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An examination of oral articulation of vowel nasality in the light of the independent effects of nasalization on vowel quality

In this paper, a summary is given of an experimental technique to address a known issue in research on the independent effects of nasalization on vowel acoustics: given that the separate transfer functions associated with the oral and nasal cavities are merged in the acoustic signal, the task of teasing apart the respective effects of the two cavities seems to be an intractable problem. The results obtained from the method reveal that the independent effects of nasalization on the acoustic vowel space are: F1-raising for high vowels, F1-lowering for non-high vowels, and F2-lowering for non-front vowels. The results from previous articulatory research performed by the author on the production of vowel nasality in French, Hindi, and English are discussed in the light of these independent effects of nasalization on vowel quality.

Keywords: vowel nasality, vowel quality, articulation, acoustics, sound change.

1. *Introduction*

A traditional characterization of vowel nasality adopts a seemingly binary classification of vowel sounds based on the relative height of the velum: nasal vowels are produced with a low velum position (and, thus, air radiation from both the oral and nasal cavities), whereas oral vowels are produced with a high velum position (and, thus, air radiation from the oral cavity alone). While it is unquestionably true that nasal vowels are produced with a lowered velum, this traditional characterization carries an implicit assumption about the state of the oral cavity for the production of a nasal vowel, i.e., that the nasal vowel maintains the same articulatory characteristics as its non-nasal counterpart in all aspects except for the height of the velum. This binary view is arguably strengthened by the use of a diacritic marker to denote nasality as a secondary feature in International Phonetic Alphabet transcriptions, i.e., [˜] or /˜/. For example, the transcription [ɛ̃] implies that the vowel quality is the same as for [ɛ], and that the only articulatory difference between the two sounds is the relative height of the velum. This articulatory assumption necessarily carries a corresponding acoustic assumption: if the oral articulation of a nasal vowel is the same as its oral vowel counterpart, then any acoustic differences observed between the two vowels would be assumed to be due to nasalization itself.

These assumptions are problematic for phonetic and phonological research of vowel systems. A common practice in this research is to separate and characterize vowel categories based on acoustically measurable features, most notably the frequencies of the first two spectral formants, F1 and F2. This practice is relatively straightforward for oral vowels, since the formant frequencies are considered to arise from resonances associated with the singular oro-pharyngeal cavity beginning at the glottis and ending at the lips. Changes to the shape and/or length of this cavity result in relatively predictable formant frequency modulations, and the mapping from changes in articulation to changes in formant frequencies is mostly well understood, e.g., F1 is generally negatively correlated with tongue/jaw height, F2 is generally positively correlated with tongue anteriority, and lip rounding is positively correlated with lowering of all formants (Stevens, 2000; Johnson, 2003). However, when the velum is lowered, the coupling of the nasal cavity to the oro-pharyngeal cavity introduces additional resonances and anti-resonances to the acoustic spectrum, which are predicted to affect the spectral properties of nasalized vowels (including formant frequencies). Since the separate acoustic transfer functions associated with the two cavities are merged in the acoustic signal, changes to formant frequencies that arise independently from the two cavities cannot be teased apart when using acoustic measurements alone. Thus, given some observed difference in formant frequencies between an oral and a nasal vowel in a given language, how can one ascertain whether the difference arises from velum lowering or from a change in oral vowel quality?

In this paper, I summarize a novel methodological approach to determining the independent effects of vowel nasalization on F1 and F2 frequencies, as well as the resulting observation of the modification to the vowel space created by velum lowering. Subsequently, I present an overview of recent articulatory experiments that I have carried out on the production of vowel nasality in French, Hindi, and English, as well as how the language-specific results from these studies can be interpreted in the light of the independent effects of nasalization on the acoustic vowel space.

2. *Determining the independent effects of nasalization on the acoustic vowel space*

2.1 Data collection

The method – described in full in Carignan (2018) but summarized here – uses ultrasound and nasalance technologies to predict the effect of lingual configuration on formant frequencies of nasalized vowels, account for acoustic variation due to changing lingual posture, and exclude its contribution to the acoustic signal. Data collection took place at two sites in Sydney, Australia: the MARCS Institute for Brain, Behaviour and Development (Western Sydney University) and Macquarie University. Native speakers of six different languages/dialects participated in the study (American English, Australian English, Mandarin, Cantonese, French, and Hungarian): four males and two females, with a mean age of 31.3 (SD 7.5). All speakers were either graduate students or professional academics in phonetics and/or phonology.

The speakers were instructed to produce 20 sustained repetitions of each of the 11 vowels /i ɪ e ɛ æ a ɑ ɔ o ʊ u/. For each repetition, the speaker was instructed to sustain phonation of an oral quality of the vowel, then subsequently lower the velum during the sustained phonation while attempting to maintain tongue posture[1]. During the sus-

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[1] The method does not necessarily require constant tongue posture, since the resulting metric accounts

tained vowel productions, nasalance data and ultrasound data related to tongue shape in the midsagittal plane were co-collected. Nasalance data were captured using a Glottal Enterprises H-SEP-MU nasalance plate, consisting of two microphones separated by a baffle that surrounds the speaker's upper lip. Ultrasound images were generated using a GE Logiq e laptop, and a GE 8C-RS transducer was positioned between the speaker's mandible and larynx and held in place with an elastic headset (Derrick, Best & Fiasson, 2015). An example of the experimental setup is shown in Figure 1. Ultrasound video was captured in real time from the GE Logiq e VGA video output using an Epiphan VGA2USB Pro video grabber. The nasalance audio and ultrasound video data were co-registered on a dedicated computer, using FFmpeg software to record a continuous .AVI file at 30 fps with embedded audio sampled at a rate of 44.1 kHz.

Figure 1 - *An example of the experimental setup used to determine the independent effects of nasalization on the vowel space, including a hand-held Glottal Enterprises nasalance device and an ultrasound probe holder headset (Derrick et al., 2015). Reproduced from Carignan (2018)*

2.2 Data analysis

Analysis of the synchronized nasalance data was carried out using Praat (Boersma, Weenink, 2015). The sustained vowel productions were segmented manually according to the broadband spectrogram and corresponding waveform. The average duration for the segmented vowels was 1.77 s (SD 0.57 s). Separate amplitude tracks for the oral

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for formant variation that is due to tongue shape. However, maintaining tongue posture helps to ensure that the ultrasound image variance used to predict formant values falls within the range of image variance used to map the articulation to the acoustics.

and nasal signals were created, and nasalance was derived by calculating the proportional nasal amplitude, i.e., nasal amplitude over total amplitude. The time points associated with the minimum and maximum nasalance in each token were located automatically; these time points correspond to the most oral and most nasal parts of the token and will be referred to as the "oral point" and "nasal point", respectively. Formant estimation was performed on the combined audio from the stereo nasalance channels. Two-formant estimation at the oral and nasal time points was carried out using the Burg LPC method, with optimized parameters for each speaker and vowel, derived from a semi-automated procedure similar to Escudero, Boersma, Rauber & Bion (2009). The suitability of these optimized parameters was verified manually for each speaker and vowel via inspection of the formant tracks against a broadband spectrogram.

