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Supralaryngeal Articulatory Characteristics of Coronal Consonants /n, t, t^h, t*/ in Korean

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ABSTRACT

The present study investigates supralaryngeal articulatory characteristics of denti-alveolar (coronal) stops /t, t^h, t*/ and /n/ in /aCa/ context in Seoul Korean. An Electromagnetic Articulograph (EMA, Carstens) was used to explore kinematics of the consonants by examining the kinematic data of the tongue tip (the primary articulator for the coronal consonants), along with some additional supplementary position data of the tongue body, the tongue dorsum and the jaw. The results showed that the constriction duration was the most robust articulatory correlates of the three-way stop contrast with a pattern of /t/</t^h/</t*/. The contrast was further reinforced by the tongue body position (higher for /t^h, t*/) and the tongue tip opening displacement (less displaced for /t^h, t*/). The articulation of /n/ was quite similar to that of the lenis /t/ in terms of the constriction duration, and it was different from the oral stops in that it was produced with larger tongue tip displacement and lower jaw position than the oral stops, indicating its weak articulatory nature. The results are also discussed in comparison with those of bilabial stops with implications that the three-way contrast may be kinematically expressed differently depending on the physiological constraints imposed on the primary articulator (the tongue tip versus the lips). The present study, therefore, provides new articulatory (kinematic) data of denti-alveolar consonants in Korean, and demonstrates that the three-way stops, that have been known to differ primarily in their laryngeal settings, are indeed produced with kinematic distinctions at the supralaryngeal level.

Keywords: Korean stops, lenis, fortis, aspirated, denti-alveolar, coronal, nasal, kinematics, EMA

1. Introduction

The three-way contrastive stops in Korean, generally known as lenis, fortis, and aspirated, have long been the locus of investigation in the phonetics literature as they are typologically unusual and phonetically unique. In most languages that employ a three-way contrast in stops, they are generally classified as voiced, voiceless unaspirated and voiceless aspirated (e.g., Lisker & Abramson, 1964; Keating, 1984; Ladefoged & Maddieson, 1996; Cho & Ladefoged, 1999), which generally contrast in Voice Onset Time (VOT), definable as the timing between the initiation of the supralaryngeal release gesture and the initiation of the laryngeal gesture for voicing (Cho & Ladefoged, 1999). Cross-linguistically, their voicing contrast is in theory no more than ternary (Keating, 1984; Ladefoged & Maddieson, 1996), with each contrasting member falling onto one of the only three possible phonetic categories or features {voiced}, {voiceless unaspirated}, and {voiceless aspirated} (Keating, 1984). Korean, however, poses a challenge for such a theory of voicing contrast, because the three sets of stops in Korean are all voiceless with varying degree of positive VOTs, which have sometimes been described as 'unaspirated' (as in /t*al/ 'daughter'), 'slightly aspirated' (as in /tal/ 'moon') and 'heavily aspirated' (as in /t^hal/ 'mask'). One might therefore think that Korean would call for modification of the established binary voicing distinction in the voiceless dimension (i.e., unaspirated versus aspirated) to a

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ternary distinction (i.e., unaspirated, slightly aspirated and heavily aspirated). Such modification would have been inevitable, had VOT been the primary phonetic parameter for the three-way distinction in Korean. As Cho, Jun and Ladefoged (2002) have discussed, however, a large body of studies has uniformly suggested that difference in VOT or degree of aspiration is not a primary cue, but just one of many phonetic correlates, so that listeners are often able to differentiate the stops even without VOT cues present in the speech signal (Han, 1996; Cho, 1995, 1996; Kim, Beddor & Horrocks, 2002), and that the young generation of Korean speakers do not seem to rely on VOT cues at all to distinguish between the aspirated and lenis stops (Silva, 2006).

What other phonetic parameters would then differentiate such unusual three-way contrastive stops in Korean? Owing to their phonetic complexity, it is not easy to pin down one or a few phonetic parameters in acoustic, articulatory or aerodynamic terms with which one can define all three types of stops. Nevertheless, the generally used terms lenis, fortis and aspirated appear to capture some of their important contrastive phonetic properties.

The term fortis is used with diverse meanings (Ladefoged & Maddieson, 1996), but it often refers to either articulatory or respiratory strength engaged in speech production. In describing the sounds of the world’s languages, Ladefoged and Maddieson (1996) characterize the unaspirated Korean stop series /p*, t*, k*/ as fortis being driven by elevated ‘respiratory’ force. This is quite a rare event at a segmental level since the increased respiratory force, as they commented, is usually associated with prominence (e.g., stress or accent) at a suprasegmental level (cf., Ladefoged, 2001). The respiratory force is assumed to be reflected in heightened subglottal pressure which accompanies the more constricted glottis with stiff vocal folds (thus also termed “pressed”) along with tenser walls of the vocal tract (Dart, 1987). Its acoustic consequences are often reflected in the following vowel with a higher F0, abrupt intensity build-up, relatively undamped harmonics, and smaller or often negative H1-H2 and H1-F2 (see Cho et al., 2002 for a review and references therein). The lenis stop series /p, t, k/, on the other hand, are produced with none of those properties, and as opposed to the respiratory force, respiratory lenition appears to be responsible for some of the lenis stop characteristics such as 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 /p^h, t^h, k^h/, 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. However, the source of the glottal tension associated with aspirated stops is different from that for fortis stops in that the former is primarily due to heightened intraoral pressure caused by open (spread) glottis and longer duration of the stop closure while the latter is due to respiratory force as discussed above.

