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Sampling the progression of domain-initial denasalization in Seoul Korean

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Word-initial nasals in Korean are known to exhibit prosody-sensitive denasalization. The literature on the subject is still scarce and even the basic description of the process is debated. This study tested the speculation that inconsistencies in the literature may be explained if certain features of denasalization have developed relatively recently as part of an ongoing sound change. Based on apparent-time data from thirty-two speakers of Seoul Korean, the study explored the development of denasalization over a fifty-year period. The phonetic manifestations of domain-initial nasals were examined, along with the effects of prosodic position, place of articulation, and the height of the following vowel. The results revealed that denasalization has advanced rapidly over time, acquiring more plosive-like features of devoicing as well as a complete lack of nasality. Alveolar nasals before a high vowel were most likely to show denasalization and devoicing. Interestingly, the cumulative effect of prosody became weakest and partial denasalization was least likely for the younger group. Based on these results, we speculate that Korean denasalization is in the process of being stabilized into a discrete phrase-level process from a more general, gradient phenomenon of domain-initial strengthening, consistent with the theory of the life cycle of phonological processes.

Keywords: Denasalization; domain-initial strengthening; articulatory strengthening; fortition; Korean; sound change; rule scattering; life cycle of phonological processes; apparent time

1. Introduction

1.1. Korean denasalization

The Korean nasal phonemes /m n/ are liable to lose some or all of their nasality in their phonetic realization (Jones, 1924; Martin, 1951; Umeda, 1957; Chen & Clumeck, 1975; Cho & Keating, 2001; S.-D. Lee & Kim, 2007; Yoshida, 2008; Kim, 2011; Yoo, 2015a). This produces a fourth series of oral stop phones in the language, joining the better-known aspirated, lenis, and fortis series, e.g., [pʰ p p*].[1] Observations of Korean nasals prior to Kim (2011) often fail to mention denasalization, and it is a phenomenon of which most Korean speakers are unaware (see Kim, pp. 16–17). The few existing studies of denasalization disagree on even the basic properties of the phenomenon, such as the effects of a following vowel and the place of articulation of the nasal, the exact phonetic realization of the denasalized nasals, and the prosodic conditions in which the process occurs.

In one of the earliest mentions of Korean denasalization, Jones (1924, pp. 14–15) noted that Korean /m n/ may be realized as [mᵇ nᵈ] or [b d] before high vowels and sometimes /o/[2] (cited in Kim, 2011, p. 48). Martin (1951) partially agrees with Jones on the high

[1] The asterisk (*) is used to mark fortis obstruents.
[2] Note that Korean /o/ is phonetically close to [u]. See evidence of /o/-raising in Kang (2016, Figures 1 & 3).

vowel condition, stating the target environment of denasalization to be before /w u o/ for bilabials, though for alveolars, it was claimed to be before a front vowel. More recent studies have noted a similar, but more gradient conditioning effect by a following vowel. For example, Yoshida (2008) observed that denasalization is more frequent before /u/. These results lead to the hypothesis in Section 1.3 that denasalization is more likely before a high vowel. Regarding the place of articulation of the nasal, while Chen and Clumeck (1975) observed that bilabials are more likely to be denasalized, Yoshida (2008) and Kim (2011) found that alveolars are more often denasalized. While Chen and Clumeck (1975) is based on one informant, the latter two studies are more recent and comprehensive. Therefore, we hypothesize that denasalization is more likely for alveolars.

The literature is also inconsistent regarding the possibility of complete denasalization. Umeda (1957) stated that Korean nasals tend to be realized with a plosive release phase, as [m^b n^d]. Similarly, Yoshida (2008) concluded that denasalization is incomplete, as there was always some degree of nasality, albeit significantly weakened in initial position. In contrast, Kim (2011) demonstrated that Korean nasals can be realized with a complete lack of nasality, sometimes even with a clear plosive-like release burst at the onset of the following vowel. She also found that denasalization is possible regardless of the following vowel. In addition, Yoo (2015a) found that it is possible for Korean nasal phonemes to be realized with a short voicing lag [p^h t^h], although the duration of a voicing lag for nasals is typically much shorter than for the aspirated stops in Korean. As noted in Yoo (p. 1), this is particularly intriguing, given that Korean already has a crowded system of three contrastive oral stops, two of which are aspirated, namely the strongly aspirated stop (e.g., /p^h/) and the moderately aspirated lenis stop (e.g., /p/).[3]

Regarding the prosodic conditioning of denasalization, some studies have simply stated that word-initial nasals are targeted by this process. However, several recent studies have indicated that the effects of prosody may be more complex. Cho and Keating (2001) investigated *domain-initial strengthening* effects in the four Korean stops /t^h t t* n/. Domain-initial strengthening refers to the cross-linguistically observed fine-grained temporal and spatial expansion of segmental articulation in domain-initial position (e.g., Fougeron & Keating, 1997; Keating, Cho, Fougeron, & Hsu, 2004). Some of the most widely known correlates of domain-initial strengthening include greater linguopalatal contact, longer seal duration, and longer VOT for plosives (e.g., Cho & Keating, 2001; Fougeron, 2001). The phenomenon can be thought of as a sort of fortition that is gradient and prosody-sensitive, because its overall consequence in most languages seems to be in the direction of enhancing the consonantality of domain-initial consonants through greater constriction in the vocal tract, weaker voicing, and reduced nasality (but see Hsu & Jun, 1998, for a different pattern in Taiwanese, and Cho, 2005, for domain-initial strengthening of vowels). The effects of domain-initial strengthening are known to be generally cumulative (e.g., Fougeron & Keating, 1997) such that, for example, plosives are realized with progressively greater linguopalatal contact in Syllable (S)-initial, Word (W)-initial, Accentual Phrase (AP)-initial, and Intonational Phrase (IP)-initial position. (Note that a segment that is in IP-initial position is simultaneously in initial position of all lower prosodic domains, following the Strict Layer Hypothesis [Selkirk, 1986]. In this article we refer to initial position of the highest relevant domain [e.g., the IP] and assume that this entails being initial in all lower domains.)

While Cho and Keating do not specifically mention denasalization, they found that the minimum nasal energy, measured by RMS acoustic energy at the lowest point in the nasal consonant, was progressively lower in a higher domain, IP $<$ AP $=$ W $<$ S. Similar

[3] As part of a tonogenetic sound change, speakers with a more innovative system show comparable VOT for the lenis-aspirated contrast and use F0 as a primary cue instead (Silva, 2006).

findings have been reported for French (Fougeron, 2001, Section 3.2) and Estonian (Gordon, 1997, p. 13). The first explicit link between denasalization and domain-initial strengthening appears to have been made by Yoshida (2008, p. 20), who stated that denasalization seems to be an instance of domain-initial strengthening. The results of his nasometer study supported the trend in Cho and Keating that nasality becomes generally weaker after a stronger boundary in the order Utterance (U) = IP < AP = W < S. In direct contradiction, however, Kim (2011) did not find any such cumulative pattern in her acoustic, accelerometer, and aerodynamic study of Korean word-initial nasals. Instead, she found that AP-, IP-, and U-initial nasals are subject to denasalization without further prosodic effects (p. 98), U = IP = AP < S (AP-internal W-initial tokens were not separately examined). Thus, while the earlier studies appear to be describing a gradient phonetic process of progressive weakening of nasality, Kim's results point at a discrete process which may be formulated as in (1):

(1) Korean Denasalization: $[+\text{cons}] \rightarrow [-\text{nasal}] \,/\, {}_{\text{AP}}[\,\_\_$

Interestingly, the results from Yoo (2015a) suggest a mixture of the two systems, discrete and gradient.[4] Yoo conducted acoustic and auditory analyses of domain-initial nasals with four young (age range: 20 – 24) and four old (60+) speakers from Busan, the second largest city of South Korea, which is located in the southeast of the country near Gyeongsang Province. (Note that this dialect is suggested to show less denasalization than Seoul Korean [Yoo, 2015a]. See also Yoshida [2008], who concluded that denasalization is phonetic in Gyeongsang dialect but phonological in Seoul-Gyeonggi dialect.) One of the four younger speakers, whom we will refer to as speaker A, consistently and completely denasalized all AP-initial nasals (e.g., /m/ → [b] ~ [p^h]). However, there was also evidence of a cumulative pattern. For the other younger speakers, completely denasalized tokens were less common but were much more frequent in IP-initial position than in AP-initial position and never occurred in W-initial position. Devoicing and a voicing lag were more likely to occur in higher domains in both Speaker A's production and in combined data for all four younger speakers (Yoo, 2015b, pp. 25–26). Finally, older speakers showed no complete denasalization.

There are potential methodological issues that may have contributed to the inconsistencies outlined so far. First, the reading materials in Yoshida (2008) were assumed to elicit nasals in different prosodic positions correctly, without further instructions to the speakers or post-hoc monitoring. This can be problematic as the same sentence can be assigned different prosodic structures. For example, the sentence in (2) was intended to elicit the word /mul/ 'water' in W-initial position. However, it can also be read in AP-initial position, if the first word /i/ 'this' forms its own AP instead of forming an AP with the following /mul.ɯn/.

(2) /i mul.ɯn mas.is*.sɯp.ni.k*a/
'Does this water taste good?'

Similarly, the sentences designed for IP-initial nasals could also be read with the key nasals in AP-initial position, especially if they were read at a faster pace.

Second, indirect measurements of nasality should be interpreted with care. While Cho and Keating's data may seem to show that even nasals in IP-initial position—where

[4] Strictly speaking, whether a process is categorical or gradient requires a sensitive articulatory measurement and statistical evidence of a bimodal distribution (e.g., Turton, 2017). Yoo (2015a) does not provide independent evidence that the completely denasalized tokens form a statistically distinct category from sonorant nasal tokens.

strongest denasalization is expected—are realized with some nasality, the measurement from which nasality was inferred was RMS acoustic energy during the nasal consonant. Given Yoo's results, it is possible that nasals are realized only with voicing but without nasality, which could explain some of the apparent contradiction regarding the possibility of complete denasalization.

Finally, some studies have drawn conclusions based on data pooled across different prosodic positions, vowel contexts, or different speakers. Lee and Kim (2007) examined word-initial nasals by embedding them in a carrier sentence. Depending on how the speaker reads the sentence, however, the prosodic position of the nasal may or may not have been the position targeted by denasalization, i.e., AP-initial position. In addition, the vowel context was not controlled, as the target nasals could be followed by any of the vowels /i u o a/. Yoo's study also revealed that there is a high degree of between-speaker variation and that the process may not apply invariably even within the same speaker's production. Therefore, averaging the results may have masked cases of complete denasalization and subtle prosodic effects.

1.2. Korean denasalization as a sound change

While the methodological differences among the previous studies may explain the inconsistent observations on Korean denasalization to some extent, questions still remain. If denasalization can involve such salient phonetic features as lack of nasality, lack of voicing, and even a short voicing lag, how could earlier works such as Umeda (1957) only mention partial denasalization, if at all? Why is the vowel context of denasalization often reported to be restricted to before high or front vowels in earlier descriptions? Is denasalization categorical or gradient? And finally, is it a case of domain-initial strengthening?

