INTERSPEECH 2021
30 August – 3 September, 2021, Brno, Czechia

Leveraging Real-time MRI for Illuminating Linguistic Velum Action

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Abstract

Velum actions are critical to differentiating oral and nasal sounds in spoken language; specifically in the latter, the velum is lowered to open the nasal port and allow nasal airflow. However, details on how the velum is lowered for nasal production in speech are scarce. State-of-the-art real-time Magnetic Resonance Imaging (rtMRI) can directly image the entirety of the moving vocal tract, providing spatiotemporal kinematic data of articulatory actions. Most instrumental studies of speech production explore oral constriction actions such as lip or tongue movements. RtMRI makes possible a quantitative assessment of non-oral and non-constriction actions, such as velum (and larynx) dynamics. This paper illustrates articulatory aspects of consonant nasality, which have previously been inferred from acoustic or aerodynamic data. Velum actions are quantified in spatial and temporal domains: i) vertical and horizontal velum positions during nasal consonant production are quantified to measure, respectively, the degree of velum lowering and velic opening, and ii) duration intervals for velum lowering, plateau, and raising are obtained to understand which portion of the velum action is lengthened to generate phonologically long nasality. Findings demonstrate that velum action tracking using rtMRI can illuminate linguistic modulations of nasality strength and length.

Index Terms: speech production, speech imaging, real-time MRI, articulatory phonology, velum, nasals, nasal consonants

1. Introduction

Articulatory studies using real-time MRI data have been focused on examining lingual articulation [1, 2, 3], although the non-lingual articulatory actions such as velum movement are also readily available. In contrast, other speech imaging techniques such as electromagnetic articulography and ultrasound are ill-suited to quantifying velum actions because of the difficulty in placing sensors on the velum or because the velum motions cannot be captured reliably. RtMRI data not only is effective for the study of non-oral vocal tract actions but also offers the advantage of its non-invasive and radiation-free environment.

Existing rtMRI studies on linguistic nasalization use different quantification methods to obtain kinematic information on velum actions. These might include for example: a single image frame of velum movement obtained by visually selecting the moment of velum opening in a video sequence [4, 5], a region of interest (ROI) technique measuring mean pixel intensity used to estimate velum actions [6], and a principal components analysis using voxel intensities in the ROI computed to create velum opening and closing signals [7, 8]. These studies either used static image frames or applied indirect measures to estimate velum actions. The current study instead uses a more direct measure to quantify velum movement; the present work uses rtMRI videos to track the physical movement of the velum lowering and raising actions by calculating intensity-weighted centroids of the velum and examining its time series [9]. This centroid tracking tool has been developed for speech imaging analysis especially for studying non-oral articulatory actions [9]. The centroid tracking analysis has been used for studies on vertical laryngeal actions [10, 11, 12] as well as in initial reports on velum actions and coordination with oral gestures [13, 14, 15]. The current study demonstrates the utility of centroid tracking in capturing velum actions in nasal production in natural speech, focusing on the internal behavior of the velum gesture alone.

Unlike lingual articulatory actions having constriction goals as their target, velum gestures are considered to have a velic aperture goal—the degree of opening relative to the rear velo-pharyngeal wall [16, 17, 18, 19]—this opening allows the nasal airflow that distinctively characterizes linguistically nasal sounds. Velum gestures have been phonologically described as having velum lowering and measured in terms of this velum lowering [5, 20]. In the present study, both the opening/closing movement and the lowering/raising movement of the velum are examined by calculating the horizontal (x) and vertical (y) components of the velum actions, respectively. Articulatory indices of nasality are illustrated in this study by quantifying both the spatial and the temporal patterns of velum actions in nasal consonants.

In the first portion of this work, the strength of nasality is spatially measured in a language reported to be undergoing context-dependent partial denasalization. In Korean, there is an on-going phonological sound change process of denasalization in which nasals in syllable onset position are said to be partially (or completely) de-nasalized or 'weakened' [21, 22, 23, 24]. This denasalization phenomenon is more robust in younger people, before a higher vowel, and in a higher prosodic domain [21, 22, 23]. Still, there exists very few instrumental results offering acoustic, articulatory and/or aerodymanic data on this phenomenon [22, 24]. Using real-time MRI data, we will be in the position to quantitatively assess the velic movements in nasals; especially whether this reported phonological phenomenon of onset nasal weakening is reflected in the articulation. It is predicted that syllable onset nasals have smaller velum lowering as well as smaller velic aperture compared to syllable coda nasals. Specifically, this study focuses on how velum actions are modulated to control the degree of nasality.