As the important phonetic properties of the Korean stops are associated with differential laryngeal settings, many previous phonetic and phonological studies on Korean stops have focused on the laryngeal properties of the stops (Kim, 1965, 1970; Abberton, 1972; Abramson & Lisker, 1973; Dart, 1987; Kagaya, 1974; Hirose, Lee & Ushijima, 1974; Halle & Stevens, 1971; Lombardi, 1991; Jun, Beckman & Lee, 1998; Han & Weitzman, 1970; Hardcastle, 1973; Cho et al., 2002; Kim et al., 2002; Silva, 1992, 2006; Kang & Guion, 2008; inter alia). It follows that phonological or phonetic features used in contemporary phonological/phonetic descriptions of Korean stops are all by reference to the laryngeal specifications such as [constricted glottis], [spread glottis], [stiff vocal folds], [tense], [lax] and so on.

While the previous studies on laryngeal characteristics of Korean consonants have improved our understanding of the peculiar phonetic properties of the three-way Korean stops, however, relatively less studies have been conducted on their supralaryngeal characteristics, and thus our knowledge of them is still limited.

As a variety of experimental techniques have been developed in recent years, some researchers have indeed examined Korean three-way stops in the supralaryngeal dimension using equipments such as electromyography (EMG), electropalatography (EPG), and electromagnetic articulography (EMA). For example, results of an EMG study indicate that fortis and aspirated labials have been known to show stronger muscular activities (Kim, 1965); EPG studies have shown that the constriction degree as measured by the amount of the linguopalatal contact is generally greater and its hold-duration is longer for the fortis and aspirated /t*, t^h/ than for the lenis /t/ (Shin, 1997; Cho & Keating, 2001). More recently, in an EMA study, Son, Kim and Cho (in press) has begun to investigate supralaryngeal kinematic characteristics of the three-way stop contrast with the labial /p, p*, p^h/ series. The results can be summarized as follows:

- stops are three-way distinct in constriction degree and constriction duration (/p*/>/p^h/>/p/);

- their three-way contrast is also evident in temporal dimensions of the vocalic tongue movement with a three-way durational pattern (/p*/>/p^h/>/p/);
- the lip opening movement into the following vowel is also distinct with the fortis and aspirated /p*, p^h/ being longer than the lenis /p/; and
- consonantal difference is further reflected in V-to-V coarticulation, such that longer constriction (e.g., the fortis) triggers more reduction of V-to-V coarticulation.

In another EMA study, Son and Cho (2010) showed that the tongue dorsum position of /a/ during the lip closure for /p, p*, p^h/ varies as a function of the consonant type, such that the fortis and aspirated stops are associated with a higher tongue dorsum position compared with the lenis stop.

The results of these articulatory studies thus suggest that the Korean three-way stop contrast is indeed phonetically manifested in the supralaryngeal dimension in line with the assumption that different stops in Korean are associated with different degree of articulatory force, which is reflected in both the laryngeal and the supralaryngeal dimensions.

In the present study, we continue to explore the supralaryngeal articulatory (kinematic) characteristics of the three-way stop contrast in Korean, by using an Electromagnetic Articulograph (EMA), which allows for tracking movements of articulators such as the tongue tip, the tongue body and the jaw. This time, we focus on kinematic characteristics of denti-alveolar stop series, which have rarely been examined kinematically. In addition to the oral stops, the nasal stop /n/ is included in order to obtain a more comprehensive understanding of the supralaryngeal characteristics of the denti-alveolar consonants in Korean. In the following section, we will discuss specific research questions that bear on kinematic characteristics of these stops.

The first question is how the denti-alveolar consonants (/n, t, t^h, t*/) are kinematically realized by their primary articulator, the tongue tip. As was the case with the labial series examined in Son et al. (in press), we examine various kinematic parameters (the tip constriction degree and duration, the consonantal closing and opening movements), so that we can compare the kinematic characteristics of denti-alveolar consonants with those of labial stops.

The second specific question is whether the consonantal differences are reflected in the tongue body movement, and if so, how. The EPG data reported in Cho & Keating (2001) showed that nasal /n/ tends to be produced with less linguopalatal contact (constriction degree) than a lenis /t/, which in turn is produced with less constriction degree than either the fortis /t*/ or the aspirated /t^h/. Given that the more linguopalatal contact is likely to be accompanied by the raised tongue body, we test whether the tongue body posture differs as a function of consonant type: the more linguopalatal contact, the more raised tongue body.

The third question is how the consonantal differences are reflected in the tongue dorsum kinematics. In an articulatory study of labial consonants in CV sequences (/pa/, /p^ha/, and /p*a/) (Son & Cho, 2010), it was shown that there was more tongue dorsum lowering (this resembling the tongue posture of /a/) during the lip closure for the lenis /p/ than for the fortis /p*/ or the aspirated /p^h/. This suggests that the degree of CV coarticulation is greater for the lenis than for the fortis or the aspirated – i.e., the more lowered tongue dorsum during the closure indicates that the following vocalic gesture has progressed, showing a greater degree of overlap.

