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1 Introduction

This paper investigates the effects of phonetic factors and phonological factors on the degree of intergestural timing relations. Intergestural timing relations have recently been useful for defining coarticulation. In particular, articulatory phonology defines coarticulation as gestural overlap (Browman and Goldstein 1989, Byrd 1996, Zsiga 1995). Manuel (1987:179) characterizes it as “patterns of coordination, between the articulatory gestures of neighboring segments, which result in the vocal tract responding at any one time to commands for more than one segment.” Figure 1 shows gestural overlap along the time dimension.

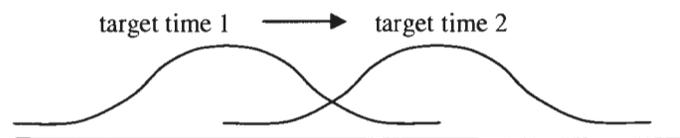


Figure 1. Coarticulation as gestural overlap.

Coarticulation always happens between close segments in some domain. This paper focuses on vowel-to-vowel coarticulation in Korean, assuming a traditional idea that VCV sequences are realized by means of an underlying V-to-V articulatory mode, with a superimposed consonantal gesture (Öhman 1966). In addition, the magnitude of vowel-to-vowel coarticulation varies according to the resistance of the intervening consonant (Recasens 1984). For example, Recasens et al. (1997) found that the effects of vowel-to-vowel coarticulation were greater across bilabials than across alveopalatals when the second vowel was fixed as /a/. However, my study examines the effect of the intervening consonants (alveolars vs. palatals) on the degree of vowel-to-

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vowel coarticulation in V_1CV_2 sequences and the effect of V2 (/i/ vs. /a/) on the degree of vowel-to-vowel coarticulation.

In addition to phonetic effects, this study investigates whether and how much high-level phonological rules such as palatalization directly affect low-level fine phonetic details such as vowel-to-vowel coarticulation. As is well known, in Korean, coronals /t, t^h/ become palatals [dʒ, tʃ] before /i/ in the environment of a morpheme boundary as is illustrated in (1).

(1) a. input	b. assimilated forms	c. glosses
mat+i	madʒi	'eldest child'
kot+i	kodʒi	'plainly, as it is'
kut+i	kudʒi	'intentionally'
mut+hi+ta	mutʃida	'bury+Pass.+Dec.'
k'it ^h +i	k'itʃi	'end+Nom.'

Cho's (1998) electropalatography study showed that palatal consonants derived from palatalization (e.g. [dʒ] in /mat+i/ 'the eldest child') involve more contact in the palatal region than alveolars in tautomorphic words (e.g. [d] in /mati/ 'knot'). However, his data mingled complex factors such as morpheme boundaries, phonetic difference, and phonological rules. Thus, this study attempts to tease phonetic factors apart from phonological factors along with morpheme boundaries. Further, there have been very few investigations into the effect of phonological rules on the degree of vowel-to-vowel coarticulation (Benus 2005, Cho 1998, Yun 2005, Zsiga 1995). A more crucial purpose of this paper is to find evidence that coarticulation is conditioned by palatalization. The next section will summarize research questions and hypotheses.

2 Questions and Hypotheses

2.1 Research Questions

First, this study questions consonantal effects on intergestural timing relations, i.e., whether there is any difference in the degree of V-to-V coarticulation between palatals and alveolar stops as the intervening consonants. The second question centers on vocalic effects, i.e., whether there is any difference in the degree of V-to-V coarticulation between a front high /i/ and a low back /a/ as the second vowel. Third, the effects of phonological rules on V-to-V coarticulation are explored, i.e., whether the application of palataliza-

tion directly affects the degree of V-to-V coarticulation. On the basis of these questions, I attempt to explore the possibility that the different inter-gestural timing organization can be represented in the lexicon. Further, I pursue the interface model of phonetics and phonology by showing that phonological rules may be directly related to the phonetic fine details such as coarticulation.