One possibility is that the patterns of Korean denasalization have extended their scope over time, to apply in a wider range of contexts and to manifest progressively more obstruent-like features. Specifically, it can be posited that discrete, categorical denasalization in (1) as found in Kim (2011) is a result of *rule scattering*, originating from a more general, phonetically-driven process of domain-initial strengthening. Rule scattering is a notion proposed within the theory of *the life cycle of phonological processes* which assumes a modular, feed-forward architecture of grammar (Bermúdez-Otero, 2010, 2015; Robinson, 1976; see also Turton, 2017). Bermúdez-Otero (2015) describes the main proposition of the theory as follows:

> "A phonetic phenomenon that is at first exhaustively determined by extra-grammatical factors (physics and physiology) becomes ever more deeply embedded in the grammar of a language, first as a language-specific gradient process of phonetic implementation, later as a categorical phonological rule applying in increasingly narrow morphosyntactic domains, until it eventually escapes phonological control altogether."

A diagrammatic representation of the life cycle of phonological processes in Bermúdez-Otero and Trousdale (2012) is reproduced in **Figure 1**. In this theory, rule scattering refers to the phenomenon in which a process operating at one component of the grammar (e.g., phonetics) enters a higher-level component (e.g., phrase-level phonology) without ceasing to apply in the original component. An oft-cited example is palatalization of /s/ in English (Zsiga, 1995). In sequences such as 'miss you,' /s/ is palatalized before /j/ via a gradient post-lexical process of gestural overlap. Simultaneously, a categorical

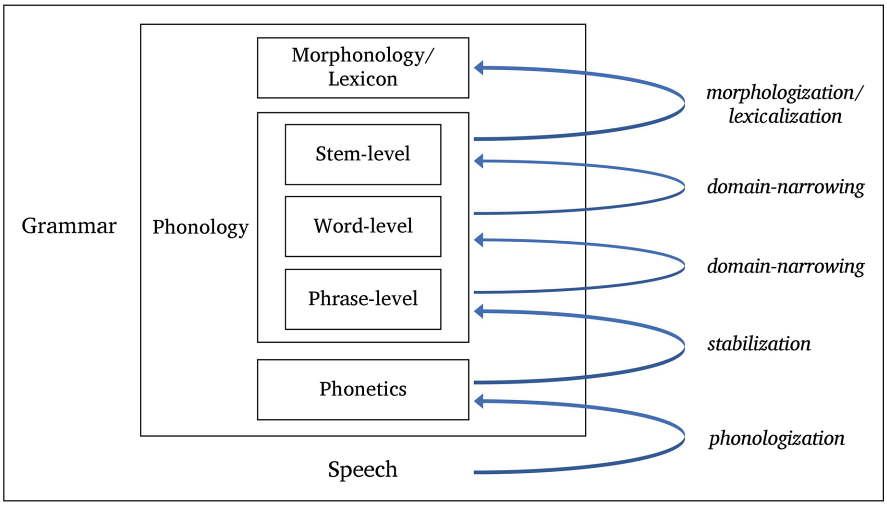

Figure 1: The life cycle of phonological processes (after Bermúdez-Otero & Trousdale, 2012).

rule of palatalization is found in the stem-level derivation of words such as *succession* from *success*.

Within this theoretical framework, the differences between Speaker A and the other younger speakers from Yoo (2015a) may be explained in the following way. Although the specific details will have to be verified empirically, the general phonetic process of domain-initial strengthening as applied to nasals is assumed to affect a range of phonetic dimensions including nasality, stop seal duration, and voicing in a gradient manner as a rough function of the strength of the prosodic boundary. This process is most likely physiologically motivated at the very initial stage of its life cycle (See Fougeron & Keating, 1997, p. 3737, for a possible explanation based on increased articulatory effort or energy in initial position), before entering into the language-specific phonetic component. For speakers such as Speaker A, this process may have been reinterpreted as a phrase-level phonological process targeting all AP-initial nasals, which changes the value of the feature [nasal] in a discrete manner. This step is known as *stabilization* (**Figure 1**). Crucially, domain-initial strengthening would still operate on parameters including nasality and voicing, accounting for the gradience found in Speaker A's data with respect to the rate of voiceless plosive realization. For the other speakers, the process may only exist as part of the language-specific domain-initial strengthening in the phonetic component, and may not yet have stabilized into the phonological component.

The lack of a gradient prosodic effect in Kim (2011) may have been because her subjects (age: 20 – 31) had a system similar to Speaker A (age: 24) with a discrete denasalization rule. In addition, her study examined only nasality and no other articulatory or acoustic dimensions in which gradience from the phonetic component may have surfaced. On the other hand, the lack of finding of a discrete rule of denasalization in earlier studies could be because complete and categorical denasalization is a relatively new development, with innovative speakers like Speaker A appearing only recently. Thus, the main objective of this study is to investigate the phonetic realization of initial nasals over time and examine the effects of *age*, *prosodic position*, *following vowel*, and *place of articulation*. Due to the qualitative nature of the methodology (Section 2.2), this study will not be able to directly test theory-specific hypotheses such as whether Korean denasalization is undergoing a process of stabilization. Instead, the present study is intended to serve as the first step towards this goal, exploring more general patterns in the development of denasalization.

1.3. Hypotheses

The hypotheses evaluated in the present study are the following.

1. Over time, the phonetic realization of denasalization has proceeded in the order [N → N^D → D → T → T^H] (Capitalized IPA symbols are used to refer to both alveolar and bilabial nasals, e.g., [N^D] indicates [m^b n^d].)
2. Complete denasalization (i.e., realization with no remaining nasality [D, T, T^H]) is more likely:
   (a) for younger speakers
   (b) in a higher prosodic domain
   (c) before a high vowel
   (d) for alveolar nasals
3. The realization of a nasal phoneme as a voiceless plosive [T] and a voiceless plosive with a voicing lag [T^H] is more likely:
   (a) for younger speakers
   (b) in a higher prosodic domain
   (c) before a high vowel
   (d) for alveolar nasals

2. Methods

2.1. Speakers and materials

This study adopted an apparent-time method to investigate how phonetic realization of domain-initial nasals has changed over time in Seoul Korean. The data were drawn from the Speech Corpus of Reading-Style Standard Korean. The Corpus started being developed by the National Institute of the Korean Language in 2002 and became available for distribution in 2005 (The National Institute of Korean Language [NIKL], 2005). It contains recordings of 60 male and 60 female speakers of Seoul-Gyeonggi dialect, reading 930 sentences from 19 well-known short stories and essays. For the present study, a total of 32 speakers (with birth years ranging from 1932 to 1982) were chosen to represent three age groups, which consisted of the same number of male and female speakers. The grouping and the choice of speakers were intended to maximize the age range covered in the data, while making the mean ages distinct among the age groups and comparable across gender. There are 15–20 years between each group's mean age. **Table 1** gives details of the subject groups in this study.

Of 930 sentences recorded, 145 sentences containing one or more domain-initial nasals were chosen for the present study. The sentences were selected to obtain a balanced number of bilabials and alveolars, and sufficient tokens in different prosodic positions followed by a range of different vowels. Out of a total of 5840 tokens, 4446 tokens without a nasal consonant in the vicinity were used in the analysis. See Section 2.3 for further detail.

Table 1: Subject information. The age was calculated by subtracting the subject's year of birth from the year of recording in 2003.

Age groups	Female		Male		Total
	Age range	Mean age	Age range	Mean age	No. of speakers
Younger: Below 35	23–29	25.5	21–31	25.5	12
Middle: 35–54	42–51	46.0	36–54	43.8	10
Older: Over 54	57–68	61.2	56–71	63.0	10

2.2. Analyzing the realization of nasals

The selected tokens of nasal phonemes were classified into five categories of phonetic realization based on auditory and acoustic evidence. The categories were adapted from Yoo (2015a) based on the presence or absence of three main acoustic characteristics of nasality, voicing during the consonant, and a voicing lag:

- Category (1) Sonorant nasals [N]
- Category (2) Partially denasalized nasals [N^D]
- Category (3) (Pre-)voiced non-nasals [D]
- Category (4) Voiceless non-nasals [T], and
- Category (5) Voiceless non-nasals with a voicing lag (of more than 10 ms) [T^H]

These categories are presented in order from less to more obstruent-like realizations of nasals. **Figure 2** provides a canonical example for each of the five categories of realization. The spectrogram in **(1)** shows an example of Category (1), displaying the typical features of sonorant nasals including nasal formants, voicing, relatively high amplitude, and a relatively smooth transition into the following vowel. Category (2) for partially denasalized nasals is exemplified in **(2)**. There is clear visual evidence that the nasal consonant is divided into two parts, with the first part realized as a sonorant nasal and the second part

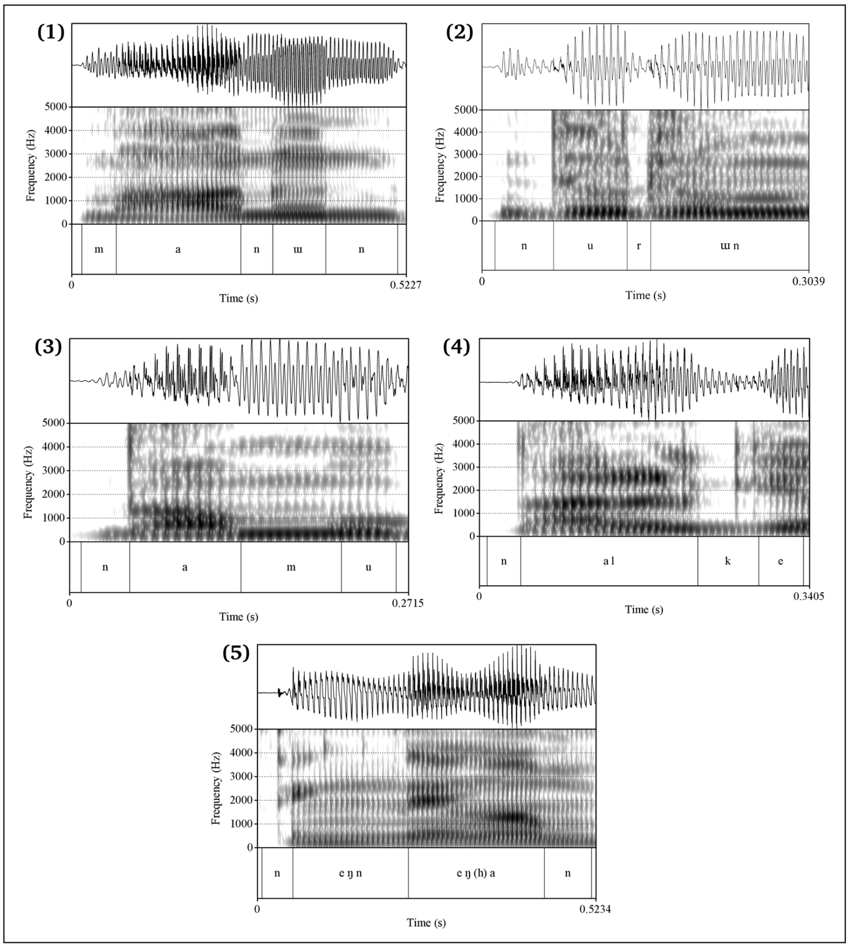

Figure 2: Examples of the five categories of realization of nasal phonemes in initial position: Category (1) Sonorant nasals [N]; Category (2) Partially denasalized nasals [N^D]; Category (3) (Pre-)voiced non-nasals [D]; Category (4) Voiceless non-nasals [T], and; Category (5) Voiceless non-nasals with a voicing lag of more than 10 ms [T^H]. The tier below the spectrogram shows the underlying phonemes.

as a non-nasal. The second part shows much less acoustic energy than the first part, and the boundary with the following vowel shows a sharp transition, with a burst-like energy transient. The spectrogram in **(3)** gives an example of Category (3) for voiced non-nasals and looks similar to the second part of the nasal consonant in **(2),** with prevoicing but without nasal formants. Category (4) in **(4)** demonstrates the realization of an underlying nasal phoneme as a voiceless non-nasal without a voicing lag. There is neither voicing lead, as in the example in **(3),** nor a voicing lag which is longer than 10 ms, as in **(5)**. Finally, a clear example of Category (5) is provided in **(5),** with a voicing lag of 29.5 ms.

