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Supralaryngeal articulatory signatures of three-way contrastive labial stops in Korean

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ABSTRACT

This study investigates how the three-way contrastive bilabial stops (/p*,p^h,p/, called fortis, aspirated and lenis, respectively) in word-medial position in Korean are distinct kinematically at the supralaryngeal articulatory level. Results of a magnetometer experiment with seven speakers of Seoul Korean showed that the three-way contrastive stops in VCV sequences (V=/i/ or /a/) are indeed manifested at the supralaryngeal level—not only in consonantal articulation, but also in vocalic articulation of their adjacent vowels. Several specific points have emerged. First, stops were three-way distinct in constriction degree and constriction duration (/p*/ > /p^h/ > /p/). Second, their contrast was also evident in temporal dimensions of the vocalic tongue movement with a three-way distinct pattern (/p*/ > /p^h/ > /p/), and of the lip opening movement with a two-way distinction (/p*,p^h/ > /p/). Third, consonantal strength was further reflected in V-to-V coarticulation, such that longer constriction triggered more reduction of V-to-V coarticulation. However, there was a case (for /i/ in carryover direction) in which coarticulatory reduction was still observed even when the duration was factored in, showing duration-independent V-to-V coarticulatory resistance associated with the fortis and aspirated stops. Fourth, stable coordination was observed between the lip constriction and the vocalic tongue movement which is in line with previous findings in Japanese and English, suggesting cross-linguistic similarities in consonant–vowel gestural coordination regardless of the rhythmic structure of a given language.

1. Introduction

When phoneticians describe the sounds of a particular language, the first question that they consider may be how the sounds of the language can be described by a limited set of phonetic parameters or features that have been known to exist in the world's languages. In this regard, Ladefoged and Maddieson (1996) wrote:

> We believe that it is possible to set up a system of phonetic parameters each of which contains categories that taken as a whole, will distinguish all the potential contrasts within human languages. The system also allows for differences between one language and another to be described by different values along the parameters. (Ladefoged & Maddieson, 1996, p. 6)

This highlights the need for a phonetic theory to be able to describe sound patterns in a particular language with 'explanatory adequacy' based on the universal phonetic feature system. Additionally, a good phonetic description of a sound system should also be able to provide enough information of how each sound in the language is produced in a unique and language-specific way in comparison with sounds in other languages that share the same phonetic features. In a cross-linguistic survey paper observing VOT patterns in 18 languages, Cho and Ladefoged (1999) argued for phonetic arbitrariness. They demonstrated that VOT values in a given language are arbitrarily chosen by the language, independent of the phonological opposition in that language, suggesting that simply [voiceless] or [aspirated] features cannot capture how the native speakers of the language actually pronounce the stops. As this study implies, by describing sounds using the universally applicable phonetic features or parameters, we may achieve the goal of providing simplified theories of phonetic description; such practice, however, is vulnerable to the fallacy of *dicto simpliciter* with little attention paid to the goal of describing the sound system of the language with observational adequacy. The present study is aimed at achieving this goal by exploring the language-specific phonetic substance of phonological contrasts in Korean. It examines detailed kinematic properties of three-way contrastive stops at the supralaryngeal level in Korean, complementing our knowledge of Korean stops that has been skewed toward their laryngeal characteristics.

Korean has a three-way series of stops that are often described as 'fortis' (as in /p*ul/ 'horn'), 'lenis' (as in /pul/ 'fire') and

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'aspirated' (as in /pʰul/ 'grass'). They are all voiceless, largely differentiated by varied degrees of positive VOT (shorter for the fortis, intermediate for the lenis, and longer for the aspirated), although the distinction by VOT between the lenis and the aspirated stops appears to have begun disappearing among the young generation of Korean speakers (Silva, 2006). The fortis stop series /p*,t*,k*/ (also known as 'tense' stops) are also produced with a higher F0, abrupt intensity build-up, relatively undamped harmonics, and smaller or often negative H1–H2 and H1–F2. Many of these acoustic characteristics are generally reflected in the following vowel, largely due to laryngeal (vocal fold) tension (see Cho, Jun, & Ladefoged (2002) for a review and references therein), possibly linked with elevation of the respiratory force (Ladefoged & Maddieson, 1996) as evident by heightened subglottal pressure, which accompanies the more constricted glottis with stiff vocal folds (thus also termed "pressed") and tenser walls of the vocal tract (Dart, 1987). The lenis stop series /p,t,k/, on the other hand, are produced with none of those properties, showing a lower F0, gradual intensity build-up, more damped harmonics, and breathiness which are all attributable to lax vocal folds. Finally, while the aspirated stop series /pʰ,tʰ,kʰ/, as the term indicates, are characterized primarily by a substantial amount of aspiration (longer VOT), they share some properties with fortis stops, especially in a higher F0 in the following vowel, which may again be caused by the tension of the vocal folds.

Given the importance of laryngeal settings that are responsible for some of the phonetic properties of the Korean stops, a great number of phonetic and phonological studies on Korean stops have focused on the laryngeal properties of the stops (e.g., Dart, 1987; Halle & Stevens, 1971; Han & Weitzman, 1970; Hardcastle, 1973; Hirose, Lee, & Ushijima, 1974; Kagaya, 1974; Kim, 1970; Jun, Beckman, & Lee, 1998; Lombardi, 1991; *inter alia*). Although there have been many fewer studies available in the literature with respect to supralaryngeal characteristics of the Korean stops, some previous articulatory studies do suggest that there are some supralaryngeal articulatory reflexes of the three-way stop contrast. For example, it has been reported that articulatory closure duration is longer and the linguopalatal contact (between the tongue tip/blade and the palate for alveolar stops) is larger for fortis and aspirated denti-alveolar stops /t*,tʰ/ than for the lenis /t/ both in word- or phrase-initial position (Baik, 1997; Cho & Keating, 2001; Kim, 2004; Kim, Honda, & Maeda, 2005) and in word-medial position (Kim et al., 2005; Shin, 1997); and lip muscle activities are more pronounced for fortis and aspirated labial stops /p*,pʰ/ (Kim, 1965) than for the lenis /p/ in word-initial position. In an articulatory study examining the tongue body movement for velar stops in Korean, Brunner, Fuchs, Perrier, and Kim (2003) argued that closure duration in word-medial position is the most important articulatory parameter as it makes a clear three-way distinction with the fortis being longest, the aspirated being intermediate and the lenis being shortest (see also Brunner, Fuchs, & Perrier, 2011). Furthermore, in stroboscopic cine-MRI data, Kim et al. (2005) and Kim, Maeda, and Honda (2010) showed that fortis and aspirated stops in both word-initial and medial positions are produced with longer closure duration than lenis stops across the three places of articulation (bilabial, alveolar and velar) in line with previous studies. Most importantly, fortis and aspirated stops were found to be produced with tongue raising (for alveolars and velars) in coordination with larynx raising, showing the complex synergistic motor control associated with the fortis and aspirated stops.

These observations therefore suggest that Korean stops do differ at the level of supralaryngeal articulation, but our knowledge of their articulatory characteristics at the supralaryngeal level is still limited, especially in terms of their kinematic characteristics. Moreover, despite the fact that consonantal articulation often influences vocalic articulation (Löfqvist, 2006; Öhman, 1967; Recasens, 1984, 1987), studies of consonantal influence on vowels in Korean have also been limited to how the laryngeal settings of the three-way stop series influence the acoustic realization of the following vowel. The present study, therefore, aims to obtain a more comprehensive understanding of the supralaryngeal characteristics of the three-way contrastive stops in Korean by looking into not only consonantal articulation, but also its influence on adjacent vocalic articulation.

To achieve this goal, an articulatory experiment was carried out with a magnetometer (EMA, Electromagnetic Articulography) that directly and systematically observed articulatory kinematic characteristics of the three-way contrastive stops in Korean. In order to explore how the consonantal differences are further reflected in the vocalic articulation which spans the consonantal articulation, both the consonantal and the vocalic kinematic characteristics were examined concurrently in word-medial position. To this end, the present study explored production of VCV sequences where the test consonants were bilabial stop series /p*,pʰ,p/ and the adjacent vowels were /i/ and /a/. The present study will therefore not only fill the empirical gap in the literature on the supralaryngeal characteristics of Korean stops and their influence on neighboring vocalic gestures, but it will also balance out our knowledge of the typologically unusual Korean stops in both laryngeal and supralaryngeal articulatory dimensions. It should be noted, however, that since the present study investigates stops in (intervocalic) word-medial position, the results to be reported may not represent their articulatory characteristics in word-initial or phrase-initial positions. In what follows, specific research questions will be discussed in connection with this purpose.

1.1. Research questions

One of the most fundamental questions of the present study is how the three-way contrastive stops are kinematically expressed directly in the consonantal articulatory dimensions such as consonantal lip constriction and lip closing movement. This question entails another question as to whether supralaryngeal articulatory distinction of the stops can be expected as a result of differential articulatory tension between them. As has already been discussed, increased muscular tension in the vocal folds and the laryngeal walls has been observed with the fortis and aspirated stops, which makes them distinct from the lenis counterpart. Some studies have suggested that increased muscular tension may also be involved in supralaryngeal articulation of the fortis and aspirated stops. For example, in an electromyographic study, Kim (1965) showed increased lip muscle activities with /p*/ and /pʰ/ relative to /p/, which was used as one of the facts that supported the need of the feature [tense] in describing Korean stops. Another related study is Cho and Keating's (2001) electropalatographic (EPG) study which showed larger linguopalatal contact for /t*/ and /tʰ/ than for /t/. Kim et al. (2005, 2010) also showed that the tongue and larynx movements are coordinated in expressing the articulatory tension. These studies, taken together, suggest that tension is applied to the fortis and aspirated stops at both the laryngeal and supralaryngeal articulatory levels. This is indeed related with the notion of the feature [tense] for general tense phonemes including vowels and consonants discussed by Jakobson, Fant, and Halle (1952), and more specifically for English voiceless aspirated stops by Perkell (1969). They suggested that the articulatory tension associated with tense consonants is related to resisting increases in intraoral pressure, which is linked with greater tension of the relevant part of the tongue, and that such increased tension could be present throughout the entire vocal tract.

In the present study, we will further explore how the feature [tense] may be kinematically expressed by examining two articulatory dimensions: degree of lip constriction and lip closing movement kinematics. If the muscular tension extends to the lips for the fortis and aspirated stops, the lip tissues will be compressed more, resulting in greater degree of lip constriction between the upper and the lower lips. Furthermore, tension of the lips may be further observed kinematically in the lip closing (and possibly lip opening) movement characteristics, especially in the movement velocity. Given that movement peak velocity is positively related to the articulatory force or effort (Nelson, 1983; Perkell, Zandipour, Matthies, & Lane, 2002), and given that the articulatory tension may come from some kind of articulatory force, lips with greater muscular tension are likely to move faster than laxer lips, which would be reflected in the peak velocity of the lip closing gesture.

Lip closing kinematics can be considered further from a theoretical point of view in the framework of a mass–spring Task Dynamic model (e.g., Saltzman & Munhall, 1989), adopted by Articulatory Phonology (Browman & Goldstein, 1990, 1992; Goldstein, Byrd, & Saltzman, 2006). In the Task Dynamic gestural model, a linguistically significant vocal tract constriction, dubbed 'gesture,' is defined by dynamical parameters such as target, stiffness and activation duration, resulting in different kinematic (movement) characteristics, which lead to phonological or lexical contrasts (see Hawkins, 1992, for an overview for non-specialists). As the three-way Korean stops are phonologically contrastive, one can hypothesize that lip closing gestures for the Korean stops are specified with different settings of dynamical parameters, which results in a three-way distinction. In particular, the stiffness parameter in the model controls the speed of articulation, so that the higher the stiffness value, the faster the articulatory movement (see Cho (2006) for further discussion). If differential muscular tensions were involved in supralaryngeal articulation of the stops, they would be reflected in different stiffness values, resulting in different movement velocities for movements of the same magnitude.

Our next question is whether the consonantal differences are further reflected in vocalic articulation at the supralaryngeal level. Quite a few acoustic phonetic correlates of the three-way stop series have been observed in the acoustically defined vowel, with most of them related to differential laryngeal settings for different stops. As introduced earlier, some studies have shown that vowels contain substantial information about the preceding consonant type, so that listeners are able to make distinctions even in the absence of the closure and the release burst noise (Cho, 1996; Kim, Beddor, & Horrocks, 2002). Although acoustic differences arising with F0, amplitude rising time, and H1–H2 (indicative of creakiness versus breathiness) have been known to be primary laryngeal cues present in the vowel, one cannot entirely refute that the acoustic signal of the vowel contains the supralaryngeal articulatory information of the stops, from which listeners would have benefited in the perceptual experiments. Given that the effects of consonants on the vowel are inevitable consequences of the temporal coexistence (overlap) between consonantal and vocalic gestures, an important question here is whether the vocalic gestures are influenced by the three-way stop distinction—i.e., whether articulatory tension associated with tense consonants would influence articulation that is involved not only in producing consonantal gestures, but also in producing vocalic gestures.