2.2 Hypotheses

First, with respect to consonantal effects in VCV sequences, palatals have been known as stronger barriers to vowel interaction than alveolar stops. One reason is that articulation of palatals is more robust, in that palatals involve raising and fronting of the tongue dorsum whereas alveolars involve tongue-tip or blade touching. Second, palatal affricates show longer duration than alveolar stops (alveolars 91 ms vs. palatals 139 ms; $F_{(1,4210)} = 680.98$, $p < 0.001$). Thus, the following hypothesis is proposed:

- (H1) The degree of V-to-V coarticulation is smaller in words with palatal affricates than in words with alveolars as intervening segments.

Second, as for V2 in V_1CV_2 sequences, it is reasonable to think that a high front /i/ is a stronger attractor to vowel-to-vowel coarticulation than /a/. The rationale behind this assumption is also related to articulatory properties of both vowels. A high front /i/ is the most resistant to coarticulation and therefore it is not likely to coarticulate to other vowels, but other vowels are likely to be influenced by /i/. Degree of articulatory constraint (DAC: Recasens et al. 1997) also supports this in that /i/ has the maximal DAC value of 3, while /a/ has lower DAC value of 2. Thus, I suggest the following hypothesis:

- (H2) The degree of V-to-V coarticulation is greater in words with a high front /i/ than in words with a low back /a/.

Last, but of more interest, is the role of phonological rules in inter-gestural timing relations. Here I follow two assumptions. One is Cho's (1998) suggestion that intergestural timing relations are more variable between morphemes than within morphemes in the input. This gives the possibility that gestural overlap may be greater in the words which undergo palatalization. Second, application of a phonological rule directly increases the degree of V-to-V coarticulation, causing greater gestural overlap between vowels (Yun 2005). These assumptions lead to the following hypothesis:

- (H3) The degree of V-to-V coarticulation is stronger in assimilated forms than in unassimilated forms.

Hypothesis (3) is intriguing in predicting that although the phonemic string such as VCV in the surface is identical, phonetic fine details are conditioned by palatalization. The next section introduces ultrasound experiments to look into articulatory results directly.

2.3 Experimental Methods

Subjects. Ten native speakers of Korean participated in the production of Korean words. Six were males and four females. Their ages ranged from 20 to 30.

Materials. Table 1 shows the materials for testing hypotheses (1) and (H2). Both (a) and (b) and (c) and (d) were planned as comparisons in order to measure the consonantal effect on the degree of V1 coarticulation. The intervening consonants varied between palatals and alveolars, while V2 was fixed as either /i/ or /a/. In order to test hypothesis (2), both (a) and (c), and (b) and (d) were planned as comparisons. In this case, the intervening consonants were fixed either as palatals or as alveolars, while V2 varied between /i/ and /a/.

1 st vowel	Fixed /i/		Fixed /a/	
	a. Test words	b. Control words	c. Test words	d. Control words
a	madʒi	madi	madʒa	mada
ə	kaɪlkədʒi	kaɪlkədi	kaɪlkədʒa	kaɪlkəda
o	kodʒi	kodi	kodʒa	koda
u	kudʒi	kut ^h i	kutʃa	kut ^h a
i	hitʃida	hit ^h ida	hitʃada	hit ^h ada

Table 1: Stimuli to test hypotheses (1) and (2)

Table 2 shows the stimuli to test hypothesis (3). The words in (a) are the real words with morpheme boundaries which undergo palatalization. Those in (b) are the real words which do not undergo palatalization and have underlying palatals. However, V₁CV₂ sequences in the surface are identical.

V1	a. assimilated words		b. non-assimilated words	
a	madʒi	'the eldest'	madʒi	'unwillingly'
ə	kailkədʒi	'autumn harvest'	səlkdʒi	'dishwashing'
o	kodʒi	'plainly'	kodʒi	'high ground'
u	kudʒi	'intentionally'	talkudʒi	'ox cart'
i	hitʃida	'scatter'	sitʃida	'go past by'

Table 2: Stimuli to test hypothesis (3)

Design. Each word was uttered five times by each subject. In total, 5438 tokens of words were produced, and their tongue images were analyzed.