The indices of all of the ultrasound frames located between the oral and nasal points of the vowel tokens in each recording were logged[2], and these ultrasound images were subsequently filtered and processed separately for each speaker in MATLAB (The Mathworks Inc., 2015) using Temporally Resolved Articulatory Configuration Tracking of Ultrasound software (TRACTUS; Carignan, 2014b): images were downsized via bicubic interpolation to 20% of the original resolution (in order to reduce dimensionality), a region of interest (RoI) around the bounds of the movement of the tongue surface was selected, and the down-sampled pixels in the RoI were used as dimensions in principal components analysis (PCA) modeling. PCs which independently explained at least 1% of the image variance were retained, yielding between 12 and 15 total PCs for each speaker.

Due to the orthogonal nature of the components, the PC scores are able to be used as independent variables in regression models. Thus, two separate regression models (for F1 and F2) were created for each speaker. Each model included formant values as the dependent variable and the ultrasound PC scores related to the oral time point of each token as independent variables, effectively mapping the lingual articulation to the formant structure when the velum is closed. These linear models were subsequently used to predict formant values for the corresponding nasal point of each token, using the ultrasound PC scores from the nasal acoustic time points as predictor variables. The result represents formant values (in Hz) that are predicted by tongue posture alone, without any acoustic influence of nasalization. Thus, differences between predicted and measured formant values at the nasal time point can be assumed to be independent effects of nasalization. However, it is nevertheless possible that a portion of the difference between predicted and measured formant values at the nasal time point might be due to model error or to formant frequency modifications that arise from non-lingual oral articulation (e.g., labial configuration). To control for these possible sources of error, formant predictions and measurements were also made at the oral time point of each token, in order to obtain baselines of error for the oral models. The oral model errors were averaged for each vowel category, and these vowel-specific error baselines were subtracted from the measured formant values at the nasal point of the corresponding vowel tokens. In this way, each data point was corrected for vowel-specific error in the linear mapping, yielding a more conservative estimate of differences

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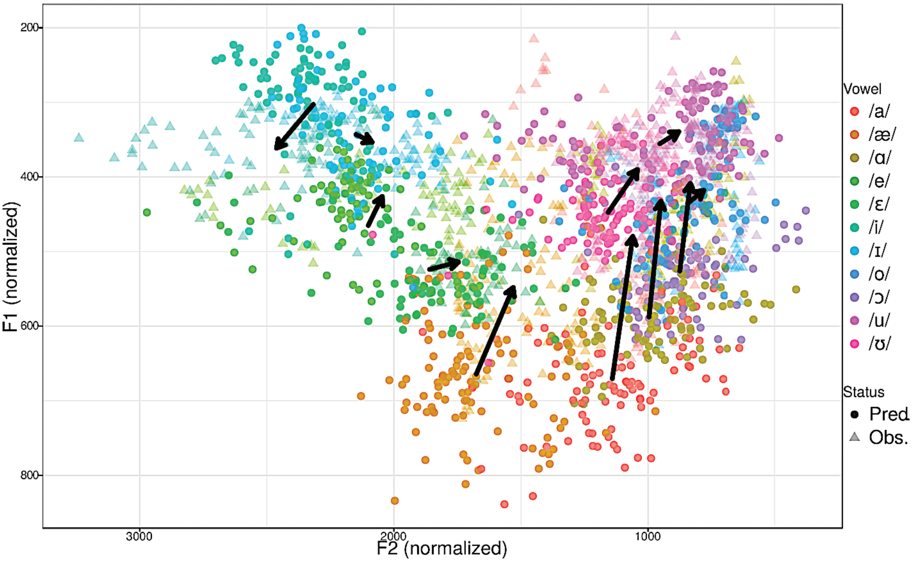
[2] The average number of total frames for each speaker was 4791 (SD 1372).

between predicted and measured formant values observed for the nasal time point. Finally, in order to combine the vowel spaces of the different speakers, formant values were normalized for each speaker via Lobanov transformation before translation back to Hz using the grand mean and average SD, in order to preserve the within-speaker normalized structure while retaining interpretability of the results.

2.3 Results

Figure 2 displays the vowel-corrected formant values measured at the nasal time points of the tokens, obtained using the method described above. The opaque colored dots are formant values predicted by tongue shape, while the transparent colored triangles are formant values that were actually observed. The arrows connect the means of the predicted values (start of the arrow) and observed values (end of the arrow). The overall pattern suggests that the independent effects of nasalization on the acoustic vowel quadrilateral are F1-raising of high vowels (vowels with F1 ≤ 350 Hz), F1-lowering of non-high vowels (vowels with F1 ≥ 350 Hz), and F2-lowering of non-front vowels (vowels with F2 ≤ 2000 Hz). The cumulative effect of these formant frequency modifications resembles a counter-clockwise chain shift: low vowels raise and retract in the vowel space, encroaching on the acoustic space of the mid-back vowels, which also raise and retract, encroaching on the acoustic space of the high-back vowels, which also raise and retract.

Figure 2 - *Acoustic vowel space of speaker-normalized and vowel-corrected formant values for nasalized productions. Opaque colored dots represent formant values predicted by lingual ultrasound images; transparent triangles represent actual measured values. Arrows connect the means of the predicted and measured categories. Reproduced from Carignan (2018)*



It is reasonable to question whether these systematic modifications to the formant structure of nasalized vowels might be perceived by listeners as changes in vowel quality. Indeed, perceptual evidence suggests that this may be the case. With regard to F1, Beddor, Krakow & Goldstein (1986) and Krakow, Beddor & Goldstein (1988) observed that listeners can attribute an increase in F1 for nasalized high vowels to either a lower tongue position or an increase in degree of nasalization, and they can attribute a decrease in F1 for nasalized low vowels to either a higher tongue position or an increase in degree of nasalization. Similarly, Wright (1975, 1986) found that listeners perceived nasalized [ĩ] as lower and more retracted than oral [i] and nasalized [ã] as higher than oral [a]. With regard to F2, Delvaux (2009) has shown that F2-lowering alone is sufficient to trigger the percept of nasality on synthesized vowels in French, and Beddor (1993) suggests that the increased F1-F2 proximity of non-front nasal vowels observed for Hindi, Turkish, Igbo, and English (Beddor, 1982) should result in perceptual retraction compared to their oral counterparts – she notes, however, that this retraction is not necessarily well supported in the perceptual vowels spaces of Wright (1986).

By and large, these perceptual effects of nasalization mirror the independent acoustic effects of nasalization on the vowel space observed above: F1-raising of high vowels, F1-lowering of low vowels, and (arguably) F2-lowering of non-front vowels. This suggests that velum lowering creates an acoustic pressure on the vowel space, and that this pressure can be perceived by listeners as systematic shifts in vowel quality. It is, thus, of great interest to determine whether this acoustic-perceptual pressure can lead to subsequent changes in the production of nasal vowel quality by speakers, i.e., whether speakers make modifications to the *oral* articulation of nasal(ized) vowels in response to the acoustic-perceptual modifications that arise from velum lowering – either enhancing the acoustic-perceptual shifts or compensating for them. In the following sections, the results from studies on the oral articulation of phonological and phonetic vowel nasality in French, Hindi, and English will be summarized and discussed in the light of these independent effects of nasalization on the F1/F2 vowel space.

