The role of the pharynx and tongue in enhancement of vowel nasalization: A real-time MRI investigation of French nasal vowels

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Abstract

Complexity in the acoustics of nasal vowels has long been acknowledged but complexity in their articulation has received less attention. A growing body of research suggests that velopharyngeal (VP) opening is complemented by other articulatory gestures which may enhance or counteract the acoustic outcomes of VP opening. In this paper we consider the role of pharyngeal aperture and lingual position in producing the phonemic distinction between oral and nasal vowels in Northern Metropolitan French. The results of a real-time MRI study of one female speaker confirm earlier findings related to tongue height and retraction. The results also suggest a role for the lower pharynx in centralizing the F1 of nasal vowels. Consideration is also given to the effect of the lowered velum on the acoustic transfer function of the oral tract of nasal vowels. We conclude that these articulations enhance some of the well-known acoustic consequences of VP coupling associated with the production of nasal vowels. This supports and extends the hypothesis that the acoustic characteristics of nasalization can be attained by a family of speech gestures that include, but are not limited to, the opening of the VP port.

Index Terms: vowel nasalization, rt-MRI, pharynx, articulation

1. Introduction

Nasal vowels are characterized by some degree of coupling between the nasal and oral cavities. This coupling occurs by way of the velopharyngeal (VP) port and its acoustic–perceptual outcome is regarded as *nasalization*. Nasalization introduces an additional spectral resonant pattern associated with the nasal cavity to the spectral resonant pattern associated with the oral cavity. Apart from the so-called "velic opening hypothesis" [1, 2, 3], in much of the literature on vowel nasalization, oral and nasal/nasalized vowel congeners (e.g. [ɛ] and [ɛ̃]) are often compared as if the only substantive physical difference between them is the presence or absence of VP coupling [4, 5, 6]. However, recent work suggests that lingual and labial configuration may differ for oral versus phonetically nasal [7, 8] and phonemically nasal [9, 10] vowels. However, this tendency does not appear universal, at least not for phonemically nasal vowels [11].

It is well known that VP coupling significantly alters the acoustic spectrum of vowels [12, 13, 14]. Aside from changes in formant amplitude and bandwidth due to the addition of acoustic poles and zeros, formant frequencies themselves may be modified. According to Fujimura and Lindqvist's model based on sweep-tone measurements of vocal tract output, "[A]ll formants of a nasalized vowel shift monotonically upwards" with increased VP aperture [15, p. 551]. However, a considerable body of subsequent evidence suggests that this may not always be the case. F1-lowering may result from the nasalization of low vowels when the degree of nasalization is sufficient to introduce a high-amplitude nasal formant [16]. Thus, heavily nasalized low vowels may manifest a lowered F1. Using a speech model based on French data from MRI and CT scans, Serrurier and Badin [17] observed the influence of velic lowering alone on the acoustic space circumscribed by [a, i, u]. They found that the F1 range of a "pure oral" vowel space (glottis to lips) was centralized, and reduced by about 68%, when compared with the range of a "pure nasopharyngeal" vowel space (glottis to nostrils): the F1 range was reduced from ≈ 260–700 Hz to ≈ 370–510 Hz. F2 was lowered for both [i, a] and raised for [u], lowering F2 of the vowel space overall, and reducing the range by almost 89%: the F2 range was reduced from ≈ 600–2350 Hz to ≈ 950–1150 Hz. These results are broadly consistent with earlier analog simulations of VP coupling performed by Feng and Castelli [18], who observed both F1- and F2-lowering for nasalization of the French vowel space. Carignan [19] observed a lowered F2 in Northern Metropolitan French (NMF) [ɑ̃, ɛ̃] v. [a, ɛ] (11/11 speakers) and in [ɔ̃] v. [o] (9/11 speakers). Though it has been claimed that front (high F2) vowels are more often perceived as nasalized, the effects are often weak or limited to only a few vowels [20, 21, 22]. In NMF, F2-lowering alone may help trigger the percept of nasality [23].