In addition to the obvious criteria that naturally follow from the definition of the categories—e.g., auditory and acoustic evidence of nasality for Category (1), the presence of voicing pulses for Categories (1) – (3), and the exact duration of a voicing lag for Categories (4) and (5)—we also made use of the following cues for categorization. First, when it was difficult to judge whether a token was nasalized, nasalization of the following vowel often provided a secondary cue. This was especially the case in post-pausal positions where nasals were often very short in duration, and nasal perception largely relied on the presence of vowel nasalization.

Second, Category (1) was ruled out if there was a salient acoustic burst. A plosive-like release indicates a sudden release of the pressure built up in the oral cavity, which is only possible when the velum is raised (Kim, 2011, p. 56). While the presence of a burst could be used to rule out Category (1), we could not exclude the other categories based on the lack of a burst. This is because the presence of a burst was inconsistent for Category (3) tokens due to modulation of the airflow by the vocal folds. During a voiced closure, air flows into the oral cavity for only about one third of the time, which makes the intraoral pressure during a voiced stop much lower than during a voiceless stop. In addition, for many tokens in Category (2), the duration corresponding to [b] or [d] was often very brief, leaving insufficient time for the pressure to build up. Finally, a burst can be masked by aspiration noise, leading to a practical difficulty in deciding whether there is a burst (Yoo, 2015a).

While we strove for a clear and systematic categorization scheme, the phonetic manifestation of denasalization is gradient in reality and the data frequently bore out this fact. For example, tokens judged as Category 1 varied from being fully nasalized to only weakly nasalized, with weakly nasalized tokens resembling those in Category 3. These were all classified in Category 1, given the clear auditory evidence of nasality. In contrast, some Category 3 tokens visually resembled Category 1 tokens despite being an obvious oral stop from the auditory evidence. This is because non-nasals can also exhibit energy around the second or even third formant in the presence of strong voicing. There were also cases in which the tokens judged as Category 1 were similar to those in Category 2 with weakening of amplitude toward the boundary with the following vowel and a burst-like transient. However, these were still grouped into Category 1 because nasality did not appear to cease before the vowel to create an audibly oral release and because there was a smooth transition of formants into the vowel. The boundary between Categories (3) and (4) was also difficult to draw. While proper pre-voicing would involve at least several pulses of voicing before the vowel onset, tokens with one or more clear and visible pulses of voicing were consistently assigned to Category (3).

Such ambiguous cases were judged by the second author, a trained phonetician who is not a native speaker of Korean. A total of 138 tokens (2.4%) were double-checked in this way. The two authors agreed in the majority of cases, and disagreements of more than one step on the hierarchy of denasalization were very rare. For the tokens on which there was disagreement, the authors discussed them and reached a consensus before including them in the analysis. In a double-blind categorization of an additional 100 tokens, the inter-coder agreement was 90.5%, discounting the slight differences in the implementation of the 10 ms threshold distinguishing T and T^H, most of which were close to the threshold. The distinction between T and T^H was later discarded in the statistical analyses. Including all disagreements, the agreement rate was 86.0%. The second author was not supplied with information which might have unconsciously biased his judgement, such as the prosodic position and age of the speaker. However, it was inevitable that there were hints about the speaker's age in the voice and about the prosodic position that are obvious even to a non-Korean phonetician, e.g., the existence of preceding acoustic silence.

While not without shortcomings, such a manual and qualitative categorization was deemed the best method for this study. First, in the absence of articulatory data such as nasal flow measurements, it is not evident which acoustic measurements should be made to determine the level of nasality in the consonants. Second, given the complex nature of Korean denasalization—which involves numerous dimensions including the level of nasality, timing of cessation of nasality, voicing, amplitude, duration, release bursts, aspiration, and dynamic change in the amplitude and spectrum—it is difficult to imagine that an approach involving an automatic quantification of denasalization from the acoustic signal would lead to a better understanding of the pattern than a multidimensional approach involving human auditory perception and visual observation. For example, the amplitude of a nasal consonant is typically higher than its oral counterpart. However, lower amplitude is not a reliable indication of denasalization, at least in Korean, because many sonorant nasals can be realized with little energy, and pre-voiced non-nasals often had much higher amplitude than these.

2.3. Factors

The within-group factors considered in the present study were prosodic position of the nasal, height of the following vowel (vowel height), place of articulation, and presence or absence of neighboring nasals.

The prosodic position of each token was determined manually based on the criteria in Jun (2000) and the model of Korean prosody in Jun (1996). Closely following the method in Cho and Keating (2001, p. 161), the Utterance was added as a possible prosodic domain above the Intonational Phrase. The Utterance was defined as the domain that is preceded by a pause greater than break index number 3 in K-ToBI (Jun, 2000), usually corresponding to a complete sentence punctuated by a period.

All tokens were in initial position of an Accentual Phrase (AP), Intonational Phrase (IP), or Utterance (U). Nasals in other positions were not considered as they were expected to be consistently in Category (1) [N] (Kim, 2011; Yoo, 2015a), and this was confirmed by a preliminary examination of the corpus. (There were W-initial tokens which approximated Category [2], showing weakening of nasal formants toward the boundary with the following vowel. However, an accurate analysis of such subtle changes in nasality would require the use of more sensitive equipment than was available to us, such as an accelerometer, dual-chamber airflow masks, or nasometer.) Because the speakers read the sentences in different prosodic phrasings, each speaker contributed a different number of tokens.

The vowel contexts covered in this study included all eight contrastive monophthongs of Korean and two of the glide + vowel sequences that can occur after a nasal onset. **Table 2** shows the grouping of these vowels into three types according to vowel height.[5] The glide + vowel sequences were categorized according to the quality of their initial element. While it is not known which exact phonetic mechanism is responsible for the

[5] Vowel backness was considered in the original design but our preliminary examination showed that vowels of the same height had similar effects on the rate of denasalization, in line with the literature (**Section 1.1**) suggesting that vowel height seems to be a more important factor than vowel backness.

Table 2: Categorization by vowel height.

Quality	Vowels
High	/i/ /jʌ/ /u//ɯ//wʌ/
Mid	/e/ /ɛ/ /o/ /ʌ/
Low	/a/

effect of a following vowel on nasal realization, the initial sound of the glide + vowel sequence is assumed to be more relevant as it is the part that directly follows the nasal. The tokens followed by glides were included in the study because there were relatively fewer tokens followed by a high vowel, especially /i/.

The grouping of the monophthongs is based on the IPA illustration of standard Seoul Korean (H.-B. Lee, 1999) and Kang's (2016) large-scale acoustic study of the vowels in the same corpus. Given Kang's findings of an ongoing vowel-shift-like change involving /o/-raising, /u/-fronting, and /ɯ/-fronting, one may question whether /o/ should be grouped with /u/ rather than with /ʌ/. While this alternative grouping could be argued to better reflect the innovative system of some younger speakers, the current grouping is considered more appropriate given the entire age range of the speakers.

In a small proportion of the tokens, the actual realization of the vowel was markedly different from what is expected from the orthography, due to the use of a more colloquial variant, e.g., /ne/ 'you' as [ni] and /mwʌ/ 'what' as [mo] or [mʌ]. In such cases, the tokens were categorized according to the vowel phoneme most closely represented by the phonetic realization.

The presence or absence of a neighboring nasal was controlled for, as we believed such a nasal could confound the other variables. Although Kim (2011, p. 56) noted that denasalization can occur even after a coda nasal, it is still highly possible that the frequency and/or degree of denasalization is affected by another nasal in the context, for example by coarticulation that is independent from the process of denasalization. A detailed examination of a younger male speaker who showed the highest rate of denasalization revealed that he produced significantly less denasalization when the preceding syllable contained a nasal coda or an NV sequence. On the other hand, having a tautosyllabic nasal coda or being followed by an NV syllable did not reduce the rate of denasalization. Thus, only nasals in the syllable preceding the target initial nasal were taken into account. **Table 3** lists the number of tokens in each category of the four within-group factors as well as the two between-group factors.

2.4. Statistical analyses

Bayesian binomial mixed-effect models were run using the *brms* package in R (R Core Team, 2020). Unlike frequentist linear models, Bayesian models require as input a prior distribution that embodies our beliefs about a model parameter. Following common practice, weakly informative (regularizing) priors were used for all models (Gelman, Simpson, & Betancourt, 2017). Weakly informative priors assume the null hypothesis by assigning the highest probability mass to parameter values that correspond to no difference between groups. As recommended in Gelman (2019), we used a student-t distribution centred around zero with $df = 3$ and scale = 2.5 for the intercepts, slopes, and standard deviations. By this prior, we are making the assumption that 68% of the values will lie between –2.5 and 2.5 in log odds space, which corresponds to 7.6% and 92.4% in probability terms. This is considered a conservative, lenient prior, which allows a very wide range of values.

Table 3: Breakdown of tokens by six predictor variables.

Factor	Categories	All tokens	Tokens used in analysis
Vowel height	High	1932	1438
	Mid	2164	1610
	Low	1744	1398
Prosodic position	U	692	692
	IP	1401	1342
	AP	3747	2412
Place of articulation	Alveolar	2734	2094
	Bilabial	3106	2352
Neighboring nasal	Not preceded by a nasal consonant	4446	4446
	Preceded by a coda nasal (C)VN #**N**	982	0
	Preceded by nasal + vowel NV #**N**	412	0
Age	Older	1939	1528
	Middle	1804	1392
	Younger	2097	1526
Gender	Male	3091	2392
	Female	2749	2054
Total		5840	4446

The output of a Bayesian model is a posterior distribution which represents our updated beliefs about model parameters, having seen the data. Based on the posterior distribution, a 95% credible interval (CI) can be obtained, which allows us to quantify our level of uncertainty about a model parameter, i.e., we can be 95% certain that the true values of the model parameter lie within the CI. Thus, our results will be presented in terms of the mean of the posterior and 95% CI. For more on Bayesian data analysis and the differences between the frequentist and Bayesian approach, see Vasishth, Nicenboim, Beckman, Li, and Kong (2018).

We ran three separate models, one for each of the three hypotheses introduced in Section 1.3. Our five-level outcome variable was turned into three key binary variables[6] relevant for these hypotheses: complete_denasalization, devoicing, and category_2. That is, in order to test if complete denasalization is more likely as a function of factors such as age and prosodic position, we used a binary outcome variable which groups Categories (1) and (2) into one level and the rest of the Categories into the other level. To test if more extreme

[6] The rationale for our chosen method of statistical analysis is as follows. The simplest method would have been to treat the outcome variable as an ordinal variable rather than a nominal variable, and to run ordinal logistic regression instead of multinomial logistic regression. An ordinal logistic regression model is more parsimonious because the model would return only one coefficient describing adjacent pairs of the outcome levels instead of a separate coefficient for every possible pair. However, when an ordinal logistic regression model was fitted using *clmm* from the *ordinal* package, it violated the proportional odds assumption, indicating that the outcome variable cannot be treated as an ordinal variable. On the other hand, multinomial logistic regression models frequently experience convergence issues and are highly complicated to interpret when there is a large number of multi-level factors. In addition, this model cannot incorporate a random-effects structure which is crucial for between-subject comparison in an experiment with a repeated-measures design (i.e., when the same participants provide data points in each condition of a predictor variable, e.g., prosodic position). Therefore, we sought to overcome the issues of model convergence, interpretability, and statistical validity by adopting Bayesian models and splitting the outcome variable into several binary variables of direct relevance.

realization is found in younger age groups, for example, the binary variable devoicing was used by grouping Categories (1) – (3) versus the rest. Finally, the variable category_2 was created by singling out Category (2) from the others, to see if there is statistical support for the pattern we observed from our data that this category is less likely to occur in younger speakers' speech. Category (2) was considered separately because, as will be shown in **Figure 3**, this category was an exception to the pattern that younger speakers produced a higher proportion of the categories above (1). That partial denasalization is less common for the younger group is particularly interesting because it suggests that gradience on the time dimension is disappearing over time.

