NASALS AND NASALIZATION: THE RELATION BETWEEN SEGMENTAL AND COARTICULATORY TIMING

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ABSTRACT

Cross-language acoustic and perceptual studies in our lab test the hypothesis that certain aspects of variation in the temporal extent of vowel nasalization are linked to concomitant, inversely related variation in the duration of a flanking nasal consonant. Data from English, Thai, and Ikalanga are reported that support this hypothesis, and phonological phenomena consistent with the observed patterns of variation are considered.

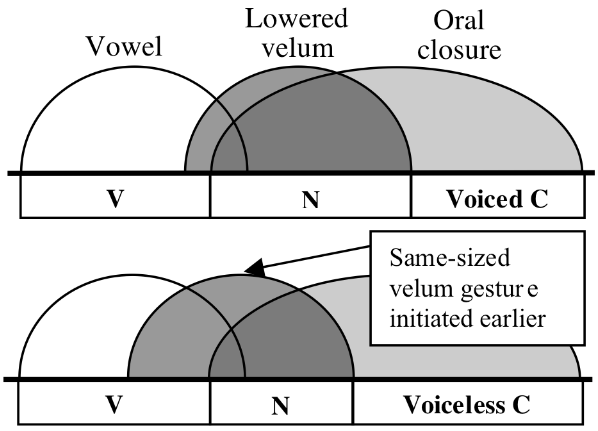
Keywords: articulatory co-variation, coarticulatory nasalization, perceptual equivalence.

1. INTRODUCTION

The temporal and spatial extent of vowel nasalization varies depending on phonetic context and prosodic structure. For example, in vowels followed by a nasal (N) and then oral (C) consonant, coarticulatory nasalization is more extensive when C is voiceless than when it is voiced (e.g., Malécot [12]) or when C is a fricative (Busà [3]; Ohala and Busà [14]). Prosodic influences on vowel nasalization include greater nasalization in tautosyllabic than heterosyllabic VN sequences (Cohn [5]; Solé [21]) and in stressed than unstressed syllables (Krakow [11]; Vaissière [22]). The height and duration of the vowel itself also matter, with lower (Bell-Berti [2]) and longer (Whalen and Beddor [23]) vowels tending to be more heavily nasalized in nasal contexts.

In recent years, research in our lab concerning contextual variation in vowel nasalization has been unified by the hypothesis that some aspects of variable vowel nasalization are due to variation in the temporal alignment of the nasal and oral gestures for N. Under this hypothesis, more extensive vowel nasalization in productions of, for example, /Vns/ compared to /Vnt/, or /Vnt/ compared to /Vnd/, is due not to an increase in nasalization per se but rather to earlier onset of a roughly constant-sized nasal gesture relative to tongue-tip raising for /n/ in the first member of these comparisons. If this hypothesis is correct, then production measures should show a trade-off in the relative durations of vowel nasalization and N: the duration of N should be inversely related to the extent of its coarticulatory influence on a flanking vowel.[i] This relation is represented schematically in Figure 1 for the effects of a voiceless post-nasal C (lower panel), where earlier initiation of the velum gesture would, relative to a voiced context (upper), yield temporally more extensive vowel nasalization and a shorter acoustic nasal murmur. A similar trade-off is predicted as a consequence of post-nasal frication.

Figure 1: Schematic representation of the consequences for vowel nasalization, nasal murmur, and post-nasal oral constriction if the velum gesture is initiated earlier in voiceless than in voiced contexts.



This paper provides an overview of our experiments with American English, Botswanan Ikalanga, and Thai as they pertain to the temporal interplay between vowel nasalization and N duration. The languages were chosen in large part because they differ in the segmental contexts in which VN sequences are phonotactically permissible. The primary focus is on production data, which will be shown to be generally consistent with the temporal alignment hypothesis, although some languages show little effect of context on nasals or nasalization. Reported in less detail is cross-language research on perception of the interplay between $\tilde{V}$ and N testing whether, given that vowel nasalization and a flanking nasal are in a temporal trading relation in production, listeners hear these cues for nasality as perceptually equivalent.