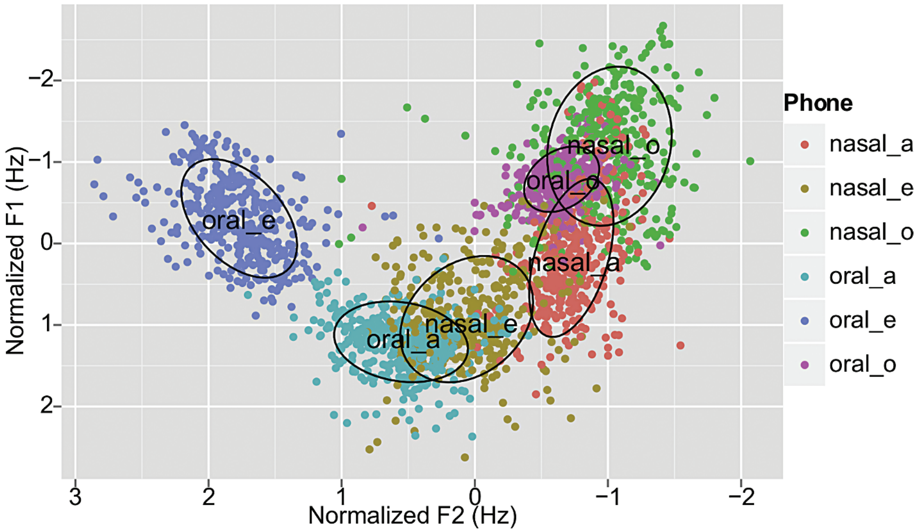
3. *Oral articulation of phonological vowel nasality*

3.1 French

Northern Metropolitan French (NMF) – defined as the variety of French spoken in urban areas of France, north of the Midi–Provence southern line – is a compelling language variety for the study of vowel nasality for a variety of both historical and synchronic reasons. In particular, the phonological three nasal vowel system /ɛ̃ ɑ̃ ɔ̃/ of modern NMF is said to be undergoing a "push chain shift" (Fónagy, 1989; Maddieson, 1984; *inter alia*). Specifically, impressionistic reports claim that /ɛ̃/ is lowered and retracted, nearing the space of [ɑ̃]; that /ɑ̃/, in turn, is "pushed", retracting and raising near the space of [ɔ̃]; and that /ɔ̃/, in turn, is raised, becoming more [õ]-like. To a large extent, this counter-clockwise chain shift resembles the vowel quality modifications due to nasalization outlined in Section 2.3, with the exception of the lowering of /ɛ̃/, which is expected to undergo slight F1-lowering due to nasalization (see Figure 2). Understanding the specific oral articulatory configurations involved in the manifestation of this chain shift would help determine if the impression of a chain shift in the NMF nasal vowel system arises primarily from the acoustic pressure on the vowel space created by velum lowering (i.e., whether the reported chain shift is merely acoustic-perceptual), or whether NMF speakers actually modify their oral articulations of the nasal vowels in a way that mirrors the acoustic modulations due to velum lowering.

In Carignan (2014a), articulatory and acoustic data relating to the productions of three oral–nasal vowel pairs /a/-/ɑ̃/, /ɛ/-/ɛ̃/, and /o/-/ɔ̃/ were recorded from 12 female NMF speakers. Lobanov normalized formant measurements for the speakers' productions of 10 repetitions of French CV lexical items containing these six vowels are shown in Figure 3. The advanced nature of the reported nasal vowel chain shift is evidenced clearly: the realization of /ɛ̃/ is lowered and retracted to such a degree that it occupies an acoustic space that is posterior to the realization of /a/, and the realization of /ɔ̃/ is raised to such a degree that it occupies an acoustic space even higher than the realization of /o/. The results suggest that the (acoustic) realization of the NMF nasal vowel system is actually closer to [ɐ̃ ɔ̝̃ õ̝] than implied by the IPA transcriptions [ɛ̃ ɑ̃ ɔ̃], transcriptions that are traditionally used to describe these vowels in NMF.

Figure 3 - *Speaker-normalized formant values for the vowels /ɑ/ ('oral_a'), /ɑ̃/ ('nasal_a'), /ɛ/ ('oral_e'), /ɛ̃/ ('nasal_e'), /o/ ('oral_o'), and /ɔ̃/ ('nasal_o'). Reproduced from Carignan (2014a)*



Articulatory data related to tongue and lip posture were recorded using electromagnetic articulography systems made by Carstens Medizinelektronik GmbH: the AG500 Electromagnetic Articulograph, located in the Speech Dynamics Laboratory in the Beckman Institute at the University of Illinois at Urbana-Champaign, Illinois, USA, and the AG200 Electromagnetic Midsagittal Articulograph, located at

Grenoble Images Parole Signal Automatique (GIPSA-lab) at l'Université Stendhal, Grenoble, France. Two speakers were recorded using the AG500 in Illinois, and 10 speakers were recorded using the AG200 in Grenoble. For each speaker (on both systems), three sensors were adhered along the midsagittal line of the tongue at even intervals, beginning ≈ 1 cm behind the tip of the tongue, ending as far back along the tongue as could comfortably be reached, with a sensor at the midpoint between these two. The vertical and horizontal positions of these sensors were used to measure tongue height and anteriority, respectively. Additionally, two sensors were placed on the lips: one on the vermilion border of the upper lip, and the other one on the vermilion border of the lower lip, in order to measure the degree of labial aperture and lip protrusion.

With regard to the vowel pair /ɛ/-/ɛ̃/, the independent acoustic effect of velum lowering observed in Section 2.3 suggests that F1 and F2 should both lower slightly for the nasalization of [ɛ]. The acoustic results from Carignan (2014a) showed that /ɛ̃/ was realized with a higher F1 and lower F2 compared to /ɛ/ for all 12 speakers. With regard to oral articulation, /ɛ̃/ was produced with a lower and more retracted tongue position than /ɛ/ for all 12 speakers, with no consistent overall labial articulatory differences for /ɛ̃/ compared to /ɛ/. In light of the independent acoustic effects of nasalization for [ɛ], these results suggest that in NMF: (1) the acoustic realization of F1 for /ɛ̃/ is not, in fact, due to nasalization, but to tongue height; and (2) the acoustic realization of F2 for /ɛ̃/ is due to a combination of nasalization and tongue retraction.

With regard to the vowel pair /a/-/ɑ̃/, the independent acoustic effect of velum lowering suggests that F1 should lower to a large degree, and that F2 should lower slightly, for the nasalization of [a]. The acoustic results from Carignan (2014a) showed that /ɑ̃/ was indeed realized with a lower F1 and F2 compared to /a/ for all 12 speakers. With regard to oral articulation, very few speakers produced /ɑ̃/ with a higher tongue position compared to /a/; in fact, most speakers produced /ɑ̃/ with a *lower* tongue position. However, 11/12 speakers produced /ɑ̃/ with a more retracted tongue position compared to /a/, and all 12 speakers produced /ɑ̃/ with greater lip rounding (via lip protrusion and/or smaller lip aperture) than /a/. In light of the independent acoustic effects of nasalization for [a], these results suggest that in NMF: (1) the acoustic realization of F1 for /ɑ̃/ is due to a combination of nasalization and lip rounding (but not tongue height); and (2) the acoustic realization of F2 for /ɑ̃/ is due to a combination of nasalization, tongue retraction, and lip rounding.