To prevent the combinatorial explosion of the levels of the variables, the variables neighboring nasal and gender were removed, as they were not crucial to testing our hypotheses. When included as a main effect, gender did not show a robust effect as zero was well within the CI. On the other hand, neighboring nasal turned out to be a significant factor, and therefore it was still important to control for its effect. Thus, we used a subset of the dataset which only included those tokens without nasal neighbors (4446 tokens).

The resulting fixed factors were age (older, middle, younger), position (AP, IP, U), vowel (low, mid, high), and place of articulation (poa) (bilabial, alveolar) with the first level of each factor specified as the intercept. To understand the importance of the factors position, vowel, and place of articulation in different age groups, two-way interaction terms were also included between these variables and age. The random intercept for subject was added. The resulting R formula is shown below.

(3) brm(outcome ~ age : position + age : vowel + age : poa + age + position + vowel + poa + (1|subject))

The R script used in the present study can be found in the osf repository, along with a table of raw data (https://osf.io/fn52e/).

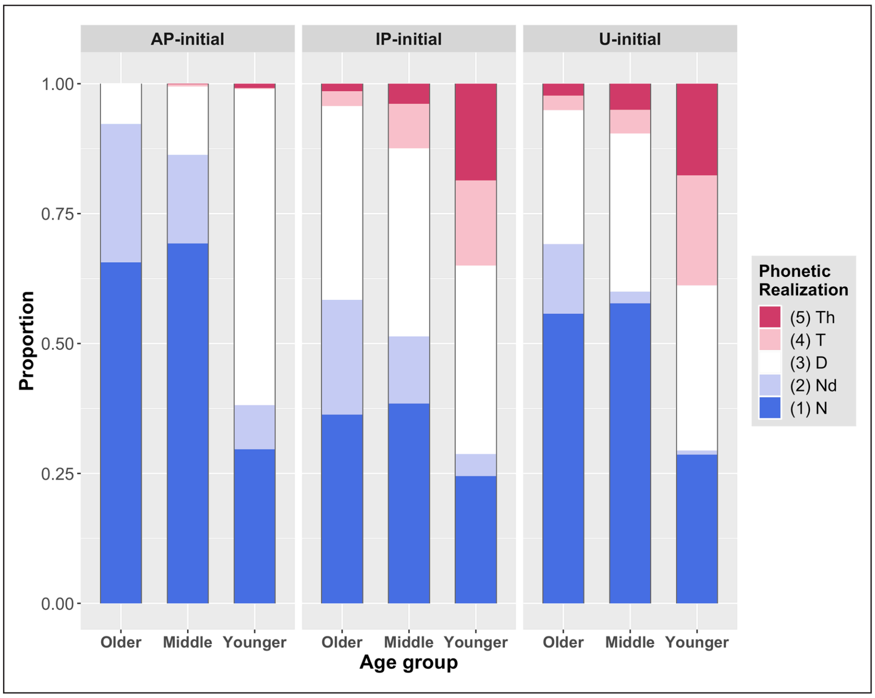

Figure 3: Average proportion of nasals in the five categories of realization for three age groups. Separate panels show the nasal's prosodic position, AP-initial (left), IP-initial (middle), and U-initial (right).

3. Results

3.1. A change in the phonetic realization of domain-initial nasals

Figure 3 shows average proportions of nasals in each category of realization across three age groups when the nasal is in AP-initial, IP-initial, and U-initial position. (Note that this graph is a visualization of the raw data with 4446 tokens, and is not adjusted for the effects of factors not shown here.) While Category (4) [T] and Category (5) [T^H] were very rare in general, they became increasingly frequent from the older group (1.6%, 0.9%) to the middle group (3.4%, 2.0%) to the younger group (6.9%, 7.2%). The proportion of Category (3) [D] more than doubled in the younger group (51.0%) from the middle (22.7%) and the older group (22.4%). On the contrary, Category (2) [N^D] progressively became a less preferred variant, with its proportion dropping from 22.9% in the older group to 13.5% in the middle group, and to 6.4% in the younger group. The proportion of Category (1) [N] also fell from the older (52.2%) and the middle group (58.3%) to the younger group (28.4%). Overall, the results were consistent with Hypothesis 1: Over time, the phonetic realization of denasalization has proceeded in the order [$N \rightarrow N^D \rightarrow D \rightarrow T \rightarrow T^H$].

3.2. Complete denasalization

In this section, we examine Hypothesis 2 that complete denasalization—Category (3) [D], Category (4) [T], and Category (5) [T^H], as represented respectively by white, light pink, and dark pink bars in **Figure 3**—is more likely in younger speakers' production, in a higher position, before a high vowel, and for alveolar nasals. The results of the Bayesian model supported the hypothesis. To make the interpretation easier, predicted probabilities were calculated manually using the model estimates and the posterior samples. (The fixed-effects estimates from the three Bayesian models in this study can be found in the Appendix under "Additional Files.") The predicted probability that the older group will denasalize an AP-initial nasal was 0.075 with a 95% CI of [0.04, 0.13]. The same probability was slightly higher for the middle group at 0.128 [0.072, 0.206] and much higher for the younger group at 0.627 [0.513, 0.735].

There was a robust statistical difference between the younger group and the other two groups. The difference in the predicted probability between the younger group and the middle group was 0.499 [0.355, 0.624]. Given that zero is not included in the CI, the model provides strong support that complete denasalization is more likely for the younger group than for the middle group in AP-initial position. The difference between the younger group and the older group was even greater at 0.552 [0.433, 0.666]. Again, the CI is entirely above zero, suggesting that the group difference is highly robust. On the other hand, the difference between the middle and older group was 0.053 [–0.026, 0.140], much smaller than the other between-group comparisons. Although zero is within the CI, 91.3% of the probability mass lay above zero, indicating that we can conclude with 91.3% confidence that denasalization is more likely in the middle than in the older group in AP-initial position.

Similarly, for IP-initial position, the probability of complete denasalization became higher as the average age of the group decreased, with 0.369 [0.249, 0.510] for the older group, 0.449 [0.316, 0.587] for the middle group, and 0.733 [0.618, 0.831] for the younger group. The difference between the middle and older group was 0.080 [–0.114, 0.258]. As 19.7% of the probability mass lay below zero, the results are inconclusive regarding a definite difference between these two groups. On the other hand, the difference between the younger and middle group was 0.284 [0.108, 0.450] and that between the younger and older group was 0.364 [0.188, 0.520]. With the CI entirely in the positive side, these results provide compelling evidence that the younger group is more likely to show complete denasalization than the other two groups in IP-initial position.

The findings were also similar for U-initial position. The probability of complete denasalization was 0.338 [0.213, 0.486] for the older group, 0.437 [0.299, 0.582] for the middle group, and 0.751 [0.636, 0.843] for the younger group. The difference between the middle and older group was 0.099 [–0.102, 0.290]. The CI included zero with 83.6% of the probability lying above zero, indicating that there is only 83.6% certainty that complete denasalization is more rather than less likely in the middle group compared to the older group. The difference between the younger and middle group was 0.314 [0.129, 0.480], and the difference between the younger and older group was 0.413 [0.235, 0.570]. These differences in the predicted probabilities strongly suggest that the younger group is more likely to denasalize a U-initial nasal than the middle and older group. The results so far are consistent with Hypothesis 2(a) with the order of Older ≦ Middle < Younger.

Next, we examine the effect of prosodic position and vowel height within each age group. **Figure 4** shows a marginal effects plot which takes into account the imbalances in the token counts and holds the effect of place of articulation constant. The general pattern in **Figure 4** is that IP-initial and U-initial tokens show higher probabilities of complete denasalization than AP-initial tokens within each age group. Our statistical analyses supported these observations. Recall that the predicted probabilities of denasalization in AP-, IP-, and U-initial position were 0.075, 0.369, 0.338 for the older group, 0.128, 0.449, 0.437 for the middle group, and 0.627, 0.733, and 0.751 for the younger group. For the differences between IP and AP position, and between U and AP position, the CI was entirely above zero for all three groups (full results are available from the osf repository https://osf.io/fn52e/). On the other hand, none of the three groups showed any compelling evidence for a difference between U and IP position, as zero was well within the CI. Thus, there is a partial support for Hypothesis 2(b) with the order of AP < IP = U.

Another interesting pattern from **Figure 4** is that, for the younger group, the probability of denasalization seems to depend less on prosodic position than for the other groups, as the probability is similarly high in all three positions. The modelling results supported this observation. For all pairwise comparisons across the three age groups, the difference between U and IP position was not significant. In contrast, the difference between IP and AP was significantly smaller for the younger than for the middle group (–0.214 [–0.316, –0.108]) and for the younger than for the older group (–0.188 [–0.309, –0.077]). Similarly for the contrast between U and AP, the difference was significantly smaller for

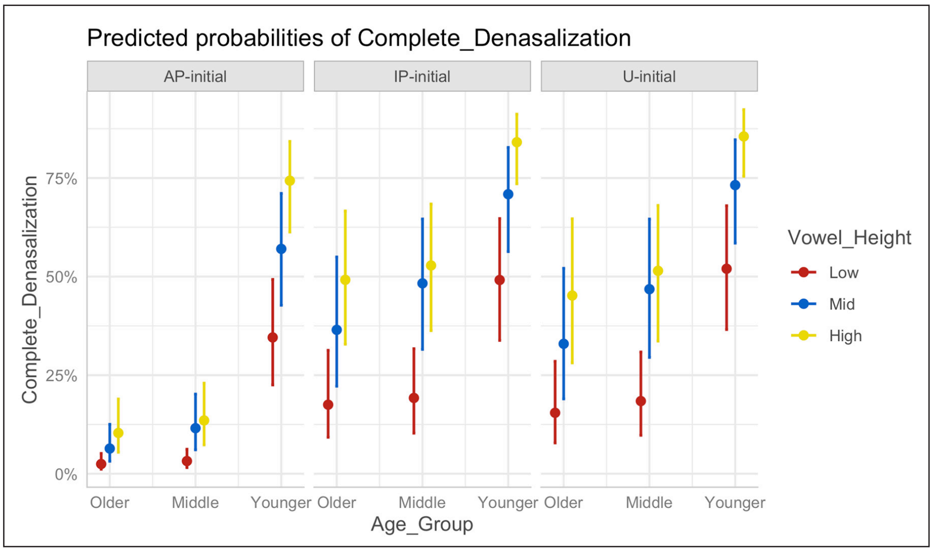

Figure 4: Predicted probabilities of complete denasalization by age group. Separate panels show the nasal's prosodic position, AP-initial (left), IP-initial (middle), and U-initial (right), and the different colors show vowel height, Low (red), Mid (blue), and High (yellow).

the younger compared to the middle group (–0.184 [–0.299, –0.071]) and for the younger compared to the older group (–0.139 [–0.269, –0.018]). These findings suggest that the effect of prosody is stronger for the older and middle group than for the younger group.