2. TEMPORAL RELATIONS BETWEEN $\tilde{V}$ AND N IN PRODUCTION

2.1. Measurements

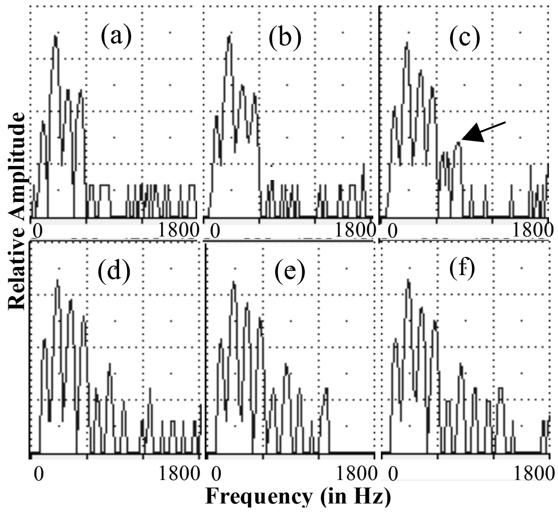
Four to six speakers of each language were recorded reading randomized word lists targeting VN sequences, with the purpose of the lists being masked by fillers. Acoustic measures included vowel duration, duration of vowel nasalization, nasal consonant duration, and duration of flanking oral consonants. Acoustic onset of vowel nasalization was determined by inspecting FFT spectra in 10 ms increments across the vowel. Nasalization onset was identified as the first spectrum with an identifiable low-frequency nasal formant and/or a broadening of F1 bandwidth and lowering of F1 amplitude, as illustrated in Figure 2 for contextually nasalized English /i/. The corresponding spectrographic and waveform displays were also consulted, with the latter typically showing a decrease in overall vowel amplitude at nasalization onset.[ii]

2.2. Effects of obstruent voicing on temporal alignment

In some languages, nasal consonants are substantially shorter before voiceless than before voiced consonants. We applied the temporal measures described above to VNC sequences produced by speakers of English and Ikalanga to determine whether shortening of pre-voiceless N occurs and, if so, whether N shortening co-occurs with greater vowel nasalization. That is, our goal was to determine whether the schematic relation in Figure 1 is upheld. Note that, as represented in the figure, earlier initiation of a constant-sized velum gesture would also result in a longer post-nasal oral constriction, a prediction we tested by assessing the relation between N and C durations.

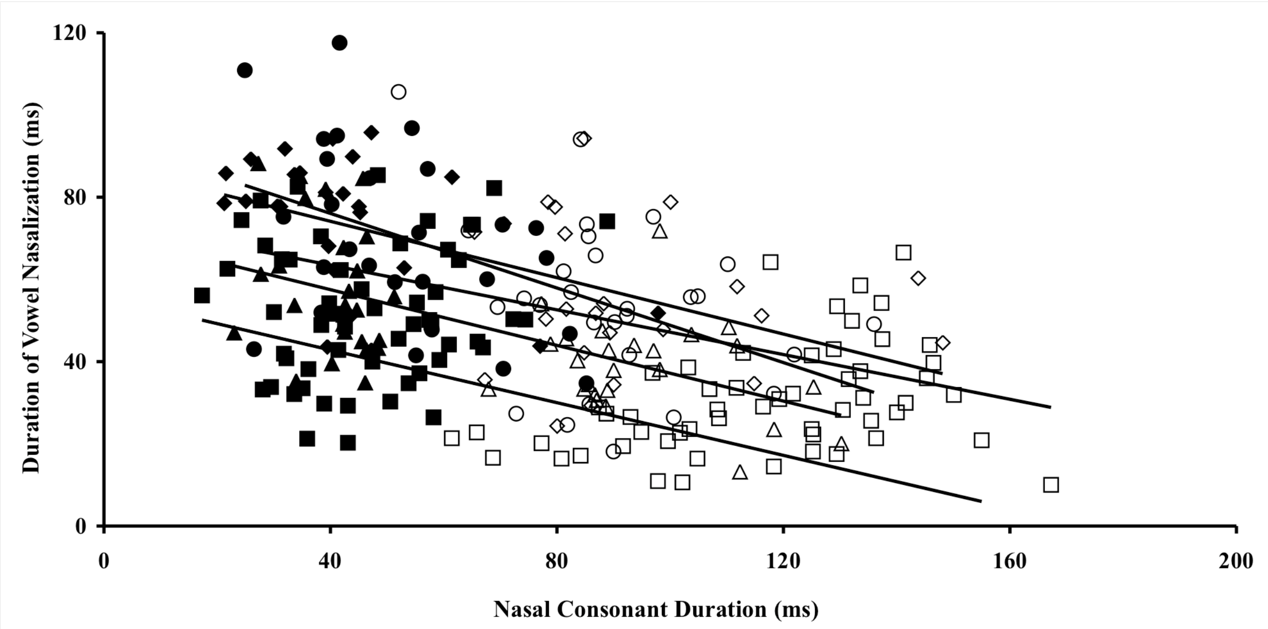
For American English, which is known to show substantial N shortening in pre-voiceless position (e.g., Raphael et al. [17]), five speakers were recorded reading word lists containing /ɛnC/ (e.g., *spend*, *spent*, *dens*, *dense*). Figure 3 plots the