The hypothesized influence of the consonantal articulation on the vocalic articulation is more likely to be observed if consonantal and vocalic gestures share articulators, so that the vocalic movement is often modified as the articulatory configuration for the consonant changes. For example, in his numerical model of coarticulation, Öhman (1967) discussed the consonant–vowel dependency based on the degree to which the tongue body is involved in both the consonantal and vocalic articulations—i.e., the dependency was greater for the velar consonant (which involves the tongue body as its primary articulator) but smaller for the apical consonant (which involve the tongue tip as its primary articulator). Given the assumption that the lip closing gesture for a labial stop is independent from the tongue body gesture for the vowel (e.g., Fowler & Saltzman, 1993), one can predict that labial consonant and lingual vowels may be coproduced independently, showing a superposition of the consonant on the vowel as discussed by Öhman (1967). This CV independence is also predictable, at least in theory, in the framework of Articulatory Phonology in which the lip aperture gesture and the tongue body gesture occur independently on separate articulatory tiers at the gestural level. Browman and Goldstein (1990) state "[t]he gestures…are organized into articulatory tiers, where the tiers are defined using the notion of articulatory independence" (p. 346). However, the lip aperture gesture and the tongue body gesture are not expected to be entirely independent at the articulatory level, because both gestures are articulatorily implemented with a shared articulator, the jaw: Lip opening and closing movements are influenced by the movement of the jaw, which also mediates the tongue (vocalic) movement due to the jaw–tongue mechanical linkage (e.g., Fletcher & Harrington, 1999). It is thus expected that even bilabial consonantal articulation would influence vocalic articulation at least to some degree. The present study thus examines the consonantal–vocalic interaction at the articulatory level in order to understand the extent to which consonantal characteristics in Korean are to be reflected in the vocalic articulation.

It should be noted, however, that the release movement may be characteristic of the consonantal articulation (Browman, 1994; Nam, 2007a, 2007b), so that the lip opening movement may not be entirely attributable to the vocalic gesture, but it may also reflect, at least partially, consonantal characteristics. This means that the lip opening movement is likely conditioned not only by the tongue body movement into the vowel, but also by the release movement out of the consonant. This would certainly call for a caution when interpreting the lip opening data in the present study as the two effects appear to be hard to tease apart. We nevertheless believe that much of the lip opening movement is controlled by the jaw–tongue mechanical linkage for the following vocalic gesture.

In connection with the consonant–vowel dependency question, we continue to explore potential effects of the three-way stop contrast on the vocalic articulation, by asking whether the consonantal effect is reflected in vowel-to-vowel coarticulation. If the vocalic movement kinematics turn out to be influenced by the consonant type, the consonantal effect would also be likely to be reflected in V-to-V coarticulation. Previous studies have often discussed degree of V-to-V coarticulation in terms of the articulatory constraints of the intervening lingual consonants (see Recasens, 1999, for a comprehensive review on this point). In an acoustic study of V-to-V coarticulation in Korean, Shin (1997) showed that the three-way contrast among denti-alveolar stops (/t*,t^h,t/) as indeed reflected in degree of V-to-V coarticulation, so that the fortis /t*/ and the aspirated /t^h/ induced lesser degree of V-to-V coarticulation than the lenis /t/. Shin attributed the observed pattern to the differential degree of linguopalatal contact for different stops—i.e., the more linguopalatal contact associated with /t*/ and /t^h/ induced lesser degree of V-to-V coarticulation, which is in line with Recasens (1984, 1987) who showed a positive relationship between the coarticulatory resistance and the amount of tongue dorsum contact involved in the articulation of the intervening consonant. The present study, however, departs from Shin (1997)'s study in two important aspects. First, it examines the effect of bilabial consonants on V-to-V coarticulation where consonantal articulation is minimally restrictive of the vocalic articulation. Second, it directly observes the V-to-V coarticulatory pattern from the articulatory movement trajectories to investigate the actual articulatory patterns. The present study will therefore allow us to test whether the consonant type still influences V-to-V coarticulation even when the primary articulators of the intervening consonant are lips that are known to be minimally restrictive of the vocalic articulation. It will also consider whether the hypothesized consonantal effects on V-to-V coarticulation can simply be accounted for by the temporal distance between vowels that may vary with the consonant type or whether the vocalic lingual movement itself is modified in accordance with intervening consonantal strength.

Another question that the present study aims to answer is whether the hypothesized modification of the vocalic articulation as a function of consonant type would affect the coordination relationship between the consonantal and vocalic gestures. Löfqvist (2006) showed that in Japanese the tongue body movement for the vowel is modified according to consonantal closure duration (short for monomoraic /m/ and long for bimoraic /mm/), so that the timing relationships between the tongue movement onset and the lip constriction onset, and between the tongue movement offset and the lip constriction offset are maintained, regardless of the durational difference of the consonants. Similar patterns were observed in American English as well (Löfqvist & Gracco, 1999). As pointed out by Löfqvist (2006), the results in Japanese and English, which are typologically different in their rhythmic structures (mora-timed versus stress-timed), alluded to the cross-linguistic similarities in the consonant–vowel coordination regardless of the rhythmic structure of the language. The rhythmic typology of Korean is controversial as to whether it is syllable-timed, stress-timed or mora-timed (e.g., M. Cho, 2004; Mok & Lee, 2008; Seong, 1995). A relatively recent acoustic study (Mok & Lee, 2008) suggests that while Korean shows a mixed pattern of syllable-timing and stress-timing (in line with Seong, 1995), it is more on the syllable-timing side. Regardless of whether it is strictly syllable-timed or not, the rhythmic structure of Korean appears to be different from that of Japanese or English, allowing us to test the generalizability of the consonant–vowel coordinative relationships in the present study.

Finally, the results of the present study, taken as a whole, will give us an opportunity to consider how the stops in Korean that have been traditionally defined in terms of their laryngeal settings can be re-defined, taking into account their supralaryngeal articulatory characteristics. In particular, we will contemplate the phonetic nature of the 'fortis' and 'lenis' stops which make the Korean consonantal system unique from other languages, and discuss its broader implications for general theories of phonetic description.

2. Method

The kinematic aspects of consonantal and vocalic articulations associated with the three-way contrastive bilabial stops /p*,p^h,p/ (fortis, aspirated, and lenis, respectively) in Korean were examined in VCV contexts, using Electromagnetic Articulography (EMA, Carstens Articulograph AG200).

2.1. Participants

Seven native speakers of Seoul Korean (four female and three male students at Hanyang University, Seoul) in their early or mid 20s participated in the EMA experiment. They were naïve as to the purpose of the experiment and were paid for their participation.

2.2. Speech materials

In the speech materials developed for the present study, bilabial stops /p*,p^h,p/ were selected as test consonants, so that the characteristics of their consonantal lip movement could be observed with minimal interference from the lingual movement of the surrounding vowels, and at the same time the characteristics of the vocalic articulation itself could be observed with minimal influence from the consonantal gesture. The test stops were examined in two different contexts. The first context was a homorganic V1CV2 as in /iCi/ and /aCa/, so that the lip closing and opening movement characteristics could be examined without undue effects that might come from complex tongue movements when heterorganic vowels were included. The second context was a heterorganic V1CV2 context as in /aCi/ and /iCa/, which was used to examine effects of the intervening stops on kinematic characteristics of the tongue raising and lowering movements (/a/-to-/i/ versus /i/-to-/a/), and on degree of V-to-V coarticulation.

2.3. Procedures

The EMA experiment was conducted at the Hanyang Phonetics and Psycholinguistics Lab (HPPL) at Hanyang University in Seoul. Both articulatory and acoustic data were recorded simultaneously in the speech production booth. Acoustic data were recorded with a condenser headset microphone (Shure WH-30) at a sampling rate of 44 kHz. The kinematic data of the lips and the tongue body movement were acquired using an EMA (Carstens Articulograph AG200), a magnetometer system of a three-transmitter assembly built in a plastic helmet (as can be seen in the left panel of Fig. 1). As shown in the right panel of Fig. 1, eight sensors (transducers) were used in the experiment. Three sensors were attached on the tongue (i.e., the tongue dorsum (a), the tongue midsection (b), and the tongue tip (c)); two sensors were on the maxillary and mandibular central incisors (i.e., upper and lower jaws, d–e); two sensors on the upper and lower lips each at the vermilion borders (f–g); and finally one sensor on the nose bridge (h). (Note that the locations of the sensors on the tongue body differed slightly from speaker to speaker for anatomical reasons, but the tongue dorsum sensor (a) was placed on the rearmost point which was about 4.1–5.8 cm from the tongue tip when the subject's tongue was pulled out.) The two sensors on the nose ridge (h) and on the maxillary central incisors (d) were used as reference points with which to correct for the head movement inside the helmet.

The kinematic raw data were sampled at 200 Hz, low-pass filtered at a cut-off frequency of 20Hz, and corrected for unwanted head movements. With the obtained data, a Cartesian coordinate system was created by rotating the data. For this, a flat plastic bite plate was used with two extra sensors attached to it, so that the maxillary occlusal plane obtained by the two coordinate points on the bite plate became the horizontal (x) axis of the data, and the y axis became perpendicular to the occlusal plane (see Cho (2005), de Jong (1995), Tabain (2003) and Westbury (1994) for similar data processing procedures). All the filtering and rotation processes were performed by the TAILOR program (Carstens' data processing program). It should be noted that tongue and lip movement signals obtained in such a Cartesian coordinate system contain the contribution of the jaw—i.e., the lips are in general closed or opened by joint activity of the jaw and the lips, and the tongue is mechanically linked to the jaw, so that, for example, the tongue movement is at least partly coupled with the jaw rotation (see Fletcher & Harrington (1999), for a review). In the present study, however, the contribution of the

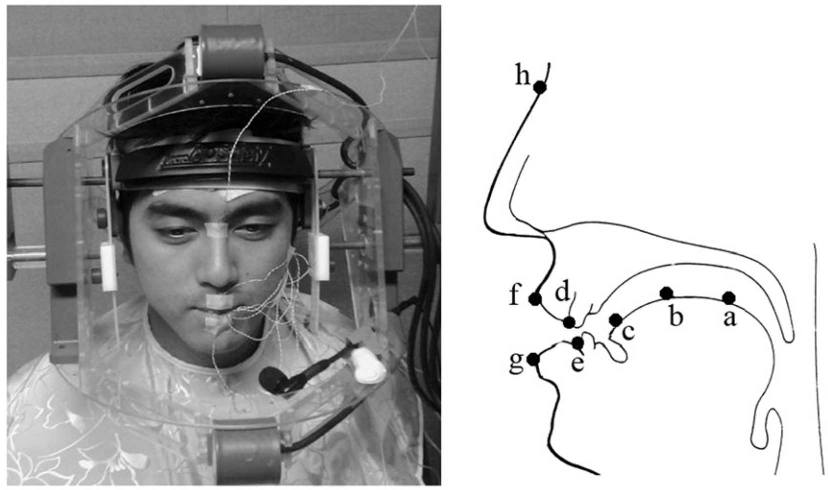

Fig. 1. The experimental setting of the EMA system and locations of sensors: (a) the tongue dorsum; (b) the tongue midsection; (c) the tongue tip; (d–e) the maxillary (upper) and mandibular (lower) central incisors; (f–g) the upper and lower lips; and (h) the nose bridge.

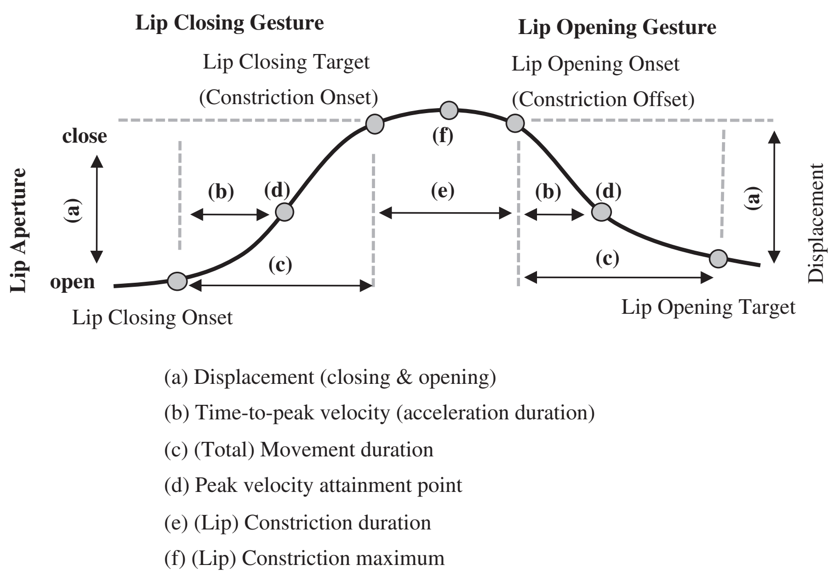

Fig. 2. Schematized lip closing and opening movement trajectories with an indication of the measured kinematic variables.

jaw was not factored out from the lip and the tongue movement signals, following Löfqvist (2000, 2006) and Löfqvist and Gracco (1997, 1999) and many others (e.g., Byrd, 2000; Byrd & Saltzman, 1998; Cho, 2006, 2008; Tabain, 2003; Tabain & Perrier, 2005). An important assumption underlying this methodological convention is that speakers have joint motor control of multiple articulators during speech production for achieving the desired speech outputs (see Löfqvist & Gracco (1997), for concepts of motor control; Perkell (1997), for related discussion; and Saltzman & Munhall (1989), for a gestural account based on the Task Dynamic model). We are therefore interested in examining movements of the lips and the tongue as "end effectors" in the synergistic motor control system (Löfqvist, 2006). Independently, we did not correct for the jaw contribution in obtaining the lip and tongue movement data, so that the obtained results could be easily compared with results of Löfqvist (2006) and Löfqvist and Gracco (1999) for testing the generalizability of the invariant consonant–vowel coordination.