The final question is how the consonantal differences are marked by the jaw height. Although the jaw is known to contribute to both vocalic and consonantal articulations, little has been known about its contribution to the three-way stop contrast in Korean. The jaw height is generally thought to vary with different manners of articulation (e.g., stops > nasals > lateral) (Lindblom, 1983), which is largely in line with the sonority hierarchy. Given that the sonority hierarchy is closely related with consonantal strengthening (the more constricted, the less sonorous), we test whether the three-way contrastive stops, which are known to differ in constriction degree, are further differentiated in terms of the jaw height. We also test how the nasal /n/ is further differentiated from other oral stops in terms of the jaw height.

2. Method

An Electromagnetic Articulograph (EMA, Carstens Articulograph AG200) was used to obtain the movement data of the tongue articulation (by the tongue tip, the tongue body, and the tongue dorsum) and the jaw articulation. The data collection was carried out at the Hanyang Phonetics and Psycholinguistics Lab (HPPL). The EMA system has a helmet with a three transmitter assembly, lined up in the midsagittal plane (as seen in the left panel of Figure 1).

As shown in the right panel of Figure 1, three sensor coils were attached to the tongue with approximately equal distances from the tongue tip to the tongue dorsum; two sensor coils were attached to the upper and lower lips, which were separated by approximately 1 cm when the lips are naturally closed; and one sensor coil was attached to the lower incisor to obtain the jaw movement data. As reference points, two additional sensor coils were attached to the upper incisor and the nose bridge, which were used to correct for the head movement inside the helmet.

Post-processing procedures were administered to obtain the final data set, using the software Tailor provided by Carstens and the software Matlab. Using the occlusal plane as the x-axis, the raw data were dynamically rotated as the occlusal plane was used as the x-axis (Westbury, 1994, Cho, 2005, among others). (Note that the occlusal plane was obtained with a flat plastic bite plate to which two extra sensor coils were attached. The two coordinate points on the bite plate were used, which served as the basis for the x axis, and the y axis was perpendicular to this occulsal (x axis) plane.) The two reference points (points **d** and **h** in Figure 1) were used for dynamic correction, so that any unwanted head movement inside the helmet was removed. Kinematic data were sampled at 200 Hz and smoothed by a low-pass filter of 20 Hz. Note that each sensor coil (attached to articulators) generates alternating voltages which are inversely proportional to the distance to the three-transmitters (attached to the helmet). These voltages provides the positional information of each sensor coil (see a detailed experimental procedure in Son & Cho (2010) and Son et al. (in press)).

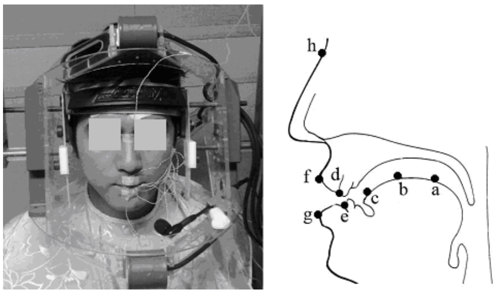

Figure 1. Locations of sensor coils: (a) the tongue dorsum; (b) the tongue body (c) the tongue tip; (d)-(e) the maxillary (upper) and mandibular (lower) central incisors; (f)-(g) the upper and lower lips; and (h) the nose bridge.
(This figure was adopted from Figure 1 in Son & Cho (2010).)

2.1 Participants

Five native speakers of Seoul-Korean (three male and two female) participated in the EMA experiment. None of them had speech or hearing deficits. They were either undergraduate or graduate students in their early-twenties or mid-twenties. They were paid after the experiment. All subjects were naive to the purpose of the experiment.

2.2 Speech material

The coronal nasal /n/ and coronal stops /t/, /t^h/ and /t*/ were used in a homorganic /a/ vowel context /aCa/: /ana/, /ata/, /at^ha/, and /at*a/. Randomly ordered VCV sequences were presented on a computer screen with four repetitions. Speakers were asked to read the given sequence as naturally as possible at a comfortable speech rate. In total, 80 tokens were collected (4 (Consonant type) X 4 (Repetition) X 5 (Speakers)).

2.3 Measurements

We analyzed the vertical movements of the tongue tip, the tongue body, the tongue dorsum, and the jaw. MVIEW (Tiede, 2005, a software for data processing and measuring developed by Haskins Laboratories) was used to demarcate important articulatory landmarks such as the articulator movement onset, the peak velocity (of closing and opening movements), the constriction maxima, the closing onset, the opening onset, the opening maxima. In the following, we specify kinematic measurements of each articulator used in data analysis.

Kinematic measures of the tongue tip (TT) movement. We measured some spatio-temporal aspects of the tongue tip (TT) vertical movement. Kinematic measures we used for the tongue tip movement are shown in Figure 2 and listed below:

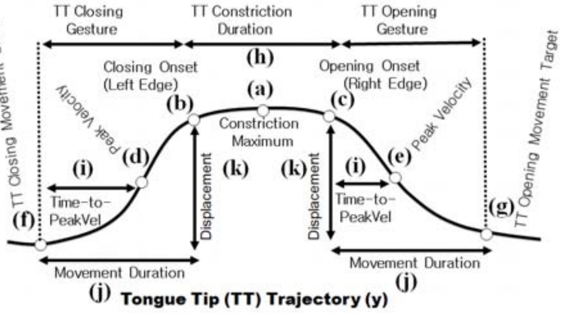

Figure 2. Schematized tongue tip (TT) movement trajectory.