Figure 2: Consecutive spectral sections (panels (a)-(f)) in 10 ms increments for /i/ from English /dim/ (*deem*). Onset of acoustic nasalization occurs in panel (c), where the arrow indicates the nasal formant in the F1 vicinity; F1 bandwidth also broadens.



relation between the duration of N and the duration of vowel nasalization for approximately 50 tokens of /ɛnC/ from each of the speakers. Trend lines calculated for each speaker's productions are also given; R^2 statistics ranged from .27 to .45. Although not all of the variation in vowel nasalization is accounted for by N duration—the total nasalization ($\tilde{V}$ plus N) being greater in voiced than in voiceless contexts—the predicted inverse relation between $\tilde{V}$ and N durations holds for all speakers (see also Cohn [5] and Malécot [12]). Moreover, this relation holds not only across voicing contexts, but also for finer-grained temporal differences within the voiceless context. That is, when only the $VNC_{[voiceless]}$ tokens (closed symbols) in Figure 3 are considered, the inverse relation between $\tilde{V}$ and N durations continues to hold, albeit with somewhat less steep trend lines ($R^2 \approx 0.2$ for $VNC_{[voiceless]}$). That the co-variation is due in part to earlier onset and earlier offset of the velum gesture relative to the oral cavity configuration is supported as well by C durations (not plotted here due to space): across voicing contexts, oral C duration is inversely related to N duration (see also Malécot [12]). Similarly, within the voiceless context, the shorter the N in $VNC_{[voiceless]}$ is, the longer the post-nasal oral constriction.[iii] Early onset of the velum gesture in $VNC_{[voiceless]}$ is presumably a manifestation of the resistance of voiceless stops to "nasal leakage"

Figure 3: Scatterplot showing inverse relation between nasal consonant and vowel nasalization duration for /ɛnC/ tokens from 5 American English speakers. Symbol shape denotes tokens from a given speaker. Closed symbols = $VNC_{[voiceless]}$ and open = $VNC_{[voiced]}$. A trend line is provided for each speaker.



(Ohala and Ohala [15]) and to other effects of velum raising (e.g., Hayes and Stivers [10]) that might diminish their voiceless percept.

A different timing pattern emerges for VNC sequences in Ikalanga, which show no influence of voicing on nasalization. In Ikalanga, as in other Bantu languages, NC sequences are traditionally analyzed as prenasalized ^{N}C (Mathangwane [13]; but see Downing [6] for a cluster analysis). Most VNCVs in Iklanaga are voiced, although $NC_{[voiceless]}$ occur in borrowed words, including some common words. In the experiment, six Botswanan Ikalanga speakers read word lists that included voiced VNCV (e.g., [da^{n}da]), voiceless VNCV (e.g., [ke^{n}ta]), and voiced NCV (e.g., [^{n}dulo]; initial voiceless NC do not occur). The resulting temporal measures in Figure 4 give no evidence of N shortening in pre-voiceless contexts and, perhaps consequently, show no increase in vowel nasalization in $NC_{[voiceless]}$ relative to $NC_{[voiced]}$ contexts.[iv] While there is slight evidence of an inverse relation between $\tilde{V}$ and N durations in Ikalanga, contrary to English it is the voiceless context that has longer N and less extensive vowel nasalization. Total nasalization ($\tilde{V}$ plus N durations) is the same for the voiced and voiceless VNCV contexts (122 ms); the bottom panel shows that the duration of initial N (in NCV), where there is no preceding vowel, is the same (121 ms) as $\tilde{V}$ plus N duration for VNCV sequences.