In the experiment, all the stimuli were presented on the computer screen in random order with four repetitions for six speakers but with three repetitions for one speaker due to a technical error near the end of the recording session for this speaker. The VCV tokens were all produced in isolation. All speakers were instructed to read the target syllables on the computer screen as comfortably and naturally possible. The resulting number of tokens were 324 (3 stops $\times$ 2 vocalic contexts (/a,i/) $\times$ 4 (3 for one speaker) repetitions $\times$ 7 speakers $\times$ 2 sets (homorganic VCV and heterorganic VCV).

2.4. Measurements

2.4.1. Measurements for homorganic V1CV2 data (V1 = V2)

Lip aperture measures: The lip opening and closing movement data were obtained by combining horizontal and vertical position signals for the upper and the lower lip sensors into one dimension—i.e., Lip Aperture (Byrd, 2000; Byrd & Saltzman, 1998; Cho, 2006, 2008). The Euclidean distance between the two lip sensors was used as an index of Lip Aperture. As shown in Fig. 2, there are two movement events associated with Lip Aperture—i.e., lip closing and opening movements. Kinematic measures for each lip opening and closing movement shown in Fig. 2 were as follows:

- *Displacements (closing and opening) (mm)*: The spatial difference between the onset and the target of the lip closing and opening movements (Fig. 2a)
- *Time-to-peak velocity (acceleration duration) (ms)*: The temporal interval from the movement onset to the timepoint of peak velocity of the movement (Fig. 2b)
- *(Total) Movement duration (ms)*: The temporal interval from the onset to the target of the movement (Fig. 2c)
- *Peak velocity (cm/s)*: The actual peak velocity value for the movement (Fig. 2d)
- *Constriction duration*: The interval between the closing target attainment point (left edge) and the opening onset point (right edge) (Fig. 2e)
- *Lip constriction maximum:* The lip constriction maximum during the constriction duration (Fig. 2f)

The spatial measures which were consonantal were the lip closing displacement and lip constriction degree measures (as measured by the lip aperture values). Lip constriction degree values (as the lip aperture values) were taken at both edges of lip constriction as well as the lip constriction maximum point during the constriction duration. The temporal measures for the consonantal gesture were the lip closing movement duration, time-to-peak velocity (acceleration duration), and the constriction duration. Time-to-peak velocity was included as an additional durational measure, the variation of which could be indicative of the variation of stiffness. Stiffness is a dynamical parameter which is expected to influence time-to-peak velocity and peak velocity (the higher the stiffness value, the shorter time-to-peak velocity and the higher the peak velocity), but without a change in displacement (see Cho (2006), for a review). The lip closing peak velocity was to see whether the consonantal constriction formation would be different in movement speed as a function of three-way stop contrast.

The kinematic measures for the lip opening movement were all associated with the following vocalic gesture, which were examined to see whether the kinematics of the lip opening vocalic gesture would characterize different types of stops.

2.4.2. Measurements for heterorganic (asymmetrical) V1CV2 data (V1 ≠ V2)

Kinematic measures. The tongue movement data for h eterorganic VCV sequences were obtained to examine whether the kinematics of the transconsonantal tongue body movement would be affected by the type of consonant that is assumed to be superimposed on the vocalic lingual articulation. The tongue movement data were obtained from the sensor attached on the tongue dorsum (Fig. 1a) in both the vertical (y) and the horizontal (x) dimensions, but because of the complex tongue movement patterns, we followed Byrd (2000) and Cho (2008) to include only upward (raising) and downward (lowering) tongue movement data in the y axis. Kinematic measures for the tongue movement (/a/-to-/i/ and /i/-to-/a/) were similar to the lip movement measures, as schematized in the lower panel of Fig. 3, including displacement, movement duration, time-to-peak velocity (acceleration duration), and peak velocity.

Intergestural timing measures. In order to examine whether the intergestural timing between the consonantal gesture and the vocalic gesture would vary as a function of consonant type, three specific timing intervals were measured following Löfqvist (2006):

- *Tongue movement onset relative to lip closing onset (*Fig. 3*a)*
- *Tongue movement onset relative to lip constriction onset (*Fig. 3*b)*

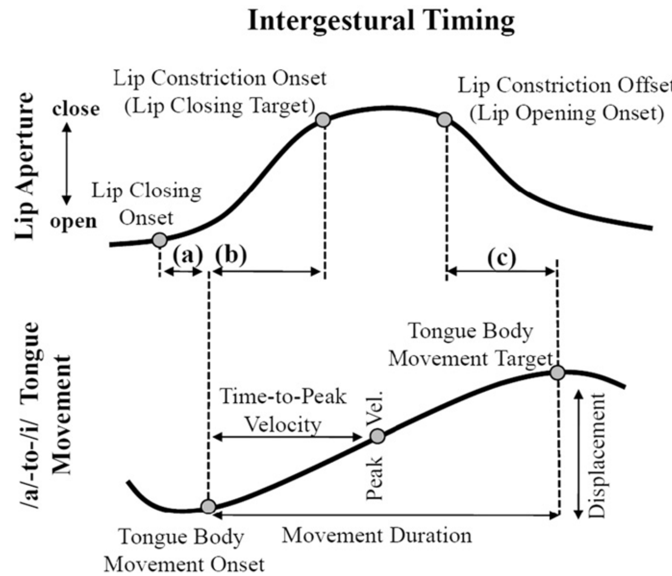

Fig. 3. Schematized intergestural timing measures between consonantal and vocalic gestures: (a) the tongue movement onset relative to the lip closing onset; (b) the tongue movement onset relative to the lip constriction onset (left edge); and (c) the tongue movement offset (target) relative to the lip constriction offset (right edge).

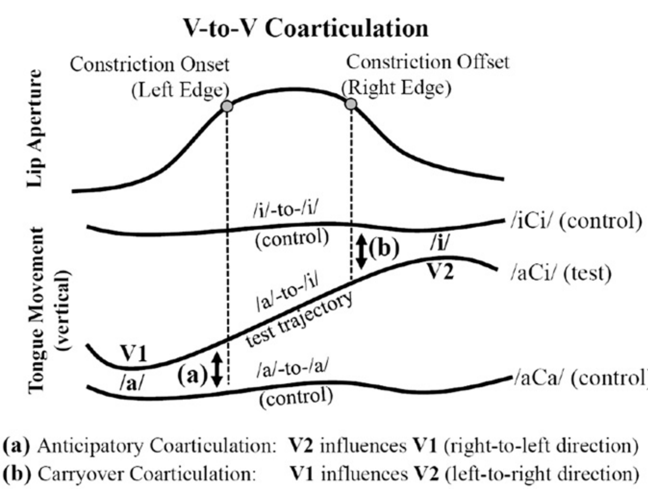

Fig. 4. Schematized V-to-V coarticulatory measures: The spatial distances between the test condition (V1 ≠ V2) and the control condition (V1 = V2) measured at (a) the left edge of lip constriction (anticipatory coarticulation) and (b) the right edge of lip constriction (carryover coarticulation).

- *Tongue movement offset (target) relative to lip constriction offset (release) (*Fig. 3*c)*

V-to-V coarticulation measures. The degree of V-to-V coarticulation as a function of intervening consonant type was examined in the vertical tongue movement dimension in both anticipatory and carryover directions for /aCi/ and /iCa/. The degree of anticipatory coarticulation means how much the influence of the following vowel (encroaching vowel) can be anticipated in the production of the target vowel (encroached vowel) before the consonant. As schematized in Fig. 4a, it was measured at the left edge of lip constriction defined as the spatial distance between V1 in the test condition (V1 ≠ V2) and V1 in the control condition (V1 = V2). (The left edge measurement point is comparable to the generally used acoustic measurement point near the end of V1.) Similarly, the degree of carryover coarticulation means how much articulatory characteristics of V1 (encroaching vowel) is carried over into the following target vowel (encroached vowel), which was measured at the right edge of lip constriction, again defined as the spatial distance between V2 in the test condition and V2 in the control condition (Fig. 4b). The measured coarticulatory variables were:

- *anticipatory coarticulation of* /i/ *and* /a/ (measured at the left edge of the consonant): for /a/ (Fig. 4a), the spatial distance at the left edge of lip constriction between two /a/s in the /aCi/ test trajectory versus the /aCa/ control trajectory, indicative of how much /a/ in /aCi/ is influenced (encroached) by the following vowel /i/ in comparison with the first /a/ in the /aCa/ control condition; for /i/ (figure not shown), similar to /a/ except for the difference in the test vowel sequence.
- *carryover coarticulation of* /i/ *and* /a/ (measured at the right edge of the consonant): for /i/ (Fig. 4b), the spatial distance at the right edge of lip constriction between two /i/s in the /aCi/ test trajectory versus the /iCi/ control trajectory, indicative of how much /i/ in /aCi/ is influenced by the preceding /a/ in comparison with the second /i/ in the /iCi/ control condition; for /a/ (figure not shown), similar to carryover articulation in /i/ except for the difference in the test vowel sequence.

2.4.3. Measurement tool and marking kinematic landmarks

The kinematic landmarks for lip and tongue movement gestures such as the onset, the peak velocity point, and the target of the movement were identified by using MVIEW, a matlab-based program developed at Haskins Laboratories (Tiede, 2005). The onset points were defined algorithmically as a point in time at which the movement velocity reached 20% of the peak velocity after the zero-crossing point in the velocity profile, and similarly as a mirror image the target points were defined when the velocity value reached 20% of the peak velocity before the zero-crossing point in the velocity profile.

2.5. Statistical analysis

In evaluating the effects of the factors such as Consonant type and Vowel context on various kinematic and timing measures, repeated measures ANOVAs (RM ANOVAs) were run using SPSS version 17. In RM ANOVAs, the individual means of the seven subjects per each condition were used as the units of analyses (see Max & Onghena, 1999). The within-subject factors were Consonant type (fortis, aspirated, lenis), Vowel context (/iCi/, /aCa/), and Vowel type (/a/-to-/i/ and /i/-to-/a/). Note that the homorganic vowel context factor was used in examining how the lip opening and closing movements vary as a function of Consonant type; and the heterorganic vowel type factor (/a/-to-/i/, /i/-to-/a/) was employed in examining the consonantal effect on the tongue body movement and V-to-V coarticulation. In order to avoid violating the sphericity assumption, which is likely to occur when a factor has more than two levels like the Consonant type factor in the present study, Huynh-Feldt corrected degrees of freedom were used in generating F ratio and p values (Huynh & Feldt, 1970). As a result, degrees of freedom and error terms in integer were often reduced to fractional values, as reported in the present study (e.g., $F[2, 10] \rightarrow F[1.6, 9.6]$). Posthoc pairwise comparisons were conducted, whenever it was necessary to determine the difference between levels within a factor at the significance level of $p<0.05$. In some cases, Pearson product-moment correlation and linear regression analyses were conducted in order to examine relationship between two dependent variables, for example, between constriction duration of the consonant and the tongue movement duration or between constriction duration and the degree of V-to-V coarticulation. Finally, to examine whether the variation in constriction duration would affect the degree of constriction and V-to-V coarticulation, the Analysis of Covariance (ANCOVA) was employed with the constriction duration factor as a covariate (regressor).

3. Results

3.1. Lip constriction degree and duration in homorganic VCV context

Lip constriction degrees measured at the three articulatory points, the constriction onset (left edge), the constriction maximum point, the constriction offset (right edge), all showed significant effects of Consonant type ($F[1.4, 8.6]=13.4$; $F[1.3, 7.8]=25.12$; $F[1.4, 8.6]=17.82$, respectively, all at $p<0.005$). As shown in Fig. 5a, at both edges of the lip constriction, there were two-way distinct patterns with the fortis and aspirated stops being more constricted than the lenis stop ($/p^*/=/p^h/)>/p/$ (posthoc pairwise comparisons, $p<0.05$) (the smaller Lip Aperture values, the greater the constriction degree), but at the point of the constriction maximum the pattern became three-way: $/p^*/>/p^h/>/p/$ ($p<0.05$). Constriction duration also revealed a significant consonant effect ($F[1.2, 7.4]=54.63$, $p<0.0001$), with a three-way distinct pattern of $/p^*/>/p^h/>/p/$ (Fig. 5b), in line with a three-way constriction degree at the constriction maximum. As shown in Fig. 5c, results of regression analyses revealed a close relationship between constriction degree and constriction duration ($R^2=0.2$, $F[1, 158]=39.05$, $p<0.0001$)—i.e., the longer the constriction duration, the greater the constriction degree (the smaller the Lip Aperture value). This relationship was further confirmed by results of one-way ANCOVA—i.e., there was a significant main effect of the covariate factor, Constriction duration ($F[1, 158]=6.47$, $p<0.01$) on constriction degree at the constriction maximum, and the effect of Consonant type became insignificant when Constriction duration was factored in ($F[2, 158]=1.36$, $p>0.1$).