In the second portion of this work, velum actions with respect to short and long nasal consonants are examined to understand whether the non-oral velum gesture contributes to the length distinction, in addition to the component oral gesture. Articulatory studies on short and long consonants show that geminates (long consonants) have temporally longer lingua-

http://dx.doi.org/10.21437/Interspeech.2021-1823

palatal contact for oral closure/constriction duration [1, 2, 3, 25], as well as longer oral plateau duration for this action [26]. However, whether the non-constriction gestures lengthen as well for long consonants is not well documented. In the present study, a short coda nasal and a long nasal consonant (created across a word boundary, also called a 'juncture' geminate) in Korean are compared with regard to their velum duration. Korean short and long nasals are distinguished by acoustic duration factors such as oral closure duration and consonant to vowel ratio [27, 28, 29], but articulatory studies on Korean nasals and their velum behavior are scarce. The experiment tests whether velum duration differentiates these short versus long consonants, separately investigating the intervals of lowering, plateau, and raising of the velum actions.

The goal of this study is to understand the internal velum actions in the production of Korean nasal consonants in varying contexts of nasality. Velum magnitude is examined for onset and coda nasals, with the prediction that onsets exhibit articulatory correlates of weak nasality based on phonology of Korean. Additionally, velum duration is compared between short and long nasals, which are known to differ in length in their oral constriction actions.

2. Methods

Words containing nasal consonants were elicited from five native speakers of Korean. The speakers were in their mid 20s to early 30s at the time of the experiment. One speaker was born and raised in Incheon (S1), and the rest were from Seoul (S2-S5). Target items included were word-initial (/#n/; "#" marks a word boundary) and word-final nasals (/n#/), and long nasals spanning across a word boundary (/n#n/; a juncture nasal). Nasal sequences were elicited by combinations of words (i.e., nouns and numbers) ending and/or beginning with an alveolar nasal consonant /n/. Each item, placed in a frame sentence, was repeated 7-8 times in several prosodic conditions—Word and Accentual Phrase boundaries are examined here. Stimuli used in the experiment are listed in Table 1.

Table 1: *Stimuli used in the rtMRI experiment.*

	Noun	Number + Classifier
Onset nasal (/#n/)	[hatp*a] 'fishcake bar'	[**n**ɛ kɛ] 'four'
Coda nasal (/n#p/, /n#t/)	[ɕ^{h}ilp^{h}a**n**] 'blackboard'	[pɛk kɛ] 'a hundred' [tasʌt kɛ] 'five'
Juncture nasal (/n#n/)	[ɕ^{h}ilp^{h}a**n**] 'blackboard'	[**n**ɛ kɛ] 'four'

2.1. Data acquisition

RtMRI data of the midsagittal vocal tract and audio data were acquired using a rtMRI protocol developed at USC for speech production research [30, 31]. Speech imaging data were acquired with a field of view of 200 x 200 mm, a spatial resolution of 84 x 84 pixels, and a temporal reconstruction rate of 83 frames per second [32, 33]. The acquired data included the entire midsagittal plane of the vocal tract, allowing dynamic visualization of the lingual and velic articulation. Data collection followed the approved USC IRB protocol.

2.2. Data analysis

Articulatory landmarks of the velum (VEL) gestures—i.e., lowering onset, target, raising onset, and offset—were computed from the kinematic trajectories of the vertical and horizontal velum centroids, using an automated centroid tracking tool (see [9]) and the MVIEW find_gest algorithm [34]. Centroids are the intensity-weighted center positions of an object within a defined vocal tract region. In this analysis a triangular vocal tract region was selected to track velum movements while minimizing tongue body intrusion into the region (Figure 1).

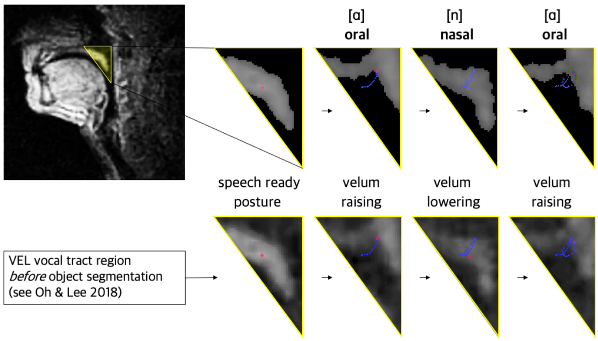

Figure 1: *Velum centroid tracking example for [ana].*

Figure 1 illustrates (from left to right) velum actions during a speech ready state (velum is lowered for breathing), as well as during the production of oral vowels (velum raised) and during a nasal consonant (velum lowered). In each image frame, the current centroids are marked with a red circle and past paths of centroids are marked with blue dots. Notice that velum moves in a diagonal direction, rather than raising and lowering strictly vertically.