Krakow *et al.* [24, p. 1146] observed that the F1 variation inherent in nasalization is similar to acoustic changes associated with tongue height and jaw position. For example, a relative increase in F1 may be attributed to either a lowered tongue/jaw position or an increase in nasal coupling (especially for high vowels), and a decrease in F1 may be attributed to either a raised tongue/jaw position or an increase in nasal coupling (for low vowels). Lingual height centralization is also well-documented typologically for phonemic nasal vowels: in a variety of languages, under the influence of nasalization, high vowels are transcribed as lower and low vowels are transcribed as higher [25, 1, 26]. It is possible that this articulatory centralization of the vowel space—an enhancement of the acoustic centralization associated with nasalization—is goal-driven. Given the perceptual confusion between F1 change due to VP coupling with F1 change due to lingual configuration, there is likely a tendency for the acoustic centralization of the vowel quality (due to nasalization) to be misperceived as articulatory centralization. Following Ohala [27], this misperception may lead to consistent, systematic changes in tongue height as a concomitant of nasal vowel phonologization.

The predicted effects of VP coupling on the frequency of F1 and F2 can thus be generalized as follows: F1 is centralized

(i.e., raised for high vowels and lowered for low vowels), and F2 is lowered. However, F1 and F2 are most typically modulated independently of VP coupling. F1 is determined mostly by the vertical position of the tongue in the oral cavity, and can also be modulated by expansion or constriction of the lower pharynx [28, 29, *inter alia*]. According to the principles of Perturbation Theory [30], if a constriction is formed near a velocity antinode of a standing wave, then the frequency of that wave will decrease. Conversely, if a constriction is formed near a velocity node of a standing wave, then the frequency of that wave will increase. Given its proximity to a node in the velocity wave of F1, a constriction in the lower pharynx is predicted to raise F1 [29]. F2 frequency is most typically modulated by forward–backward movement of the tongue body [29, p. 203], but both F1 and F2 frequency can be lowered by a constriction and/or protrusion of the lips.

This raises the question: since multiple articulations may give rise to a change in F1 and F2 frequency, given an observed change β in F1 or F2 during the production of a nasal vowel, how can the articulatory cause of β be determined from the acoustic signal alone? We believe it is unlikely that this can be done, at least using current methods of acoustic analysis. In the acoustic signal, VP coupling and the activity of other oropharyngeal articulators are confounded, both giving rise to β, though with unknown contributions. Given this limitation, our research group has promoted an articulatory approach to vowel nasalization [7, 10, 19]. In the present article, we use dynamic real-time magnetic resonance imaging (rt-MRI) to further explore this problem.

We digress for a moment to clarify the IPA transcriptions of NMF nasal vowels used in this study. The IPA transcriptions for [ɛ̃, ɑ̃, ɔ̃] are conventional for the French phonetics literature [31]. It is not clear, however, that these transcriptions are intended to represent the synchronic oral articulation of these vowels. Instead, the transcriptions of the nasal vowels seem to be based on historical underlying forms. The situation is further complicated by the fact that /ɑ/ and /ɔ/ rarely—never, for some speakers—appear in open syllables in modern NMF. Therefore, /ɑ/ and /ɔ/ should not be compared to /ɑ̃/ and /ɔ̃/ in open syllables. Furthermore, the most recent French vowel chart sanctioned by the International Phonetic Association does not include the contrast between central [a] and back [ɑ]; only [a] is standard [31, p. 78].

2. Justification for rt-MRI study

Using synchronized articulatory EMA and acoustic data, Carignan [19] investigated how speakers of NMF use lingual and labial configurations to distinguish oral and nasal vowel counterparts. He found that, for [ɔ̃] compared to [o], 7 of 11 speakers manifest an F1 which is lower than predicted by the lingual configuration for this vowel. Crucially, this lower F1 frequency is not predicted by the acoustic centralization of F1, either, since [ɔ̃] is not a low vowel. This articulatory/acoustic discrepancy is manifested in one of two ways:

1. F1 of [ɔ̃] is lower than F1 of [o]; however, there is no significant difference in the height of the tongue between [ɔ̃] and [o].
2. The tongue is lower for [ɔ̃] than for [o], a lingual configuration which is predicted to raise F1; however, there is no significant difference between F1 of [ɔ̃] and F1 of [o].