From **Figure 4**, it is also clear that vowel height has a systematic effect on the probability of complete denasalization, such that denasalization is more likely before a higher vowel. According to our model, the predicted probability of denasalization before a given vowel is always significantly lower than that before a higher vowel, for all three age groups. The CI of the probability was entirely above zero, with only one exception. This exception was for the difference between high and mid vowels for the middle group. The CI was 0.047 [–0.011, 0.107] with 93.9% of the probability mass lying above zero. This indicates that there is 93.9% probability that denasalization is more likely before a high vowel than before a mid vowel. Overall, these results provide compelling evidence for Hypothesis 2(c) with the order of Low < Mid < High.

Next, the effect size for vowel height was compared across the age groups. There was only limited evidence that vowel height has a greater effect in a younger group. Between the mid and low vowel context, the difference in the probability of denasalization was 0.091 [–0.012, 0.187] greater for the middle than older group, with 96.1% of the probability lying above zero. Between the high and low vowel context, the probability was 0.088 [–0.027, 0.199] greater for the younger than older group, with 93.6% of the probability above zero. Finally, between the high and mid vowel context, the probability was 0.083 [0.001, 0.163] with 98.0% of the probability above zero. For the rest of the comparisons, less than 90% of the CI was on either side of zero, suggesting that the difference is not robust. Given the pattern in **Figure 4**, the difference in the effect of vowel between the younger and the other groups seems to stem mainly from the AP-initial tokens, as the middle and older group do not show much denasalization regardless of the height of the following vowel in AP-initial position.

Lastly, our results showed a consistent effect of place of articulation. For the older group, the probability of denasalization was 0.036 [–0.010, 0.084] higher for alveolars than bilabials, with 93.8% of the probability lying above zero. For the middle and younger group, the probability was 0.082 [0.028, 0.136] and 0.124 [0.074, 0.179] higher for alveolars than bilabials, respectively. This provides strong support for Hypothesis 2(d) that alveolars are more likely to be denasalized than bilabials.

There was some evidence that the effect of place of articulation is greater for a younger group. The probability difference between alveolar and bilabial denasalization is 0.046 [–0.025, 0.116] greater in the middle than in the older group, with 90.3% of the probability mass above zero. The difference was 0.042 [–0.030, 0.119] greater in the younger than in the middle group with 86.5% of the probability lying above zero. This does not constitute compelling evidence for a difference between these two groups in terms of the strength of the place of articulation effect. Finally, the difference was 0.088 [0.018, 0.162] greater for the younger than for the older group. As zero lies outside the CI, we can conclude that the effect of place of articulation is stronger for the younger group than for the older group.

3.3. Devoicing

In this section, we focus on the voicing parameter as relevant for Hypothesis 3 which states that devoicing of a domain-initial nasal is more likely for younger speakers, in a higher position, before a high vowel, and for alveolar nasals.

Before discussing statistical results, we first examine the tokens with a voicing lag more closely. **Table 4** provides the mean and the maximum values of VOT in milliseconds for all tokens in Category (5) [T^H] as produced by each age group and in each prosodic position. Minimum values are not given as they were always close to 10 ms, which was the cut-off point between Category (4) and Category (5). Although the token number in

Table 4: Mean and maximum values of VOT (ms) for Category (5) [T^H] tokens in each age group (rows) and prosodic position (columns). Figures in brackets are token counts.

	AP-initial		IP-initial		U-initial	
	Mean	**Max**	**Mean**	**Max**	**Mean**	**Max**
Older	– (0)	–	16.1 (9)	31.5	14.4 (4)	16.2
Middle	25.5 (1)	25.5	15.2 (16)	29.0	17.3 (11)	27.7
Younger	22.7 (8)	39.0	17.5 (55)	44.6	15.6 (46)	29.5

each prosodic position increases as the age decreases, the average VOT does not vary much across the age groups. It is interesting to compare these results with the VOT measurements for the aspirated stop /t^h/ and the lenis stop /t/ in Cho and Keating (2001, p. 173). While exact average durations of VOT are not given, the values shown in the figure are roughly around 60 ms for the aspirated stop /t^h/ and 30 ms for the lenis stop /t/ in U-initial position, 35 ms and 20 ms in IP-initial position, and 25 ms and 15 ms in AP-initial position. Taking into account that there were also tokens in Category (4) [T] whose VOT values fall in the range 0 – 10 ms (25, 48, and 106 tokens in the older, middle, and younger group, respectively), and that the remaining, vast majority of tokens were not realized with a voicing lag, the average VOT for nasal consonants would be well separated from that of the lenis stop. Nevertheless, the maximum values of VOT in **Table 4** are similar to or above the average VOT of the lenis stop in matched prosodic positions, suggesting potential perceptual confusion between the nasal stop and the lenis stop in Korean.

The results of the Bayesian model with the outcome variable devoicing supported our observation from **Figure 3** that devoicing of domain-initial nasals is more likely in younger speakers' speech. For AP-initial position, the predicted probability of devoicing was 0.001 with a CI of [0.000, 0.004] for the older group. For the middle and younger group, the probability was 0.005 [0.001, 0.013] and 0.006 [0.001, 0.014], respectively. For IP-initial position, the probability of devoicing was 0.033 [0.012, 0.070] for the older group, 0.102 [0.043, 0.192] for the middle group, and 0.304 [0.180, 0.454] for the younger group. Finally, for U-initial position, the probability was 0.033 [0.010, 0.075] for the older group, 0.074 [0.027, 0.151] for the middle group, and 0.383 [0.237, 0.547] for the younger group.

The group differences were highly robust except for the following three cases. For AP-initial position, the difference between the middle and older group was 0.003 [–0.001, 0.012] with 94.4% of the probability mass lying above zero. In other words, our model indicates that with 94.4% probability, the middle group is 0.3% more likely to show devoicing than the older group. Similarly, within AP-initial position, the difference between the younger and middle group was 0.002 [–0.008, 0.01] with only 68.0% of the probability lying above zero. This result does not support a group difference one way or the other. Finally, for U-initial position, the difference between the middle and older group was 0.041 [–0.021, 0.122] with 90.3% of the probability lying above zero. For all the other pairwise comparisons across age groups for each prosodic position, the group difference was robust with a CI that lay entirely above zero (Older $<$ Middle $<$ Younger). The group difference between the younger and older group for U-initial position was as high as 0.350 [0.196, 0.519]. Overall, there is strong support for Hypothesis 3(a) that a younger speaker is more likely to realize domain-initial nasals with devoicing.

Next, we investigate the effect of prosodic position and vowel height within a given age group. **Figure 5** shows a marginal effects plot for the probability of devoicing. Generally, the probability of devoicing becomes greater in a higher position and the effect of position appears to become stronger as the average age of the group decreases.

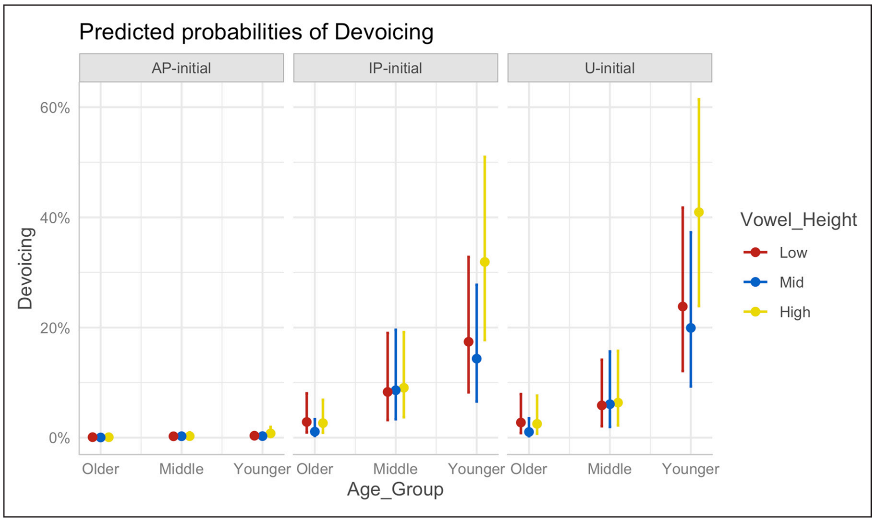

Figure 5: Predicted probabilities of devoicing by age group. Separate panels show the nasal's prosodic position, AP-initial (left), IP-initial (middle), and U-initial (right), and the different colors show vowel height, Low (red), Mid (blue), and High (yellow).

This stems largely from the fact that devoicing is generally unlikely for the two older groups regardless of position, whereas it becomes more likely in a higher position for the younger group.

These observations are statistically supported. Our Bayesian model provided compelling evidence that devoicing is more likely in IP- and U-initial position than in AP-initial position for all three groups. The CI for the difference in the probability was always above zero. On the other hand, zero was well within the CI for the difference between IP and U-initial position for the older and middle group. This indicates that devoicing is not more or less likely between IP- and U-initial position for the older and middle group. For the younger group, however, there was some support for a difference as the probability of devoicing was 0.079 [0.000,0.163] higher for U-initial than for IP-initial position, with 97.4% of the probability lying above zero. Therefore, Hypothesis 3(a) is partially supported with the order of AP < IP ≦ U.

Regarding the strength of the effect of prosodic position, we found the opposite pattern from Section 3.1. That is, while the effect of prosodic position was weakest for the younger group for complete denasalization, it was strongest for the younger group for devoicing. The younger group always showed a greater difference in the probability of devoicing than the middle and older group between two prosodic positions, with a CI that does not include zero. The only exception to this was that the difference between the U- and IP-initial position was greater for the younger than for the older group by 0.079 [–0.002, 0.166] with 97.1% of the probability lying above zero. On the other hand, the middle and older group were not very different from each other except for the difference between IP- and AP-initial position. The difference was greater for the middle group by 0.066 [0.001, 0.157] with 97.6% of the probability above zero.

Furthermore, **Figure 5** suggests that the effect of vowel height emerges most clearly in higher prosodic positions produced by the younger group; nasals followed by a high vowel are more likely to be devoiced than those followed by a mid or low vowel. Our statistical results supported this observation. The only robust vowel difference was found for the younger group, between high and low vowels (0.114 [0.041, 0.187]) and between high and mid vowels (0.143 [0.075, 0.216]). In addition, these differences are significantly greater for the younger group than for the middle and older groups, with zero lying outside the CI. Overall, these results are consistent with Hypothesis 3(b) with the order of Low = Mid < High, for the younger group.

Similar to the findings in Section 3.2, alveolars were more likely to be devoiced than bilabials. The size of the effect was very small for the older and middle groups, while it was more substantial for the younger group. For the older group, the probability for the alveolars was 0.012 [–0.003, 0.033] higher than for the bilabials with 94.0% of the probability lying above zero. For the middle group, there was no evidence for a significant difference as alveolars were 0.011 [–0.018, 0.048] more likely to be devoiced than bilabials with only 77.1% of the probability above zero. Lastly, for the younger group, the probability difference was 0.119 with a CI of [0.059, 0.178] which did not include zero. Additionally, these group differences were statistically significant between the younger group and the two other groups. The alveolar-bilabial difference was 0.108 [0.042, 0.173] greater for the younger than for the middle group, and it was 0.108 [0.046, 0.169] greater for the younger than for the older group. Again, this is presumably because devoicing is rarely found for the older and middle group regardless of the place of articulation of the nasal. These results lend support to Hypothesis 3(d) that alveolars are more likely to be devoiced, although the effect is limited to the younger group which yields a sufficient number of cases of devoiced nasals for this effect to emerge.