Measurements included duration of *temporal intervals* for velum lowering, plateau, and raising (see Figure 2 upper labels), as well as spatial magnitudes of velum aperture, including absolute vertical and horizontal *displacement* values from the movement onset to its maximum (velum lowering [y-component] & velum opening [x-component] degree) and the absolute x and y *extrema* positions of the velum centroids when the velum is maximally lowered (velum lowering & opening extrema). Velum extrema are indicators of how far away and in which direction the velum has moved from the pharyngeal wall, which can give rise to changes in the amount of airflow through the nasal port, thus controlling the degree of nasality. Velum lowering measurements used for data analysis are displayed in Figure 2 (velum *opening* displacement & extremum values, not shown in the figure, are computed from the horizontal VEL centroids).

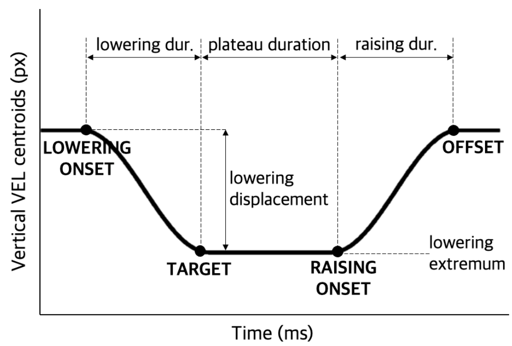

Figure 2: *VEL lowering spatiotemporal measurements based on temporal landmarks.*

3. Results

Linear mixed effects models with subjects and items as random effects and Tukey's post-hoc tests were used for statistical testing with a significance level set at $p < .05$. The results on the velum spatial kinematics are compared between syllable onset versus coda nasals (a fixed effect of syllable position), testing whether the velum actions (i.e., displacement and extremum) in the onset are weaker and thus involve smaller magnitude than those in the coda. The temporal results of velum actions (velum lowering, raising, and plateau durations) include comparisons between the short nasals (coda nasals) and the long nasals (juncture geminate nasals) with nasal length as a fixed effect.

3.1. Velum spatial actions

3.1.1. *Velum displacement*

The linear mixed effects models suggest that the amount of velum lowering ($F(1, 137.98) = 70.276$, $p < .001$) as well as the degree of velum opening ($F(1, 118.32) = 181.37$, $p < .001$; Figure 3) differentiate onset nasals versus coda nasals. The post-hoc tests indicate that nasals in onsets have smaller velum displacement than coda nasals (for both lowering and opening magnitude, /#n/ vs. /n#p/: $p < .001$; /#n/ vs. /n#t/: $p < .001$), while no magnitude difference is found between two contextually differing codas (/n#p/ vs. /n#t/).

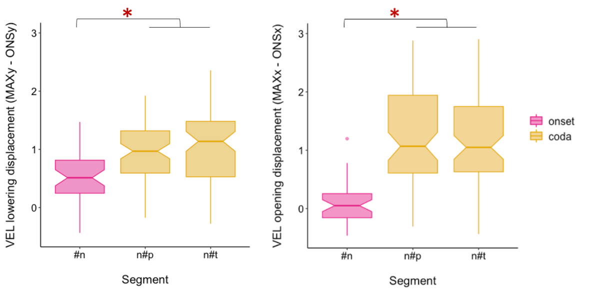

Figure 3: *Velum lowering & opening displacement.*

3.1.2. *Velum extremum*

In addition to velum displacement, velum extremum values—i.e., absolute spatial positions when velum is at its lowest posture—are examined. No effect of syllable position is found in the velum lowering extremum ($F(1, 105.65) = 2.631$, $p = .108$), suggesting that the velum's vertical extremum positions are indistinguishable between onset and coda nasals. On the other hand, velum opening extremum distinguishes onset nasals from coda nasals ($F(1, 149.3) = 319.91$, $p < .001$; Figure 4), onset nasals having smaller opening extrema than both coda nasals ($p < .001$). Again, no difference in opening extrema is observed between two coda nasals.