Procedures. An ultrasound machine was utilized in the Arizona Phonological Imaging Lab in the Department of Linguistics at the University of Arizona. The frontness of the tongue body was measured on the basis of ultrasound images captured from the pictures. To see the relative tongue-body frontness, the distances from the palate to the tongue body line were measured at two points (the furthest back and front of the palate), using Palatron (Mielke et al. 2005). Next, frontness values were calculated based on the two points with the following formula:

$$\log_{10}(\text{distance at furthest back point}/\text{distance at front point})$$

A higher value indicates a fronter position of the tongue body.

3 Results

3.1 (H1): Palatals as Stronger Barriers to V-to-V Coarticulation

Figure 2 shows the overall consonantal effect on the degree of anticipatory vowel-to-vowel coarticulation when V2 was either /i/ or /a/. Interestingly, contrary to Hypothesis (1), back vowels such as /a, ə, o, u, i/ were articulated further front before palatals than before alveolars ($F_{(1,4224)} = 20.57$, $p < 0.001$). These results indicate that there was more prominent anticipatory coarticulation before palatals than before alveolars regardless of the following vowels.

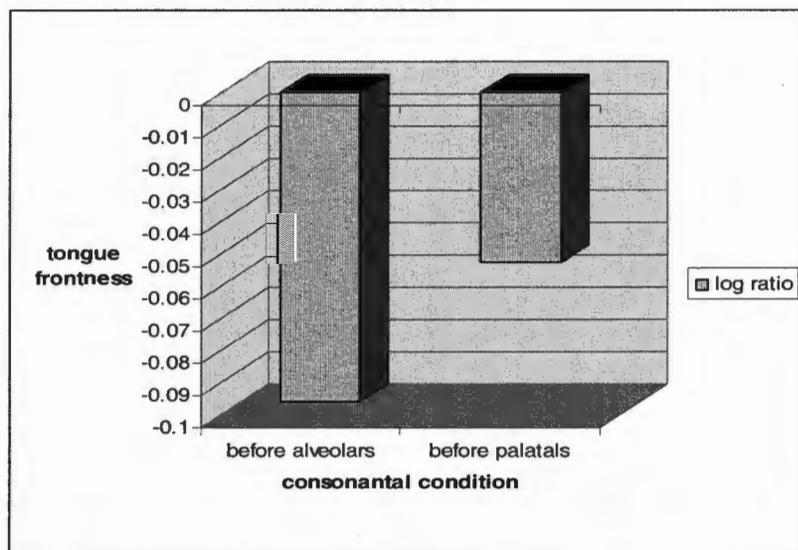


Figure 2. Consonantal effects on the degree of V1 coarticulation
 $(F_{(1,4224)} = 20.57, p < 0.001)$.

The average log values in Figure 2 belie variation according to the various types of first vowels and the fixed second vowels. First, Figure 3 shows the frontness of the back vowels within the fixed /i/ condition according to the different back vowels. Each of five pairs shows sequences of back vowels (/a, ə, i, o, u/) followed by palatals or alveolars followed by a fixed vowel /i/. The left bars in each pair refer to the frontness of the back vowels before palatals, while the right ones refer to frontness of each back vowel before alveolars. Each back vowel, both before palatals and before alveolars, was articulated fronter than the same ones in monosyllabic forms. These indicate that back vowels underwent anticipatory V-to-V coarticulation. Of interest is that, as in the overall results, there were significant effects of the intervening consonants within the fixed-/i/ condition ($F_{(4,2101)} = 176.17, p < 0.05$). In other words, the back vowels were articulated fronter before palatals than before alveolars in the fixed-/i/ condition, as illustrated in Figure 3.