3.4. Partial denasalization

Another interesting pattern that can be observed from **Figure 3** above is that while all the other categories which reflect a degree of strengthening, Category (3) – (5), grew more frequent as the average age of the group decreased, Category (2) for partial denasalization [N^D] showed the opposite trend; Category (2) became *less* frequent as the average age of the group decreased. In particular, the younger group rarely produced partially denasalized forms, as a majority of tokens were realized with a complete lack of nasality.

A Bayesian model with the outcome variable partial denasalization supported this pattern. The predicted probability of partial denasalization for AP-initial position was 0.266 [0.167, 0.378] for the older group, 0.159 [0.088, 0.249] for the middle group, and 0.104 [0.057, 0.169] for the younger group. For IP-initial position, the probabilities were 0.163 [0.092, 0.251], 0.093 [0.047, 0.159], and 0.033 [0.014, 0.065] for the older, middle, and younger group, respectively. Finally, for U-initial position, the same probabilities were 0.147 [0.077, 0.241], 0.026 [0.007, 0.061], and 0.012 [0.002, 0.032]. The group differences within each prosodic position were statistically supported. Except for the difference between the younger and middle group for AP- and U-initial position, more than 92% of the probability mass lay *below* zero, indicating a significant age difference in a given position. The probability difference between the younger and middle group for the AP- and U-initial position was in the expected direction (negative), but only 87.4% and 83.8% of the probability mass was below zero, respectively. The highest probability difference was found between the younger and older group for AP-initial position, which was –0.162 with a CI of [–0.288, –0.045]. Taken together, these results suggest that partial denasalization is found more frequently in an older speaker's speech within each level of prosodic position.

Moving on to the effects of position and vowel height within a given age group, **Figure 6** provides a visual representation of these effects on the probability of partial denasalization. First, it is clear that the direction of these effects is the reverse of what was observed for the probability of complete denasalization and devoicing. The effect of position seems to be that partial denasalization is generally more likely in a lower position, with the strongest effects found in the older group. The effect of vowel height is similar to before: the higher the vowel, the greater the probability of partial denasalization. However, unlike in Section 3.2 and Section 3.3, this effect appears strongest in the older group.

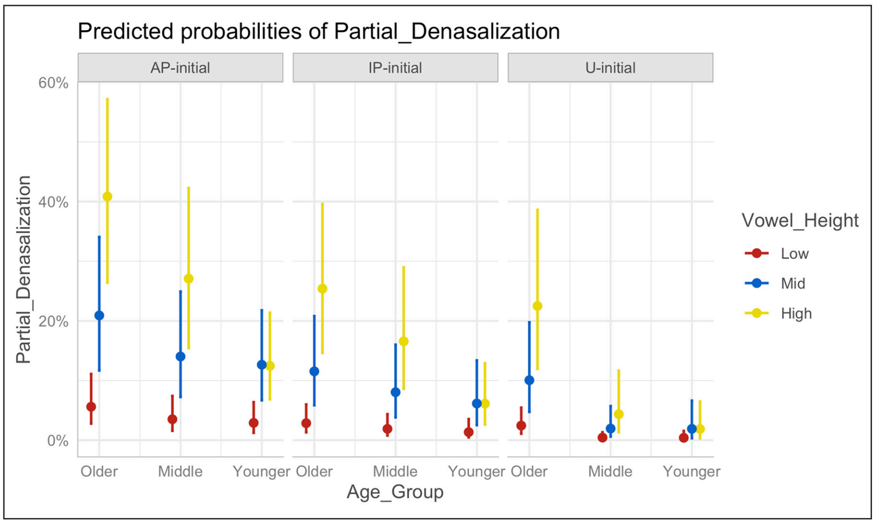

Figure 6: Predicted probabilities of partial denasalization by age group. Separate panels show the nasal's prosodic position, AP-initial (left), IP-initial (middle), and U-initial (right), and the different colors show vowel height, Low (red), Mid (blue), and High (yellow).

The results of our statistical analyses corroborated these observations. For each age group, all pairwise comparisons between a higher and a lower position showed a negative difference with at least 96% of the probability mass lying below zero. One exception was for the difference between U- and IP-initial position for the older group, which was –0.016 [–0.076, 0.044] with only 71.3% of the probability below zero. Overall, this suggests that partial denasalization is less likely in a higher position.

Statistical support for group differences in the effect size for prosodic position was not very robust. There were only four pairwise comparisons for which more than 80% of the CI was on either side of zero. The difference between the U-initial and IP-initial position was greater for the middle group than for the younger group by 0.046 [–0.006, 0.106] with 96.1% of the probability above zero. The difference between the U-initial and AP-initial position was also greater for the middle than for the younger group by 0.041 [–0.041, 0.129], but with only 82.7% of the probability above zero. The two remaining cases were for the IP-AP difference, which was bigger for the older group than the middle group (0.036 [–0.034, 0.105] with 85.1% above zero) and for the older group than the younger group (0.031 [–0.039, 0.101] with 81.40% above zero). Thus, the only substantial difference was that partial denasalization is more likely in IP-initial than in U-initial position to a greater extent for the middle group than for the younger group.

For the effect of vowel height, the statistical results were consistent and compelling. For every pairwise comparison between a higher vowel and a lower vowel condition for each age group, the probability difference was positive with a CI that excludes zero. Group differences were also supported, as all but one of the pairwise comparisons indicated that the vowel effect was weaker in a younger group with at least 95% of the probability mass lying below zero. The only exception was for the mid-low vowel difference which was greater by –0.025 [–0.081, 0.021] for the younger than for the middle group, with only 85.6% of the probability below zero. In other words, the difference was slightly smaller for the younger group with 85.6% certainty. These results indicate that partial denasalization is more likely before a higher vowel, and that this effect is progressively weaker in a younger group. The group difference appears to be at least partly due to the number of partially-denasalized tokens in each group. As shown in **Figure 3**, there are gradually fewer tokens of Category (2) in a younger group and in a higher prosodic position. These trends are generally mirrored in **Figure 6**, where the vowel height effect becomes progressively weaker in a younger group and in a higher prosodic context.

Finally, the effect of place of articulation on partial denasalization was only significant for the older group. Alveolars were more likely to show partial denasalization by 0.060 [0.018, 0.107] for the older group. These group differences were also robust, as the alveolar-bilabial difference was greater by –0.055 [–0.107, –0.007] for the middle than for the older group. It was also greater by –0.069 [–0.126, –0.014] for the younger than for the older group. These results are interpreted to mean that the effect of place of articulation is stronger for the older group than for the other two groups.

3.5. Individual variation

The findings from Sections 3.2 – 3.4 suggest that, while complete denasalization and devoicing became more frequent among younger speakers, partial denasalization became less frequent. This may indicate that speakers in the younger group have stabilized gradient phonetic denasalization into the discrete phrase-level process in (1), as discussed in Section 1.1.

(1) Korean Denasalization: [+cons] → [–nasal] / $_{AP}$[_

If true, it remains to be explained why around 25% of the tokens in each prosodic position by the younger group were still realized as sonorant nasals, despite meeting the structural description of the process (1). One possibility is that sonorant nasal realizations could have been produced by the speakers in the younger group who have not yet stabilized the process of denasalization, whereas those who have invariably denasalize all AP-initial tokens. Similarly, it is possible that there are speakers who show discrete denasalization in the middle and older group, masked by averaging of the results within the groups. In this section, we examine these possibilities with individual analyses.

A plot resembling **Figure 3** was produced for each speaker to examine the patterns of speaker variation in the phonetic realization of domain-initial nasals. There was a high degree of individual variation, in line with the previous findings that individuals vary in terms of which and how many levels of prosodic domains they distinguish by domain-initial strengthening (e.g., Keating et al., 2004, Section 8.4.1). Due to limitations of space, only the graphs of the most conservative speaker and the most innovative speaker from each age group are presented (**Figures 7 – 9**). These individuals showed the highest and the lowest overall proportion of Category (1) [N], respectively, in their age groups.

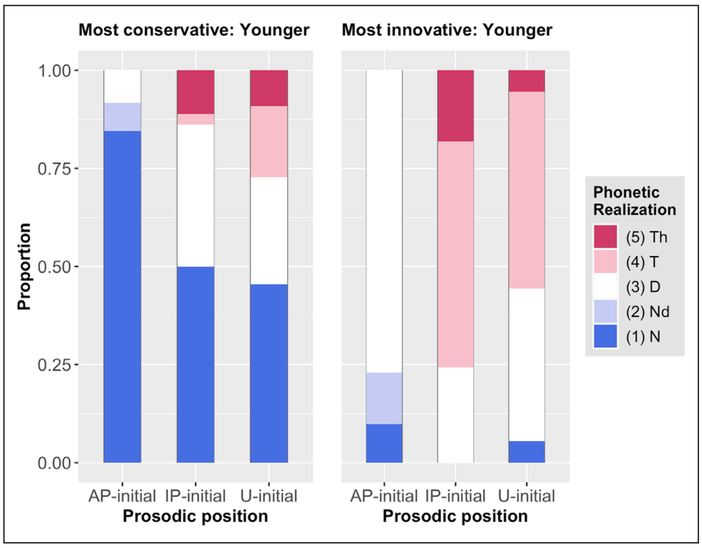

Figure 7: The proportion of each category of phonetic realization in AP-, IP-, and U-initial position. The left panel shows the most conservative speaker and the right panel the most innovative speaker from the younger group.

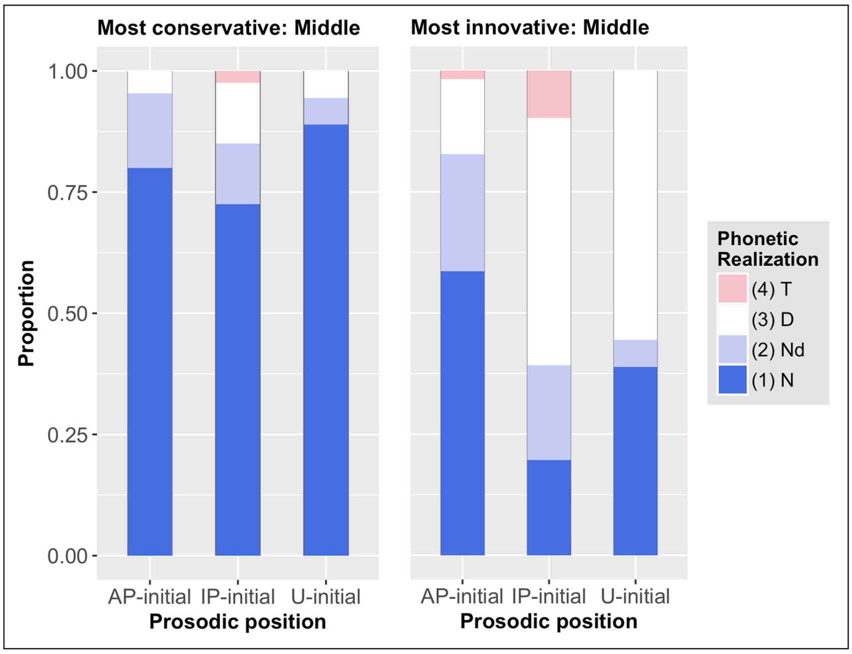

Figure 8: The proportion of each category of phonetic realization in AP-, IP-, and U-initial position. The left panel shows the most conservative speaker and the right panel the most innovative speaker from the middle group.

