relatively small.

There seems to be no difference in the degree of coarticulation at the onset and the offset of transitions in the velar stop contexts, which follows from the observation that F2 variances does not significantly differ. Since a velar stop and a vowel share a common articulator, which is the tongue body, the velar stop can immediately coarticulate with a vowel as discussed in Sapir (1921), Heffner (1950), Ladefoged (1975), and Keating (1993). This articulatory accommodation between a velar stop and a vowel appears to operate both on the preceding and the following stops, resulting in almost the identical magnitude of modification at the transitions. This indicates that the tongue body position of a velar stop has evidently moved toward the region where the vowel is articulated, especially in the transitions into and out of the vowel articulation.

The center frequencies of the F2 distribution at VC bursts converge on around 1,100 Hz to 1,600 Hz whereas the offset frequencies converge to a stop's locus value. This suggests that the tongue body gesture of the preceding vowel is not extended to the postvocalic stop burst, indicating that the stop is more likely articulated independent of the preceding vowel. It seems that the tongue body has already arrived at a neutral position when the postvocalic stop is released, and there are no vocalic resonant frequencies from the preceding vowel. Rather, the burst is influenced by the resonance of the neutral tongue body position, probably schwa /ə/.

3. C-to-V coarticulation in the vertical dimension

3.1 Assumption and Hypothesis

An F1 frequency has been known as an indication of constriction degree (Johnson 1997; Kent & Read 1992), and has been also used in many experiments as a measure of oral closing-opening degree or jaw raising-lowering movement (Summers 1987; Harrington, Fletcher & Beckman 1996). For example, Kent & Read (1992) assert that a very low F1 frequency usually means that the vocal tract is constricted to some degree for a consonant and that the F1 transition appears to be a cue to manner of production (degree of constriction). Therefore, F1 should be theoretically zeroed in a stop context. Moreover, a greater degree of constriction will be associated with higher jaw position, which acoustically causes a lower F1 frequency.

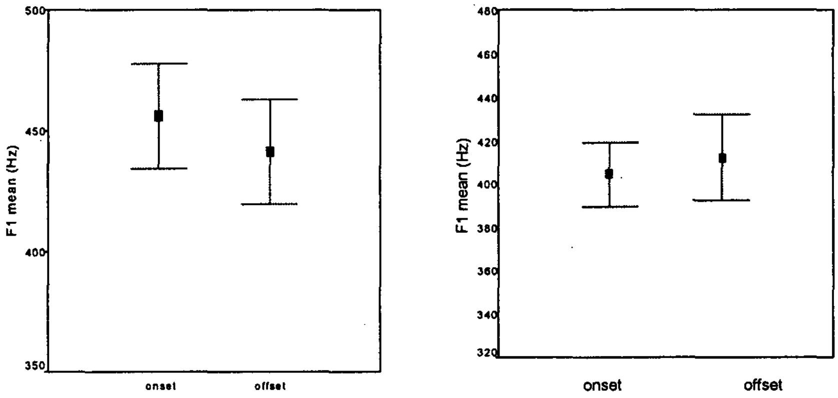
Lee (1999) reports that an F1 onset frequency is higher in a fricative-to-vowel transition than in a stop-to-vowel transition because the degree of the oral constriction is lower in the fricative than in the stop. Due to the higher constriction degree of the stop, the onset of an F1 transition starts at a lower F1 frequency, which indicates that a vowel is articulated out of a very highly constricted consonant. Then, I hypothesize that the F1 frequency will be higher at the onset of transition than at its offset if the same asymmetry observed in the horizontal coarticulation occurs in the vertical dimensional coarticulation.

3.2 Data and Methods

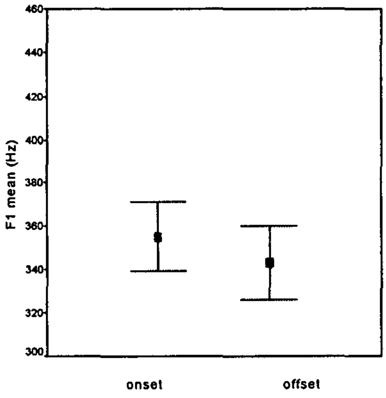
The same data were utilized as in the experiment in section 2, and the first formant frequencies were measured at two points: at the onset and offset of F1 transitions. F1 onset/offset values were obtained from the Waves formant trajectories display, and the frequencies were confirmed by the frequency of the first spectral peaks. In most cases, the frequencies acquired from the formant trajectories accorded with the first peaks of the spectra, but when they did not precisely agree, spectral peak values were taken for data. F1 was not clearly shown in burst regions because of a relative lack of lower frequency energy, and so unfortunately, F1 measurements at bursts could not be carried out in this experiment. Therefore, the onset and offset frequencies were the sole basis for comparison across the five vowel contexts in CVC structures.

3.3 Results

Figure 7 shows a comparison of F1 onset and offset mean frequencies for speaker 1. In each stop context, F1 mean frequencies were calculated over all five vowels for the sake of consistency, since F2 frequencies were compared in terms of variances across all the vowel contexts. The onset means seem to be higher than the offset means for labial and velar stops in (a) and (c), but the means are not significantly different as obtained by an independent sample t-test (t = 0.013, p=0.342 for the labial stop contexts, t=-0.626, p=0.532, t=1.065, p=0.289) The alveolar stop shows a reverse configuration in (b): the offset frequency is higher than that of onset, but again, the difference is not statistically significant. The results for speakers 2 and 3 show almost the same pattern as speaker 1 except the case of the alveolar stop for speaker 2 (t=1.573, p<0.05), which is shown in Table 4.