Velum extrema patterns for three individual speakers are presented in Figure 5 (results for S1 and S5 are excluded because of a small number of existing datapoints for onset nasals [S1: four out of 16 tokens; S5: one out of 16 tokens]; the individual variations will be further described in the Discussion).

The individual results also show that lowering extremum positions are highly overlapping between onsets and codas and not differentiated (S3: $p = .541$; S4: $p = .098$), except for S2 (onset extremum is higher than coda extremum, $p < .001$). Onsets and codas are in fact more separated by the velum opening extrema, exhibiting a bimodal distribution. For all three speakers, onset nasals have less extreme velum opening. This indicates that velum positions when maximally lowered are closer to the pharyngeal wall in the Korean syllable onset nasals compared to the coda nasals ($p < .001$).

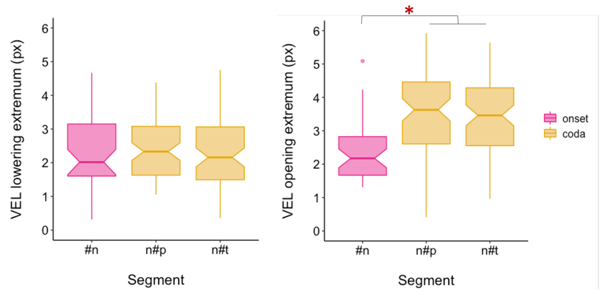

Figure 4: *Velum lowering & opening extremum.*

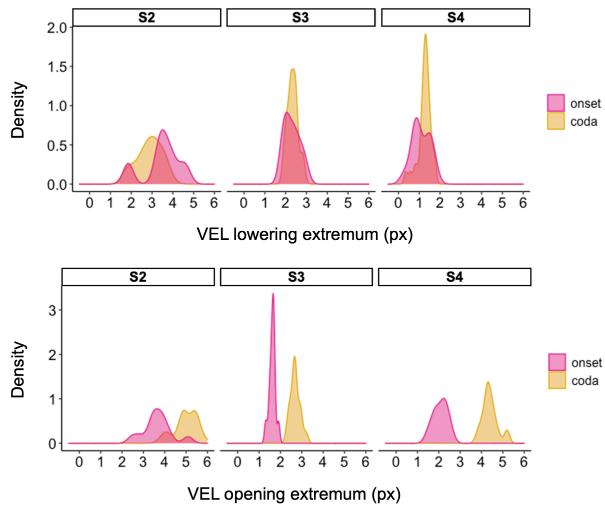

Figure 5: *VEL lowering extremum (top) & VEL opening extremum (bottom) for each speaker.*

3.2. Velum duration

Duration intervals of the velum gestures are investigated to observe which portions of the velum movement, if any, contribute to phonological length distinctions between the short and the long juncture nasal consonants.

The velum plateaus—that is, the time the velum remains at its lowest posture—do not differentiate short and long nasals ($F(1, 176.38) = 0.475$, $p = .492$; Figure 6). In fact, the velum plateau duration is short in general, the majority of data points being scattered around 20 msec (Figure 7).

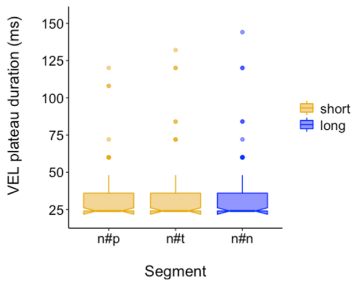

Figure 6: *Velum plateau duration.*

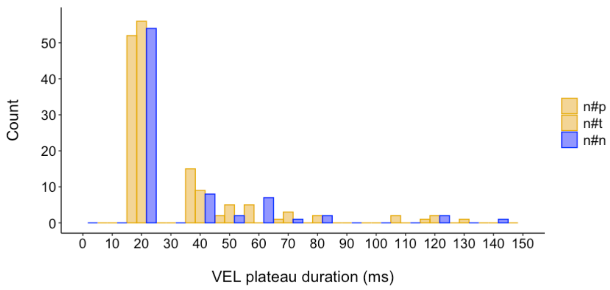

Figure 7: *Histogram of velum plateau duration.*

Next, velum lowering and raising durations are examined separately. Figure 8 shows that velum lowering duration does not distinguish the two nasals with different categorical length, but velum raising duration is significantly different between the short and the long juncture nasal consonants ($F(1, 175.78) = 23.948$, $p < .001$). Post-hoc comparisons for velum raising duration further show that short coda nasals have shorter raising duration than long geminate nasals (/n#p/ vs. /n#n/ & /n#t/ vs. /n#n/; all $p < .001$), while the two short nasals are not differentiated by raising duration.