Carignan [19] also investigated the labial configuration of [ɔ̃]–[o] in order to determine if these articulatory/acoustic discrepancies could be accounted for by labial configuration. Since lip protrusion and smaller labial aperture are predicted to lower all formants, evidence of either of these articulations for [ɔ̃] compared to [o] could help explain the lower F1 observed for these 7 speakers' production of [ɔ̃]. However, lip protrusion and/or smaller labial aperture for [ɔ̃] compared to [o] were only observed for 3 of the 7 speakers. In other words, all together, 4 of 11 NMF speakers manifest F1 for [ɔ̃] v. [o] which cannot be accounted for by the acoustic effect of VP coupling, lingual configuration, or labial configuration.

Given this evidence suggesting that F1 modulation of some NMF nasal vowels is not caused by either nasalization or lingual/labial configuration, we decided to determine if the pharyngeal configuration—which can also modify F1 and has been shown relevant in the production of Brazilian Portuguese nasal vowels [32]—could play a role. Since the pharynx is an area of the vocal tract which has traditionally been inaccessible to all but the most invasive and/or hazardous methodologies, we chose to use structural rt-MRI to observe pharyngeal aperture in nasal/oral vowel pairs.

3. Methodology

The subject is a 27 year-old native female speaker of the NMF dialect, born in Paris. The current study is part of a larger research project which will include two more NMF speakers. A word list consisting of six French lexical items was used, with the target vowel occurring in an open syllable preceded by [p], in order to minimize lingual coarticulation during the target vowel. The word list includes: *paix* /p**ɛ**/ 'peace', *pain* /p**ɛ̃**/ 'bread', *papa* /pap**a**/ 'daddy', *paon* /p**ɑ̃**/ 'peacock', *pôt* /p**o**/ 'pot/jar', and *pont* /p**ɔ̃**/ 'bridge'. The target words were placed in the carrier phrase *Il retape* X *parfois* 'He retypes *X* sometimes'. With the order randomized, phrases were presented to the speaker in the 3T Siemens Trio MRI scanner at the Beckman Institute for Advanced Science and Technology, at the University of Illinois. The speaker was instructed to repeat the phrase at a normal rate, until the noise of the scanner ceased (about 5 minutes). Due to variation in speaking rate and the start of speech after scanner initialization, an unequal number of tokens was collected for each lexical item: *papa* (101), *paon* (123), *paix* (104), *pain* (101), *pôt* (105), and *pont* (101).

rt-MR images were obtained using partially separable functions [33, 34], allowing for a relatively high frame rate during multi-slice imaging. Specifically, we achieve around 25 fps for each of four simultaneous slices with this method. A slice was placed at each of the following four locations in the vocal tract; the position and orientation of each slice was selected during restful breathing:

1. Oral cavity (OC): A coronal slice placed at the horizontal midpoint of the tongue body, located ≈ 2.6 cm from the tongue tip.
2. Velopharynx (VP): An oblique slice, rotated $\approx 45^\circ$ from the transverse plane, running through the VP port.
3. Mediopharynx (MP): A transverse slice placed in the mediopharynx, located ≈ 5.2 cm above the glottis.
4. Lower pharynx (LP): A transverse slice placed in the lower pharynx, located at the epiglottis, ≈ 2.6 cm above the glottis.

The placement and orientation of these slices is illustrated in the left image in Figure 1, with an example of a resulting LP slice in the right image. Image resolution of each slice is 128 x 128

voxels, and the resolution of each voxel is 2.2 mm x 2.2 mm x 8.0 mm (through-plane depth). Videos of the MP slice for [ɛ] ("paix_mp.mov") and [ɛ̃] ("pain_mp.mov") are available online.

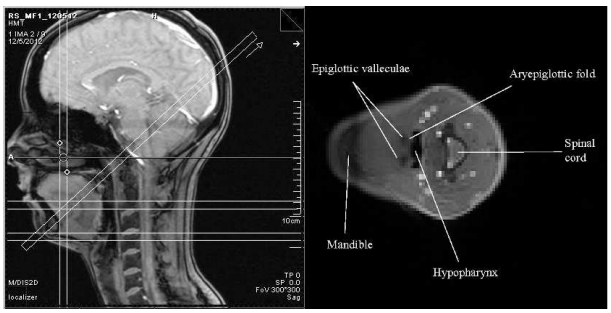

Figure 1: *Orientation of MRI slices (left) and example of LP slice with anatomical structures labeled for reference (right).*