As for Vowel context (/iCi/ versus /aCa/) effects, results showed that constriction degree and duration were not influenced by the flanking vowel context. There was no significant effect either on the constriction degree at any of the three measurement points (constriction onset, $F[1, 6]=0.1$; constriction maximum, $F[1, 6]=2.86$; constriction offset $F[1, 6]=0.15$, all at $p>0.1$) or on the constriction duration ($F[1, 6]=4.69$, $p=0.074$), nor was there a Vowel context by Consonant type interaction.

3.2. Lip closing (consonantal) kinematics in VCV (/iCi, aCa/)

Lip closing kinematic measures did not show robust consonant-induced variation. In the spatial dimension (Fig. 6a), there was a significant effect of Consonant type on displacement ($F[1.8, 10.9]=4.39$, $p<0.05$), showing that the magnitude of displacement was significantly greater for the aspirated stop than for the lenis stop ($/p^h/>/p/$, at $p<0.05$), while there was no significant difference between the fortis and the other two. In the temporal dimension (Fig. 6b), there was no main effect of Consonant type on either movement duration or acceleration duration (time-to-peak velocity) ($F[1.3, 8]=0.75$; $F[1.2, 7.4]=1.49$, respectively, at $p>0.1$). Consonant type did not influence peak velocity ($F[1.7, 10]<1$), either (Fig. 6c). Overall, movement duration and peak velocity remained consonant, while the fortis and aspirated $/p^*,p^h/$ tended to have larger displacement than the lenis /p/.

Vowel context generated significant effects on lip closing displacement and peak velocity. There was a significant effect on lip closing displacement ($F[1, 6]=49.07$, $p<0.005$) (Fig. 6d), with a greater displacement when the flanking vowels were /a/s

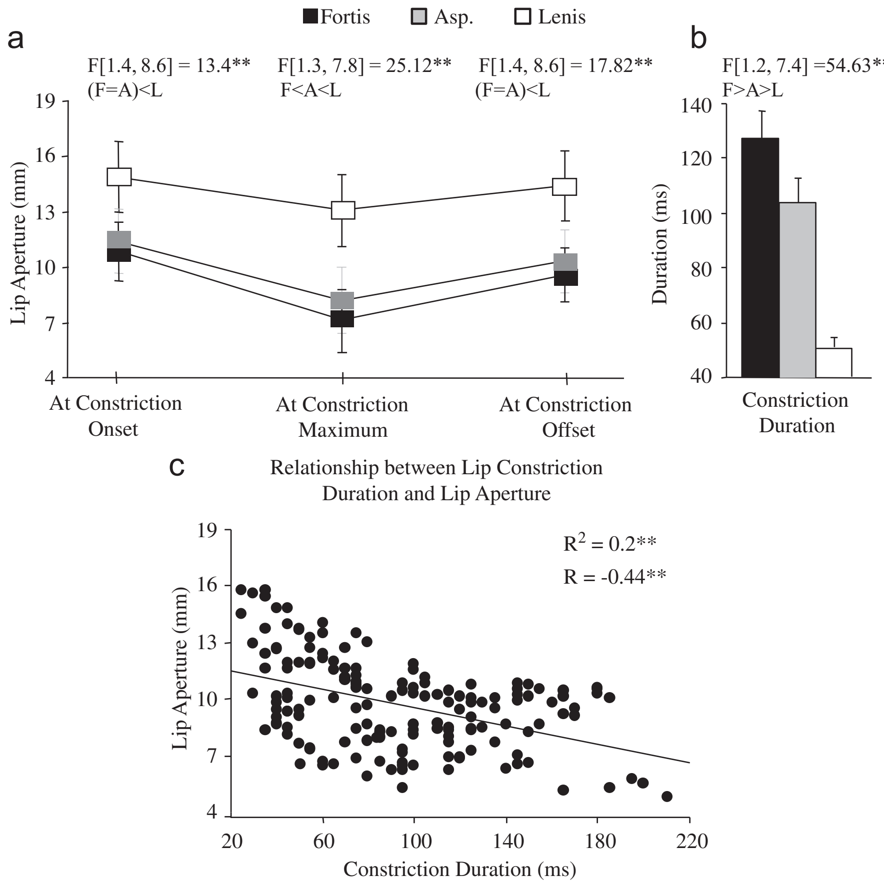

Fig. 5. Effects of Consonant type on (a) constriction degree, (b) duration, and (c) their relationship. '*' refers to a significance level at $p<0.05$ and '**' at $p<0.005$. Results of pair-wise posthoc comparisons are indicated with '<' or '>' when the difference between levels was significant at $p<0.05$, and with '=' when non-significant.

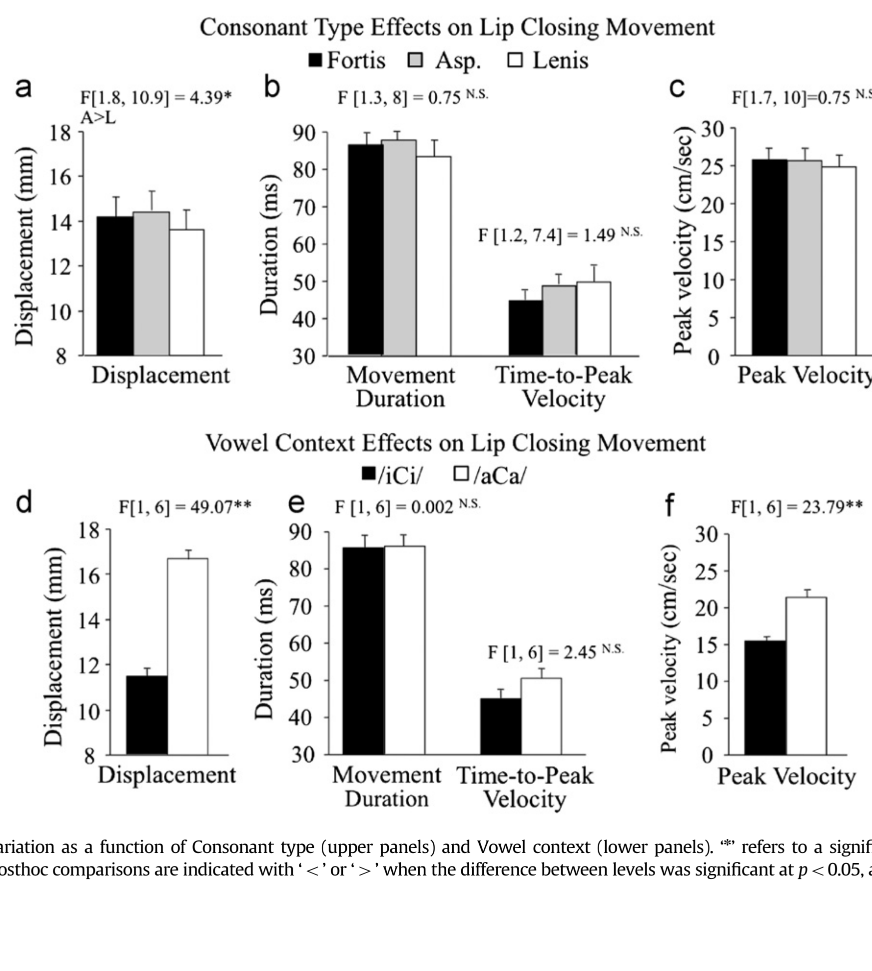

Fig. 6. Lip closing kinematic variation as a function of Consonant type (upper panels) and Vowel context (lower panels). '*' refers to a significance level at $p<0.05$ and '**' at $p<0.005$. Results of pair-wise posthoc comparisons are indicated with '<' or '>' when the difference between levels was significant at $p<0.05$, and with '=' when non-significant.

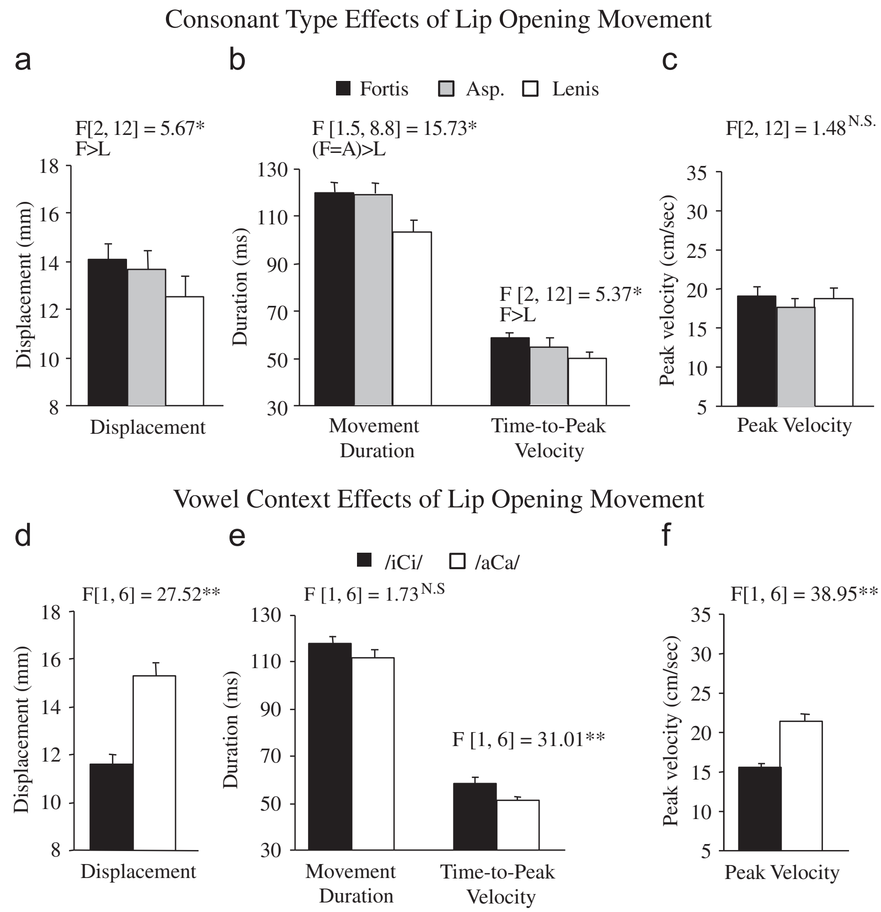

Fig. 7. Lip opening (vocalic) kinematic variation as a function of Consonant type (upper panels) and Vowel context (lower panels). '*' refers to a significance level at $p<0.05$ and '**' at $p<0.005$. Results of pair-wise posthoc comparisons are indicated with '<' or '>' when the difference between levels was significant at $p<0.05$, and with '=' when non-significant.

versus /i/s. (/aCa/ > /iCi/). As shown in Fig. 6f, peak velocity was also significantly affected by Vowel context ($F[1,\ 6]=23.79$, $p<0.005$) with higher peak velocity in /aCa/ than in /iCi/. That is, the larger lip closing displacement in /aCa/ accompanied an increase in movement speed. As shown in Fig. 6e, however, Vowel context, did not give rise to significant effects on movement duration of lip closing ($F[1,\ 6]<1$) and acceleration duration ($F[1,\ 6]=2.45$, $p>0.1$). No measures showed significant interactions between Consonant type and Vowel context.

3.3. Lip opening (vocalic) kinematics in VCV (/iCi, aCa/)

Consonant type induced significant effects on the lip opening (vocalic) kinematics in both spatial and temporal dimensions. Lip opening displacement was significantly affected by Consonant type ($F[2,\ 12]=5.67$, $p<0.05$), with a greater displacement for the fortis /p*/ than for the lenis /p/ (/p*/ > /p/) (Fig. 7a). The durational measures, movement duration and time-to-peak velocity, showed significant main effects ($F[1.5,\ 8.8]=15.73$; $F[2,\ 12]=5.37$, respectively, at $p<0.05$). As shown in Fig. 7b, movement duration was longer for the fortis /p*/ than for the aspirated and lenis counterparts (/p*/ > (/p^h/ = /p/)), and time-to-peak velocity was also longer for the fortis /p*/ than the lenis /p/ (/p*/ > /p/), while the difference between /p^h/ and the other two was not significant. Movement duration, however, showed a significant Consonant type x Vowel context interaction, which stemmed from slightly different consonant-induced durational patterns between /iCi/ and /aCa/ contexts—i.e., (/p*/ = /p^h/) > /p/ in /iCi/ context versus /p*/ > /p/ in /aCa/ context. Peak velocity did not show a significant main effect of Consonant type (Fig. 7c)—i.e., the spatiotemporal variation as a function of Consonant type did not induce variation in lip opening movement speed.