With regard to the vowel pair /o/-/ɔ̃/, the independent acoustic effect of velum lowering suggests that both F1 and F2 should lower slightly for the nasalization of [o]. The acoustic results from Carignan (2014a) showed that /ɔ̃/ was indeed realized with a lower F1 for just over half of the speakers (8/12) and a lower F2 for the majority of speakers (10/12), in comparison to /o/. However, only two speakers produced /ɔ̃/ with a higher tongue position than /o/; on the contrary, the majority of speakers produced /ɔ̃/ with a lower tongue position compared to /o/. Moreover, only six of the 10 speakers who realized /ɔ̃/ with a lower F2 than /o/ manifested any evidence of lingual retraction for /ɔ̃/ compared to /o/. With regard to labial articulation, just over half of the speakers (8/12) produced /ɔ̃/ with a smaller labial aperture than /o/. However, five speakers produced /o/ with greater lip protrusion than /ɔ̃/. These results suggest that both /o/ and /ɔ̃/ are characterized by some degree of lip rounding, but that the articulatory strategies used to produce this rounding are different for the two vowels (i.e., greater labial protrusion for /o/ vs. smaller labial aperture for /ɔ̃/), and that these strategies vary across speakers. In light of the independent acoustic effects of nasalization for [o], these results suggest that in NMF: (1) the acoustic realization of F1 for /ɔ̃/ is due to a combination of nasalization and lip rounding (speaker dependent); and (2) the acoustic realization of F2 for /ɔ̃/ is due to a combination of nasalization, tongue retraction (speaker dependent), and lip rounding (speaker dependent).

3.1.1 Summary of articulatory results in the light of the acoustic effects of nasalization

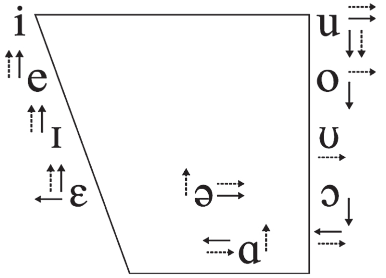
The results from Carignan (2014a) reveal that the independent acoustic effects of nasalization are observed in the NMF nasal vowel system in the majority of cases: the only exception is a higher F1 for /ɛ̃/ compared to /ɛ/, which is posited to be due to a lower tongue position for /ɛ̃/. In some cases, adjustments in oral articulation did not yield the predicted corresponding acoustic adjustments, e.g., a lower tongue position for /ɑ̃ ɔ̃/ yet lower measured F1, which is posited to be due (at least partially) to nasalization. In many other cases, oral articulatory adjustments were observed that are predicted to yield acoustic adjustments which mirror (and perhaps enhance) the acoustic effects of nasalization, e.g., lip rounding for /ɑ̃ ɔ̃/ and more retracted tongue position for /ɛ̃ ɑ̃ ɔ̃/. Taken together, these results suggest that the acoustic chain shift in the NMF nasal vowel system is due in part to the independent acoustic effects of nasalization on the vowel space, and that in some cases oral articulatory configurations are involved in ways that enhance these acoustic modulations.

3.2 Hindi

In comparison with the three nasal vowel system of NMF, vowel nasality in Hindi involves a richer system that occupies a much larger area of the vowel space. In fact, the 10 phonemic oral vowels /i e ɪ ɛ ə ɑ ɔ ʊ o u/ each have corresponding phonemic nasal counterparts: /ĩ ẽ ɪ̃ ɛ̃ ə̃ ɑ̃ ɔ̃ ʊ̃ õ ũ/ (Ohala, 1999; Sharma, 1958). This allows for a more complete comparison between the acoustic and oral articulatory modifications in Hindi and the independent acoustic effects of nasalization on the larger vowel space. In Shosted, Carignan & Rong (2012), articulatory and acoustic data relating to the productions of nonce words created in Devanagari script were collected from four bilingual Hindi-English speakers (three females). The target items included all 20 phonemic oral and nasal vowels. Articulatory data were collected using the Carstens AG500 in Illinois, with the same sensor placement as described for Carignan (2014a). In addition to the two sensors placed on the upper and lower lips, two additional sensors were placed at the corners of the mouth in order to obtain more complete information about labial aperture.

Unlike for NMF, where vowel nasality was often observed to involve increased lip rounding, no differences in labial configuration were observed for any of the 10 Hindi nasal vowels in comparison to their oral counterparts. However, both acoustic and lingual articulatory differences were observed; a summary of these differences is shown in Figure 4, with dashed arrows representing shifts in F1/F2 and solid arrows representing shifts in vertical/horizontal tongue position of the nasal vowels in comparison with their oral counterparts. Overall, the tongue was generally observed to be lower for back nasal vowels, more anterior for low nasal vowels, and higher for front nasal vowels, in comparison with their oral counterparts. These movements were generally supported by corresponding changes in formant frequencies that are predicted by these specific lingual shifts, e.g., a higher tongue position for the front nasal vowels is accompanied by concomitant lower F1 values.

Figure 4 - *Summary of acoustic shifts (dashed arrows) and lingual articulatory shifts (solid arrows) of Hindi nasal vowels in comparison to their oral vowel counterparts. Reproduced from Shosted et al. (2012)*



However, there are a number of cases in which acoustic differences were observed without any differences in tongue posture, as well as some cases in which lingual articulatory differences were observed without any acoustic changes. With regard to F1, /ə̃ ɑ̃/ were realized with lower F1 values than /ə ɑ/ but no differences in tongue height, and /ɔ̃ õ/ were produced with a lower tongue position than /ɔ̃ õ/ but no differences in F1. With regard to F2, /ɑ̃ ɔ̃ ʊ̃ õ/ were realized with lower F2 values than /ɑ ɔ ʊ o/, respectively, but either no differences in horizontal tongue position (for /ʊ̃ õ/) or a more anterior tongue position (for /ɑ̃ ɔ̃/). Morever, /ɛ̃/ was produced with a more anterior tongue position than /ɛ/ but no difference in F2.

3.2.1 Summary of articulatory results in the light of the acoustic effects of nasalization

Overall, the results from Shosted et al. (2012) suggest that a clockwise lingual articulatory shift may be in progress for the nasal vowel system of Hindi: back vowels are lowered, low vowels are fronted, and front vowels are raised. This pattern is directly contrary to the pattern observed in NMF, wherein the nasal vowel system is undergoing a counter-clockwise chain shift. Moreover, the pattern of these articulatory modifications in Hindi is generally opposed to the pattern of the independent effect of nasalization on the acoustic vowel space observed in Section 2.3. For the most part, the lingual articulatory shifts observed in Hindi were accompanied by concomitant shifts in acoustic vowel quality, although there are a number of cases in which discrepancies between articulation and acoustics were observed. Strikingly, in each of these cases, the pattern of the discrepancy matches the pattern of the independent acoustic effect of nasalization on the vowel space: F1 was lower than predicted by tongue height for /ə̃ ɑ̃ ɔ̃ õ/ – either a lower F1 was observed without any change in tongue height or a lower tongue position was observed without an accompanied rise in F1 – and F2 was lower than predicted by tongue anteriority for /ɛ̃ ɑ̃ ɔ̃ ʊ̃ õ/ – a lower F2 was observed without any change in horizontal tongue position, a more fronted tongue position was observed without an accompanied rise in F2, or a more fronted tongue position was observed along with a lower F2. Finally, lower F2 values were observed for all non-front vowels compared to their oral vowel counterparts, which is the precise pattern that was observed in Section 2.3 for the independent effect of nasalization on F2 frequency. Taken together, these results for Hindi suggest that, although lingual articulatory shifts were observed that arguably oppose the effect of nasalization on formant frequencies (unlike the pattern observed in NMF), whenever a discrepancy was observed between these articulatory shifts and the measured acoustics, the discrepancy matches the pattern of the independent acoustic effect of nasalization on the vowel space in every case.

