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An ultrasound study on articulatory variations of Korean [n][*]

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Ahn, Miyeon and Gwanhi Yun. 2026. An ultrasound study on articulatory variations of Korean [n]. *Linguistic Research* 43(1): 185-208. The present study aims to explore the articulatory consequences of three types of Korean [n] - canonical, inserted and nasalized - that are derived from phonologically different input representations. We hypothesized that the three [n] sounds are articulatory variants arising from differences in speakers' distinct production planning, shaped by their consideration of phonological rule applications. An ultrasound study was conducted to test this hypothesis, and the data revealed that, for half of the participants, ascending tongue tip gestures were observed in the order of canonical, nasal and inserted, corresponding to increasing phonological processing complexity, while the other half did not show this pattern. Speakers' production of articulatory variants suggests that they make extra articulatory efforts to reach the target more precisely for phonologically more complex variants and that they plan their speech to deliver their rule applications. **(Hankyong National University · Daegu University)**

Keywords Korean [n], canonical, inserted, nasalized, ultrasound study

1. Introduction

Phonetic variation arises due to both linguistic (e.g., speech rate or phonological contexts) and non-linguistic (e.g., gender or emotional state) factors (Clopper and Turnbull 2018; Purse et al. 2021). It is therefore unsurprising that a speech sound often sounds quite different across diverse phonetic environments, as it is influenced by adjacent sounds, known as coarticulatory effect.

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In the present study, we explore phonetic variants that emerge despite of identical phonetic/phonological environments. With a specific focus on Korean /n/, we examine how articulatory variants arise from phonemically identical output representations. In Korean, the surface [n] sounds presumably originate from three distinct underlying inputs, as illustrated in Table 1.

Table 1. The three types of Korean [n] sounds and example words

	Types	Example words			gloss
		Underlying form		Surface form	
a.	canonical	/sʌŋn̠jaŋ/	→	[sʌŋn̠jaŋ]	'matches'
b.	inserted	/tʃom_jak/	→	[tʃomn̠jak]	'mothballs'
c.	nasalized	/taml̠jʌk/	→	[tamn̠jʌk]	'courage'

The [n] sound in (a) represents a canonical example (henceforth, a canonical [n]), where the surface output form [n] directly corresponds to its underlying input. As in (b), the [n] may be an inserted segment (henceforth, an inserted [n]), as the underlying input does not contain a corresponding [n] sound. This [n] is epenthesized as a result of a phonological rule application that triggers the insertion of a [n] sound before a high vocoid in Korean (i.e., ø → [n] / __ [i, j]) (Han 1994; Hong 2003, 2006; Jun 2015, 2021). The [n] in (c) indicates a nasalized output segment (henceforth, a nasalized [n]) derived from an underlying liquid input, which undergoes a change from a liquid /l/ to a nasal [n] during the derivation (Han 1993; Iverson and Sohn 1994; Seo 2001, 2004).

From the perspective of phonological rule application, the canonical [n] does not involve any rule applications, as both the underlying and surface forms contain the same segment. That is, the mapping /n/ ~ [n] involves no phonological change. This input-to-output mapping, or the phonological derivation, is therefore straightforward and unlikely to be considered complicated in terms of phonological rule application. In contrast, the mapping ø ~ [n] in cases of inserted [n] may be considered rather complicated, as it requires the application of a phonological rule that inserts an additional segment that is absent from the underlying input whenever the phonological conditions are met. The nasalized [n] can also be considered complicated, as it still involves a segmental transformation, the change from /l/ to [n]. In summary, in term of phonological rule application, the canonical [n] is relatively less complicated, whereas both the inserted [n] and the nasalized [n] are fairly more complicated because they are phonologically derived, i.e., they involve active phonological processes.

Comparing the inserted [n] and the nasalized [n], then, it is arguably the case that the phonological change involved in the nasalized [n] is less radical than that involved in the inserted [n]. The change from /l/ to [n] requires only phonological featural modification, specifically a change in the manner of articulation from a liquid to a nasal, whereas the ø ~ [n] mapping introduces epenthesis, namely, the insertion of an entirely new segment that is not present from the underlying input representation. The degree to which a rule application is complicated may be partly calculated by quantifying the number of phonological features that a rule deletes, adds, or alters (Lee 2004: 139). Under this definition, the nasalized [n] (/l/ → [n]) involves the modification of two feature values, i.e., [−nasal] → [+nasal] and [+liquid] → [−liquid]. In contrast, the inserted [n] requires the addition of multiple features, including [−continuant], [−delayed release], [+nasal], [−liquid], [−tense], [−aspirated], among others. Thus, the inserted [n] may be considered to involve more complicated phonological rule applications than the nasalized [n].

In sum, considering the differences between the three output nasals and their respective input correspondents, the hierarchy of the input-output phonological difference would then be defined as follows: Δ /n/ ~ [n] (the canonical [n]) < Δ /l/ ~ [n] (the nasalized [n]) < Δ ø ~ [n] (the inserted [n]). Under this hierarchy, the canonical [n] exhibit the smallest degree of phonological difference between the input and output, the inserted [n] the largest, and the nasalized [n] falls in between.

We hypothesize in this study that as the input–output difference increases, the phonological rules applied to an output become more complex, which in turn generates greater cognitive load for language users. Therefore, as language users experience greater cognitive load, phonological complexity increases. In this discussion, phonological complexity is defined, from a cognitive perspective, as the cognitive load that language users experience during phonological processing, arising from complex derivational procedures. Thus, phonological complexity herein refers to complexity in phonological processing, in contrast to previous studies that define it in terms of the structural complexity of a phonological system in a language (Maddieson 2007) or learnability (Gierut 2007).