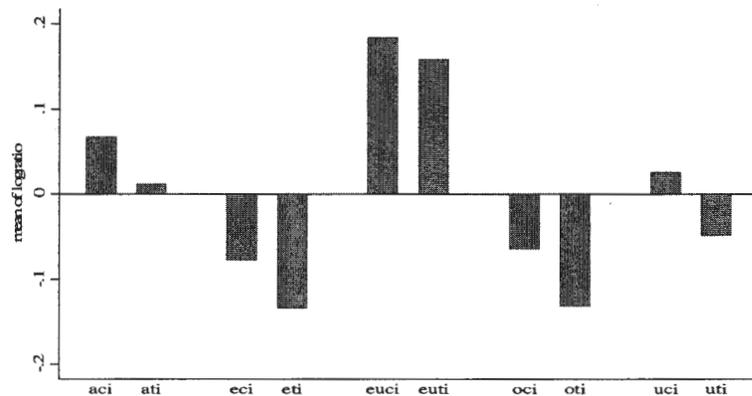


Figure 3. The effects of the consonants on the frontness of back vowels (V1) when V2 is fixed as /i/ ($F_{(4,2101)} = 176.17, p < 0.05$).

In addition, among the five pairs, there were significant effects of consonants only in the cases of back vowel /ə/ (the second pair; $p < 0.05$), while there was no significant effect of consonants in the cases of other back vowels /a, i, o, u/ ($p > 0.05$), as seen in Figure 4.

Next, 1-factor ANOVA of simple effects was performed to see the consonantal effects within the fixed-/a/ environments. Figure 4 shows that there were significant effects of intervening consonants on the degree of V-to-V coarticulation within the fixed-/a/ environments ($F_{(5,2104)} = 18.19, p < 0.001$). The left bars in each pair refer to the frontness of the back vowels before palatals, while the right ones refer to the frontness of each back vowel before alveolars. Like the overall patterns with the fixed-/i/ condition, back vowels like /a, ə, i, o, u/ were produced fronter before palatals than before alveolars. Further, interestingly, there were significant consonantal effects with four pairs (/ə, i, o, u/) ($p < 0.05$), while a back vowel /a/ only showed nonsignificant consonantal effects ($p > 0.05$).

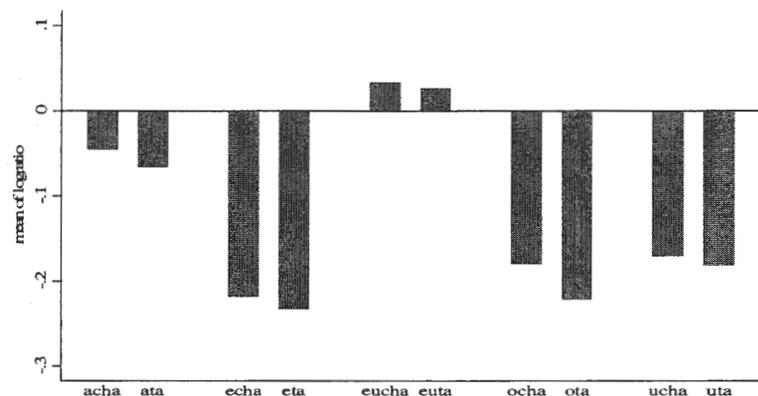


Figure 4. The effects of the consonants on the frontness of back vowels when V2 was fixed as /a/. ($F_{(5,2104)} = 18.19, p < 0.001$)

In sum, these results reveal that back vowels were articulated significantly fronter before palatals than before alveolars, within both the fixed-/i/ and fixed-/a/ conditions, as a result of stronger anticipatory coarticulation, which is exactly the opposite of what Hypothesis (1) predicted. That indicates that alveolars inhibit vowel-to-vowel coarticulation or interaction more than palatals. This study provides very interesting results about the status of palatals vs. alveolars in Korean V-to-V coarticulation. In Section 5, it will be discussed in more detail why palatals are weaker barriers and facilitate V-to-V coarticulation.