4. *Oral articulation of phonetic vowel nasality*

The studies presented in the previous section provide evidence of oral articulatory modifications for the production of vowel nasality in two typologically unrelated languages, French and Hindi. Since vowel nasality is phonologically contrastive in both of these languages, it might be argued that these articulatory modifications arose diachronically through a process of co-phonologization with velum lowering. In other words, as nasality became part of the phonological representation of the vowels in these languages, the oral articulatory modifications became part of the phonological representation as well, in ways that either mirror the natural effects of nasalization on vowel quality (e.g., French) or oppose the natural effects of nasalization on vowel quality (e.g., Hindi). This suggests that these oral articulatory modifications may have existed at some stage before nasality was phonologized, when vowel nasality in these languages was merely contextual. However, any possible oral articulations that may have, at one time, been phonetic responses to contextual nasalization have since been phonologized (in the sense of Hyman, 2008). Thus, it is important to explore the possibility of oral articulatory shifts not only in phonemic vowel nasality, but in phonetic vowel nasality as well. In this section, two studies on the oral articulation of phonetic vowel nasality in North American English (NAE) are described. The results from these studies suggest that the two somewhat opposing patterns observed previously for French and Hindi both have synchronic analogues in contextual vowel nasality of NAE.

4.1 Articulatory compensation for vowel nasality in North American English

In Carignan, Shosted, Shih & Rong (2011), articulatory and acoustic data were used to observe whether American English (AE) /i/ and /ɑ/ manifest different degrees of tongue height when they are nasalized, i.e., when they are followed by tautosyllabic nasal consonants. These two vowels were chosen specifically to test the possibility of articulatory modifications in response to the effect of nasalization on F1 at the two extreme ends of the vowel height dimension (i.e., F1-raising for high vowels and F1-lowering for non-high vowels). Accordingly, if AE speakers adjust tongue height in order to enhance the effect of nasalization on F1 frequency, a lower tongue position is expected for nasalized vs. oral /i/, and a higher tongue position is expected for nasalized vs. oral /ɑ/. However, if AE speakers adjust tongue height in order to compensate for the effect of nasalization on F1 frequency, a higher tongue position is expected for nasalized vs. oral /i/, and a lower tongue position is expected for nasalized vs. oral /ɑ/. Finally, if AE speakers do not adjust tongue height in response to the effect of nasalization on F1 frequency, then the predicted acoustic effects are expected to be observed for the contextually nasalized variants of both vowels, i.e., higher F1 for nasalized vs. oral /i/, and lower F1 for nasalized vs. oral /ɑ/.

4.1.1 Data collection and analysis

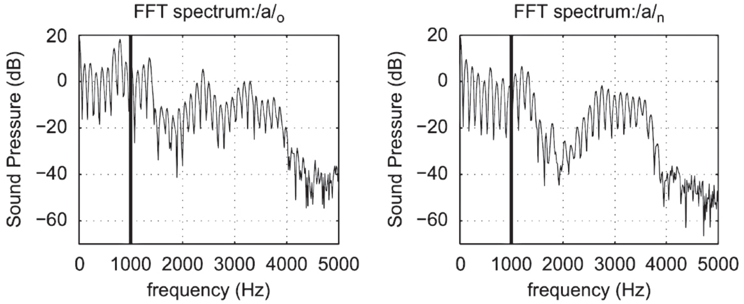
In order to test these hypotheses, data related to tongue position, nasal airflow, and acoustics were collected from four male native AE speakers' productions of nonce words containing either /i/ or /ɑ/. 108 CVC nonce words were used as stimuli, with three randomized blocks in the experiment. The tokens had two types of nuclei (/i ɑ/, represented orthographically in the stimuli by 'ee' and 'ah', respectively), six types of onset consonant (/p b t d k ɡ/), and nine types of coda consonant (/p b m t d n k ɡ ŋ/). Tongue position data were obtained using the Carstens AG500 in Illinois, with three sensors adhered to the tongue mid-line in the same way as previously described for French and Hindi. In order to measure nasal flow, participants wore a vented Scicon NM-2 nasal mask (Scicon R&D, Inc., Beverly Hills, CA), connected to a Biopac TSD160A pressure transducer (Biopac Systems, Inc., Goleta, CA). The signal was digitized at 1 kHz and recorded using custom-written scripts (Sprouse, 2006) running in MATLAB. The EMA and aerodynamic data were synchronized using the pulse signal generated by the Sybox-Opto4 unit from the AG500 system. Audio data were captured using a Countryman Isomax E6 directional microphone (Countryman Associates, Inc., Menlow Park, CA) positioned 4-5 cm from the corner of the mouth.

The nasal flow signal was filtered using a 75 Hz 5th order low-pass Butterworth filter, and it was used to segment the nasalized portion of the contextually nasalized vowels. For each nasalized token, the beginning of the segment was defined by the onset of anticipatory nasalization in the filtered nasal flow signal, and the end of the segment was defined as the end of voicing in the acoustic signal. The three repetitions of each speaker's nasalized token (e.g. Speaker 1's /kim/) were used to calculate an average proportion of the vowel that was nasalized. This average proportion was then applied to the vowels of the matching oral tokens (e.g. Speaker 1's three repetitions of /kib/ and /kip/), and tongue height measurements were made at the temporal midpoint of this portion of both the nasalized and oral vowels. These time points were also used for taking acoustic measurements of F1 center of gravity (COG), which was calculated in the band 0-1000 Hz for /ɑ/ and 0-500 Hz for /i/.

4.1.2 Results

With regard to /ɑ/, no difference in tongue height was observed between the nasalized and the oral contexts. However, F1 COG was found to be significantly lower for nasalized /ɑ/ compared to oral /ɑ/. An example of the spectral shift for nasalized /ɑ/ can be seen in Figure 5. These results suggest that, since no lingual adjustments were made in the nasalized context, the F1-lowering effect of nasalization on the realization of /ɑ/ was observed. With regard to /i/, a somewhat opposing pattern was found: although no difference in F1 COG was observed between the oral and nasalized contexts, /i/ was produced with a higher tongue position in the contextually nasalized context compared to the oral context. These results suggest that, precisely *because* a lingual adjustment was made in the nasalized context – specifically, a raising of the tongue body, which is predicted to result in a lowered F1 frequency – the F1-raising effect of nasalization on the realization of /i/ was offset by the lingual adjustment. In other words, no net acoustic change was observed because the separate acoustic effects of the two articulations (i.e., F1-raising due to velum lowering and F1-lowering due to tongue raising) effectively counteracted one another.