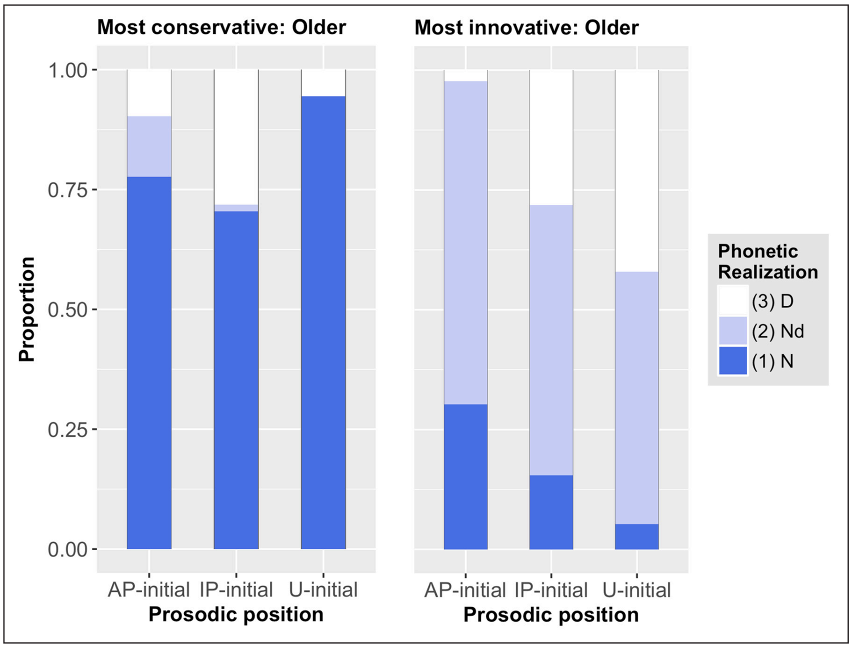

Figure 9: The proportion of each category of phonetic realization in AP-, IP-, and U-initial position. The left panel shows the most conservative speaker and the right panel the most innovative speaker from the older group.

While the differences among the age groups are still visible with greater proportions of higher categories found in the order of the younger, middle, and older group, the extent of within-group variation is striking. In particular, the younger group showed the greatest variation. For instance, **Figure 9** shows that the most innovative speaker from the younger group produced 100% of the IP-initial tokens with complete denasalization (Category [3] or above), whereas the most conservative speaker from the same group produced 50% of the IP-initial tokens as sonorant nasals (Category [1]). In terms of the range of phonetic realization, the most innovative speaker produced nearly all tokens in Categories (3) – (5), whereas another speaker (not shown here) produced almost all tokens in Categories (1) or (3). There was also a speaker whose realization was nearly always in Categories (1), (3), or (5).

Earlier, we discussed the possibility that the younger group may be subdivided into two groups in which one group shows discrete denasalization by realizing all AP-initial nasals without any nasality, whereas the other group shows gradient, prosodically-sensitive denasalization. To test this, we fitted a non-Bayesian binomial logistic regression for each of the twelve speakers in the younger group with complete denasalization as the outcome variable and the main effects of position, vowel, and place of articulation as the fixed effects. The results showed that nine out of twelve younger speakers showed no statistically significant effect of prosodic position, whereas two out of twelve speakers showed a greater probability of complete denasalization in a higher domain ([AP < IP] = U). The remaining speaker was an exception, showing the order of [AP > IP] = U. Thus, these results are in line with the view that complete denasalization is no longer a function of prosody for some younger speakers.

That said, there was no speaker who denasalized 100% of all tokens that were initial in an AP or larger domain; even the most innovative speaker produced 9.8% of AP-initial nasals as sonorant nasals and an additional 13.1% of AP-initial nasals as partially-denasalized nasals. However, the nine speakers did produce a higher percentage of completely denasalized tokens corresponding to Categories (3) – (5) compared to the rest of the speakers. Above 50% of the tokens in each position were completely denasalized for the nine speakers and above 70% of the tokens in each position were completely denasalized for five of them. These results will be discussed further in conjunction with the notion of rule scattering in Section 4.2.

4. Summary and discussion

4.1. Summary of results

This paper presents an apparent-time study of the phonetic realization of domain-initial nasals produced by 32 speakers of Seoul Korean born between 1932 and 1982, with the goal of understanding the diachronic development of domain-initial strengthening in Korean nasals. This section will summarize the results in relation to the three hypotheses stated in Section 1.3.

First, the results were consistent with Hypothesis 1: Over time, the phonetic realization of denasalization has proceeded in the order [N → N^D → D → T → T^H]. While Category (1) [N] and Category (2) [N^D] became progressively less frequent in a younger group, Category (3) [D] was more frequent in the younger group compared to the two other groups. In addition, Category (4) [T] and (5) [T^H] also became progressively more frequent from the older to the younger group. This is interpreted to suggest that the younger group is leading the sound change toward a denasalized and devoiced variant for domain-initial nasals.

Second, whether a nasal is realized with complete denasalization (Categories [3] – [5]) was influenced by various different factors, either fully or partially supporting Hypothesis 2 that complete denasalization is more likely:

(a) for younger speakers (Older < Middle < Younger for AP,
Older = Middle < Younger for the other positions)
(b) in a higher prosodic domain (AP < IP = U)
(c) before a high vowel (Low < Mid < High)
(d) for alveolar nasals (Bilabial < Alveolar)

In addition, the interaction effects revealed that prosodic position became a less important factor for the younger group compared to the other groups, whereas place of articulation became a stronger factor for the younger group than for the older group. There was also limited evidence that the effect of vowel grew stronger for the younger group than for the middle and older group.

Third, denasalization with extreme features such as consonant devoicing and a voicing lag was also found to be conditioned by various factors mostly in the direction predicted by Hypothesis 3. The realization of a nasal phoneme as a voiceless plosive with or without a voicing lag was found to be more likely:

(a) for younger speakers (Older < Middle < Younger)
(b) in a higher prosodic domain (AP < IP < U for the younger group but AP < IP = U for the other groups)
(c) before a high vowel (Low = Mid < High only for the younger group)
(d) for alveolar nasals (Bilabial < Alveolar only for the younger group)

Furthermore, the effect size of the factors prosodic position, vowel height, and place of articulation was always greater for the younger group than for the other groups.

Fourth, our results suggested that partial denasalization has been disappearing quickly as a phonetic variant of domain-initial nasals (Older > Middle > Younger). Partial denasalization was also *less* likely in a higher position (AP > IP > U), more likely before a higher vowel (Low < Mid < High), and for the older group, more likely for alveolar nasals. While there was only weak and inconsistent evidence that the effect size of prosodic position varied across the age groups, the effect of vowel height and place of articulation was clearly stronger for the older than for the other two groups.

Finally, we also reported the high individual variation in the phonetic realization of domain-initial nasals. Notably, prosodic position was not a significant factor for nine out of twelve younger speakers suggesting a possibility that denasalization has become a categorical process for these speakers. Nevertheless, all speakers produced at least some tokens in Category 1 [N] and 2 [N^D].

4.2. Korean denasalization as a product of stabilization of domain-initial strengthening

The results in the present study are compatible with the account of Korean denasalization proposed in Section 1.2, which posits that Korean denasalization has originated from the more general phenomenon of domain-initial strengthening. While domain-initial strengthening is known to be a gradient phonetic process by which segments in a higher prosodic position show progressively enhanced articulatory gestures, Korean denasalization can rather be defined as a discrete phrase-level phonological process described in (1).

(1) Korean Denasalization: $[+\text{cons}] \rightarrow [-\text{nasal}]\ /\ {}_{\text{AP}}[\ \_$

Specifically, we proposed that the discrete process would arise as a result of stabilization, which refers to the reinterpretation of a language-specific phonetic process as a phrase-level phonological process within the theory of the life cycle of phonological processes (Bermúdez-Otero, 2010, 2015; Robinson, 1976). Given this definition of Korean Denasalization, only a subset of the younger speakers in this study is assumed to have the discrete Korean denasalization rule in their grammar, while others lack the rule and only exhibit gradient denasalization as a result of domain-initial strengthening.

The older group and the middle group, with mean ages of 62.1 and 44.9, respectively, showed greater rates of complete denasalization in IP-initial position than in AP-initial position. This is in line with previous studies which used nasal airflow (Fougeron, 2001) or RMS acoustic energy measurements (Cho & Keating, 2001) to infer that the velum position is generally higher in initial nasal consonants in a higher domain. Taken together with the previous finding that complete denasalization is not found in initial position of domains lower than the AP (Kim, 2011; Yoo, 2015a), it indicates that the rate of complete denasalization is progressively greater in a higher domain (S and W < AP < IP = U). (The lack of a cumulative effect for U-initial nasals will be discussed in Section 4.5.)

On the other hand, the effect of prosody for complete denasalization was found to be significantly weaker for the younger group than for the other two groups. This may suggest that denasalization has become stabilized as shown in (1), at least for some speakers. In addition, the frequency of partial denasalization in the form [m^b n^d] became progressively lower as the average age of the group became younger. This is also consistent with the view that denasalization affects the feature [nasal] categorically for the younger speakers. Speculatively, the rapid reduction in partially denasalized forms may be because a highly precise articulatory phasing is needed between the gestures of the velum raising and the stop release. This would be particularly difficult, given that the acoustic duration of initial nasal consonants in Korean tends to be very short. This need for precise phasing is different from fully nasal stops for which the velum raising gesture can extend into the vowel. Thus, if domain-initial strengthening leads to a greater and earlier velum raising and gives rise to partially denasalized forms, this might explain why these forms quickly develop into completely denasalized forms.

It is interesting that domain-initial strengthening of nasal consonants affects voicing as well as nasality in Korean, a pattern which has not been reported in the domain-initial strengthening literature except in Yoo (2015a). For example, Cho and Keating (2001) did not examine voicing for /n/ in their study of domain-initial strengthening in Korean stops /t^h t t* n/, presumably because /n/ was expected to be voiced in all positions. The pattern by which nasal consonants are realized with no voicing and sometimes with a short voicing lag in higher domains resembles how plosives show greater VOT in higher domains in a range of languages (Keating et al., 2004). Cho and Keating (Section 3.2.3) found that VOT for the lenis stop /t/ and the aspirated stop /t^h/ in Korean was longer in a higher domain-initial position, making a robust four-way distinction among prosodic levels (W < AP < IP < U). Our results showed that while voiceless plosive realizations with or without a voicing lag for nasal phonemes are very rare in the older group, their frequency increases gradually in the middle group and the younger group, almost always in IP- and U-initial position (AP < IP ≦ U). This highlights the similarities in the pattern of domain-initial strengthening between the nasals and lenis stops in Korean.

Contrary to the pattern for complete denasalization, the effect of prosodic position on devoicing was stronger for the younger group than for the other groups. This is interpreted to suggest that while the effect of domain-initial strengthening on nasality may have stabilized for some younger speakers, the effect on voicing is still largely a gradient phenomenon. The smaller effect of position for the middle and older group seems to be simply because devoicing is rare in general, and the effect of position has yet to emerge.

As mentioned in Section 3.5, an important aspect of the theory of the life cycle of phonological processes is that even after a discrete process has entered a higher level component in the grammar (in our case the phonological component), the original process may continue to operate in a lower component (the phonetic component). This predicts that domain-initial strengthening should still affect various parameters including nasality and voicing in a gradient manner alongside the discrete process of denasalization in younger speakers' speech. This may explain why the individual analyses showed that at least some tokens were realized with nasality even for the individuals who realized a majority of the tokens with complete denasalization regardless of prosodic position.