- **(a)** Constriction maximum during the TT constriction (Fig. 2a).
- **(b)** Constriction degree at the TT closing onset (the left edge of the constriction) (Fig. 2b).
- **(c)** Constriction degree at the TT opening onset (the right edge of the constriction) (Fig. 2c).
- **(d)** Peak velocity of the TT closing movement (Fig. 2d)
- **(e)** Peak velocity of the TT opening movement (Fig. 2e)
- **(f)** TT closing movement onset (Fig. 2f).
- **(g)** TT opening movement target (Fig. 2g).
- **(h)** Constriction duration from the TT closing onset to the TT opening onset (Fig. 2h).

- **(i)** Time-to-peak velocity (acceleration duration) from the TT closing movement onset to its peak velocity time point, and from the TT opening onset to its peak velocity time point (Fig. 2i).
- **(j)** Movement duration from the TT closing movement onset to the TT closing onset, and from the TT opening onset to the TT opening movement target (Fig. 2j).
- **(k)** Displacement as the spatial (vertical) difference between the TT closing movement onset and the TT closing onset, and between the TT opening onset and the TT opening movement target (Fig. 2k).

The tongue body position during the consonant closure. We measured the constriction degree of the tongue body corresponding to the tongue tip constriction maximum point in time. (As discussed in the introduction, this measure was used to test whether the tongue body is raised more when the consonant is produced with more constriction degree.)

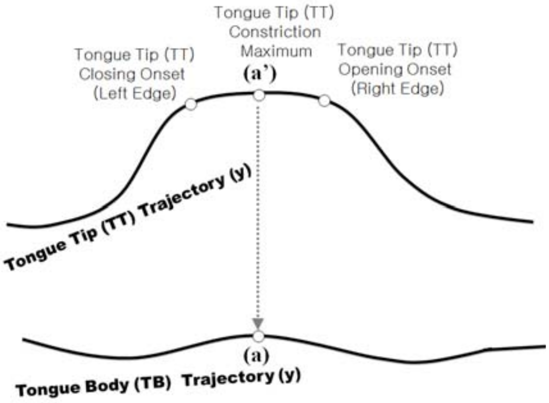

Figure 3. Schematized tongue body trajectory during the tongue tip gesture.

Measures of the tongue dorsum (TD) position. We measured the tongue dorsum (TD) position at various time points of the tongue tip movement in order to see how much the vocalic articulation overlaps with the tongue tip gesture. The measurement points of the tongue dorsum position are shown in Figure 4 and listed below:

- **(a)** TD at the TT constriction maximum (Fig. 4a).
- **(b)** TD at the tongue tip closing onset (left edge of the constriction) (Fig. 4b).
- **(c)** TD at the tongue tip opening onset (right edge of the constriction) (Fig. 4c).
- **(d)** TD at the peak velocity of the tongue tip closing movement (Fig. 4d)
- **(e)** TD at the peak velocity of the tongue tip opening movement (Fig. 4e)
- **(f)** TD at the tongue tip closing movement onset (Fig. 4f).
- **(g)** TD at the tongue tip opening movement target (Fig. 4g).

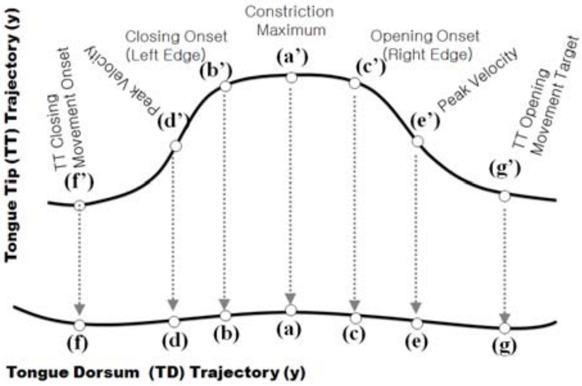

Figure 4. Schematized tongue dorsum trajectory during the tongue tip gesture.

The jaw height. We estimated the jaw height by measuring the vertical jaw position value of the jaw maximum point in time which typically occurs during the tongue tip closure as shown in Figure 5.

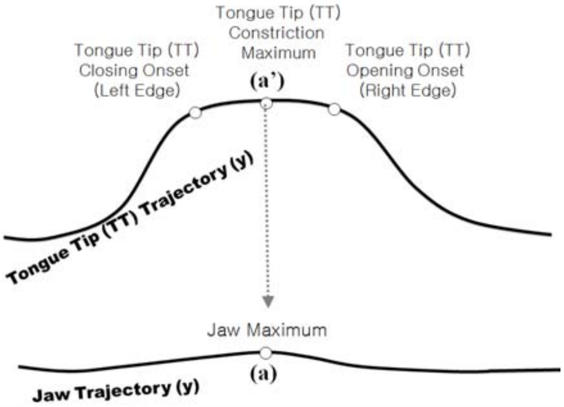

Figure 5. Schematized jaw trajectory during the tongue tip gesture.