3.2 (H2): Front Vowels as Stronger Attractors to Coarticulation

Figure 5 shows the average log values for back vowels between words with a high front /i/ as a second vowel and words with a low back /a/ for ten subjects. As is illustrated, there was a highly significant effect of the second vowel on the degree of anticipatory V1 coarticulation ($F_{(1,4216)} = 168.30, p < 0.001$). As expected by Hypothesis (2), back vowels were articulated fronter before /i/ than before /a/. The left bar with a lower value refers to the further back position of the back vowels before /a/ in V_1CV_2 sequences, while the right bar, with a higher value, refers to the further front position of the identical back vowels before /i/ in V_1CV_2 sequences.

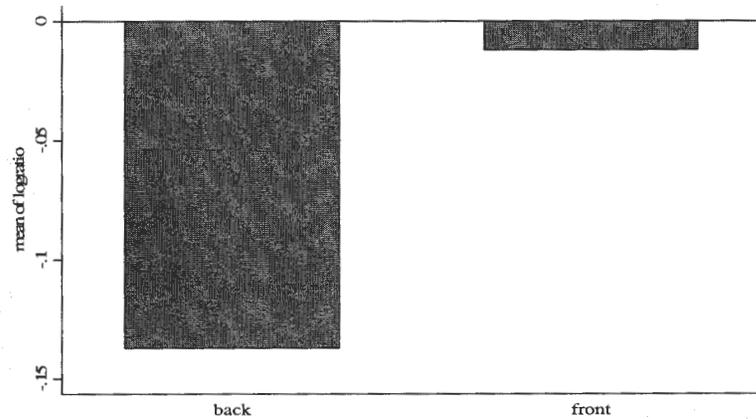


Figure 5. Vocalic effects on the degree of coarticulation ($F_{(1,4216)} = 168.30$, $p < 0.001$).

These results also confirm Öhman's (1966) original idea that consonants are superimposed on the stream of vowels by showing vowel-to-vowel coarticulation across the intervening consonants.

In order to see whether and how the two types of intervening consonants influence the degree of V-to-V coarticulation, post-hoc analyses of simple effects were conducted. First, one-factor ANOVA was performed to see the effects of vowels on the tongue-body backness within palatal environments. There was a highly significant simple effect of the vowels (/i/ vs. /a/) on the degree of tongue body backness ($F_{(5,2058)} = 20.73$, $p < 0.001$). Back vowels were articulated fronter before /i/ than before /a/ with palatals fixed as an intervening consonant. In particular, among the five pairs, back vowels such as /a, i, u/ were produced significantly fronter before /i/ than before /a/ ($p < 0.05$), while back vowels such as /ə, o/ were not ($p > 0.05$).

Next, one-factor ANOVA of simple effects revealed that there was a highly significant effect of the second vowels on the degree of tongue body backness of V1 ($F_{(5,2147)} = 18.32$, $p < 0.001$). The back vowels were articulated fronter before /i/ than before /a/, which supports Hypothesis (2). Specifically, back vowels such as /a, i, o, u/ were significantly fronter before /i/ than before /a/ ($p < 0.05$), while a back vowel like /ə/ was not ($p > 0.05$).

In sum, overall, the results above support Hypothesis (2). As expected, the back vowels were produced fronter before /i/ than before /a/, which indicates that back vowels were more influenced by /i/ than /a/. This is not only

in accord with the hypothesis that there is stronger anticipatory coarticulation before /i/ than before /a/, but also supports the concept of DAC in the sense that the higher-DAC segments like /i/ are more likely to have an influence than lower-DAC segments like /a/. Second, in both the fixed-alveolar and fixed-palatal conditions, back vowels were articulated fronter before /i/ than before /a/. Third, there was a significant interaction between the intervening consonants (alveolars vs. palatals) and the second vowels, as mentioned (/i/ vs. /a/).