As for the effects of Vowel context, the /aCa/ context yielded significantly greater lip opening displacement and higher peak velocity compared to /iCi/ context (main effects, $F[1,\ 6]=27.52$ and $F[1,\ 6]=38.95$, respectively, at $p<0.005$) (Fig. 7d–f). Vowel context, however, did not influence movement duration ($F[1,\ 6]=1.73$, $p>0.1$), despite the fact that /aCa/ was associated with larger and faster lip opening movement. Time-to-peak velocity showed a significant effect of Vowel context ($F[1,\ 6]=31.01$, $p<0.005$), but as shown in Fig. 7e, it did not pattern with displacement and peak velocity—i.e., time-to-peak velocity was shorter in /aCa/ than in /iCi/, even though lip opening movement was larger and faster in /aCa/.[1]

[1] We do not have an explanation for why time-to-peak velocity (acceleration duration) of the lip opening movement was shorter for /aCa/ than for /iCi/ when the movement was larger and faster for /aCa/ than for /iCi/. But the fact that there was no increase in the overall movement duration for /aCa/ (versus /iCi/) may be interpreted in dynamical terms as indicating that the observed vowel context effect on the lip opening movement is modulated by a change in target (amplitude) without a change in stiffness—i.e., an increase in the target value alone induces an increase in both displacement and peak velocity, but not in duration (see Beckman, Edwards, & Fletcher (1992) and Cho (2006) for discussion on kinematic manifestations of different dynamical parameter settings). We do not, however, elaborate on this point further in the discussion section to stick to the main research questions of the study.

3.4. Transconsonantal V-to-V tongue movement kinematics in the vertical dimension

The tongue body movement (/a/-to-/i/ and /i/-to-/a/) kinematics showed robust consonantal effects on the vocalic articulation, especially in movement duration and peak velocity, while the movement displacement was not affected by the intervening consonant type. The basic pattern was a longer and slower tongue body (vocalic) movement for a stronger consonant. As shown in Fig. 8a–c, Consonant type generated a significant main effect on V-to-V movement duration ($F[1.9, 11.2]=12.97$, $p<0.005$), showing a three-way distinct pattern of /p*/ > /p^h/ > /p/, and peak velocity yielded a two-way distinct pattern of (/p*/=/p^h/) < /p/. Consonant type, however, did not show a significant effect on displacement ($F[2, 12]=2.64$, $p>0.1$), showing no spatial modification of the vocalic movement as a function of the intervening consonant type.

As for the effects of Vowel type (/a/-to-/i/ versus /i/-to-/a/), all three kinds of kinematic measures, displacement, movement duration and peak velocity revealed significant effects as shown in Fig. 8d–f. /i/-to-/a/ tongue movement, compared to /a/-to/i/ tongue movement, was larger in displacement (main effect, $F[1, 6]=23.06$, $p<0.005$), higher in peak velocity (main effect, $F[1, 6]=9.15$, $p<0.05$), and longer in movement duration (trend, $F[1, 6]=4.94$, $p=0.07$) and time-to-peak velocity ($F[1, 6]=7.96$, $p<0.05$). That is, asymmetric kinematic patterns were found between the upward (/a/-to-/i/) and the downward (/i/-to-/a/) tongue movements, with the downward /i/-to-/a/ movement being larger, longer and faster than the upward /a/-to-/i/ movement. But crucially, there was no interaction between Consonant and Vowel types on any of the kinematic measures, showing that the consonantal effects on the vocalic tongue movement were consistent regardless of Vowel type.

3.5. Relationship between lip constriction duration and tongue movement duration

In conjunction with V-to-V tongue movement data in the heterorganic vowel context (V1 ≠ V2), lip constriction duration was measured once more in the heterorganic vowel context in order to examine the relationship between variations of lip constriction duration and tongue movement duration in the same vocalic context. The results confirmed the three-way distinction of /p*/ > /p^h/ > /p/ in lip constriction duration ($F[1.5, 8.7]=66.12$, $p<0.005$), as was the case in the homorganic vocalic context (V1 = V2) reported in Section 3.1. Fig. 9 showed comparisons of lip constriction duration and vocalic tongue movement duration (Fig. 9a) and the regression plot between them. Regression analyses with lip constriction duration (as a regressor) against tongue movement duration revealed a close relationship between the two variables ($R^2=0.42$, $F[1, 161]=117.9$, $p<0.0001$), suggesting that a significant amount of variation in the tongue

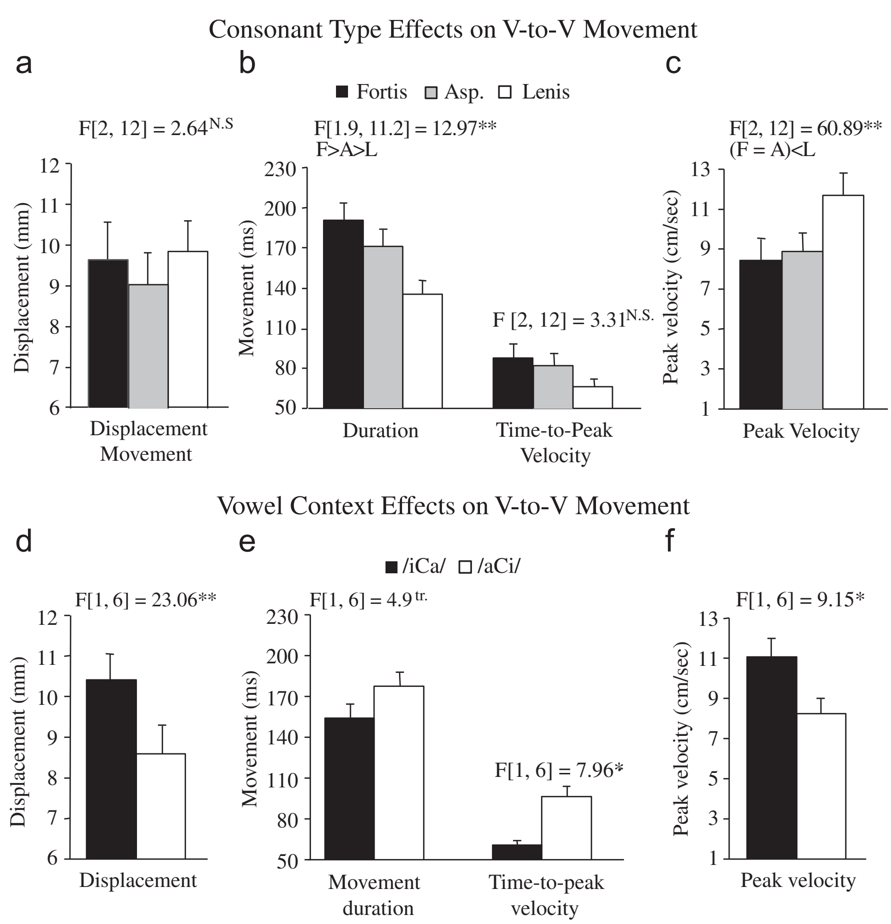

Fig. 8. Kinematic variation of the vertical tongue body movement as a function of Consonant type (upper panels) and Vowel context (lower panels). '*' refers to a significance level at $p<0.05$ and '**' at $p<0.005$. Results of pair-wise posthoc comparisons are indicated with '<' or '>' when the difference between levels was significant at $p<0.05$, and with '=' when non-significant.

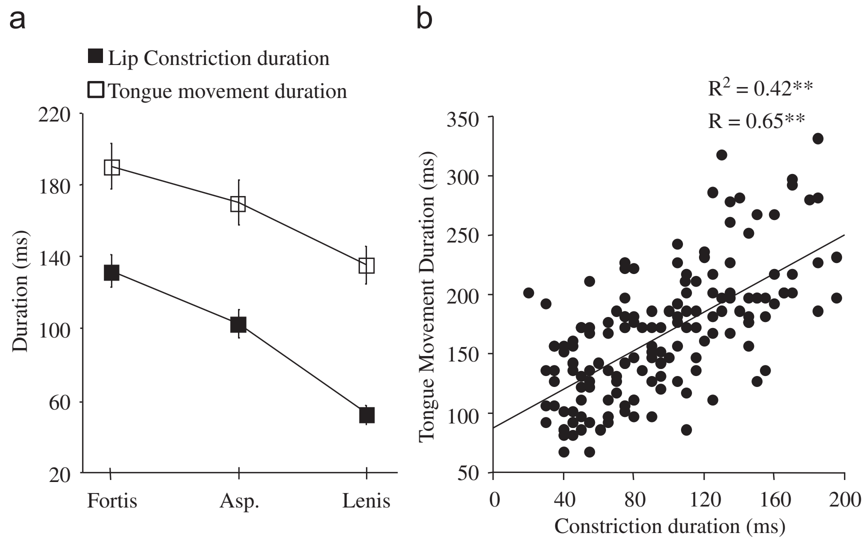

Fig. 9. Comparisons of the lip constriction duration and the tongue body movement duration (a), and their relationship (b).

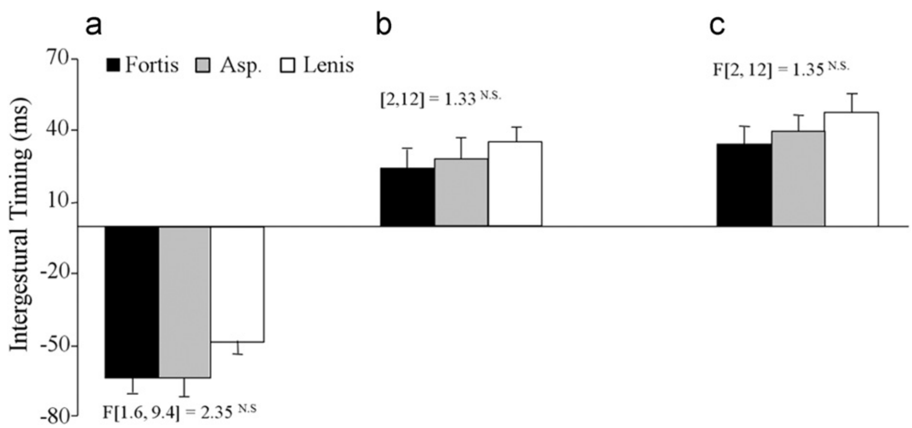

Fig. 10. Consonantal–vocalic intergestural timings: (a) the tongue movement onset relative to the lip closing onset; (b) the tongue movement onset relative to the lip constriction onset (left edge); and (c) the tongue movement offset (target) relative to the lip constriction offset (right edge).

movement duration (c.a. 42% of the variation) can be accounted for by the lip constriction duration.

3.6. Consonantal–vocalic intergestural coordination

As shown in Fig. 10, there were no significant effects of Consonant type on any of the three intergestural timing measures—i.e., the onset of the tongue body movement relative to the onset of the lip closing movement; the onset of the tongue body movement relative to the onset of the lip constriction (left edge); and the offset (target) of the tongue body movement relative to the offset (right edge) of the lip constriction (F[1.6, 9.4]=2.35, F[2, 12]=1.33; F[2, 12]=1.35, respectively, all at $p>0.1$).

3.7. V-to-V coarticulatory variation as a function of consonant type

Anticipatory (right-to-left) V-to-V coarticulation at the left edge of lip constriction. There was a main effect of Consonant type (F[1.5, 8.8]=8.39, $p<0.05$) and Vowel type (F[1, 6]=26.92, $p<0.005$) on anticipatory coarticulation, showing a lesser degree of V-to-V coarticulation across the fortis /p*/ and the aspirated /p^h/ than across the lenis /p/, (/p*/=/p^h/) < /p/, and a lesser degree of coarticulation for /i/ in /i̲Ca/ than for /a/ in /a̲Ci/ (/i/ < /a/). There was, however, a significant Consonant type by Vowel type interaction (F[1.7, 10.3]=6.59, $p<0.05$), due to the fact that the consonant effect reached significance only in anticipatory coarticulation in /a/ (i.e., /a/ in /a̲Ci/), as shown in Fig. 11a.

In linear regression analyses, the degree of anticipatory coarticulation in /a/ was regressed against lip constriction duration to test whether the observed V-to-V coarticulatory reduction associated with the fortis and aspirated /p*,p^h/ was duration-dependent or not. Results showed a significant relationship between the two variables (R^2=0.22, F[1, 80]=22.45, $p<0.0001$), indicating that a significant proportion of variation in V-to-V anticipatory coarticulation in /a/ can be accounted for by lip constriction duration of the intervening stop that varies as a function of Consonant type (Fig. 11c). (Note that /i/ did not show significant correlation, either, as shown in Fig. 11b.) Results of one-way ANCOVA confirmed the relationship—i.e., there was a significant main effect of the covariate factor, Constriction duration (F[1, 80]=6.09, $p<0.05$) on the degree of anticipatory coarticulation for /a/, and the effect of Consonant type became insignificant when Constriction duration was factored in (F[2, 80]=1.58, $p>0.1$). These results from regression analyses and ANCOVAs together indicate that the consonant-induced variation of anticipatory coarticulation for /a/ in /a̲Ci/ is attributable in large part to lip constriction duration—i.e., the farther the encroached vowel (i.e., /a/) is separated from the encroaching (following) vowel (i.e., /i/) by longer lip constriction duration (associated with /p*,p^h/), the lesser the degree of anticipatory coarticulation.