2.4 Statistical analysis

We conducted repeated measures analyses of variance (RM ANOVA) (Max & Onghena, 1999). For each subject, each data point corresponds to the mean score of the estimated values of each articulator movement (the tongue tip, the tongue body, the tongue dorsum, and the jaw). F-ratios and p-values (with Huynh-Feldt corrected degrees of freedom and error terms) are reported ($p<0.05$) (Huynh & Feldt, 1970). Posthoc pairwise comparisons were carried out when differences between levels within a factor needs to be determined ($p<0.05$). The possibility of correlation between two variables are examined as we use Pearson product-moment correlation and linear regression coefficients ($p<0.05$).

3. Results

3.1 The tongue tip (TT)

3.1.1. The tongue tip constriction degree and duration

There was no main effect of Consonant Type on the constriction degree of the tongue tip gesture at the TT closing onset (constriction onset), the TT constriction maxima, and the TT opening onset (constriction offset) (F[3,12]=1.98; F[3,12]=2.12; F[3,12]=2.75, respectively, all at $p>0.05$) (Figure 6a). This suggested that the TT constriction degree was not a robust measure for the consonant distinction at least for the denti-alveolar coronal consonants. It is, nevertheless, worth noting that all three measures shown in Figure 6a show some direction in which the nasal /n/ tends to be produced with a smaller (weaker) constriction degree than the oral stops; and that among oral stops, the lenis /t/ tends to be produced with a smaller constriction degree than the other two, stronger, stops /t^h, t*/.

Constriction duration, however, showed a significant effect of Consonant Type: it was shorter for /n, t/ than for /t^h, t*/ (F[3,12]=109.17, $p<0.0001$) (Figure 6b). There was no significant corelation between constriction duration and constriction degree ($r=-0.12$, $p>0.05$) (Figure 6c).

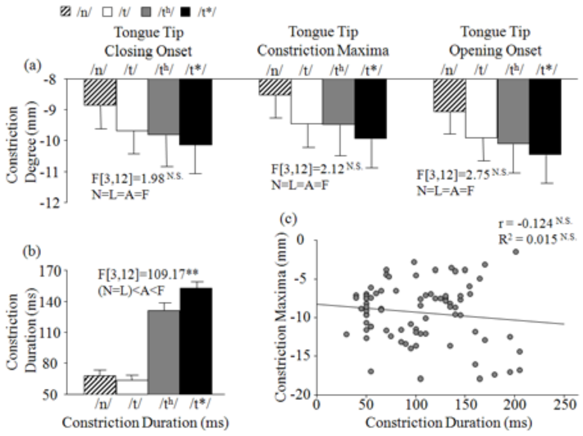

Figure 6. Effects of Consonant type on (a) the constriction degrees at three points in constriction duration (closing onset, constriction maxima, and opening onset), (b) the constriction duration, and (c) the covariate relation between constriction duration and constriction maxima. ('*' refers to $p<0.05$; '<' indicates significant difference between levels, and '=' no statistical difference. For example, N=L means there is no difference between the nasal /n/ and the lenis /t/; N<L means the measured mean value is significantly larger for the lenis /t/ than for the nasal /n/.)

3.1.2 Kinematics of the tongue tip (TT) closing movement

There was no significant main effect of Consonant Type on any kinematic measurement of the tongue tip closing movement. For example, the two durational measures, the time-to-peak velocity and the TT closing movement duration revealed no difference among the test consonants /n, t, t^h, t*/ (Figure 7a). Neither the spatial measure, displacement (Figure 7b) nor the peak velocity (Figure 7c) showed significant effects of Consonant Type.

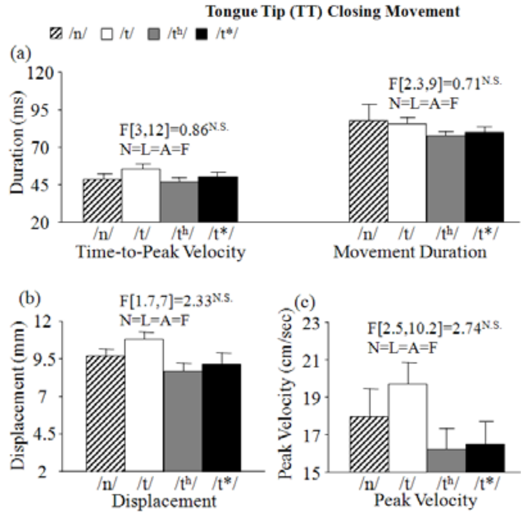

Figure 7. Effects of Consonant type on (a) the tongue tip closing movement durations (time-to-peak velocity and movement duration), (b) the spatial (vertical) displacement during the tongue tip closing movement, and (c) the peak velocity in the tongue tip closing movement. ('*' refers to $p<0.05$; '<' indicates significant difference between levels.)

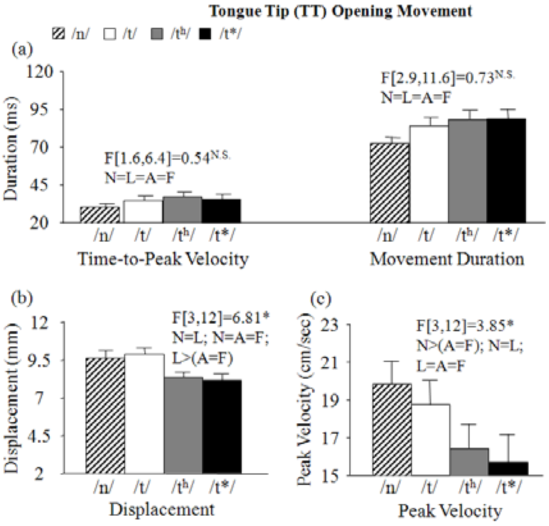

Figure 8. Effects of Consonant type on (a) the tongue tip (TT) opening movement durations (time-to-peak velocity and movement duration); (b) the TT opening displacement; and (c) the peak velocity in the tongue tip opneing movement .('*' refers to $p<0.05$; '<' indicates significant difference between levels.)