3.3 (H3): Phonological Enhancement of Coarticulation

Figure 6 shows the average log values for the back vowels before derived palatals and before underlying palatals for ten subjects. The left bar with a higher value refers to further front position of back vowels before derived palatals, while the right bar with a lower value refers to further back position of back vowels before underlying palatals. As illustrated, there was a highly significant effect of the phonological status of the palatals on the degree of anticipatory coarticulation ($F_{(1,2109)} = 39.42, p < 0.001$). As predicted by Hypothesis (3), back vowels were articulated fronter before derived palatals than before underlying palatals.

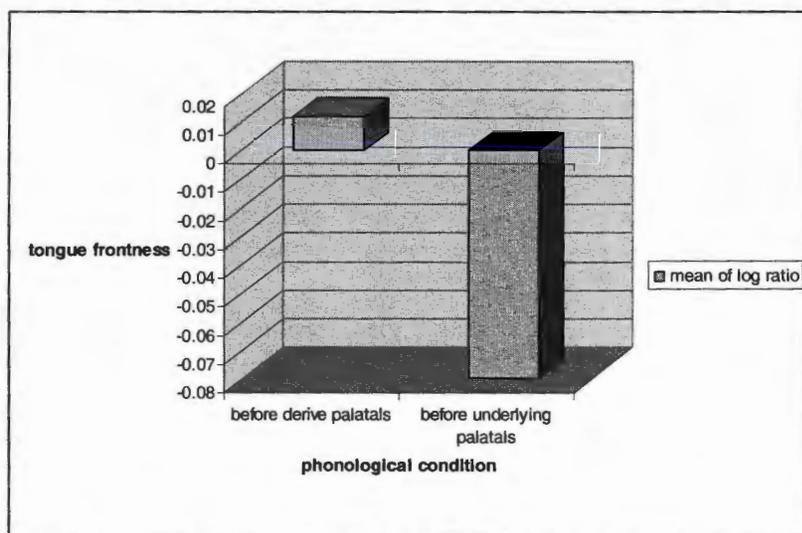


Figure 6. Overall phonological effects on the degree of anticipatory vowel-to-vowel coarticulation ($F_{(1,2109)} = 39.42, p < 0.001$).

These results support Hypothesis (3), indicating that intergestural timing relations between vowels are more overlapped in palatalized words than in nonpalatalized words.

4 Discussion

4.1 Why Are Palatals Not Stronger Barriers to V-to-V Coarticulation?

Some might wonder about the explanation based on the featural combination of both consonants. In feature geometry, alveolars can be represented as [coronal, +anterior], while (alveo)palatals are represented as [coronal, -anterior]. Since alveolars are articulated further front than palatals, if back vowels are likely to be influenced by the following consonants, they are more likely to be produced further front before alveolars than before palatals. However, our results do not fit into such featural explanation. Thus, feature-based models are not sufficient to account for low-level phonetics such as V-to-V coarticulation.

However, an alternative possible explanation I suggest is the notion of "mutual compatibility" of the gestures (Recasens 1984, 1990, Recasens et al. 1997). What is referred to as "mutual compatibility" is the degree that coarticulatory effects depend on how much the gestures of neighboring segments resist coarticulatory overlap. That is, the notion is directly reflected in DAC values, as mentioned earlier. However, DAC wrongly predicts that the degree of V-to-V coarticulation should be less before palatals than before alveolar stops, because the former have maximal DAC value. Therefore, it is necessary to look into mutual compatibility from a different point of view. Thus, it is proposed that the degree of coarticulation can depend on what types of gestures two or more segments share. From such a perspective, the tongue body is raised to produce both palatals and a front high /i/, and the tongue body is also involved in the production of /a/. Thus, a synergistic effect of the tongue-body gesture arises among vowels and the intervening palatal, strengthening the gestural overlap between vowels. Otherwise, the tongue-body-raising gesture of palatals might have attracted the back vowels further forward than the tongue-tip gesture of alveolars because palatals have more attracting articulatory robustness with which influence the preceding vowels. In brief, the intervening palatals can act as a bridge to connect vowels because of the shared property of tongue-dorsum gesture. That is why palatals facilitate the stronger V-to-V coarticulation.