However, whether or not denasalization has become a categorical phenomenon and whether there is evidence of an overlaid effect of a gradient phonetic process cannot be directly tested in the present study. In order to test these claims, a more sensitive articulatory instrument must be used to estimate the amount of nasality or the velum height as a continuous measure—see Bermúdez-Otero and Trousdale (2012, p. 7) who argue for the necessity of sensitive articulatory data in order to strictly determine articulatory discontinuity.

In sum, our results revealed significant differences between the age groups in the patterns of the phonetic variation of domain-initial nasals, indicating a pattern of historical development that is compatible with the account of Korean denasalization proposed in this study. While there was substantial individual variation, the diachronic pattern could be discerned thanks to the relatively large amount of data compared to prior studies on related topics which were based on articulatory data from three or four speakers. At the same time, further research involving more direct measurements of nasality and velum movement would be useful in confirming and complementing our findings.

4.3. The effect of vowel height and place of articulation

One of the main findings in this study was that denasalization of domain-initial nasals was more likely before a higher vowel. This effect may share the same phonetic origin as the cross-linguistic phenomenon that the order of distinctive vowel nasalization is from low to high vowels (Chen, 1972) and that for oral vowels, higher vowels tend to be produced with a higher velum position than lower vowels (Van Reenen, 1982, p. 99). Similarly, trained listeners are more likely to perceive an 'oral' vowel as nasal if the vowel is low.

There are two possible explanations for this. The first relies on the fact that there is a mechanical connection between the tongue body and the velum, involving for instance the palatoglossus muscle (Harrington, 1946; Moll, 1962). As Ohala (1975) argues, however, this simple mechanical explanation cannot account for the finding in electromyographic studies that the velum position for various vowels was 'actively' controlled by the muscles involved (e.g., Bell-Berti, 1976; Fritzell, 1969). Thus, an alternative explanation was offered by Lubker (1968), that low vowels are more resistant than high vowels to spectral changes caused by velopharyngeal opening. This is because the acoustic effect of added nasalization is mainly in the lower region of F1's range (House & Stevens, 1956; Fant, 1970), which means that in a high vowel a nasal formant will be close to and merge perceptually with the F1 and change the perceived height. Because low vowels have a high F1, they are perceptually less affected by nasality than high vowels, and more variation in velum position may be tolerated in low vowel environments (Ohala, 1975). A lower velum position may then become an acceptable and potentially phonologized characteristic of low vowels, contrasting with high vowels which require a higher velum position. However, this explanation is weakened by the finding by Wright (1986) that the nasal formant has magnetic effects which not only cause high and some mid-vowels to be perceived lower but also low vowels to be heard higher.

It is also known that the velum movement and the amount of nasal coupling in nasal consonants are highly variable according to the phonetic context (Van Reenen, 1982, pp. 129–131). For American English, it was found that nasal consonants were produced with a higher velum within a high vowel context than within a low vowel context. And it was not simply the highest point of elevation but the entire locus of velum movement which shifted depending on the vowel (Kuehn, 1976, pp. 98–99).

Following the above, if domain-initial strengthening has the effect of raising the velum in initial nasal consonants by a given amount, this velum raising will lead to a greater denasalization for nasals before a high vowel, as nasals before a high vowel are already expected to be realized with a higher velum than those before a low vowel. This may then initiate a listener-based sound change, as proposed by Ohala (1992). That is, the unintentional effect of velum raising in nasals may be misinterpreted by the listener as a systematic and inherent property of nasals, triggering a sound change starting from a high vowel context.

Our results also showed that alveolars were more likely to be denasalized than bilabials. A contributing factor might be that denasalizing an alveolar nasal may be more perceptually salient than denasalizing a bilabial nasal. This is because the release phase of an alveolar oral stop is more likely to create high frequency energy due to frication during the release, whereas a release of a bilabial oral stop tends to be weaker and less salient. Furthermore, our results suggested that alveolars were also found to be more prone to devoicing. This may be understood as a result of the aerodynamic and physiological constraints that make voicing harder to sustain for closure further back in the vocal tract (Ohala, 1983, pp. 194–201). These factors could then make alveolar nasals more prone to denasalization and devoicing by articulatory modifications of domain-initial strengthening. These listener-based explanations for the effects of vowel height and place of articulation are consistent with the findings that these effects tended to be greater for the younger group than for the other groups. This is because it would take time, even generations, for listeners' misinterpretation of an unintentional physiological effect to be reflected in their production, catch on, and become a community-level sound change. From the finding that the interaction effect for age and place of articulation was more robust than that for age and vowel height, we may infer that the place of articulation factor has started to influence production more recently than the vowel height effect.

4.4. Another explanation of the origin of denasalization

While the explanations above may account for the effects of age, prosodic position, vowel height, and place of articulation, it is not obvious why we find partially-denasalized forms [mᵇ nᵈ], especially in older speakers' production. An interesting explanation can be found in Ohala (1997) based on mis-timing of velum raising, originally proposed to account for *emergent stops*. Emergent stops spontaneously appear between a sonorant and a *buccal* obstruent, as in English warmth [wɔɹm**p**θ]. Buccal obstruents are obstruents produced further forward than the point of velic opening. These segments must be realized with a raised velum as, otherwise, they will not be audible as air will simply escape through the nasal port. Emergent stops appear when the velic closure is desynchronized with respect to the oral obstruent and is made during the sonorant—in this case, a nasal—giving rise to a transient stop homorganic with the sonorant. Ohala suggested that this explanation could be extended to Korean denasalization. As there is a greater pressure to maintain a high velum position during a high vowel to preserve the acoustic quality, nasal consonants which are preceded by a high vowel may be more susceptible to an early velum raising in anticipation for the high velum position in the vowel.

While this explanation has an advantage in accounting for the partially denasalized realizations of initial nasal consonants over the explanation in Section 4.3 based on discrete anticipation of velum position, the two explanations do not necessarily contradict each other and both may have contributed to the emergence of Korean denasalization.

4.5. Presence of pause as a factor

One result from the present study that is perhaps unexpected is that the probability of complete denasalization and devoicing was not higher for U-initial nasals compared to IP-initial nasals, except for the younger group in the case of devoicing. This leads to a violation of the strictly cumulative trend of (W <) AP < IP < U. One possible explanation may be found in a listener-based theory of sound change (e.g., Ohala, 1992). Assuming that domain-initial strengthening indeed provides a perceptual cue to a prosodic boundary, the role of denasalization in signaling a prosodic boundary may be less critical in U-initial position than in lower positions. This is because a preceding pause before an U-boundary already serves as a strong boundary cue.[7] Thus, listeners may perceive domain-initial strengthening as a salient marker of a prosodic boundary only in the absence of other stronger cues such as a substantial pause. This may lead to a perception-driven sound change whereby domain-initial strengthening in U-initial position becomes weaker. However, this account fails to explain why phrase-final lengthening before an IP-initial position, which serves as a clear boundary marker, fails to achieve similar effects as a preceding pause before an U-boundary.

An alternative, physiology-based explanation is that complete denasalization is less likely after a pause because the velum is typically lowered at resting position. On the other hand, unless there is a nasal segment in the vicinity—the context which was excluded in the present study—the velum is not likely to be fully lowered in the middle of an utterance. Assuming that the velum moves upward by a given degree by domain-initial strengthening, complete denasalization is less likely to happen if the velum movement starts at a lower position. This implies that the preceding segment may be an important conditioning factor for denasalization. For example, denasalization may be more likely in the context of i#n than a#n, assuming that the velum is higher in /i/ than in /a/. Further research is required to test such hypotheses.

4.6. Implications for domain-initial strengthening

The pattern of domain-initial strengthening of Korean nasals has implications for the understanding of domain-initial strengthening in general. One of the explanations proposed for domain-initial strengthening is that it is related to longer durations of initial segments (Fougeron & Keating, 1997; Cho & Keating, 2001). While shorter durations would result in the undershoot of articulatory targets (Lindblom, 1963; Moon & Lindblom, 1994), longer durations of domain-initial segments would allow time for the targets to be fully achieved or even to be overshot. Investigating the domain-initial strengthening of Korean /t^h t t* n/, Cho and Keating (2001) discovered a particularly strong correlation between linguopalatal contact and duration (both articulatory and acoustic) of these segments across different prosodic positions. They found that for durations above 80 ms, peak contact area remained similar, suggesting that 80 ms is sufficient time to reach a contact target and segments shorter than 80 ms would be subject to articulatory undershoot. Based on this, they suggested that in Korean, the undershoot mechanism may account for the systematic fine-grained articulatory variation across different prosodic positions.

However, this account is problematic in light of the patterns with nasal consonants. Reduction of nasality in domain-initial position cannot be a consequence of fully achieving the articulatory target of a nasal phoneme. Similarly, the realization of a nasal phoneme as a voiceless plosive or even a plosive with a short voicing lag cannot be explained this

[7] In a similar vein, see Cho, McQueen, and Cox (2007) who found evidence of a perceptual benefit across a Word boundary but not across an IP boundary.

way, unless one makes a counterintuitive assumption that nasal consonants are specified as [–nasal, –voice].

Among other possible mechanisms of domain-initial strengthening proposed by Fougeron and Keating (1997, p. 3737), the pattern with Korean nasals appears to be best explained by an account based on increased articulatory effort or energy. Fougeron (2001, Section 4.3.3) discussed this account in greater detail with regard to the patterns found in French. Adopting the definition of 'articulatory effort' by Straka (1963, p. 91) as contraction of the muscles involved in the positioning of the articulators for a given segment, Fougeron suggested that reduced nasality in initial nasals could be caused by reduction in the relaxation of the levator-palatini, the muscle responsible for elevating the velum (Bell-Berti, 1993). This general account in terms of greater muscle contraction is also preferable to the articulatory undershoot account as it can potentially account for a wider range of effects, including increased linguopalatal contact and initial vowel glottalization as outlined in Fougeron (p. 132).

5. Conclusions

The present study found evidence that the phonetic realization of domain-initial nasals in Korean, as captured in apparent-time data, has significantly changed over a fifty-year-period. This auditory-acoustic investigation of the phonetic variation in initial nasals revealed the multi-dimensional and dynamic nature of the phenomenon. The tendency for nasal consonants to be realized with more obstruent-like features in initial position, such as lack of nasality, lack of voicing, a release burst, and even a short voicing lag has increased over time, probably progressing in the order [$N \rightarrow N^D \rightarrow D \rightarrow T \rightarrow T^H$]. We also found evidence that denasalization and devoicing of initial nasals are generally more likely for alveolar nasals and before a high vowel. Importantly, the cumulative effect of prosodic position, in which complete denasalization became more likely in a higher domain-initial position, weakened in the younger group. In addition, partial denasalization in the forms [m^b n^d] became increasingly rare as the age of the speaker decreased. Taken together, these results support the view that, for a subset of the younger speakers, Korean denasalization is a discrete phrase-level phonological rule which has stabilized from a gradient process of domain-initial strengthening, in keeping with the theory of the life cycle of phonological processes (Bermúdez-Otero, 2010, 2011, 2015; Robinson, 1976).

Additional File

The additional file for this article can be found as follows:

- **Appendix.** An excel file containing the fixed effects estimates from the three Bayesian models run in this study. DOI: https://doi.org/10.5334/labphon.203.s1

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Competing Interests

The authors have no competing interests to declare.

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