In summary, while only English VNCV sequences showed clear evidence of the predicted inverse relation between N duration and the temporal extent of vowel nasalization, the Ikalanga data nonetheless suggest a relatively constant-sized nasal gesture across VNCV (and NCV) sequences. It is noteworthy that the existing literature provides

Figure 4: Durations of oral and nasalized portions of vowels, and of nasal (N) and oral (C) consonants, in VNCV and NCV sequences, averaged across productions of 6 Ikalanga speakers. Duration of acoustic nasality ($\tilde{V}$+N in VNCV) is constant across the sequence types.

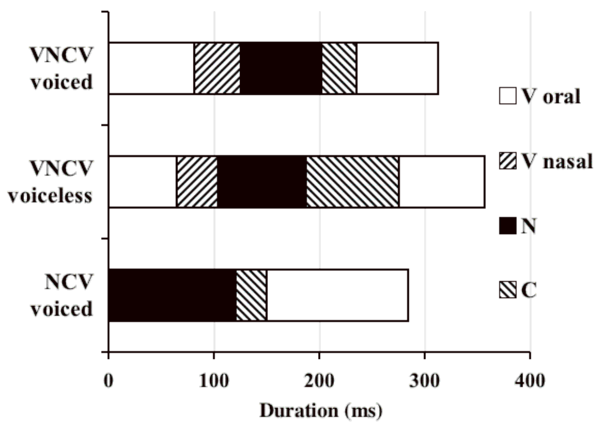
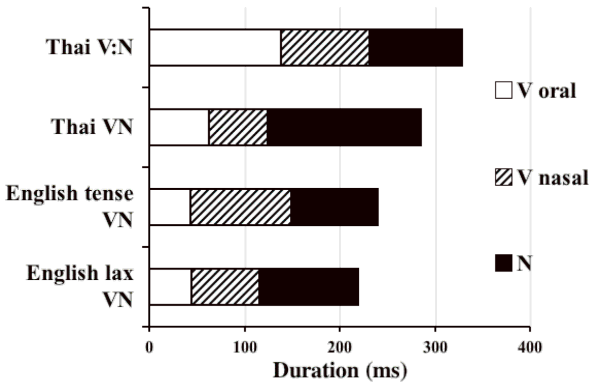


Figure 5: Durations of oral and nasalized portions of vowels and of nasal consonants (N) in CVN sequences, averaged across productions of 4 speakers of Thai (upper bars) and 6 speakers of English (lower bars). The Thai data are from Onsuwan [16].



additional evidence of Ṽ – N co-variation in VNC sequences triggered not by voicing, but by frication. Busà [3] found that, in some Italian dialects, N is shorter and vowel nasalization temporally more extensive in $VNC_{[fricative]}$ than $VNC_{[stop]}$ sequences, and Hattori et al. [9] reported a similar pattern in Japanese.

2.3. Effects of vowel length on the relation between Ṽ and N

A second context effect investigated in our studies, in this case for Thai and English, is the influence of vowel length on the temporal relation between vowel nasalization and flanking nasals. Thai has contrastive vowel length, and nasal coda duration in Thai is inversely related to vowel duration (Roengpitya [18]). Onsuwan [16], in our lab, investigated whether N duration in Thai was also inversely related to the temporal extent of coarticulatory vowel nasalization. Using the acoustic measures described above, Onsuwan analyzed an extensive set of CV(:)N (e.g., /bén/, /be:n/, /bam/, /bà:m/) words and nonsense items produced by four Thai speakers. In a separate study, we investigated essentially the same question for English tense and (shorter) lax vowels for productions of CVN words (e.g., *seen*, *sin*, *pain*, *pen*) by six American English speakers (Sefton and Beddor [20]).