This view of phonological complexity opens up the question of how phonological rule applications are associated with articulatory variation. It is commonly assumed that when speakers plan their speech, the production process is staged (Levelt et al. 1999). Once a lexical representation is selected after an intended message is conceptualized, its component phonemes are activated, and then phonologically encoded inputs are sent to articulation. During the stage of phonological encoding, phoneme activations occurring serially rather than simultaneously (Sevald and Dell 1994). It may be assumed then that, as for the phonological difficulty in a reading task, phonemes that are present in the spelling can be relatively easily retrieved. In contrast, phonemes that are absent from the orthographic form require speakers to plan their speech differently, resulting in increased processing difficulty.

In research exploring the relationship between phonological encoding and word duration, Yiu and Watson (2015) showed that phonological difficulty in production partly account for variability in word duration, such that lengthening may occur when speakers require additional processing time during phonological encoding, as it allows more planning time during the procedure. If phonological difficulty extends the production process and influences phonological selection, then phonological complexity is likely to play a role in speakers' production planning as well.

In this study, we hypothesize that phonological complexity influences speakers to adjust their speech planning such that, as complexity increases, their articulatory gestures vary accordingly. Specifically, if speakers' production reflects phonological processing complexity, we would expect the articulation of the phonologically complex nasals to differ from that of less complex ones. As phonological complexity increases, speakers are likely to require more time for production planing; thus, the articulatory gestures for the complex inserted [n] variant may differ from those of the least complex canonical [n] variant, with the medially complex nasal [n] variant falling in between. The purpose of this study, then, is to explore whether phonological processing complexity is linked to production planning by examining the three types of Korean [n] sounds. Although these sounds are phonemically identical, they may still exhibit articulatory variation, with tongue gestures becoming more or less extended depending on the phonological complexity involved. To investigate this, we designed an ultrasound study to examine the articulatory consequences of the three [n] variants.

2. Methods

2.1 Participants

Ten Korean-speaking participants (4 males and 6 females) were recruited from a university campus. All participants were in their 20s, native speakers of Seoul-Gyeonggi dialect of Korean, and none reported any hearing or speaking difficulties. Participation was voluntary, and participants were compensated for their time and contribution for the study.

2.2 Materials and procedure

Table 2 displays 45 bisyllabic target words involved in the reading list.[1] They were in the format of (C)VN._GV(C), where N (nasal) was either /m/ (15 out of 45 targets) or /ŋ/ (30 out of 45), followed by one of the three [n] variants and a G (glide). Syllable-final consonants were restricted to labials or velars in order to more precisely identify the inserted [n] or nasalized /l/ in the recorded image data and accurately extract tongue images corresponding to alveolar nasals. If the preceding consonants are alveolars, their primary articulators – namely, tongue blade and tip – overlap with those of [n]. Consequently, it may be difficult to determine whether the observed tongue configuration reflects the inserted or nasalized [n]. Since the inserted [n] typically appears between a nasal and a glide, we controlled phonological environments for the canonical and nasalized variants to be comparable to that of the inserted [n]. Each target word was embedded in the carrier phrase ‘ikʌn (this is) __’ to ensure a prosodic consistency.

Participants were invited to a sound-attenuated phonetics lab for the production experiment. The reading material was presented in a randomized order on an iPad screen positioned at eye level. One phase set consists of four phrases (the carrier + target word) and the participants were instructed to read one phrase at a time while keeping a ultrasound transducer fixed on their jaw. An ultrasound imaging

1 The word list may not be evenly distributed with respect to frequency and lexical composition, in that some of the list are Sino-Korean words while others are native Korean, and in terms of morphological composition, some of them are compounds, whereas some are not. It was challenging to collect an equal number of words across the three conditions as the set of words containing the inserted [n] words were limited. It should be noted that this imbalance may have some effect.

system using a MicrUS EXT-1H and Articulate Assistant Advanced (AAA) were used to capture and record the tongue gestures. The participants were asked to repeat the entire procedure four times.

Table 2. Wordlist for reading

Pre -C	canonical /n/ → [n]		inserted ø → [n]		nasalized /l/ → [n]	
/m/	/namnjʌ/	man and woman	/kam_jʌm/	infection	/tamljʌk/	courage
	/samnjʌn/	three years	/kʌm_jʌk/	quarantine	/kamljʌk/	resilience
	/samnjʌ/	three daughters	/kɨm_jʌn/	no smoking	/samljʌŋ/	Samryeong
	/kamnjʌŋ/	Kamnyong	/ham_jaŋ/	developing	/kamljaŋ/	losing
	/samnjaŋ/	Samnyang	/kjʌm_jaŋ/	humility	/hamljaŋ/	content
/ŋ/	/ʧhaŋnjʌŋ/	Changnyong	/ʧaŋ_jʌm/	enteritis	/kaŋljʌl/	intensity
	/kaŋnjʌŋ/	Kangnyong	/saŋ_jʌŋ/	playing	/ʧaŋljʌl/	fierce
	/toaŋnjʌk/	east side	/thoŋ_jʌk/	translation	/toŋljʌk/	power
	/saŋnjaŋ/	kindness	/kjʌŋ_jʌŋ/	management	/haŋljʌl/	lineage
	/sʌŋnjaŋ/	match	/ʧʌŋ_jʌl/	passion	/ʧhʌŋljaŋ/	refresh
	/soŋnjʌŋ/	year-end	/koŋ_jaŋ/	offering	/ʧhoŋljʌk/	full force
	/kuŋnjʌ/	court lady	/poŋ_jaŋ/	serving	/ʧhoŋljaŋ/	total amount
	/taŋnjo/	diabetes	/koŋ_joŋ/	public	/toŋljo/	colleague
	/suŋnjuŋ/	rice water	/jaŋ_juk/	nurture	/phuŋlju/	taste
	/paŋnjo/	micturition	/tɨŋ_joŋ/	elevation	/nɨŋljul/	efficiency
/k/	/sokni/	inner teeth	/mak_il/	manual labor	/pakli/	small profit
	/okni/	protruding teeth	/sok_ip/	inner leaf	/phokli/	profiteering
	/s*ʌkni/	rotten teeth	/pak_ip/	Gourd leaf	/kuklip/	national