Figure 5 - *Acoustic spectra of oral /ɑ/ (left) and nasalized /ɑ/ (right) from a speaker of American English. The vertical line represents the frequency cutoff for calculation of center of gravity measurements. Reproduced from Carignan et al. (2011)*



4.1.3 Summary of articulatory results in the light of the acoustic effects of nasalization

The results from Carignan et al. (2011) suggest that speakers of AE employed compensatory adjustments of tongue height during the production of contextual vowel nasality, but only in restricted contexts. Previous studies suggest that there is as much as twice the variation in F1 for AE /a/~/ɑ/ vs. /i/ (Hillenbrand, Getty, Clark & Wheeler, 1995; Perkell, Nelson, 1985). The reduced variation for /i/ may be due to the proximity of its acoustic neighbor /ɪ/: increased variation in F1 for either of these two categories could result in acoustic overlap and, subsequently, a possible merger. However, /ɑ/ has no near acoustic neighbor of this type in AE; therefore, increased variation in F1 for /ɑ/ may be acceptable without any phonological consequence. Taking this into account, it is possible that the AE speakers produced /i/ with a slightly higher tongue body in the context of anticipatory nasalization as a way of compensating for F1-raising due to velum lowering, thus helping to prevent an oral-nasal phonemic split and/or prevent an acoustic merger with /ɪ/. However, the same speakers did not employ such compensatory articulation for nasalized /ɑ/, since there is no immediate phonological consequence for the resulting decrease in F1 frequency that arises from nasalization.

The fact that the AE speakers employed a compensatory articulatory adjustment in nonce words suggests that this adjustment is a phonetic and "purely synchronic" action (i.e., an online cognitive response), rather than a lexicalized articulatory modification. As a point of comparison to the observations from Carignan et al. (2011), the following section investigates a phonological process of North American English that, itself, involves lingual adjustments, in order to investigate whether the acoustic effects of contextual vowel nasalization might have any impact on the manner in which these lingual adjustments have become lexicalized in nasal vs. oral environments.

4.2 Articulatory enhancement of vowel nasality in North American English

Most dialects of North American English exhibit acoustic raising/tensing of the low vowel /æ/ in at least some phonological contexts, including a raising-falling trajectory before nasals (e.g., [beən] *ban*) over much of North America, and a less widespread raising pattern with a rising trajectory before /g/ (e.g., [bejg] *bag*). Previous studies have argued that the acoustic manifestation of pre-nasal raising, specifically, could be due to acoustic consequences of nasalization in some speakers, rather than to lingual dynamics (De Decker, Nycz, 2012; Baker, Mielke & Archangeli, 2008). In order to explore the lingual articulatory basis of /æ/-raising across North American English dialects, Mielke, Carignan & Thomas (2017) collected acoustic and ultrasound data from a regionally diverse group of 22 native English speakers (14 males, age range 20-72) from geographic regions of the United States and Canada known to exhibit distinct patterns of /æ/-raising – as well as a male speaker from Newfoundland and a female speaker from the United Kingdom, where /æ/-tensing is not expected to occur, as a basis for comparison.

4.2.1 Data collection and pre-processing

The stimuli consisted of 170 English words and English-like nonwords, each of which was presented three times in the experiment. These included 41 stimuli with /æ/ followed by a range of consonants, and in most cases preceded by a labial consonant or no consonant. Additional stimuli were included as distractors for the purpose of this study; these stimuli included /æ/ as well as the other vowels along the front diagonal of the vowel space /ɑ ɛ ej ɪ i/. Data collection occurred at two sites: 20 people participated at the Phonology Laboratory at North Carolina State University in Raleigh, North Carolina, USA, and four speakers participated at the Sound Patterns Laboratory at the University of Ottawa in Ottawa, Ontario, Canada. At both labs, data collection occurred inside a sound-attenuated booth, with ultrasound image acquisition at 60 fps occurring on a Terason t3000 ultrasound machine, running Ultraspeech 1.2 (Hueber, Chollet, Denby, & Stone, 2008), and using a microconvex array transducer (8MC3 in Raleigh and 8MC4 in Ottawa). Articulate Instruments headsets were used for probe stabilization (Scobbie, Wrench, & van der Linden, 2008), and audio was recorded in Audacity using a head-mounted omnidirectional microphone and SoundDevices USBPre2 preamplifier.

Phone-level segmentations of the audio recordings were made using the Penn Phonetics Lab Forced Aligner (P2FA; Yuan, Liberman, 2008); closure intervals of stops were hand-corrected as necessary. After segmention, the frequencies of the first three formants were measured at 5 ms intervals during all vowel intervals using a Praat script that automatically selected the best measurement parameters for each vowel token based on the similarity of the measured formant frequencies and bandwidths to a set of previous measurements from the Raleigh Corpus of interviews (Dodsworth, Kohn, 2012). Formant frequencies were normalized by speaker using Lobanov transformation.

4.2.2 Articulatory signal generation and analysis

Both the ultrasound images and the formant measurements were used to create time-varying lingual articulatory signals for each speaker. These signals were based on the front diagonal of the acoustic vowel space (normalized F2 - normalized F1, or Z2-Z1, where "Z" refers to *z*-scores), since much of the acoustic variation between raised and un-raised /æ/ falls along this axis (Labov, Rosenfelder & Fruehwald, 2013). The articulatory signal related to acoustic Z2-Z1 will be referred to as "lingual Z2-Z1" because it represents the lingual component of movement along the front diagonal of the vowel space.

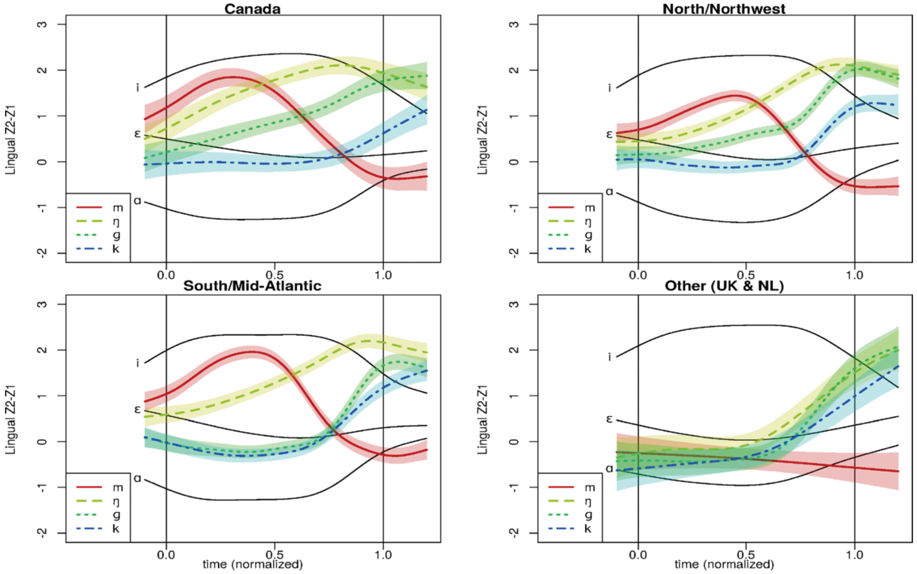
In the same manner as outlined in Section 2.3, the ultrasound images were processed separately for each speaker using TRACTUS (Carignan, 2014b), yielding PC scores representing independent axes of variation within each speaker's ultrasound image set. 20 PCs were retained for each speaker, which explained a total of 66%-80% (mean: 73.95%) of the variance in each speaker's image set. For each speaker's data set, a linear regression was performed with dependent variable Z2-Z1 and independent variables PCs 1-20. The data included every frame in the interval of the vowels [ɑ æ ɛ ej ɪ i]. The coefficients from the linear regression model were used to transform the articulatory PC score matrix to match the articulatory diagonal, resulting in a lingual posture signal composed of a single score for each ultrasound frame. For any given ultrasound frame, the higher the score is the more raised and fronted the tongue body is. Since it is derived from ultrasound images instead of acoustic data, the articulatory signal is continuous throughout the recording, even during consonant and silence intervals.