Figure 5 presents the overall results for Thai and English: the VN contexts with the longer nasal codas (short VN in Thai and lax VN in English) co-occur with significantly less extensive vowel nasalization. Although the total duration of acoustic nasalization (Ṽ plus N) is not precisely constant across long (tense) and short (lax) vowel contexts, VN sequences in both languages exhibit the predicted trade-off in the relative durations of vowel nasalization and N. Moreover, the trade-off holds for individual speaker's productions for each of the Thai speakers and for five of the six English speakers.

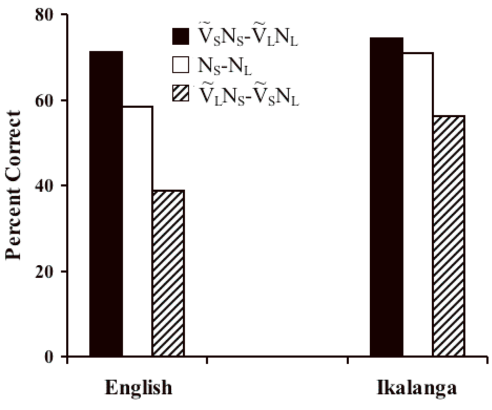
3. PERCEIVED EQUIVALENCE OF NASALS AND NASALIZATION

Thus our production studies, together with the existing literature, support the hypothesis that some aspects of contextual variation in vowel nasalization are linked to inversely related variation in the duration of a following nasal consonant. These findings have led us to hypothesize that, in the face of the articulatory interplay between Ṽ and N, listeners will treat nasality on vowels and consonants as perceptually equivalent. To test this hypothesis, we edited natural tokens of Ikalanga /gaba/ and /gamba/, which sound like perfectly acceptable possible but non-occurring words in English, creating (a) a 9-step N continuum from 0 to 70 ms of [m] murmur and (b) two degrees of vowel nasalization, slight nasalization (where the final 30 ms (20%) of /a/ was nasalized) and heavier nasalization (final 75 ms (50%) nasalized). Using a trading relations paradigm (Fitch et al. [7]), three types of discrimination pairs were created. All stimulus pairings had a constant-sized (34 ms) difference in N duration. *Nasal-only* pair members, N_S-N_L (where $_S$ = shorter and $_L$ = longer N), differed only in N duration (i.e., [gã$m_S$ba]-[gã$m_L$ba]. *Different nasality pairings*, $\tilde{V}_S N_S$- $\tilde{V}_L N_L$, differed in Ṽ and N, with one pair member having slight vowel nasalization and shorter N, and the other heavier nasalization and longer N ([g$\tilde{a}_S m_S$ba]-[g$\tilde{a}_L m_L$ba]). *Similar nasality* stimuli, $\tilde{V}_S N_L$- $\tilde{V}_L N_S$, also differed in Ṽ and N but with the opposite pairing of these manipulations so that total nasalization across the VN sequence was more nearly constant ([g$\tilde{a}_L m_S$ba]-[g$\tilde{a}_S m_L$ba]). (See Beddor et al. [1], for a more detailed presentation of the perceptual paradigm, albeit for a different set of stimuli.)

If listeners hear vowel and consonant nasality as perceptually equivalent they should poorly discriminate the *similar nasality* trials, and be more accurate in discriminating *different nasality* trials, even though the two trial types have the same-sized acoustic differences between pair members (i.e., in both, vowel nasality differed by 45 ms and N duration by 34 ms). The predicted outcome should hold especially for speakers of a language (e.g., English) in which $\tilde{V}$ and N systematically co-vary in production, although we speculated that all listeners, even if their language has little $\tilde{V}$-N co-variation (e.g., Ikalanga), might show some evidence of perceived equivalence.