2.3 Data analysis

Upon collecting all the experimental data, tokens that lacked [n] insertion where it was expected were considered insertion failures and were discarded. In particular, 72 tokens from the recordings of two works /kɨm_jʌn/ 'no smoking' and /ham_jaŋ/ 'developing' exhibited extremely low rates of [n]-insertion (i.e., below 10%) and were therefore excluded from further articulatory analyses. In total, 409 tokens were also removed from consideration in the articulatory analyses for the tongue images because they were judged to be the cases in which [n]-insertion did not occur. Incomplete recordings were also excluded. Although Seoul Korean speakers' [n]-insertion is morpheme-dependent in that they insert the epenthetic [n] after a free stem or a prefix, but not after a bound root (Han 1994; Jun 2021), the participants in the current study exhibited gradient [n]-insertion patterns, with some instances of insertion and others without, even within identical contexts - indicating either variability or adherence to orthographic cues. The rest of valid ultrasound data were sent for tongue contour extraction.

Figure 1 (a) shows an example ultrasound midsagittal image of a Korean [n] in [namnjʌ] 'male and female', a the mid-point of the syllable-initial [n]. Since the goal of the study was to investigate the tongue front placement in relation to the height of the nasal [n], the tongue front region in the extracted image was selected for analysis, as indicated by the white box in the figure. The left side of each image represents the tongue back, and the right side corresponds to the tongue front. The white box highlights the tongue front region. Insofar as the main target phoneme in this study is the alveolar [n], and the primary active articulator involved in its production is the tongue front – specifically, the tongue blade and tip, which raise toward the alveolar ridge – this box indicates the region of interest. The degree of tongue raising within this region was used to compare the height of the alveolar [n] consistently across the three types of [n] sounds.

In examining the region of interest, the tongue body contour was divided into three parts, following the method in Allen et al. (2013). The 'tongue root' region (I) was located at 45° to the leftward of center, while the tongue dorsum region (II) was designated at 25° rightward of center. The remaining portion of the tongue contour was considered as the tongue front part region (III), the main interest in this study.

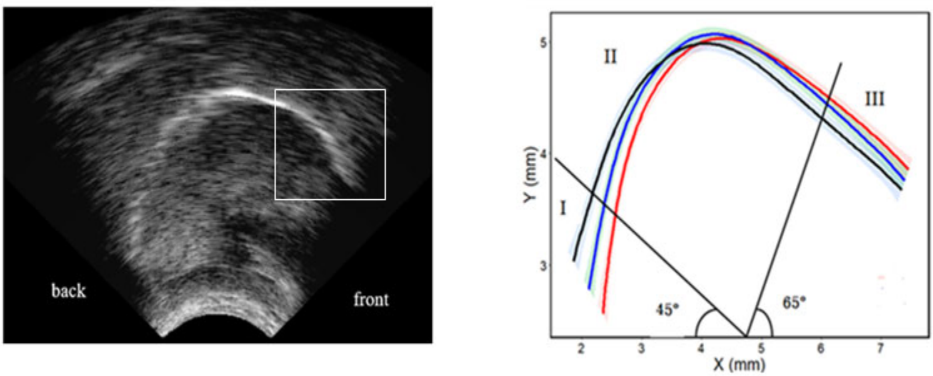


Figure 1. (a) An ultrasound image of Korean [n] (left)
(b) Tongue root I; tongue dorsum II; tongue front III (right)

To quantify tongue configuration, the extracted ultrasound images were overlaid with tongue contours by drawing tongue body lines using the "Edit Splines" function in AAA. Since the tracking method available in the current version of AAA requires manual intervention, all midsagittal tongue contours were manually traced by connecting 36 points along the tongue body line using a computer mouse and the "Edit Splines" function in AAA (Heyne et al. 2019; Mielke 2015). The tongue contours were then extracted as a series of 36 (x-y) coordinates. The x-axis represents tongue anteriority, while the y-axis corresponds to tongue height. The tongue splines were exported based on 36 fan line overlaid on the images by clicking the 'Export' button in the 'Spline Workspace' window, resulting in 36 x-y coordinates being saved to Excel files. The adjusted tongue contours were subjected to a Smoothing Spline Analysis of Variance (henceforth, SSANOVA) for the statistical analysis (Davidson 2006a; Gu 2002, 2014). This method visualizes tongue shape during articulation across the three different Korean [n] sounds, and is useful for determining whether there are significant differences between the smoothing splines that best fit for the data sets being compared. However, Cartesian coordinate-based SSANOVA has been pointed out to be less appropriate particularly for tongue tip or root data due to regional warping and wider confidence intervals (Mielke 2015). To overcome this drawback, the Cartesian coordinates of the tongue contours were converted to polar coordinates, with angular coordinate θ and radian coordinate r. These were then transformed back into Cartesian coordinates for visualization, following a polar

SSANOVA model (Mielke 2015; Heyne et al. 2019; Hussain and Mielke 2021).

Similarly to Cartesian SSANOVA, in the polar SSANOVA, significant differences between the two tongue contours were assessed by examining whether their confidence intervals overlapped. All SSANOVA figures displayed 95% confidence intervals with shaded regions. Overlapping intervals indicate non-significance, while non-overlapping intervals suggest a statistically significant difference between the two SSANOVA tongue curves ($p<.05$) (Gu 2002; Davidson 2006).

3. Results

The analysis of the results consists of two parts. First, we examined the relative frequencies of phonetic realizations of Korean [n] sounds occurring in the three phonological contexts (section 3.1). Second, we evaluated the extent to which canonical, inserted and nasalized [n] sounds differ in the magnitude of tongue blade and tip raising, with respect to the articulatory variability (section 3.2).