3.1.3 Kinematics of the tongue tip (TT) opening movement

As was the case with the TT closing kinematics, the TT opening kinematics showed no effect of Consonant type on the two durational measures, the time-to-peak velocity and the movement duration (Figure 8a). But unlike the TT closing movement, the TT opening kinematics *did* show a significant effect of Consonant Type on the spatial displacement (F[3,12]=6.81, p<0.05) (Figure 8b): The lenis /t/ exhibited a greater displacement than the other stops (/t^h, t*/), while no significant difference between the nasal /n/ and another oral stop was observed. Peak velocity also showed a significant Consonant Type effect (F[3,12]=3.85, p<0.05) (Figure 8c), such that the TT opening movement was faster for the nasal /n/ than for the aspirated /t^h/ and the fortis /t*/.

3.2 The tongue body position at the tongue tip constriction maximum point in time

Although there was no significant effect of Consonant type on the TT constriction maxima (as reported in Section 3.1.1), the tongue body position, which was measured at the TT constriction maximum time point, varied systematically as a function of Consonantal Type. As shown in Figure 9, the tongue body position was lower for the /n/, intermediate for the lenis /t/, and higher for the aspirated and the fortis (/t^h, t*/), showing a pattern of /n/ < /t/ < /t^h, t*/ (F[2.5,9.9]=25.09, p<0.0001).

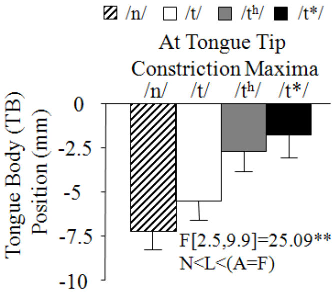

Figure 9. Effects of Consonant type on the tongue body position corresponding to the tongue tip constriction maxima point in time. ('**' refers to p<0.005 and '<' indicates significant difference between levels.)

3.3 The the tongue dorsum (TD) position at various landmark points of the tongue tip (TT) movement

The variation of the tongue dorsum (TD) position at various measurement points of the TT movement is shown in Figure 10.

During the tongue tip closing movement, there was no main effect of Consonant Type on the tongue dorsum (TD) position at the TT movement onset and at the TT closing peak velocity (Figure 10a-b) (F[1.8,7]=0.79; F[1.9,7.7]=1.25; both at p>0.05). The nasal /n/ and the stops /t, t^h, t*/ did not differ in the TD position. However, at three reference points, the TT closing onset, the TT constriction maximum, and the TT opening onset (Figure 10c-e), the TD position of the nasal /n/ was consistently lower than those of the stops (/t, t^h, t*/) (F[2.5,9.9]=6.38, p<0.05; F2.2,8.6]=15.85, p<0.005; F[2.6,10.2]= 23.19, p<0.005).

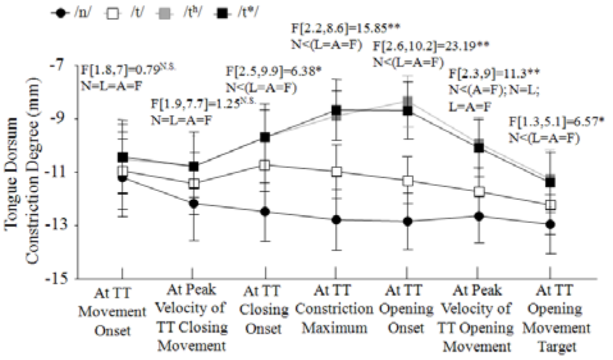

Figure 10. Effects of Consonant type on the tongue dorsum position during the tongue tip gesture. ('*' refers to p<0.05; '<' indicates significant difference between levels.)

During the TT opening, the TD position at the points of the TT peak velocity and the target (Figure 10f-g) showed a main effect of Consonant type on the TD constriction degree (F[2.3,9]=11.3, p<0.005; F[1.3,5.1]=6.57, p<0.05). As shown in Figure 10f, the consonantal effect on the TD constriction degree at the TT peak velocity was due to lower tongue dorsum position for the nasal /n/ compared to the aspirated /t^h/ and the fortis /t*/. There was no difference between the nasal /n/ and the lenis /t/, both showing similar values. Likewise, at the TT opening target time point (Figure 10g), the nasal /n/ consistently manifested lower tongue dorsum position than the other three stops.

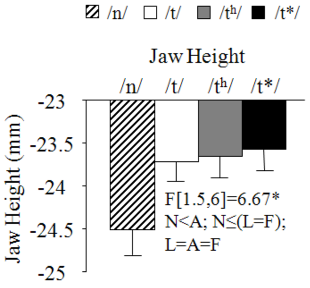

Figure 11. Effects of Consonant type on the jaw height at the jaw maxima point in time. ('*' refers to p<0.05; '<' indicates significant difference between levels; '≤' indicates a non-significant trend between levels.)