Figure 6 gives the pooled results for 23 American English and 24 Botswanan Ikalanga speakers, summing across the multiple stimulus pairings (along the N continuum) of each of the three pair types. Listeners from both language backgrounds show the predicted pattern of perceived equivalence, being least accurate on trials in which total nasality across VN was roughly constant ($\tilde{V}_L N_S$-$\tilde{V}_S N_L$)—less accurate even than for N-only (N_S-N_L) pairings, which have smaller acoustic differences between stimuli. Not surprisingly, American English listeners, exposed to systematic $\tilde{V}$-N co-variation in their language, had greater difficulty than Ikalanga listeners discriminating stimuli varying only in N (N_S-N_L) or with similar nasality ($\tilde{V}_L N_S$-$\tilde{V}_S N_L$).

Figure 6: Pooled responses of 23 American English and 24 Ikalanga listeners to three types of discrimination trials (see text). All within-language pair-wise comparisons were significant ($p < 0.05$) except for the *Different Nasality* ($\tilde{V}_L N_S$- $\tilde{V}_S N_L$) vs. *N-only* (N_S-N_L) comparison for Ikalanga.



4. DISCUSSION AND PHONOLOGICAL IMPLICATIONS

Although nasalized vowels and nasal consonants show substantial temporal variation across contexts, our production data indicate that the acoustic manifestations of nasal gestures in VN sequences have some temporal stability: contexts that trigger shorter nasal consonants have concomitantly longer anticipatory vowel nasalization. The perceptual consequence of (relative) temporal stability of nasalization across the VN sequence is that listeners are more sensitive to acoustic variation in total nasalization ($\tilde{V}$+N) than to extent of nasalization on $\tilde{V}$ or N, and experimentally respond to vocalic and consonantal nasality as though they were perceptually equivalent.

Several widely attested phonological patterns involving nasal codas are consistent with these findings. That there is greater temporal stability in the nasal gesture in VN sequences than measures of N alone would suggest is arguably in keeping with the phonological robustness of nasal codas. Some languages allow only nasals as codas, and languages that have lost (some or all) coda consonants and for which a detailed chronology of that loss can be determined (e.g., Chinese and Romance languages; Chen and Wang [4]) show diachronically and synchronically that the loss of N follows a slower trajectory than that of oral stops. Perceptual equivalence of nasality on $\tilde{V}$ and N should further contribute to N coda stability, as even an extremely short nasal murmur (with accompanying vowel nasalization) would perceptually "count" as N. At the same time, co-variation between $\tilde{V}$ and N in production, together with their tight perceptual link, should mean that listeners—especially learners—might arrive at /$\tilde{V}$/ as the representation for speakers' intended and even actual /VN/, an expectation that is borne out by the historical evolution of $\tilde{V}$ from VN in many languages. Moreover, this evolution is influenced by the same factors, such as vowel length and post-nasal voicing and frication (see Hajek [8] for a review, also Sampson [19]), that trigger the co-variation under investigation here. Thus acoustic, perceptual, and phonological findings converge in showing the systematic interplay between segmental and coarticulatory timing for nasals.

5. ACKNOWLEDGEMENTS

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[i] The temporal alignment hypothesis, and the expected inverse relation between vowel nasalization and N duration, is predicted to hold only for (certain) effects of segmental context. That the velum gesture is temporally and spatially larger in some prosodic positions than others is well established (Krakow [11], among others).

[ii] Two experimenters measured the vowels from the three languages, although not all vowels were measured by both analysts. Initially, both analysts collaboratively measured a large set of vowels from Thai and Ikalanga; subsequently, a subset of individually measured vowels was cross-checked for consistency and agreement was over 90%.

[iii] Abby Cohn and Sarah Hawkins provided valuable insights into the notion of temporal variation in VNC sequences as due to "sliding" of the nasal gesture. That this notion better accounts for variation within voiceless than within voiced contexts merits further study.

[iv] While the Ikalanga data do not show N shortening (nor do they show evidence of earlier onset of the velum gesture) in $VNC_{[voiceless]}$, note that the C portion is three times longer for $NC_{[voiceless]}$ than $NC_{[voiced]}$. Both short pre-voiceless N in English and long post-N voiceless C in Ikalanga might be viewed as means of preserving the voiced-voiceless contrast in NC sequences.