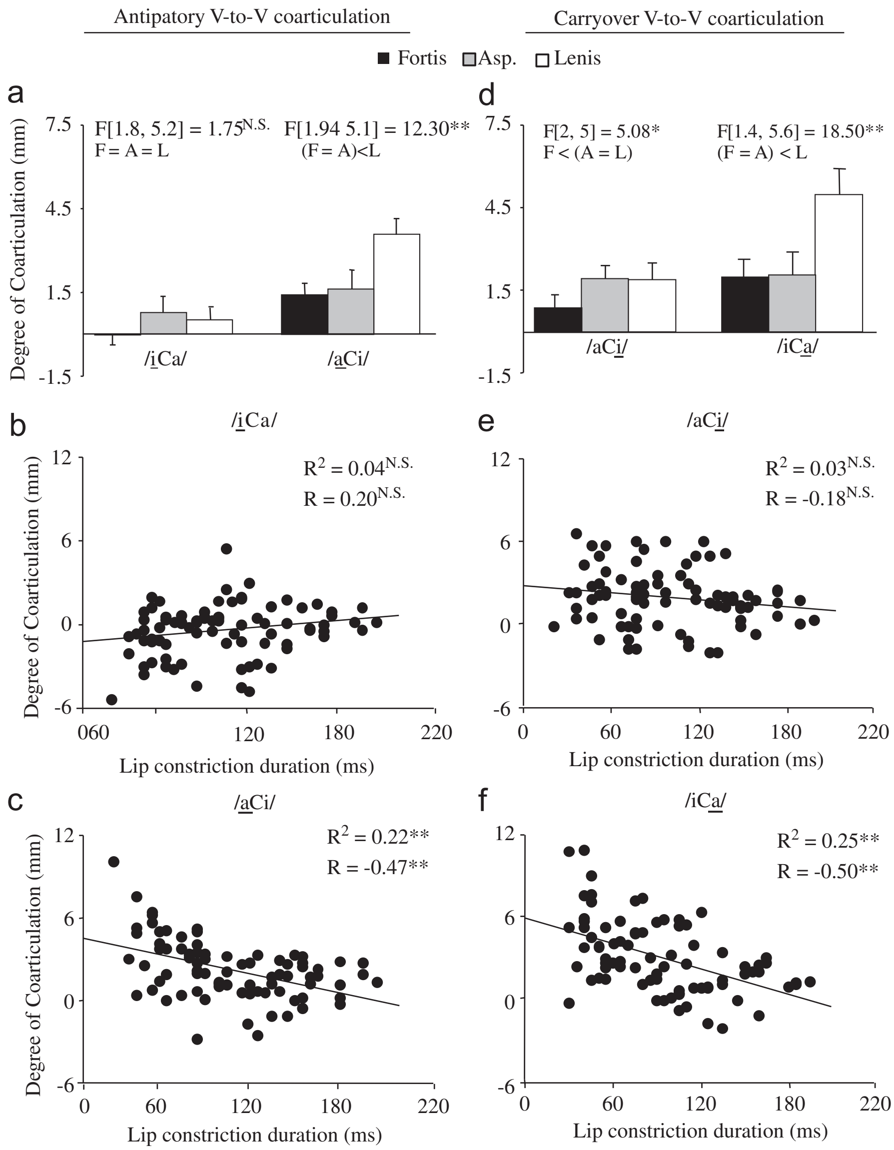

Fig. 11. Degree of anticipatory (left panels) and carryover (right panels) V-to-V coarticulation as a function of Consonant type, and its relationship with the constriction duration of the intervening consonant. '*' refers to a significance level at $p < 0.05$ and '**' at $p < 0.005$. Results of pair-wise posthoc comparisons are indicated with '<' or '>' when the difference between levels was significant at $p < 0.05$, and with '=' when non-significant.

Carryover V-to-V coarticulation at the right edge (release) of lip constriction. Carryover coarticulation showed more robust consonant effects than anticipatory coarticulation. There was a significant main effect of Consonant type ($F[1.34, 8]=14.69$, $p < 0.005$), revealing a three-way distinct pattern of /p*/ < /p^h/ < /p/—i.e., V-to-V carryover coarticulation was smallest across the fortis /p*/, intermediate across the aspirated /p^h/, and largest across the lenis /p/. The Vowel type factor, on the other hand, unlike its significant effects found in anticipatory coarticulation, did not have a significant influence on carryover coarticulation ($F[1, 6]=2.62$, $p > 0.1$). There was again a significant interaction between Consonant type and Vowel type ($F[1.4, 8.2]=13.59$, $p < 0.005$), showing slightly different consonant effects in /aCi/ versus /iCa/ as can be seen in Fig. 11d. In /aCi/, V-to-V carryover coarticulation was smaller across the fortis than across the aspirated and the lenis stops—i.e., a two-way distinct pattern of /p*/ < (/p^h/=/p/), whereas /iCa/ showed a two-way distinct pattern of (/p*/=/p^h/) < /p/ with no difference between the fortis and aspirated stops.

Results of regression analyses (Fig. 11e and f) showed that although both /a/ and /i/ in (/iCa/ and /aCi/) showed significant effects of Consonant type on carryover coarticulation, only /a/ revealed a significant covariance relationship between lip constriction duration and degree of coarticulation ($R^2=0.25$, $F[1, 80]=26.19$, $p < 0.0001$). In one-way ANCOVAs, a trend effect of lip constriction duration on the degree of coarticulation was observed ($F[1, 80]=3.83$, $p < 0.06$) for /a/ in /iCa/ in line with their covariance relationship. On the other hand, for /i/ in /aCi/, no such relationship was found ($R^2=0.03$, $F[1, 77]=2.52$, $p > 0.1$), which was further confirmed by a null effect of lip constriction duration in ANCOVA ($F[1, 77] < 1$, $p > 0.1$).

The results thus revealed asymmetrical consonant effects on V-to-V coarticulation between /a/ and /i/ test vowels. When /a/ was the encroached (target) vowel, it showed constriction duration-dependent coarticulatory variation in both anticipatory and carryover effects—i.e., the farther the encroached vowel /a/ is separated from the encroaching vowel /i/, the greater the coarticulatory reduction. On the other hand, when /i/ was the encroached (target) vowel, a significant consonant effect was found in carryover direction (/aCi̲/) but not in anticipatory direction (/i̲Ca/). Even in carryover direction, /i/ differed from /a/ in that degree of V-to-V coarticulation for /i/ was independent of lip constriction duration, while /a/ showed a clear correlation between the intervening lip constriction duration and the degree of V-to-V coarticulation. This indicates that not all consonant-induced coarticulatory variation can be accounted for by lip constriction duration alone.

4. Discussion

The research question that motivated the present study concerns phonetic manifestation of the three-way contrastive stops /p*,p^h,p/ (fortis, aspirated and lenis) in Korean in terms of five articulatory dimensions: two were directly related to the consonantal gesture—i.e., the lip constriction and the lip closing movement, and three were related to vocalic gestures that were co-produced with the consonantal gesture—i.e., the lip opening movement, the transconsonantal tongue movement, and the transconsonantal V-to-V coarticulation. In the following sections, we will summarize and discuss the results in light of the research questions outlined at the beginning of the paper.

4.1. *Articulatory correlates of stops during consonantal production*

One of the basic questions that the present study has aimed to answer is whether, and how, the three-way contrastive stops are differentiated during the consonantal production at the supralaryngeal articulatory level. Lip constriction maximum (Lip Aperture minimum) and lip constriction duration were two articulatory measures directly related to consonantal articulation. They revealed that the fortis /p*/ was longer and more constricted than the aspirated /p^h/, which in turn was longer and more constricted than the lenis /p/, showing a three-way distinct pattern (/p*/ > /p^h/ > /p/) in both the spatial and temporal dimensions. While differences in laryngeal settings may be responsible for many of the acoustic and aerodynamic correlates (see the introduction for a review), the present results demonstrate that the three-way stop contrast in Korean is indeed expressed directly by the lip constriction characteristics at the supralaryngeal level.

We have also examined the lip closing movement that is generally seen as an essential articulatory gesture for forming the constriction of labial stops in the framework of Articulatory Phonology (Browman & Goldstein, 1990, 1992). Under this assumption, we asked whether the three-way contrastive stops /p*,p^h,p/ would also be differentiated kinematically during the lip closing movement. Results, however, showed that kinematic measures such as displacement, duration and peak velocity did not vary robustly as a function of the consonant type. Crucially, the lip closing movement for the fortis stop was *not* larger (in displacement), longer (in movement duration) or faster (in peak velocity) than that for the other two stops. The only significant kinematic effect was the difference in displacement between the lenis and the aspirated stops with the latter being larger than the former, while the fortis stop did not differ from the other two. These results therefore do not support the hypothesis that the three-way stop contrast in Korean is dynamically specified in the lip closing gesture, suggesting that the supralaryngeal characteristics of three-way contrastive stops are best expressed by characteristics of lip constriction itself, while the dynamics of the consonantal closing gesture plays a minimal role.

4.2. *Articulatory correlates of stops during vocalic production*

Another important question that the present study has aimed to answer is whether, and how, the three-way stop contrast would influence vocalic articulation, or, put differently, be reflected in vocalic articulation. The most direct articulatory dimension examined was the transconsonantal tongue movement (/a/-to-/i/ and /i/-to-/a/), which revealed robust consonant effects, especially in the temporal dimension with a clear three-way distinct pattern (/p*/ > /p^h/ > /p/)—i.e., the tongue movement was longer across the fortis, intermediate across the aspirated, and shorter across the lenis. The peak velocity also revealed a significant consonant effect with a two-way distinct pattern of /p*,p^h/ < /p/, showing *slower* tongue body movement for the fortis and aspirated stops. Another related articulatory dimension which reveals vocalic characteristics is the lip opening movement. The lip opening kinematic measures, especially displacement and duration, showed a clear-cut fortis–lenis distinction in both the spatial and temporal dimensions, as reflected in the larger and longer lip opening for the fortis stop. The aspirated stop was different from the lenis stop, but only limitedly in temporal dimension in /iCi/ context, with longer lip opening duration, compared to the lenis stop. It is thus evident in both the tongue and lip opening movement data that articulatory characteristics of three-way contrastive stops influence the neighboring vocalic articulation at the supralaryngeal level. Just as the laryngeal characteristics associated with the three-way stops are robustly reflected in the acoustically defined following vowel, so are articulatory characteristics in the (following) vocalic movements, most notably in the temporal dimension.

At this point, however, it is worth discussing whether the lip opening movement characteristics observed in the present study are purely 'vocalic.' As we briefly discussed in the introduction, some studies have suggested that the lip opening movement may be modulated, at least in part, by the release movement out of the consonant, which is 'consonantal' (Browman, 1994; Nam, 2007a, 2007b). The distinct temporal patterns of the lip opening movement may then be considered consonantal, rather than vocalic, characterizing the three-way stop contrast in Korean, to the extent that the lip opening movement is attributable to the consonantal release movement.

4.3. *(In)Dependency of consonantal and vocalic gestures*

The consonantal effects on vocalic articulations naturally lead us to consider the consonantal–vocalic relationship. As we have just discussed, there was a three-way distinct durational difference in the tongue movement as a function of consonant type, which demonstrated C–V dependency: the vocalic lingual gesture was modified by consonantal articulation. The C–V dependency was further evident in a strong positive correlation between the lip constriction (consonantal) duration and the tongue movement duration ($R = 0.65$, $p < 0.0001$).

Interestingly, however, although the three-way stop contrast gave rise to modification of the vocalic articulation as such, the effect appears to be unidirectional—i.e., the consonant type influenced the vocalic articulation, but not the other way around. The low vowel context /aCa/ would have an effect of pulling down the consonantal constriction, relative to the high vowel context /iCi/, so that lip constriction would be shortened and less constricted. Consonantal constriction, however, was invariantly maintained, not being affected by the vocalic context (iCi/ versus /aCa/).

This consonantal resistance to the vocalic influence can then be viewed as suggesting that the consonantal articulation was independent from the vocalic articulation as far as the lip constriction degree is concerned. This appears to be contradictory to studies on C–V coarticulation that have shown effects of vowels on consonantal articulation (see Recasens, 1999, for a review). The observed null effect of the vocalic context on lip constriction, however, may be in part due to the fact that the consonantal and vocalic gestures in question in the present study involve articulators that minimally interfere with each other (Fowler & Saltzman, 1993). It has been shown that the degree of V-to-V coarticulation is greater when the intervening consonants are labial than lingual, as labials are minimally restrictive of the lingual vocalic articulation while the lingual consonants are often in conflict with (lingual) vowels in their closing versus opening directions (Öhman, 1966; Recasens, 1984). Given that our test consonants were bilabial and the consonantal constriction made by the lips has a greater degree of freedom from the vocalic lingual articulation (as discussed by Fowler & Saltzman, 1993), degree and duration of lip constriction could be invariantly maintained regardless of the vocalic context. It is then plausible that the labials that have been known to interfere minimally with vocalic lingual articulation are also minimally influenced by the vocalic lingual articulation.