3.1 Labeling Analysis

To examine the relative occurrences of [n] in the three phonological contexts, phonetic labeling was performed on a total of 2,117 tokens extracted from ultrasound recordings of ten Seoul Korean speakers. Initial auditory judgment for each token was made by one of the researchers, a trained phonetician. This process yielded the number of tokens realized as [n] in canonical, inserted and nasalized contexts. To ensure reliability, the results were verified by another trained phonetician. The labeler assessed whether the the target consonant was phonetically realized as [n].

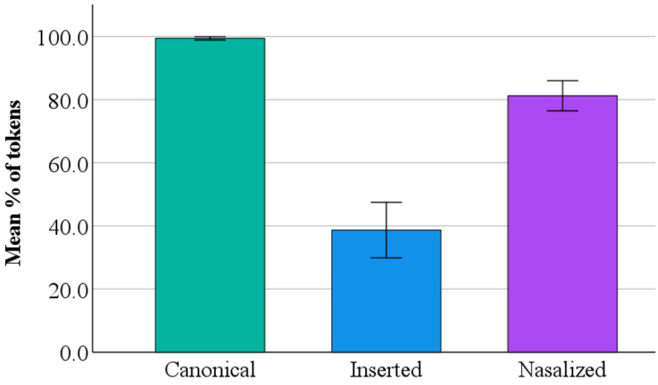


Figure 2. Percentages of tokens labeled as [n] for the canonical, inserted and nasalized [n]

Figure 2 shows the percentages of tokens realized as [n] in each of the three phonological contexts. A one-way ANOVA was conducted with phonological context as the independent variable and the rate of [n]-realization as the dependent variable to determine whether phonological context influences the applicability of each rule. The analysis showed that the differences in [n]-realization rates across the three phonological contexts were statistically significant ($F[2,57]=126.94$, $p=.000$). In addition, a post-hoc LSD test revealed significant pairwise differences among all three contexts in terms of realization rates ($p<.001$). As expected, almost all underlying /n/ segments following a nasal were realized as the [n] variant (99%). Additionally, 81% of underlying lateral /l/ segments in the nasalization context were labeled as [n] on the surface. This suggests that nasalization is not entirely obligatory for Seoul Korean speakers. Finally, in the inserted [n] context, phonological insertion occurred least frequently, accounting for 38% of instances across speakers. Phonetic variants which accounted for a vast majority of the tokens were either resyllabified forms such as [ka.mjʌm] or non-inserted forms without resyllabification of the preceding consonant such as [kam.jʌm] 'infection'. This finding does not align with previous studies that claim [n] is obligatorily epenthesized between a consonant and a glide in Sino-Korean words (Hong 2006; Lee and Lee 2006). Our phonetic labeling task indicates that Korean [n]-insertion is not obligatory but rather optional for Seoul Korean speakers. The difference in [n]-realization rates across the three phonological contexts was statistically significant ($F[2,57]=126.94$, $p=.000$).

Figure 3 presents the percentages of tokens realized as [n], categorized by the three phonological contexts and the types of preceding consonants. A two-way ANOVA revealed a significant main effect of phonological context ($F[2,57]=198$, $p=.000$), and a significant main effect of preceding consonant also emerged ($F[2,57]=8.50$, $p=.001$). Interaction between phonological context and preceding consonant was significant ($F[4,57]=7.64$, $p=.000$). Specifically, nasalized [n] was similarly frequent across all preceding consonants: 89% for [k], 85% for [m], and 78% for [ŋ]. In the inserted [n] context, [n]-epenthesis occurred most frequently when the preceding consonant was [k] (61%), followed by [ŋ] (38%). It was least common when the preceding consonant was [m] (22%). These results indicate that [n]-insertion is not obligatory and that the rates of epenthetic [n] occurrences varies depending on the preceding consonant for Seoul Korean speakers.

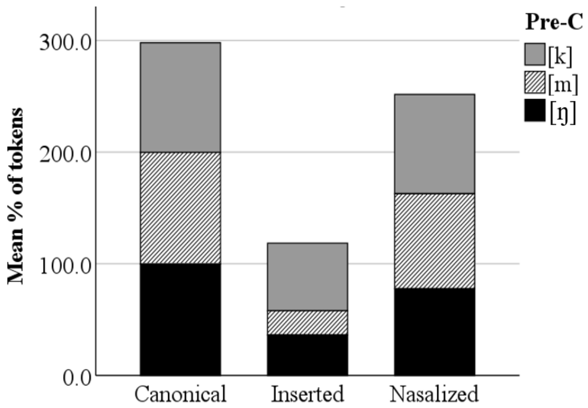


Figure 3. Percentages of tokens labeled as [n] by preceding consonants and phonological contexts

Figure 4 displays the percentages of [n] tokens in the inserted [n] context, categorized by the preceding consonant. As reported, the rates of [n]-insertion were significantly affected by the underlying preceding consonant ($F[2,17]=11.71$, $p=.001$). The highest rates of inserted [n] occurred in after /k/ condition as in /makil/ → [maŋnil] 'manual labor'. This finding is somewhat interesting, and unexpected as it was initially expected that underlying nasals such as /m/ and /ŋ/ would be more likely to trigger [n]-insertion compared to underlying /k/ (or derived nasal [ŋ]), which eventually becomes a nasal (e.g., /kamjʌm/ vs. /makip/). In other words, syllable-final /m/ and /ŋ/ tended not to induce [n]-insertion; instead, [m] appears to be resyllabified onto the onset position of the following syllable, whereas [ŋ] is likely retained in the coda position of the preceding syllable.