(a) labial stop (b) alveolar stop



(c) velar stop

Figure 7. F1 mean frequencies (speaker 1)

Table 4. F2 mean differences (speakers 2 and 3)

	speaker 2		speaker 3	
labial	$t = 0.033$	$p = 0.280$	$t = 1.639$	$p = 0.104$
alveolar	$t = 1.573*$	$p < 0065$	$t = -1.381$	$p = 0.170$
velar	$t = 0.324$	$p = 0.018$	$t = 1.425$	$p = 0.157$

3.4 Discussion

Results show that onset mean frequencies are slightly, but not significantly, higher than offset means in labial and velar stop contexts for all speakers. For the alveolar stop, the onset mean is significantly higher in the case of speaker 2, but speakers 1 and 3 show that the offset means are higher than the onset means, though the difference is not significant.

Recall that F2 variations are significantly greater at the onset of transitions than at the offset of transitions in labial and alveolar stop contexts, indicating that a vowel's coarticulatory effects of constriction location is greater in C-to-V transitions than in V-to-C transitions. However, this is not the case for the velar stop, because there is no significant difference in F2 variance, which suggests that a velar stop coarticulates to a vowel almost symmetrically going into and out of the vowel. In consideration of acoustic manifestations in the formant transitions, the asymmetrical effects of a vowel's place of articulation are not found in the opening-closing dimension of coarticulation for labial and alveolar stops.

4. The interrelation between horizontal and vertical coarticulation

Results suggest that coarticulation is not necessarily executed by a concomitant manipulation of the horizontal and vertical dimensions. In other words, while horizontal articulatory effects of a vowel are asymmetrical on pre- and postvocalic consonants, vertical articulatory effects of the vowel do not seem to be proportional to the horizontal ones. Velar stops, on the other hand, show almost symmetrical effects both in horizontal and vertical dimensional coarticulation, but it would be insufficient to conclude that coarticulatory modifications of a consonant are concurrently achieved in constriction location and degree, because labial and alveolar stops do not show such a case. In addition, Lee (1999) reports that the degree of horizontal coarticulation is not proportional to that of vertical coarticulation. In other words, the symmetrical effects on the horizontal dimensional articulations of both pre- and postvocalic velar stops are relatively great, resulting in the significant modification of their constriction location, whereas the degree of vertical coarticulation is not significant, making no appreciable modification in the constriction degree. Therefore, the results of the three stops suggest that the constriction location of a vowel may give rise to coarticulation independently of its opening gesture.

5. *Implications for phonology*

I have compared each of horizontal and vertical coarticulations between CV and VC structures and concluded that horizontal and vertical coarticulation is not necessarily executed either concomitantly or proportionally. Taking the view that phonetic nature is effectively reflected in phonological patterns (Ohala, 1974 1981, 1983, 1993), such phonetic findings imply that C-to-V place assimilation may not necessarily yield a change of a stricture feature in phonology. In other words, horizontal coarticulation might be independent of vertical coarticulation, suggesting that place assimilation would be conducted without lenition of consonant constriction. This is consistent with the observation in phonology that place assimilation and lenition processes seem to be completely independent in phonology; C-to-V place assimilation occurs predominantly in CV structures, and relatively less in VC structures, whereas lenition is generally invoked intervocalically or in VC structures (Kirchner, 1998).2) Again, lenition in postvocalic position is not induced by the opening gesture of a preceding vowel, but from the weakening in word-final position. For example, when the stops /b, d, g/ are palatalized by the following palatal vocoid, the outputs /β^{j}/, /δ^{j}/, and /γ^{j}/, which involve changes in both place and constriction degree, are not attested to in any language. Moreover, lenition patterns observed across languages do not show a simultaneous change in place features: for example, the changes like p → β, β → w, t → θ, and k → x entail a sole change in constriction degree (see Kircher, 1998 for details).

The magnitude of C-to-V place coarticulation in the dimension of constriction degree does not seem to be promoted by the phonological process of lenition. If this were the case, consonant lenition would take place in both CV and VC structures. It might be plausible that the degree of vertical coarticulation of a consonant to a single vowel, which is not significantly different in CV and VC structures, is not sufficient

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2) The velar stop was diachronically palatalized to the palatal fricative before [i] in word-initial position in Norwegian (Haugen 1938; Walsche 1965) and Swedish (Bergman 1947; Walsche 1965), but I contend that this process is not a complete consequence of coarticulation but should be complementarily analyzed from a perceptual perspective. That is, it could be motivated by maximum coarticulation, resulting in the palatal stop [c], but it seems plausible that the slight palatal affication at the release [c] is word-initially strengthened by a listener. .

to lower the target constriction of the consonant. This might be the natural coarticulatory basis for the phonological patterns of consonant lenition that consonants are lenited mostly in intervocalic position.

6. Conclusion

I have presented two acoustic experiments conduced to investigate the degree of coarticulation in CV and VC structures along two dimensions of the oral tract: front-back and open-close dimensions. The results suggest that horizontal and vertical coarticulation is not necessarily executed either concomitantly or proportionally, and that the modification induced by coarticulation with a vowel in CVC structures is merely restricted to the CV portion; that is, the prevocalic consonant is modified by the vowel in its constriction location. This is consistent with the observation that C-to-V place assimilation does not accompany consonant lenition in phonology. C-to-V place assimilation and consonant lenition are completely independent processes with respect to their conditions; C-to-V place assimilation is conditioned by the following single vowel, but consonant lenition is generally induced by both the preceding and following vowels. Therefore, the instrumental findings presented in this paper provides further evidence for the claim that phonetic coarticulation serves as a substantial basis for phonological patterns of assimilation.

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