3.4 Jaw height

A main effect of Consonant type on the jaw height was found (F[1.5,6]=6.67, p<0.05), showing that the jaw position of the nasal /n/ was significantly lower than that of the aspirated /t^h/, and that the nasal /n/ tended to be lower than the lenis /t/ and the fortis /t*/. However, we did not observe any difference in the jaw heights among stops (/t/=/t^h/=t*/).

4. Summary and discussion

In this study we have examined kinematic characteristics of denti-alveolar (coronal) /n/ and /t, t^h, t*/ in Korean by examining the tongue tip, the tongue body, the tongue dorsum and the jaw. In the following subsections, we will summarize and discuss main results of the present study.

4.1 Temporal and spatial characteristics of /n, t, th, t*/ during the stop closure

One of the important findings of the present study was that coronal consonants /t, t^h, t*/ varied quite systematically in the temporal dimension. In particular, the three-way stop contrast was clearly differentiated from each other in constriction duration showing a pattern of /t/</t^h/</t*/. This is in line with the three-way distinction previously found for the labial stop series /p/</p^h/</p*/, reported in Son et al. (in press).

Unlike the constriction duration which varied quite systematically as a function of consonant type, the constriction degree of /t, t^h, t*/ during closure did not show any difference at all. Apparently this is not compatible with results of previous studies using an electropalatography (EPG) in Korean, which showed clear differences in constriction degree (as measured by linguopalatal contact) among stops－i.e., a three-way pattern of /t/</t*/</t^h/ (Shin, 1997) or a two-way pattern of /t/</t*/=/t^h/ (Cho & Keating, 2001).

The discrepancy between the present study and previous studies in constriction degree may be due to a possibility that the experimental technique using an EPG is more sensitive to variation in constriction degree. An EPG system records the area of the linguo-palatal contact between the palate and the substantial part of the tongue. On the other hand, an EMA system used in the present study captures the vertical tongue tip position only midsagittal by tracking the flesh point movement (horizontal and vertical) of one particular articulator (the tongue tip). To complement this limitation of the EMA data, we looked at the position of the tongue body (the tongue midsection) at the time point of the tongue tip constriction maximum, which may be seen as another measure of consonantal strengthening. Results showed that the tongue body position was indeed higher for stronger consonants, showing the pattern of /t/<(/t^h/=/t*/). This is indeed comparable to the pattern found in Cho & Keating's (2001) EPG data, being indicative of the differential strength of the consonantal gesture－i.e., the fortis and aspirated stops are produced with greater articulatory force in the supralaryngeal dimension.[4]

Overall, the spatio-temporal constriction characteristics of the three-way stop contrast of /t, t^h, t*/ suggests that the three-way stop contrast, which has been generally known to be due to differences in laryngeal settings, is indeed kinematically realized in the suparlaryngeal dimension. In particular, the longer constriction duration for the fortis stop (possibly with stronger articulation) appears to be compatible with the view that the fortis stop is produced with heightened articulatory force (Son et al., in press) along with possible elevated respiratory force which may be responsible for some of the laryngeal characteristics of the fortis stop (Ladefoged & Maddieson, 1996).

The present study also compared the constriction characteristics of the three-way contrastive stops with those of /n/. It was found that the constriciton duration for the nasal /n/ was quite similar to that for the lenis /t/, showing a pattern of (/n/=/t/)</t^h/</t*/. Furthermore, the tongue body position at the constriction maximum point was lower for /n/ than for /t/, showing a pattern of /n/</t/<(/t^h/=/t*/). These results suggest that /n/ is articulatorily at least as week as the lenis /t/. The weak articulatory characteristics of /n/ may be due to the fact that /n/ is characterized primarily by the nasal flow, thus requiring a minimal constriction force enough to prevent the leakage of the airflow through the oral cavity.

4.2 The kinematics of the tongue tip (TT) movement

The present study also examined the TT opening and closing movement data with kinematic parameters such as the TT opening/closing movement duration, displacement, and peak velocity.

The TT closing movement data showed no significant consonant-induced differences in both the spatial and the temporal dimensions, suggesting that consonants /n, t, t^h, t*/ are not

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[4] The results about the tongue body position, however, may be interpreted from a slightly different perspective. The lower tongue body position for the lenis /t/ may be at least partially due to speakers' maneuver to facilitate voicing. The lenis stop /t/ is produced as voiced as some kind of intervocalic weakening phenomenon (e.g., Jun, 1995). Lowering the tongue body may be considered as the speaker's active vocal tract expansion which would facilitate maintenance of voicing during closure (e.g., Ohala, 1997).

differentiated in the tongue tip closing kinematics.

As for the TT opening movement, results showed a significant Consonant effect on the TT opening displacement: /n, t/ were produced with larger TT opening displacement than for /t^h, t*/. Results also showed that /n, t/ tended to be produced with higher peak velocity than /t^h, t*/, although the effect was only marginal. These results, together, suggest that there is a clear-cut division of consonants /n, t, t^h, t*/ into /n, t/ and /t^h, t*/, which may be based on the differential articulatory nature; weak versus strong.