As discussed above, these findings are not comparable with previous studies showing that [n]-insertion is an obligatory phonological process occurring between a consonant and [j] in Sino Korean two-root compounds (Hong 2006; Lee and Lee 2006). All stimuli used in the present study were disyllabic, two-root syllables from Sino-Korean compounds. Contrary to expectation, [n]-insertion was quite rare and varied depending on the type of preceding consonants. This novel finding calls for a reconsideration of the phonological status of the [n]-insertion rule in Seoul Korean. In other words, it may be the case that [n]-epenthesis may be optional and gradient, unlike the traditional description.

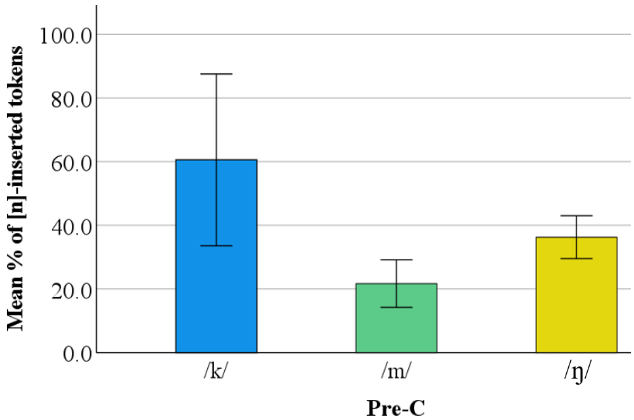
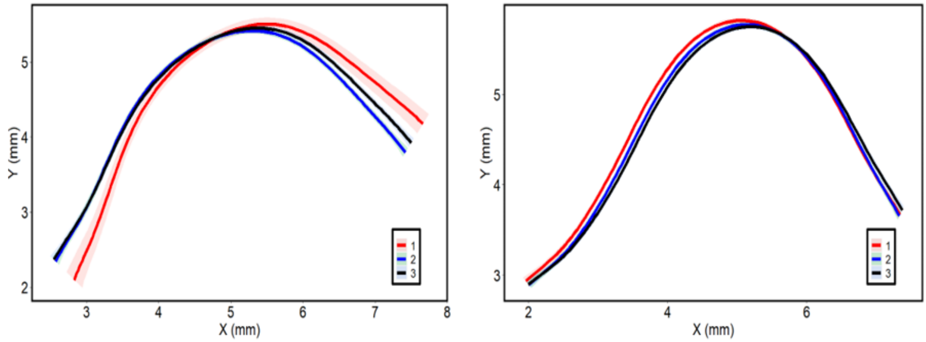


Figure 4. Percentages of tokens labeled as [n] in the inserted [n] context

In sum, the auditory judgment analysis demonstrates that inserted [n] was perceived relatively infrequently in the inserted [n] context, compared to the nasalized [n] context (38% vs. 81%). Furthermore, there was considerable variability in the likelihood of [n]-epenthesis depending on the type of underlying, preceding consonant.

3.2 Articulatory analysis

We first examine the effect of phonological environment on the tongue front position for Korean [n], focusing on the height of the tongue blade and tip at the alveolar ridge. Based on auditory judgments, only the tokens realized as [n] were included in the subsequent articulatory analyses. Tongue dorsum contours were averaged across syllable codas for each speaker. In each SSANOVA figure, tongue contours for the [n] was compared across three phonological contexts: the red curve (1) represents inserted [n], the black curve (2) represents canonical [n], and the blue curve (3) represents nasalized [n].



(a) Type I (from SK02) (b) Type II (from SK04)

Figure 5. SSANOVA comparisons of three [n] per speaker: inserted [n] (red curve: 1), canonical [n] (black curve: 2), and nasalized [n] (blue curve: 3)

Figure 5 displays two types of SSANOVA triplet comparison patterns, based on ten comparisons from ten speakers. As illustrated in Figure 5(a), Type I represents a pattern in which the tongue front is raised highest toward the alveolar ridge for the inserted [n], intermediate for the canonical [n], and lowest for the nasalized [n]. This pattern was observed among five Seoul Korean speakers (SK01, SK02, SK03, SK05, and SK08). This finding aligns with our expectations based on previous acoustic results, in that a longer closure duration for the inserted [n] is accompanied by a greater degree of tongue front raising, compared to the derived [n] (e.g., [n] in /kam_jʌm/ → [kamnjʌm] 'infection' vs. [n] in /tamlʌk/ → [tamnjʌk] 'courage'). Notably, in this type, the derived [n] was produced with less tongue front raising than the underlying /n/. This suggests that target undershoot occurred, and that phonological nasalization in this context may be incomplete with respect to tongue blade and tip raising.

Figure 5(b), on the other hand, displays a distinct pattern observed in the other five SK speakers categorized as Type II (SK04, SK06, SK07, SK09, and SK10). In this type, the tongue front positions of [n] largely overlap and appear similar across the three phonological contexts. In this figure, the tongue dorsum and tongue root appear similar across the three [n] types. Specifically, the tongue front (i.e., tongue blade and tip) is raised to the same height toward the alveolar ridge for [n] in all three phonological conditions. Focusing on the the location and height of the tongue front, and in comparison to the underlying /n/, it is evident that the inserted [n] reaches the exact articulatory target, namely, the alveolar ridge, while the derived [n] successfully preserves the place of articulation despite undergoing nasalization (i.e., /l/ → [n]).

The distribution of speakers is similar between Type I and II, and inter-speaker variation regarding the relative loci of the tongue front for [n] indicates that the speakers classified as exhibiting Type I pattern employ articulatory strategy to distinguish among the [n] sounds in different phonological contexts. Specifically, Type I speakers exhibit hyper-articulation of the inserted [n] and hypo-articulation of the nasalized [n] in terms of tongue front placement. Figure 6 presents polar SSANOVA comparisons of tongue contours for the three [n] sounds by each speaker.