To compare lingual Z2-Z1 trajectories for groups of speakers in various segmental contexts, a generalized additive mixed model (GAMM) was created using the *bam* function from the R package MGCV (Wood, 2017). Time was normalized with the start and end of the vowel interval as (0,1), and time points within the interval (−0.1,1.2) were included in the model in order to incorporate a portion of the preceding and following consonants. The GAMM included an interaction variable (Region × Context). The dependent variable lingual Z2-Z1 was modeled with an intercept for region/context, a smooth for normalized time by region/context, and a random smooth for subject. To provide comparisons for the /æ/ lingual Z2-Z1 trajectories, another GAMM was created with /ɑ ɛ i/ data instead of /æ/ and a smooth for region/vowel instead of region/context. The mean trajectories for these three vowel models are provided as reference for contextualizing the degree of tensing in the /æ/ trajectories.

4.2.3 Results

Figure 6 shows lingual Z2-Z1 trajectories (GAMM predictions) for /æ/ before /m ŋ ɡ k/. For the Other speakers (for whom /æ/-tensing was not predicted) we can see that tongue raising only occurs before the velar consonants, and only towards the end of the vowel interval, reaching its peak within the consonant closure. This raising pattern is, thus, indicative of anticipatory co-articulation with the following velar closure. However, for the speakers in the other three regions, tongue raising is also evidenced to various degrees in other contexts. For all three regions, a raising-falling pattern is evidenced for /æ/ before /m/; the peak of this gesture occurs at or just prior to the temporal midpoint of the vowel. The same pattern was also observed before /n/ (not shown in this figure), except that the tongue remains slightly raised at the end of the vowel for the alveolar closure. Tensing before /ɡ/ is not evidenced for the South/Mid-Atlantic region, however it is for both of the northern regions (i.e., Canada and North/Northwest): tongue raising begins early in the vowel interval and increases in a linear fashion until the end of the vowel, where the gesture reaches its peak for the velar consonant closure. The same pattern can be observed for /æ/ before /ŋ/, except that the magnitude of tongue raising is higher throughout the entire vowel interval compared to /æ/ before /ɡ/ for all three tensing regions, even those which display pre-/ɡ/ tensing.

Figure 6 - *Comparisons of lingual Z2-Z1 trajectories created from GAMM predictions for /æ/ before /m/ and velars /k g ŋ/. Reproduced from Mielke et al. (2017)*



4.2.4 Summary of articulatory results in the light of the acoustic effects of nasalization

The results from Mielke et al. (2017) suggest that, not only does /æ/-tensing vary across dialectal regions of North American English, but it also varies across phonological environments with regard to the temporal characteristics and magnitude of the tensing gesture. Firstly, tensing before the anterior nasals /m n/ manifests as a rising-falling lingual gesture that is particular to these contexts and not observed for other tensing environments. Since the distinctive gesture is observed for both the coronal and labial contexts, this suggests that the gesture is not due to anticipatory co-articulation (i.e., there is no lingual setting required for the following /m/, yet the gesture is still observed in the vowel). Secondly, tensing in pre-velar contexts reveals a distinction between the nasalized /æ/ (i.e., before /ŋ/) and the oral /æ/ (i.e., before /g/, but not before /k/). This suggests as well that the gesture is not due to anticipatory velar co-articulation – the gesture is not evidenced before /k/ – and that the magnitude of tensing has been been lexicalized to different degrees for the pre-oral and pre-nasal contexts – a larger magnitude has been lexicalized for /æ/ before /ŋ/.

The independent acoustic effects of velum lowering observed in Section 2.3 suggests that F1 should lower to a large degree, and that F2 should lower slightly, for the nasalization of [æ]. In stressed context, the nearest NAE vowel categories in the direction of this acoustic shift lie along the front diagonal of the vowel space (i.e., in the direction of acoustic tensing; see Figure 2). Thus, it is plausible that, at some point in the evolution of NAE: (1) the acoustic consequence of velum lowering on the quality of /æ/ was mis-perceived by listeners as acoustic tensing and, subsequently, produced with a higher tongue position; and/or (2) speakers began producing

/æ/ before nasal consonants with a higher tongue position as way of enhancing the natural acoustic effect of nasalization on the vowel. In any case, the articulatory observations from Mielke et al. (2017) suggest that tongue raising/fronting of /æ/ has been lexicalized for varieties of NAE in certain contexts (i.e., it is no longer due to anticipatory co-articulation), and that the magnitude of the articulatory gesture involved in this lexicalization is greater for contextually nasalized contexts.

5. *Discussion*

The traditional characterization of vowel nasality – as well as the use of a diacritic marker to designate nasality in phonetic and phonological transcription – carries the implicit assumption that the only articulatory distinction between oral and nasal(ized) vowels is the relative height of the velum. On the contrary, the results from the studies surveyed in this manuscript reveal that both contrastive and contextual vowel nasality can be realized with modifications to the shape and length of the oral cavity in addition to velum lowering, even in typologically unrelated languages.

In some cases, these oral articulatory modifications are predicted to result in formant frequency modulations that enhance the independent effects of nasalization on the vowel space, e.g., the counter-clockwise chain shift of the nasal vowel system of Northern Metropolitan French and /æ/-tensing in North American English. It is possible that these articulatory modifications arose diachronically due to listeners (mis-)attributing the acoustic-perceptual vowel quality change arising from velum lowering to changes in oral articulation, subsequently producing these vowels with the corresponding changes in oral articulation. Alternatively, it is possible that speakers began producing the contextually nasalized vowels with changes in oral articulation whose acoustic effects mimic the acoustic effects of velum lowering on vowel quality, as a way of enhancing the natural acoustic consequence of nasalization.

In other cases, these oral articulatory modifications are predicted to result in formant frequency modulations that oppose the independent effects of nasalization on the vowel space, e.g., the clockwise chain shift of the nasal vowel system of Hindi and compensatory tongue body raising of nasalized /i/ in American English. It is possible that these articulatory modifications act as a way of counteracting and compensating for the acoustic-perceptual vowel quality change arising from velum lowering, in order to maintain vowel categories and prevent phonemic splits and mergers. Such a response is arguably more likely for Hindi than French, due to the larger and more acoustically crowded nasal vowel system (10 vowels in Hindi vs. 3 vowels in French); likewise, it is arguably more likely for American English /i/ than /ɑ/, due to the relative proximity of the acoustic neighbor /ɪ/ in the vowel space.