The TT opening displacement pattern, however, is different from that of the lip opening kinematics reported in Son et al. (in press): Son et al showed more lip opening displacement for stronger consonants /p^h, p*/ than for the lenis /p/, which is the opposite of the TT opening displacement found in the present study—i.e., lower TT opening displacement for /t/. We do not have a clear explanation for the discrepancy: why /n, t/ are produced with a greater TT opening displacement (possibly with increased peak velocity) than /t^h, t*/, but why the opposite is true for the lip opening displacement for /p^h, p*/. One possibility that we can think of at the moment has to do with contribution of higher tongue body positions associated with the stronger consonants /t^h, t*/. The higher tongue body during /t^h, t*/ may impede the tongue lowering, constraining the tongue tip lowering as well. The lip opening, on the other hand, may be less influenced by the tongue body position, characterizing consonantal differences more directly. More work is certainly needed to test this possibility.

4.3 Consonantal influence on vocalic articulation

Another question that the present study has aimed to answer is whether the vocalic articulation may be modulated according to the assumed differential strength of the consonant type. For this, the tongue dorsum position was measured at various points during the tongue tip closing and opening movements. One of the clearest patterns that were observed in the present study was that /n/ was produced with a lowered tongue dorsum position at various measurement points (at the TT closing onset, the TT constriction maximum, the TT opening onset, the TT opening peak velocity and the TT opening movement target). This may be interpreted as suggesting that the flanking vowel /a/ is influenced less by the nasal /n/ than oral stops (/t, t^h, t*/). This is in line with the assumption that CV coarticulation is inversely correlated with the consonantal strength such that the weaker the consonantal articulation, the lesser degree of its coarticulatory influence on the following vowel (Recasens, 1999).

However, the tongue dorsum position did not vary as a function of consonant type among oral consonants (/t, t^h, t*/), indicating that the vocalic articulation is not influenced by the three-way stop contrast at least for the coronal consonants /t, t^h, t*/. This is again contradictory to the pattern found for labial stops /p, p^h, p*/, which showed systematic influence of the consonant type on the tongue dorsum articulation: the lenis /p/ was produced with lowered tongue dorsum position than /p^h/ and /p*/ (Son & Cho, 2010). Recall, however, that the present study showed lowered tongue *body* position for the lenis /t/ than for the stronger consonants /t^h/ and /t*/, which may be interpreted at least partially as vocalic characteristics of the following vowel. It is still unclear why the tongue body, and why not the tongue dorsum, showed the differential pattern as a function of the consonant type. The major difference between the coronal stop series and the labial stop series lies in that the coronal stops are produced with the tongue tip as part of the tongue which also involves the vocalic articulation, whereas the bilabials stops are produced with lips which are more independent of the vocalic tongue movement. Articulatory movement patterns may be constrained by the physiological difference, which may show consonantal effects on the tongue body position (when the tongue tip is involved for /t, t^h, t*/) or the tongue dorsum position (when the consonantal articulation is minimally restrictive of the tongue movement in the case of /p, p^h, p*/).

4.4 Consonantal effects on the jaw

In the present study, we also measured the jaw position aligned with the tongue tip constriction maximum point in time. The results showed a binary distinction (the nasal /n/ versus oral stops /t, t^h ,t*/)—i.e., the jaw is lower for the nasal /n/ than for the oral stops (/t, t^h, t*/), while no difference was observed between oral stops.

The jaw is a shared articulator among the lips (labials), the tongue tip (coronals), and the tongue dorsum (dorsals) (e.g., Browman & Goldstein, 1991), and the jaw position tends to be related with the degree of sonority: the lower the jaw, the more sonorous the sound is (e.g., Lindblom, 1983). Mooshammer et al. (2007) observed the jaw height which showed an order of /t/>/d/>/n/, which is matched with the assumed sonority hierarchy. The results of the present study showed that at least /n/ is more sonorous than the oral stops. However, given that the degree of sonority is reflected not only in the jaw height, but also in the overall opening amount of the oral cavity, the lower tongue body position for the lenis /t/ than for /t^h, t*/ does indicate that the

Korean lenis /t/ may be more sonorous than the fortis and the aspirated counterparts, which is further supported by the degree of lip aperture for labial stops reported in Son et al. (in press). It remains to be seen whether the three-way stop contrast is indeed marked by the jaw height, reflecting their sonority difference across different places of articulation including labial and velar stops.

5. Conclusion

Phonetic characteristics of the three-way stop contrast in Korean have been investigated primarily in connection with differential laryngeal settings for different consonant types. In the present study, we aimed to provide supralaryngeal articulatory (kinematic) data for the three-way stop contrast for denti-alveolar (coronal) stops /t, t^h, t*/ together with /n/, which have rarely been documented in the literature. The results show that the three-way stop contrast can be differentiated at the supralaryngeal level, especially in terms of constriction duration (/t/</t^h/</t*/), the tongue body position (higher for /t^h, t*/ than for /t/), and the tongue tip opening displacement (less displacement for /t^h, t*/ than for /t/). Furthermore, /n/ was found to pattern more closely with the lenis /t/, being characterized as articulatorily 'weak' consonants. All in all, the present study has provided more data which allow us to better understand supralaryngeal kinematic characteristics of the Korean consonants, and invite further work on kinematic characteristics of various sounds in Korean in order to obtain more balanced knowledge of the sound system of Korean.

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