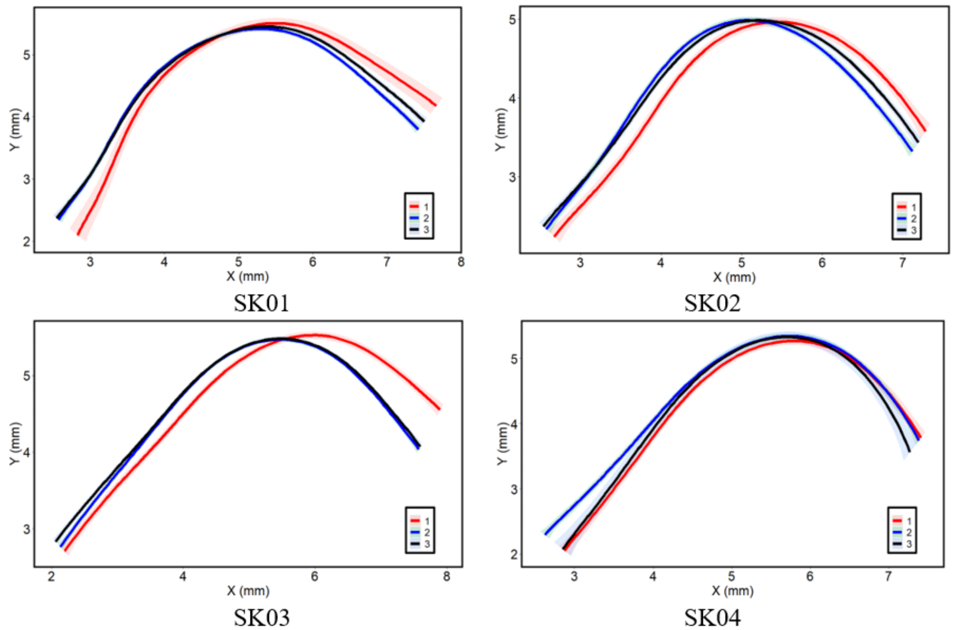
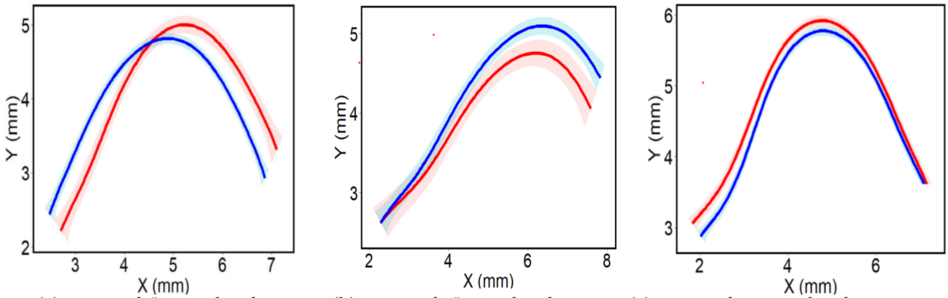


Figure 6. SSANOVA comparisons of three [n]s for ten SK speakers: inserted [n] (red curves: 1), canonical [n] (black curves: 2), and nasalized [n] (blue curves: 3)

3.2.1 Pattern variability in coda /m/ condition

We examined the effect of the preceding consonant on the variability of tongue front placement across different phonological contexts. Depending on the relative position of the tongue front, the SSANOVA comparisons were classified into three types.



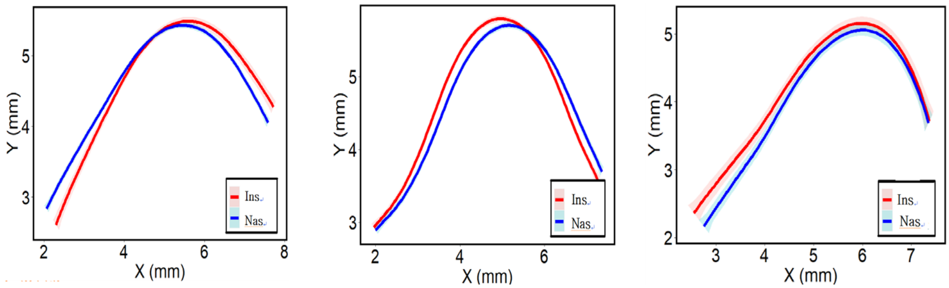
(a) Inserted 》 Nasalized (SK02) (b) Inserted 《 Nasalized (SK07) (c) Inserted ≈ Nasalized (SK09)

Figure 7. SSANOVA comparisons of two [n] sounds in the coda /m/ condition: inserted [n] (red curves) and nasalized [n] (blue curves)

Figure 7 presents comparisons of tongue contours for [n] sounds placed in the inserted (red curves) and nasalized (blue curves) contexts, when the preceding consonant was /m/. (Note that the canonical [n] was excluded to focus on the inserted and derived contexts). Figure 7(a) shows a pattern in which the inserted [n] is produced with greater fronting and higher tongue body raising compared to the nasalized [n]. This pattern parallels the general pattern observed when the preceding consonants /m/ and /ŋ/ are pooled, as reported in the previous section. This pattern – where the inserted [n] is seemingly hyper-articulated compared to the nasalized [n] - accounted for 53% of the comparison pairs. Figure 7(b) illustrates the opposite pattern, where the nasalized [n] is articulated with greater tongue front raising compared to the inserted [n]. This pattern was observed in 35% of the comparison pairs involving the /m/ condition. The least frequent pattern is shown in Figure 7(c), where no significant difference in tongue front region between the two kinds of [n] in the assimilated context (12%). Overall, the predominant pattern was the greater tongue body and tongue blade raising for the inserted [n] over the nasalized [n], possibly reflecting the longer closure duration associated with the former.