4.2 Do Phonological Rules Enhance V-to-V Coarticulation?

Our findings lead us to suggest that intergestural timing between vowels is more overlapped in palatalized words than in nonpalatalized words. While Cho's (1998) suggestion has to do with gestural overlap between consonants (alveolar vs. palatals) and vowel /i/, my proposal is the gestural overlap between vowels across or within morpheme boundaries.

Here the degree of intergestural timing relations is based on two assumptions. First, as suggested by Cho (1998), Bradley (2002), and Gafos (2002), I follow the assumption that intergestural timing relation is lexically specified in the mental lexicon. Given that, intergestural timing is less overlapped in heteromorphemic words such as /mat+i/ in the input since the presence of morpheme boundaries blocks gestural overlap. That is, the intergestural timing relation is more variable in polymorphemic words, while it is relatively fixed within morpheme boundaries. Second, since intergestural timing is more flexible across morpheme boundaries, the application of phonological rules such as palatalization causes greater gestural overlap. That is why back vowels before derived palatals are more influenced by the following vowel /i/ than those before underlying palatals, showing stronger anticipatory coarticulation.

These findings are intriguing and have important implications with regard to the interaction between phonology and phonetics. First, they reveal that high-level phonological rules affect fine phonetic details such as V-to-V coarticulation as well as C-to-V coarticulation. Second, this interaction necessitates the notion of abstract intergestural timing relations in the phonological or phonetic representation in order to capture the influence of phonological rules on coarticulation (Barry 1992, Bradley 2002, Cho 1998, Gafos 2002). Thus, the results on Hypothesis (3) provide another piece of evidence that intergestural timing relation can be incorporated into phonological representations in input and output. Barry (1992) also mentions "the implication that low-level phonetic variation may not all be accounted for free of charge by phonetic implementation and that instead the domain of phonology may need to set its bounds much closer to the fine detail of articulatory activity than has generally been acknowledged." There have been different positions on coarticulation: (i) it is purely a part of a language-particular phonetic implementation component, working independently of phonology, or (ii) it can be a part of cognitive knowledge of the speakers of specific languages (Flemming 2001). Thus, if we put the scope of coarticulation outside phonology and deal with it only in independent phonetic implementation component, it is difficult to capture the interface between palatalization and V-to-V or V-to-C coarticulation patterns. Although an intergestural timing relation

based on coarticulation involves no categorical change of features, it still can be intertwined with phonological rules by being influenced by phonological rules. Thus, the results in this experiment make it reasonable to favor a unified model of phonology and phonetics rather than two separate component models.

5 Conclusion

This study is intriguing and provides interesting implication on phonetics and phonology. First, it reveals that intergestural timing relations are highly conditioned both by phonetic gestures and by phonological rules. Second, it shows that traditional articulatory, acoustic, and feature-based accounts are not sufficient to account for the role of palatals as weaker barriers to V-to-V coarticulation. The notion of "mutual compatibility" on the basis of common gestures is necessary. Third, with respect to representations in phonology, it implies that phonological grammar can incorporate intergestural timing relations in the abstract representation to capture the fact that a high-level phonological rule affects the degree of low-level fine phonetic details such as V-to-V coarticulation (Barry 1992, Bradley 2002, Cho 1998, Gafos 2002, Yun 2005, Zsiga 1995).

Further research awaits investigations on the following topics. First is what the phonetic and phonological effects are on English palatalization environments. Second is the degree of V-to-V coarticulation between lexical palatalization rule environments and post-lexical palatalization environments in English. Third is the relation between F1/F2 coacoustical patterns and articulatory patterns.

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