The results thus appear to show dual aspects of interaction between consonant and vowel gestures: the C–V dependency was observed in the direction of the consonantal gesture influencing the vocalic articulation, whereas the consonantal articulation was independent of the vocalic gesture. However, the C–V independence may be further constrained by the articulators involved, so that involvement of different articulators (the lips versus the tongue) would more likely bring about such resistance, while involvement of a single articulator for the two opposing gestures would make them inevitably dependent on each other.

4.4. V-to-V coarticulation as a function of consonant type

The consonant–vowel dependency crystallized in the patterns of V-to-V coarticulation whose degree varied systematically with the consonant type. It was hypothesized that the stronger the intervening consonant, the lesser the degree of V-to-V coarticulation, leading to a prediction that the degree of V-to-V coarticulation would be smaller across the fortis /p*/, but larger across the lenis /p/. Our results are generally in line with this prediction, showing an overall pattern towards a smaller degree of V-to-V coarticulation across the fortis /p*/ than across the lenis /p/, while the difference between the aspirated /p^h/ and the other two was not observed. Such consonantal influence on V-to-V coarticulation adds to our cumulative evidence that the Korean three-way stop contrast is reflected in the neighboring lingual vocalic articulation. Related to this arise questions stemming from three factors that might influence V-to-V coarticulation—i.e., whether the consonantal effect on V-to-V coarticulation is comparable between anticipatory and carryover directions (the directionality factor); whether it is further conditioned by the vowel quality (closed /i/ versus open /a/) (the vowel type factor); and, more generally, whether the effect can be accounted for purely by duration (the duration factor as the covariate).

Results of the present study suggested that all three factors indeed influenced V-to-V coarticulation in a complexly interactive way. V-to-V coarticulation varied with the vowel type (/i/-to-/a/ versus /a/-to-/i/) and its directionality (anticipatory versus carryover). In the carryover (left-to-right) direction (for V2 in V1CV2), the degree of V-to-V coarticulation was smaller across the fortis /p*/ than across the lenis /p/ for both /i/ and /a/. On the other hand, in the anticipatory (right-to-left) direction (for V1 in V1CV2), only /a/ showed a comparable consonantal effect with a lesser degree of coarticulation across the fortis /p*/ or the aspirated /p^h/ than across the lenis /p/. Furthermore, the degree of V-to-V coarticulation was found to correlate positively with the lip constriction duration, but results of ANOVAs suggested that the duration dependency of V-to-V coarticulation was conditioned by the vowel type. On the one hand, when /a/ was the test (encroached) vowel, V-to-V coarticulation was purely duration-dependent in both anticipatory and carryover directions—i.e., the farther the encroached vowel /a/ is separated from the encroaching vowel /i/, the greater the coarticulatory reduction. On the other hand, when /i/ was the test (encroached) vowel, the consonantal effect was found only in carryover direction, and the effect was not purely due to the durational factor—i.e., the consonantal effect remained significant even after duration was taken into account in ANCOVAs. These results thus indicate that the consonantal effect on V-to-V coarticulation is largely explained by the V-to-V temporal interval separated by the intervening consonant, but not as an across-the-board effect since it closely interacts with the vowel quality and its directionality.

What does it mean to say then that the reduction of V-to-V coarticulation is independent from the temporal distance between the two vowels, as found with /i/ in carryover direction? It would mean that the reduction of V-to-V coarticulation across the stronger (fortis) stop is not a simple byproduct of temporal expansion of consonantal duration for the fortis stop, but the vocalic lingual movement is modified in such a way that the test vowel itself (in this case, /i/ in carryover condition) becomes stronger, resisting its coarticulation with the neighboring vowel. In this sense, we propose that the duration-independent coarticulatory reduction can be said to be a pure instance of consonant-induced coarticulatory resistance at least in the case of /i/ in carryover direction. (At the moment, we do not have an explanation of why only /i/ showed duration-independent coarticulatory reduction across the fortis stop.)

Previous studies of V-to-V coarticulation have generally been limited to cases in which differential V-to-V coarticulatory resistance is conditioned by the degree to which the part of the tongue that is involved in consonantal articulation is in conflict with the vocalic articulation. The present study has demonstrated a new case in which the labials (which are known to be minimally restrictive of the tongue body movement) also cause differential degree of coarticulatory resistance due to the hypothesized strength of the intervening consonant. This may be interpretable in terms of the lip and jaw coarticulation. The lip closing for the labials is attained at least in part by the contribution of the jaw, and the jaw movement, in turn, covaries with the tongue movement due to the jaw–tongue mechanical linkage (see Fletcher & Harrington, 1999). The observed effect of labial consonants on the vocalic V-to-V coarticulation could then be taken as a result of the lip's indirect influence on the lingual movement via its coarticulatory linkage with the jaw.

Before we move on, it is worth further discussing the asymmetric effects between /i/ and /a/. We observed that the overall degree of V-to-V coarticulation was smaller for /i/ than for /a/, independent from the consonantal effect. In an articulatory study on English V-to-V coarticulation, T. Cho (2004) provided two possible explanations for why English /i/ would be more resistant to coarticulation than English /ɑ/. The first explanation had to do with the inverse relationship between degree of coarticulatory resistance and degree of sonority as hypothesized by Lindblom (1983). The underlying mechanism for this was that a less sonorous vowel such as high vowel /i/ is produced with greater articulatory precision and therefore with lesser degree of articulatory freedom, entailing coarticulatory resistance to neighboring vowels. The second possibility was that the coarticulatory resistance was driven by the phonological vowel inventory of the language, so that /i/ would resist coarticulation more than /ɑ/ because /i/ is positioned in a crowded section in the vowel space (being contrastive with lax vowel /ɪ/) whereas /ɑ/ occurs in a vowel section with no sound to be contrastive with in that section (Manuel, 1990, 1999). Our results on Korean V-to-V coarticulation appear to support the first possibility because both /i/ and /a/ occur in a relatively sparse vowel space in Korean with no neighboring sounds in each vowel section. Coarticulatory propensity thus appears to have more to do with degree of sonority of the segment than with the phonological constraints.

4.5. Timing of consonant–vowel coordination

We also explored the consonantal effects on the vocalic articulation in terms of the coordination of lip constriction and tongue movements by examining three intergestural intervals: the timing of the onset of the tongue body movement relative to the onset of the lip closing movement; the timing of the onset of the tongue body movement relative to the onset of the lip constriction (left edge); and the timing of the offset (target) of the tongue body movement relative to the offset (right edge) of the lip constriction. All three measures turned out to remain unchanged regardless of the consonant type, maintaining three important intergestural timing patterns between the consonantal lip constriction and the vocalic tongue movement. First, the tongue movement onset started before the lip constriction onset (left edge of constriction); second, the lip closing movement toward the closure started before the tongue movement; and third, the tongue movement ended after the lip constriction offset (right edge of constriction). It certainly requires further work to determine whether these observed timing patterns are a reflex of invariance of coordination between the lip and the tongue, but what we know now is that the consonant type did not affect these three coordinative relationships between the lip and the tongue movements, showing quite comparable patterns even though the duration of the consonant varies. These consistent coordinative relationships are precisely in line with those of the lip and the tongue movements in Japanese (Löfqvist, 2006)—i.e., the temporal structure of the tongue movement was modified as the intervening labial nasal was bimoraic (long) versus monomoraic (short), resulting in the same coordinative patterns as found in the present study. Similar relationships were observed in American English as well (Löfqvist & Gracco, 1999). Based on these two studies, Löfqvist (2006) suggested that "the interarticulator programming of lip and tongue movements appears to be very similar for the two languages."

These results in Japanese, English and Korean, taken as a whole, have implications for language-specific rhythmic structure and gestural coordination systems. Japanese and American English differed in their rhythmic structures—i.e., mora-timed versus stress-timed. Korean is yet different from these two, although the exact nature of its rhythmic structure is still controversial. The unusual three-way durational contrast in Korean makes it even more different. All three languages appear to show a very similar intergestural timing relationship between the lip and the tongue movements, regardless of the rhythmic structure of the language as well as whether the language employs two-way (in Japanese) or three-way durational contrast (in Korean) for the lip constriction. It will therefore be worth pursuing this line of research with more languages to determine the extent to which the observed intergestural timing pattern can be generalized as characteristics of the human speech motor system across languages.

4.6. On defining fortis versus lenis stops at both the supralaryngeal and laryngeal levels

The results discussed so far allow us to evaluate whether the terms 'fortis' and 'lenis' that have traditionally defined primarily based on laryngeal characteristics in Korean can also be definable at the supralaryngeal level. As was mentioned at the outset, the term fortis has been argued to be based on the respiratory force associated with /p*,t*,k*/ (Dart, 1987; Ladefoged & Maddieson, 1996), and its concomitant laryngeal settings, especially with constricted glottis and its tension, have been taken to be responsible for various acoustic–aerodynamic correlates of the fortis stop. We then questioned whether there would be any systematic kinematic evidence that the fortis stop could also be definable with 'articulatory' force at the supralaryngeal level.

One way to test this was by examining movement velocity of the lip closing gesture, which is often taken to be indicative of articulatory effort or force (Perkell et al., 2002). The peak velocity for the lip closing movement was hypothesized to be greater for the fortis stop than for the lenis stop, if the articulatory force were greater for the former. But our results showed no evidence in support of this, nor did they show systematic changes in other kinematic parameters such as displacement or duration, suggesting that the articulatory force assumed to be associated with the fortis stop is not reflected in the lip closing kinematics. The null effect on lip closing peak velocity also suggests that the stiffness of the laryngeal muscles that have been known to be associated with the fortis stop is not comparable to the stiffness used in the dynamical system. Recall that a change in peak velocity was expected to occur if the value of the stiffness (as a dynamical parameter in the mass-spring gestural model) would change as a function of consonant type. All in all, the kinematics of the lip closing gesture do not show any sign of the articulatory force and the hypothesized increased stiffness associated with the fortis stop, implying that the three-way phonemic contrast of the stops is not dynamically specified in their lip closing gestures.[2]

Unlike the lip closing kinematics, however, constriction characteristics do tell us something about the different degree of articulatory force that may be involved with different stops. The most relevant findings were the clear-cut three-way distinction in constriction degree and duration (fortis > aspirated > lenis), and the pattern of gradual change in constriction degree over time during the closure. Recall that at the initial phase of closure, fortis and aspirated stops reached their constriction onset (lip closing target) with more or less the same degree of constriction, but as the constriction progressed further, the lip closure became even more constricted for the fortis stop than for the aspirated stop, eventually leading to a three-way distinction in constriction degree. That is, the lip tissue compression was substantially reinforced during the closure of the fortis stop.

A question that follows is then to what extent the lip compression degree can be accounted for by duration. Our regression analyses and ANCOVAs revealed that there was a significant relationship between constriction degree and constriction duration, and that the effect of Consonant type on constriction degree disappeared when constriction duration was factored in. Does this mean that there is a direct causal relationship between the two variables? One might argue that the fortis stop is inherently longer than the other stops, so that the longer hold-duration during closure would allow for more extreme articulation, causing the increased lip compression, in a way similar to the assumption underlying the undershoot hypothesis (Lindblom, 1963; Moon & Lindblom, 1994). Alternatively, however, the fortis

[2] Brunner et al. (2011) suggested that articulatory differences in the three-way velar (lingual) stops in Korean can be accounted for by a change in the so-called the virtual target. The virtual target is hypothetically aimed by the speaker to reach beyond physical articulatory limits, presumably in order to secure the air-tight closure for stops (Löfqvist & Gracco, 1997, 2002). Brunner et al. (2011) noted that according to Löfqvist (2000), a larger virtual target may induce a longer closure duration, which is likely observed with an increase in movement velocity. However, no such effect in our lip closing movement data suggests that the fortis–lenis distinction cannot be directly compared by the virtual target hypothesis at least for the labial stop series.

stop may indeed be associated with intrinsically greater articulatory force, which is characterized by both articulatory and temporal expansions that co-vary presumably without a causal relationship between the two. With the data we have obtained in the present study, we may not be able to resolve on a particular account, but what is clear from the results is that constriction degree and constriction duration go hand in hand. Further work will certainly be needed to understand the exact nature of the relationship between the two.

5. Conclusion

The present study has observed several kinematic characteristics of the Korean three-way contrastive stops at the supralaryngeal level. First, the three-way contrast was manifested most clearly in constriction degree and duration during the stop closure, suggesting three-way articulatory strengths (fortis > aspirated > lenis). Second, the degree of articulatory strength underlying the stops was further manifested in the vocalic movements of the neighboring vowels. The temporal dimensions of the lip opening and the tongue body movements were modified in line with the articulatory strength, showing a two-way distinction (i.e., the longer and slower movement for the stronger (fortis or aspirated) stops than for the lenis stop). The degree of consonantal strength was also systematically reflected in the degree of V-to-V coarticulation which was reduced across the stronger (fortis or aspirated) stops, though no consistent difference was found between the fortis and aspirated stops. Finally, the lip constriction was stably coordinated with the tongue body movement, showing cross-linguistic similarities in consonant–vowel gestural coordination between English, Japanese and Korean, regardless of the rhythmic structure of a given language. Building on previous findings (Cho & Keating, 2001; Kim, 1965; Kim et al., 2005, 2010; Shin, 1997), all these results suggest that a three-way 'laryngeal' contrast alone is not enough to capture the phonetic characteristics of the Korean stop series. The present study has thus provided sufficient evidence to support the claim that there exist articulatory phonetic signatures of the three-way series of Korean stops at the supralaryngeal level, which need to be more thoroughly investigated to build the basis for a complete phonetic description of the Korean stops.