3.2.2 Pattern variability in coda /ŋ/ condition

Next, when the potential trigger coda consonant was a velar /ŋ/, all SSANOVA comparisons were classified based on the relative tongue front positions of the inserted and nasalized [n] sounds. Based on this criterion, three distinct variability patterns emerged. As seen in Figure 8(a), the first pattern shows the [n] produced with greater tongue front raising in the inserted context (e.g., /saŋ_jʌŋ/) compared to the nasalized environment. This pattern was shown in two Seoul Korean speakers (20%, SK03, SK10). In contrast, the opposite pattern was found for three speakers (40%, SK01, SK02, SK04 and SK06) as seen in Figure 8(b). In this pattern, nasalized [n] was articulated with greater tongue front raising compared to the inserted [n]. The final variant comparison type, shown in Figure 8(c), exhibits no distinction in tongue front placement between the two phonological contexts. Two speakers exhibited this pattern (20%, SK07 and SK08). Overall, this inter-speaker variation showed that Type II (Figure 8(b)) emerged in more speakers than the other two types.



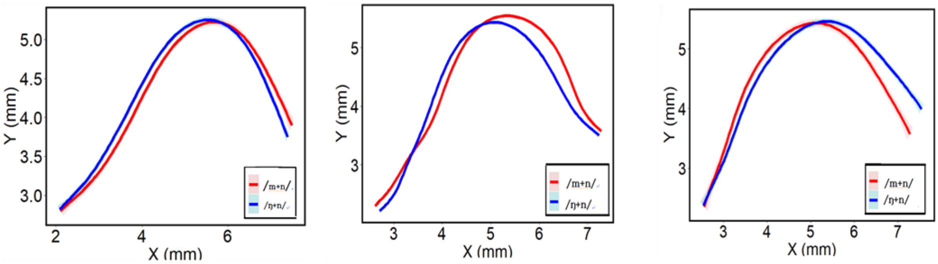
(a) Inserted 》 Derived (SK03) | (b) Inserted [n] 《 Derived [n] (SK02) | (c) Inserted ≈ Derived (SK08)

Figure 8. SSANOVA comparisons of two [n] sounds in the coda /ŋ/ condition: inserted [n] (red curves) and nasalized [n] (blue curves)

3.2.3 Consonantal effects on the [n] realization

Finally, we examined the effects of the preceding consonants on the degree of tongue blade raising, i. e., carry-over coarticulation across the three phonological contexts. Specifically, we investigated the relative positioning of tongue blade for [n] sounds when adjacent to a labial /m/ or a velar /ŋ/ in these contexts. Figure 9 illustrates the dominant C-to-C carryover coarticulatory effects, showing tongue placements of

[n] preceded by /m/ and /ŋ/ across the three phonological contexts. As seen in Figure 9(a), the canonical [n] was produced with a higher tongue blade when preceded by /m/ than by /ŋ/. The labial /m/ contributed more strongly to the raising of the tongue front of the following [n], compared to the velar /ŋ/. This predominant pattern was observed in seven out of ten Seoul speakers (70%), whereas the opposite pattern appeared in only three speakers (30%).



(a) canonical [n] (b) inserted [n] (c) nasalized [n]

Figure 9. SSANOVA comparisons of [n]s following [m] (red curves) and [ŋ] (blue curves) in the canonical, inserted and nasalized contexts

A similar pattern, i.e., a stronger coarticulatory effect of [m] over [ŋ] on the adjacent [n], was observed for the inserted [n], as shown in Figure 9(b). Raising of the tongue blade and tip was more facilitated by the preceding [m] than by [ŋ], and this pattern was also more prevalent than the opposite (52% vs. 21%). These findings indicate that the lingual movement of the primary articulator - the tongue blade and tip - for alveolar [n] was facilitated by the preceding [m], while the adjacent velar [ŋ] appears to inhibit the raising activity of the lamino-apical region of the following [n]. In other words, the greater articulatory flexibility of the lingual gesture associated with [m] may have promoted enhanced activation of the tongue blade and tip in the following alveolar [n]. Conversely, tongue back raising for [ŋ] may have interfered with the lingual gesture required for [n], as the antagonistic movements of the tongue back ([ŋ]] and tongue blade ([n]) can hinder effective tongue blade raising. In contrast, in the nasalization environment, the coarticulatory pattern diverged from those observed in the other two contexts. As depicted in Figure 9(c), tongue blade raising for [n] was greater when preceded by a velar than by a labial one (90% vs. 10%). This unexpected pattern warrants further investigation.

4. Discussion

The results indicate that the articulatory realizations of the three types of Korean [n] differ systematically, and that these articulatory variants are organized in a way that reflects underlying phonological complexity. In the following section, we address the relationship between phonological complexity and its articulatory consequences. We also consider the potential influence of coarticulatory effects and speakers' speech planning strategies.

4.1 The Relation between articulation and phonological complexity

Theories about speech production planning often assume that speech production consists of a series of distinctive processes in which speakers conceptualize the intended messages, formalize relevant linguistic structures and articulate the structures to linguistic outputs - speech (Levelt et al. 1999; Schiller 2006; Goldrick and Rapp 2007). Once lexical selection associated with the message is completed, speakers specify the relevant speech sounds based on their linguistic knowledge and allow articulators to perform the work according to this linguistic information.

The results of the ultrasound experiment in this study show that, among the three steps of speech production process, the articulation of linguistic structures is deeply engaged with the preceding stage - retrieving phonological knowledge (Alderete et al. 2021), namely, the phonological encoding. For half of the participants, greater tongue front raising was observed for the inserted [n] compared to the canonical and nasalized [n] sounds. Not only the tongue tip was raised toward the roof of the mouth but the tongue body was also more fronted for the inserted [n] compared to the other two [n] sounds. In contrast, the tongue position for the canonical [n], was significantly lower than that for the nasalized [n], with the tongue body positioned further back and the tongue tip lowered. Consequently, the tongue position for the nasalized [n] falls between those of the canonical [n] and inserted [n]. Considering the tongue positions for the three [n] sounds - arranged according to the complexity of phonological rule application - it can be argued that these various articulatory consequences are closely linked to phonological processing complexity of the [n] sounds as derived from their respective input representations.