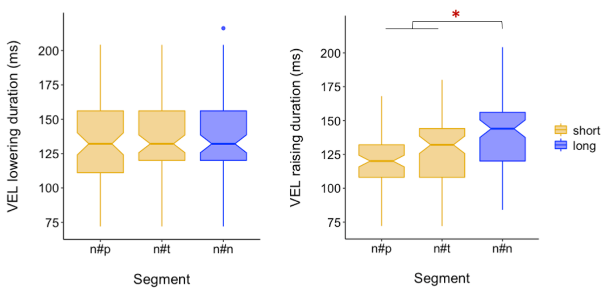

Figure 8: *Velum lowering & raising duration.*

4. Discussion

Instrumental findings on velum activities for various nasal consonants suggest that linguistic velum gestures have linguistically important fine-grained and complex articulatory characteristics. Merely defining the goal for velum actions as having a binary state of either open or closed may not be sufficiently informative in understanding linguistic phenomena.

While the lowest absolute position of the velum does not differ between the Korean onset and coda nasals, a crucial difference is found in the velic opening extremum position as a function of syllable position. That is, Korean onset nasality weakening is articulatory realized as onsets having a small velic opening, rather than lesser lowering *per se*. Furthermore, phonological contrast in length between the Korean short nasal and a long juncture nasal consonant is created by lengthening (or delaying or slowing) the velum raising movement, so that it takes longer for the velum to be completely re-sealed. Velum lowering and plateau durations, however, do not contribute to the length distinction in these nasal consonants. Thus, rather than how long the velum stays low, how long the velum remains open may be the important index of consonant nasality duration in these boundary-adjacent Korean nasals.

Directly assessing spatiotemporal patterns of velum actions in nasals illuminates how non-oral, non-constriction gestures may be controlled differently from the better studied oral constriction gestures serving phonological contrast. For example, lingual articulatory gestures have been seen to increase in oral closure or contact duration as well as oral plateau duration for long consonants compared to short consonants [1, 2, 3, 25]; velum gestures in the present data, on the other hand, have neither longer lowering nor plateau durations for long juncture geminate consonants. In English nasals, however, velum plateau duration has been shown to distinguish codas from juncture geminates [19]. This suggests that velum actions may have different mechanisms depending on the language specific intergestural coupling structures.

The rtMRI articulatory imaging data accompanied by the centroid image tracking technique [9] allows the quantification of varying degrees of nasality, which can be affected by syllable structure and associated phonological phenomena such as nasal weakening. In fact, velum actions can even be entirely non-existent when nasals undergo complete denasalization. Current results include individual variation in the amount of denasalization in Korean nasal consonants; Speakers S1 and S5's data had no quantifiable velum movements in the onset nasals exclusively except for a few tokens. For these speakers, velum gestures were in contrast identifiable in the production of coda nasals at all times. Recall that onset denasalization in Korean is known to be more robust for young speakers [23], and speaker S5 is indeed the youngest speaker (25 years old) while the average age of other four speakers is 30.5 years old. Dialectal influence may also play a role, given that Speaker S1 is born and raised in Incheon and other four subjects are from Seoul.

With the availability of quantifiable velum action data using real-time MRI, further inquiry illuminating the articulation of nasalization—including the intergestural timing between oral and velum actions—can now be tackled (see [35]). Previous documentation of oral-velum intergestural timing using rtMRI in French and English [4, 6, 19] has explored timing relations between various landmarks of the oral gesture and the initial timepoint of the velum movement. Information of the *internal* behavior of velum actions—the focus of the current study—can be further exploited to investigate other linguistically important relative timing between the oral and the velum gestures, using more extensive temporal landmarks of velum lowering and raising actions.

5. Conclusions

The real-time MRI articulatory data and findings of this study provide deeper insights into the geometry of the component velum gesture associated with nasal consonant production. The Korean data suggest that weakening in nasality may be associated with smaller velic aperture rather than with the lowest velum position during nasal production. Moreover, unlike oral constriction gestures where the durational difference between short and long consonants is found at the closure and/or plateau intervals, velum movement in the Korean long juncture geminate nasals, compared to short coda nasals, lengthen only while raising the velum. In sum, the present study illustrates the efficiency and utility of real-time MRI as an instrumental tool for understanding linguistically informative non-oral and non-constriction articulatory action dynamics.

6. Acknowledgements

This work was supported by NIH DC007124 [Narayanan].

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