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References

Baik, W. (1997). On tensity of Korean stops (electropalatographic study). *Korean Journal of Speech Sciences*, *2*, 149–158.

Beckman, M. E., Edwards, J., & Fletcher, J. (1992). Prosodic structure and tempo in sonority model of articulatory dynamics. In G. J. Docherty, & D. R. Ladd (Eds.), *Papers in laboratory phonology II: Gesture, segment, prosody* (pp. 3–86). Cambridge: Cambridge University Press.

Browman, C. (1994). Lip aperture and consonant releases. In P. Keating (Ed.), *Papers in laboratory phonology III: Phonological structure and phonetic form* (pp. 331–353). Cambridge: Cambridge University Press.

Browman, C. P., & Goldstein, L. (1990). Gestural specification using dynamically-defined articulatory structures. *Journal of Phonetics*, *18*, 299–320.

Browman, C. P., & Goldstein, L. (1992). Articulatory phonology: An overview. *Phonetica*, *49*, 155–180.

Brunner, J., Fuchs, S., & Perrier, P. (2011). Supralaryngeal control in Korean velar stops. *Journal of Phonetics*, *39*, 178–195.

Brunner, J., Fuchs, S., Perrier, P., & Kim, H.-Z. (2003). Mechanisms of contrasting Korean velar stops: A catalogue of acoustic and articulatory parameters. *ZAS Papers in Linguistics*, *32*, 15–30.

Byrd, D. (2000). Articulatory vowel lengthening and coordination at phrasal junctures. *Phonetica*, *57*, 3–16.

Byrd, D., & Saltzman, E. (1998). Intragestural dynamics of multiple prosodic boundaries. *Journal of Phonetics*, *26*, 173–199.

Cho, T. (1996). *Vowel correlates to consonant phonation: An acoustic–perceptual study of Korean obstruents*. M.A. Thesis. University of Texas.

Cho, T. (2004). Prosodically-conditioned strengthening and vowel-to-vowel coarticulation in English. *Journal of Phonetics*, *32*, 141–176.

Cho, M. (2004). Rhythm typology of Korean speech. *Cognitive Processing* *5*, 249–253.

Cho, T. (2005). Prosodic strengthening and featural enhancement: Evidence from acoustic and articulatory realizations of /a,i/ in English. *Journal of the Acoustical Society of America*, *117*, 3867–3878.

Cho, T. (2006). Manifestation of prosodic structure in articulation: Evidence from lip kinematics in English. In L. Goldstein, D. H. Whalen, & C. T. Best (Eds.), *Papers in laboratory phonology VIII* (pp. 519–548). Berlin/New York: Mouton de Gruyter.

Cho, T. (2008). Prosodic strengthening in transboundary V-to-V lingual movement in American English. *Phonetica*, *65*, 45–61.

Cho, T., Jun, S.-A., & Ladefoged, P. (2002). Acoustic and aerodynamic correlates of Korean stops and fricatives. *Journal of Phonetics*, *30*, 193–228.

Cho, T., & Keating, P. (2001). Articulatory and acoustic studies of domain-initial strengthening in Korean. *Journal of Phonetics*, *29*, 155–190.

Cho, T., & Ladefoged, P. (1999). Variations and universals in VOT: Evidence from 18 languages. *Journal of Phonetics*, *27*, 207–229.

Dart, S. N. (1987). An aerodynamic study of Korean stop consonants: Measurements and modeling. *Journal of the Acoustical Society of America*, *81*, 138–147.

de Jong, K. (1995). On the status of redundant features: The case of backing and rounding in American English. In B. Connell, & A. Arvaniti (Eds.), *Papers in laboratory phonology IV: Phonology and phonetic evidence* (pp. 68–86). Cambridge: Cambridge University Press.

Fletcher, J., & Harrington, J. (1999). Lip and jaw coarticulation. In W. J. Hardcastle, & N. Hewlett (Eds.), *Coarticulation* (pp. 144–175). Cambridge: Cambridge University Press.

Fowler, C., & Saltzman, E. (1993). Coordination and coarticulation in speech production. *Language and Speech*, *36*, 171–195.

Goldstein, L., Byrd, D., & Saltzman, E. (2006). The role of vocal tract gestural action units in understanding the evolution of phonology. In M. Arbib (Ed.), *Action to language via the mirror neuron system* (pp. 215–249). Cambridge: Cambridge University Press.

Halle, M., & Stevens, K. N. (1971). A note on laryngeal features. *Quarterly Progress Report (Research Laboratory of Electronics, MIT)*, *101*, 198–212.

Han, M. S., & Weitzman, R. S. (1970). Acoustic features of Korean /P,T,K/, /p,t,k/ and /p^h,t^h,k^h/. *Phonetica*, *22*, 112–128.

Hardcastle, W. J. (1973). Some observations of the tense–lax distinction in initial stops in Korean. *Journal of Phonetics*, *1*, 263–271.

Hawkins, S. (1992). An introduction to task dynamics. In G. l. Docherty, & D. R. Ladd (Eds.), *Papers in laboratory phonology IV: Gesture, segment, prosody* (pp. 9–25). Cambridge: Cambridge University Press.

Hirose, H., Lee, C. Y., & Ushijima, T. (1974). Laryngeal control in Korean stop production. *Journal of Phonetics*, *2*, 145–152.

Huynh, H., & Feldt, L. S. (1970). Conditions under which mean square ratios in repeated measurements designs have exact *F*-distributions. *Journal of the American Statistical Association*, *65*, 1582–1589.

Jakobson, R., Fant, G., & Halle, M. (1952). *Preliminaries to speech analysis*. Cambridge, MA: MIT Press.

Jun, S.-A., Beckman, M., & Lee, H. (1998). Fiberscopic evidence for the influence on vowel devoicing of the glottal configurations for Korean obstruents. *UCLA Working Papers in Phonetics*, *96*, 43–68.

Kagaya, R. (1974). A fiberscopic and acoustic study of the Korean stops, affricates and fricatives. *Journal of Phonetics*, *2*, 161–180.

Kim, C.-W. (1965). On the autonomy of the tensity feature in stop classification. *Word*, *21*, 339–359.

Kim, C.-W. (1970). A theory of aspiration. *Phonetica*, *21*, 107–116.

Kim, H. (2004). The representation of the three-way laryngeal contrast in Korean consonants. In Marc van Oostendorp, & J. van de Weijer (Eds.), *The internal organization of phonological segments* (pp. 263–293). Berlin: Mouton de Gruyter.

Kim, M.-R., Beddor, P. S., & Horrocks, J. (2002). The contribution of consonantal and vocalic information to the perception of Korean initial stops. *Journal of Phonetics*, *31*, 77–100.

Kim, H., Honda, K., & Maeda, S. (2005). Stroboscopic cine-MRI study on the phasing between the tongue and the larynx in Korean three-way phonation contrast. *Journal of Phonetics*, *33*, 1–26.

Kim, H., Maeda, S., & Honda, K. (2010). Invariant articulatory bases of the features [tense] and [spread glottis] in Korean plosives: New stroboscopic cine-MRI data. *Journal of Phonetics*, *38*, 90–108.

Ladefoged, P., & Maddieson, I. (1996). *The Sounds of the World's Languages*. Oxford: Blackwell.

Lindblom, B. (1963). Spectrographic study of vowel reduction. *Journal of the Acoustical Society of America*, *35*, 1773–1781.
Lindblom, B. (1983). Economy of speech gestures. In P. MacNeilage (Ed.), *The production of speech* (pp. 217–245). New York: Springer-Verlag.
Löfqvist, A. (2000). Control of closure duration in stop consonants. In *Proceedings of the fifth seminar on speech production: Models and data.* Institut für Phonetik und Sprachliche Kommunikation, Munich, pp. 29–32.
Löfqvist, A. (2006). Interarticulator programming: Effects of closure duration on lip and tongue coordination in Japanese. *Journal of the Acoustical Society of America*, *120*, 2872–2883.
Löfqvist, A., & Gracco, V. L. (1997). Lip and jaw kinematics in bilabial stop consonant production. *Journal of Speech, Language and Hearing Research*, *40*, 877–893.
Löfqvist, A., & Gracco, V. L. (1999). Interarticulator programming in VCV sequences: Lip and tongue movements. *Journal of the Acoustical Society of America*, *105*, 1864–1876.
Löfqvist, A., & Gracco, V. L. (2002). Control of oral closure in lingual stop consonant production. *Journal of the Acoustical Society of America*, *111*, 2811–2827.
Lombardi, L. (1991). *Laryngeal features and laryngeal neutralization*. Ph.D. Dissertation. University of Massachusetts, Amherst.
Manuel, S. (1990). The role of contrast in limiting vowel-to-vowel coarticulation in different languages. *Journal of the Acoustical Society of America*, *88*, 1286–1298.
Manuel, S. (1999). Cross-language studies: Relating language-particular coarticulation patterns to other language-particular facts. In W. J. Hardcastle, & N. Hewlett (Eds.), *Coarticulation: Theory, data and techniques* (pp. 179–198). Cambridge: Cambridge University Press.
Max, L., & Onghena, P. (1999). Some issues in the statistical analysis of completely randomized and repeated measures designs for speech, language, and hearing research. *Journal of Speech, Language, and Hearing Research*, *42*, 261–270.
Mok, P., & Lee, S. I. (2008). Korean speech rhythm using rhythmic measures. *A paper presented at the 18th international congress of linguists (CIL18)*. Seoul, Korea.
Moon, S.-J., & Lindblom, B. (1994). Interaction between duration, context, and speaking style in English stressed vowels. *Journal of the Acoustical Society of America*, *96*, 40–55.
Nam, H. (2007a). Articulatory modeling of consonant release gesture. In *Proceedings of the 16th international congress of the phonetic sciences* (pp. 625–628). Saarbruecken, Germany.
Nam, H. (2007b). *Gestural Coupling model of syllable structure*. Ph.D. Dissertation. Yale University.
Nelson, R. F. (1983). Detecting forest canopy change due to insect activity using Landsat MSS. *Photogrammetric Engineering and Remote Sensing*, *49*, 1303–1314.
Öhman, S. (1966). Coarticulation in VCV utterances: Spectrographic measurements. *Journal of Acoustical Society of America*, *39*, 151–168.
Öhman, S. (1967). Numerical model of coarticulation. *Journal of the Acoustical Society of America*, *41*, 310–320.
Perkell, J. (1969). *Physiology of speech production: Results and implications of a quantitative cineradiographic study. Research Monograph*, 53. Cambridge: The MIT Press.
Perkell, J. (1997). Articulatory processes. In W. Hardcastle, & J. Laver (Eds.), *The handbook of phonetic sciences* (pp. 333–370). Blackwell.
Perkell, J., Zandipour, M., Matthies, M., & Lane, H. (2002). Economy of effort in different speaking conditions. I. A preliminary study of intersubject differences and modeling issues. *Journal of Acoustical Society of America*, *112*, 1627–1641.
Recasens, D. (1984). Vowel-to-vowel coarticulation in Catalan VCV sequences. *Journal of the Acoustical Society of America*, *76*, 1624–1635.
Recasens, D. (1987). An acoustic analysis of V-to-C and V-to-V coarticulatory effects in Catalan and Spanish VCV sequences. *Journal of Phonetics*, *15*, 299–312.
Recasens, D. (1999). Lingual coarticulation. In W. J. Hardcastle, & N. Hewlett (Eds.), *Coarticulation: Theory, data and techniques* (pp. 80–104). Cambridge: Cambridge University Press.
Saltzman, E., & Munhall, K. G. (1989). A dynamical approach to gestural patterning in speech production. *Ecological Psychology*, *1*, 333–382.
Seong, C.-J. (1995). *The experimental phonetic study of the standard current Korean speech rhythm: With respect to its temporal structure*. Ph.D. Dissertation. Seoul National Univesity (in Korean).
Shin, J.-Y. (1997). *Consonantal production and coarticulation in Korean*. Ph.D. Dissertation. London: University of London.
Silva, D. J. (2006). Acoustic evidence for the emergence of tonal contrast in contemporary Korean. *Phonology*, *23*, 287–308.
Tabain, M. (2003). Effects of prosodic boundary on /aC/ sequences: Articulatory results. *Journal of the Acoustical Society of America*, *113*, 2834–2849.
Tabain, M., & Perrier, P. (2005). Articulation and acoustics of /i/ in pre-boundary position in French. *Journal of Phonetics*, *33*, 77–100.
Tiede, M. (2005). MVIEW: Software for visualization and analysis of concurrently recorded movement data.
Westbury, J. R. (1994). On coordinate systems and the representation of articulatory movements. *Journal of the Acoustical Society of America*, *95*, 2271–2273.