Vocal tract apertures were calculated by further developing methods used in Shosted *et al.* [35]. Several OC slices were examined in GIMP 2.8.2[1] as cavity references: the edges of the air/tissue boundary were manually selected and confirmed by the first and second authors. The average intensity of the voxels in the selected cavity was measured in 8 bpp (bits per pixel) space (values 0–255), and the upper-end of the range of these values was logged as a threshold, τ. τ was used to convert each MR image in Matlab 2012a[2] to a two-value image space, with each voxel having the intensity i: for any voxel with $i \leq \tau$, the voxel was changed to black; for any voxel with $i > \tau$, the voxel was converted to white. An example of applying this technique is shown in Figure 2. A region of interest (ROI) surrounding the hypopharyngeal aperture was selected after examination of various images. For each MR image, the number of black pixels in the ROI was summed and multiplied by 4.84, the squared in-plane voxel resolution. The result is a time-varying function of the aperture area. An example of this time-varying function is given in Figure 3 for the LP slice during three repetitions of an utterance. The test vowels were segmented manually using the spectrogram derived from a synchronized, noise-cancelled audio recording. Using the time points of this segmentation, the average aperture area (AAA) for each vowel was calculated by slice.

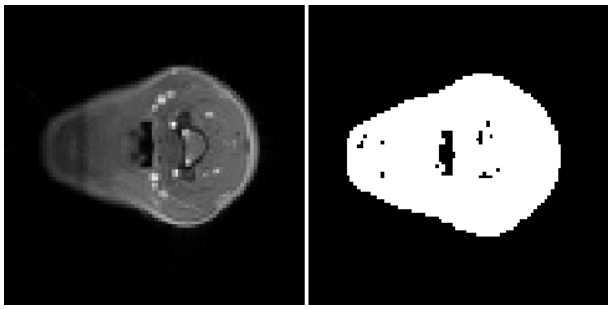

Figure 2: *Example of thresholded lower pharyngeal (LP) slice: the original image (left) and the thresholded image (right).*

[1] http://www.gimp.org

[2] http://www.mathworks.com/products/matlab

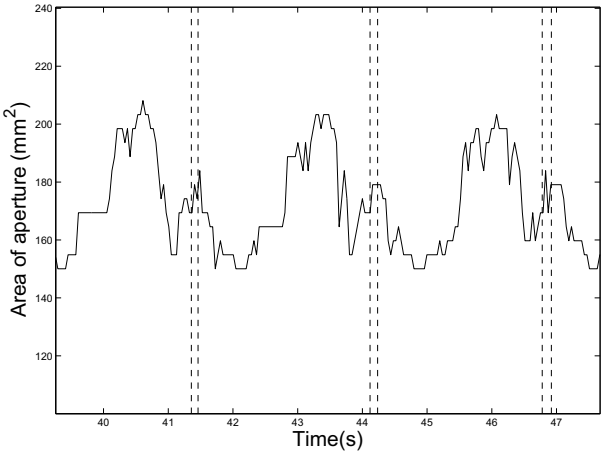

Figure 3: *AAA function of LP slice for three repetitions of "*Il retape pont parfois*". Dashed lines delineate the target vowels.*

Statistical analyses were performed on the AAA measures using one-way ANOVAs in R 2.11.1,[3] with the decision criterion $\alpha = 0.01$. In each analysis, the AAA measure was the dependent variable and vowel nasality (oral v. nasal) was the predictor variable. In this way, the results compare the differences in AAA values between oral vowels and their nasal vowel congeners (i.e., [a] v. [ɑ̃], [ɛ] v. [ɛ̃], and [o] v. [ɔ̃]).

4. Results

The average AAA values and ANOVA results are given in Table 1. The ANOVA revealed strongly significant differences ($p < 0.001$) for all significant AAA measures. Only one AAA measure, the one associated with the LP slice for [o]–[ɔ̃], was not found to be significant.