6. *Conclusion*

The results from this manuscript suggest that an accurate description of the production of vowel nasality in a given language (be it phonetic or phonological vowel nasality) cannot be ascertained without knowledge of the configuration of the entire vocal tract, and not simply the articulatory state of the velum. Moreover, this knowledge cannot be properly assessed using the acoustic signal alone, since velum lowering has been shown here to result in independent modifications to acoustic vowel quality throughout the entirety of the vowel space. Thus, the articulatory cause of changes to acoustic vowel quality cannot be determined from the acoustic signal alone. The results from the experimental method summarized here (and presented in detail in Carignan, 2018), as well as the overview of oral articulatory research on vowel nasality provided in this manuscript, therefore serve as both a caution and a challenge to linguists: perhaps it is time to question the validity of the use of acoustic measurements for researching vowel nasality, and perhaps it is time to question the traditional practice of characterizing vowel nasality in a binary fashion.

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Bibliography

Baker, A., Mielke, J. & Archangeli, D. (2008). More velar than /g/: Consonant coarticulation as a cause of diphthongization. In *Cascadilla Proceedings Project, Somerville, MA*, http://www.lingref.com/cpp/wccfl/26/paper1656.pdf. Accessed 01.07.17.

Beddor, P.S. (1982). Phonological and phonetic effects of nasalization on vowel height. Ph.D. thesis, University of Minnesota. Distributed by the Indiana University Linguistics Club.

Beddor, P.S. (1993). The perception of nasal vowels. In Huffman, M.K., Krakow, R.A. (Eds.), *Nasals, Nasalization, and the Velum* (Phonetics and Phonology 5). Academic Press: San Diego, 171-196.

Beddor, P.S., Krakow, R.A. & Goldstein, L.M. (1986). Perceptual constraints and phonological change: A study of nasal vowel height. In *Phonology Yearbook*, 3, 197-217.

Boersma, P., Weenink, D. (2015). Praat: doing phonetics by computer. *[Computer software program] available from http://www.praat.org/.*

Carignan, C. (2014a). An acoustic and articulatory examination of the ‘oral’ in ‘nasal’: The oral articulations of French nasal vowels are not arbitrary. In *Journal of Phonetics*, 46, 23-33.

Carignan, C. (2014b). TRACTUS (Temporally Resolved Articulatory Configuration Tracking of UltraSound) software suite. *[Computer software program] available from http://christophercarignan.github.io/TRACTUS.*

Carignan, C. (2018). Using ultrasound and nasalance to separate oral and nasal contributions to formant frequencies of nasalized vowels. In *Journal of the Acoustical Society of America*, 143(5), 2588-2601.

Carignan, C., Shosted, R., Shih, C. & Rong, P. (2011). Compensatory articulation in American English nasalized vowels. In *Journal of Phonetics*, 39, 668-682.

De Decker, P.M., Nycz, J.R. (2012). Are tense [æ]s really tense? The mapping between articulation and acoustics. In *Lingua*, 122, 810-821.

Derrick, D., Best, C.T. & Fiasson, R. (2015). Non-metallic ultrasound probe holder for co-collection and co-registration with EMA. In *Proceedings of 18th International Congress of Phonetic Sciences (ICPhS)*, 1-5.

Dodsworth, R., Kohn, M. (2012). Urban rejection of the vernacular: The SVS undone. In *Language Variation and Change*, 24, 221-245.

Escudero, P., Boersma, P., Rauber, A.S. & Bion, R.A.H. (2009). A cross-dialect acoustic description of vowels: Brazilian and European Portuguese. In *Journal of the Acoustical Society of America*, 126(3), 1379-1393.

Fónagy, I. (1989). Le français change de visage. In *Revue Romane*, 24(2), 225-254.

Hillenbrand, J., Getty, L.A., Clark, M.J. & Wheeler, K. (1995). Acoustic characteristics of American English vowels. In *Journal of the Acoustical Society of America*, 97(5), 3099-3111.

Hueber, T., Chollet, G., Denby, B. & Stone, M. (2008). Acquisition of ultrasound, video and acoustic speech data for a silent-speech interface application. In *Proceedings of the 8th International Seminar on Speech Production*, 365-369.

Hyman, L.M. (2008). Enlarging the scope of phonologization. In *UC Berkeley phonology lab annual report*, 382-408.

Johnson, K. (2003). *Acoustic and Auditory Phonetics*. Blackwell: Oxford.

Krakow, R.A., Beddor, P.S. & Goldstein, L.M. (1988). Coarticulatory influences on the perceived height of nasal vowels. In *Journal of the Acoustical Society of America*, 83(3), 1146-1158.

Labov, W., Rosenfelder, I. & Fruehwald, J. (2013). One hundred years of sound change in Philadelphia: Linear incrementation, reversal, and reanalysis. In *Language*, 89, 30-65.

Maddieson, I. (1984). *Patterns of sounds*. Cambridge: Cambridge University Press.

Mielke, J., Carignan, C. & Thomas, E.R. (2017). The articulatory dynamics of pre-velar and pre-nasal /æ/-raising in English: an ultrasound study. In *Journal of the Acoustical Society of America*, 142(1), 332-349.

Ohala, M. (1999). Hindi. In *Handbook of the International Phonetic Association*. Cambridge University Press: Cambridge, 100-103.

Perkell, J.S., Nelson, W.L. (1985). Variability in production of the vowels /i/ and /a/. In *Journal of the Acoustical Society of America*, 77, 1889-1895.

Scobbie, J.M., Wrench, A.A. & van der Linden, M. (2008). Head-probe stabilisation in ultrasound tongue imaging using a headset to permit natural head movement. In *Proceedings of the 8th International Seminar on Speech Production*, 373-376.

Sharma, A. (1958). *A Basic Grammar of Modern Hindi*. Central Hindi Directorate, Ministry of Education and Social Welfare: New Delhi.

Shosted, R., Carignan, C. & Rong, P. (2012). Managing the distinctiveness of phonemic nasal vowels: Articulatory evidence from Hindi. In *Journal of the Acoustical Society of America*, 131(1), 455-465.

Sprouse, R. (2006). DAQSession (Version 0.3). *[Computer software program]*. University of California, Berkeley: Berkeley, CA.

Stevens, K.N. (2000). *Acoustic phonetics*. MIT Press, Cambridge, MA.

The Mathworks Inc. (2015). *Matlab 2015a*. Natick, Massachusetts, United States.

Wright, J.T. (1975). Effects of vowel nasalization on the perception of vowel height. In Ferguson, C.A., Hyman, L.M. & Ohala, J.J. (Eds.), *Nasálfest: Papers from a symposium on nasals and nasalization*. Stanford University Language Universals Project: Palo Alto, CA, 373-388.

Wright, J.T. (1986). The behavior of nasalized vowels in perceptual vowel space. In Ohala, J.J., Jaeger, J.J. (Eds.), *Experimental Phonology*. Academic Press: New York, 45-67.

Yuan, J., Liberman, M. (2008). Speaker identification on the SCOTUS corpus. In *Proceedings of Acoustics '08*, 5687-5690.

Wood, S.N. (2017). mgcv: Mixed GAM Computation Vehicle with Automatic Smoothness Estimation. [Computer software program] available from https://cran.r-project.org/package=mgcv.