The ascending tongue tip gestures in the order of canonical, nasalized, and inserted

[n] suggest that speakers make increasing articulatory efforts, as the phonological complexity of input representations increases, to reach the target more precisely, resulting in more advanced contact between the tongue tip and alveolar ridge. This extra articulatory effort, or hyper-articulation, can be interpreted as a deliberate attempt by speakers to manifest the act of [n] insertion. An alternative interpretation of hyper-articulation is that speakers slow down their overall speech, which may reflect their phonological planning. In this view, hyper-articulation results from speakers processing phonological knowledge while concurrently preparing for upcoming speech sounds. Processing phonological knowledge (i.e., applying the relevant phonological rule) may impose a cognitive load for speakers, allowing the articulators to remain in target positions longer. Articulatorily, this results in exaggerated gestures, and acoustically, it leads to phonemically lengthened durations.

That being said, speakers appear to plan on their speech differently depending on phonological complexity. The arrangement of tongue positions in the order of the inserted, nasalized, and canonical [n] corresponds to increasing phonological complexity. This finding suggests that phonological complexity is partly responsible for the observed articulatory variation, and this interpretation aligns with accounts linking phonological difficulty to increased word duration (Yiu and Watson 2015).

4.2 Patterns of coarticulatory effects

Two distinct patterns of C-to-C coarticulatory effects were identified in the realization of the three types of Korean [n], with the more common pattern observed in the canonical and inserted [n] environments. In both environments, the [n] sounds were articulated with greater raising of the tongue blade and tip, accompanied by tongue body raising, when preceded by /m/ rather than /ŋ/. That is, a preceding /m/ facilitated the lingual movement involved in the tongue gesture for [n], resulting in more advanced tongue root fronting, greater raising of the tongue blade and tip, and higher tongue body elevation.

This facilitatory effect may stem from the flexibility of the tongue body during the production of [n], probably due to the absence of a lingual gesture in the articulation of the labial [m]. Since the gesture of tongue blade and tip is not involved in articulation of a labial consonant, the following [n] benefits from greater flexibility in the tongue front required to achieve closure at the alveolar ridge (Recasens 1999). In contrast, the velar [ŋ] requires the tongue dorsum to raise toward the velum to form a closure, which may interfere with the raising of the tongue front necessary for articulating the following [n]. This reflects gestural antagonism between tongue back and tongue front raising, making the execution of an alveolar closure more difficult (Dixit and Flege 1991). In the nasalized [n] context, however, the opposite pattern was observed. The reason for this reversal remains unclear and may be further explained by other principles, than those of gestural coordination as gestural flexibility or antagonism.

4.3 Hyper-articulation vs. mistiming or undershoot

It is well established that speakers often repair non-native illegal clusters in their native language. One repair strategy that speakers commonly adopt in their speech production across languages is inserting a vowel between the illegal clusters, a vowel epenthesis (Tarone 1987; Davidson et al. 2003). English speakers, for example, prefer inserting a vowel to repair such clusters. Davidson (2006b) experimentally demonstrated that the vocalic qualities of these inserted vowel differ significantly from those of lexical schwas. The epenthesized schwa is rather articulatory transition with an "insufficiently overlapping configuration ("mistiming")" (Davidson 2006b) which is distinct from a lexical phonological unit. This mistiming results in delayed gestural coordination, thus, a transitional a vowel-like segment would be produced. These insufficient gestures are known as 'undershooting' (Lindblom 1963) which results in decreases in segment duration with asymptotic formant frequencies. Acoustic properties of these segments thus are distinct from those of lexical ones, as they exhibit weaker and reduced characteristics.

The articulatory examination in this study revealed that the insertion of [n] in Korean is associated with increased hyper-articulation, accompanied by enhanced tongue front raising. This finding contradicts accounts of mistiming or target undershooting, as the inserted [n] involves increased lingual movement, with speakers exhibiting greater tongue fronting. In vowel epenthesis, the purpose of insertion is to repair illicit non-native phonological representation. That is, although a vowel is inserted phonotactic reasons, the resulting form should remain as close as possible to the original target acoustically. In such cases, the perceptual modification caused by vowel epenthesis should be minimal, meaning that either the inserted vowel should be the least perceptually salient segment, or the overall change should introduce the least deviation from the original input (Δ[CC~CəC] > Δ[CC~C^{ə}C]). Epentheis in Korean [n], on the other hand, appears to serve a different purpose. Failure of inserting [n] when it is expected, the production is perceived as inappropriate. In such cases, speakers appear to intentionally apply phonological rules through clearly manifested articulatory gestures. This, in turn, relates to phonological complexity: as phonological complexity increases, speakers tend to slow down their articulatory gestures and reach articulatory targets more precisely. Therefore, the hyper-articulation observed in the inserted [n] may be driven by speakers' intention to disambiguate the different types of [n] sounds in Korean.

5. Conclusion

This study examines the hypothesis that speakers plan their speech in ways that reflect their linguistic knowledge, arranging their articulatory movements in accordance with phonological complexity. The results of this ultrasound study serve as an initial investigation into how articulatory variants may be attributed to the influence of language users' phonological rule application. The ordered arrangements of tongue position, reflecting varying degrees of phonological processing complexity, can be partially be understood as speakers' planning of their speech informed by their phonological knowledge. Further investigation into the relationship between articulatory arrangements and their acoustic consequences is needed to deepen our understanding of the factors influencing speech production planning.

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