Table 1: *AAA results. In each cell, the average AAA of the oral vowel is on the left and that of its nasal congener is on the right. Light grey cells contain measures where the average AAA of the nasal vowel is smaller than that of its oral congener, and dark grey cells contain measures where the average AAA of the nasal vowel is greater than that of its oral congener.*

Slice	[a] – [ɑ̃]	[ɛ] – [ɛ̃]	[o] – [ɔ̃]
OC	287.51 – 268.88 $F(1, 222) = 36 * **$	72.17 – 202.58 $F(1, 203) = 5323 * **$	182.94 – 119.72 $F(1, 204) = 518 * **$
VP	15.64 – 94.47 $F(1, 222) = 2830 * **$	9.61 – 65.27 $F(1, 203) = 1524 * **$	0.67 – 69.81 $F(1, 203) = 2170 * **$
MP	115.76 – 76.48 $F(1, 222) = 1735 * **$	191.19 – 104.24 $F(1, 203) = 2838 * **$	120.57 – 89.6 $F(1, 203) = 592 * **$
LP	162.93 – 176.93 $F(1, 222) = 148 * **$	171.7 – 165.62 $F(1, 203) = 71 * **$	176.14 – 173.95

With regard to the OC slice, the AAA of [ɑ̃] is smaller than that of [a], suggesting a smaller oral cavity due to a higher lingual position for [ɑ̃]. The OC AAA of [ɛ̃] is greater than that of [ɛ], suggesting a larger oral cavity due to a lower lingual position for [ɛ̃]. The OC AAA of [ɔ̃] is smaller than that of [o], suggesting a smaller oral cavity due to a higher lingual position for [ɔ̃]. These results are consistent with the counter-clockwise chain shift in the acoustic realization of nasal vowels previously

[3] http://www.r-project.org

described for NMF [36, 37, 38, 39]. Carignan has confirmed the articulatory nature of this chain shift with EMA data [19].

With regard to the VP slice, not surprisingly, all of the nasal vowels have a larger AAA than their oral vowel congeners. This is to be expected, since the primary difference between nasal vowels and their oral congeners is the relative presence or relative absence of VP coupling.

With regard to the MP slice, all of the nasal vowels have a smaller mediopharyngeal aperture than their oral vowel congeners, suggesting more retracted tongue position for the nasal vowels across the board.

With regard to the LP slice, the AAA of [ɑ̃] is larger than that of [a], suggesting a larger hypopharyngeal cavity for [ɑ̃]. The LP AAA of [ɛ̃] is smaller than that of [ɛ], suggesting a smaller hypopharyngeal cavity for [ɛ̃]. The LP AAA of [ɔ̃] is smaller than that of [o], but this difference did not reach significance.

Of great interest to the current research is the inverse relationship between the AAA of OC and LP slices for most of the vowel pairs. Specifically, [ɑ̃] has a smaller OC AAA but a larger LP AAA when compared with [a]. Conversely, [ɛ̃] has a larger OC AAA but a smaller LP AAA when compared with [ɛ]. Although this inverse relationship is not observed for [o]–[ɔ̃] (i.e. both the OC and LP values are smaller for [ɔ̃] than for [o]), the LP AAA difference is slight (=2.18 mm^2) and did not reach significance.

5. Discussion

The results of this study suggest that pharyngeal articulation plays a secondary role in the articulatory configuration of the nasal vowels of the NMF dialect. There are (at least) four articulatory variables which are predicted to change the F1 frequency of nasal and nasalized vowels: VP coupling, tongue height, labial aperture, and hypopharyngeal aperture. VP coupling is predicted to centralize the vowels along F1. Tongue height has an inverse relation with F1 frequency (i.e., a higher tongue position lowers F1 frequency and a lower tongue position raises F1 frequency). Labial aperture has a positive relation with the frequency of all formants (i.e., a labial expansion will raise all formant frequencies and a constriction will lower all formant frequencies). Finally, hypopharyngeal aperture has an inverse relation with F1 frequency (i.e., an expansion in the hypopharynx will raise F1 frequency and a constriction will lower F1 frequency). The inverse relationship between the OC and LP AAA measures for most of the vowel pairs in this study suggests that both tongue height and hypopharyngeal aperture are used to enhance the acoustic effects of nasalization for the nasal vowels of NMF.

The F1 frequency of [a]—a relatively low vowel with a relatively high F1 frequency—is predicted to lower under the effects of nasalization. Additionally, [ɑ̃] manifested smaller OC AAA (interpreted as higher tongue position) than [a], which is also predicted to result in a lower F1 for [ɑ̃] compared to [a]. Furthermore, [ɑ̃] manifested greater LP AAA than [a], which is also predicted to result in a lower F1 for [ɑ̃] compared to [a]. Therefore, there are at least two oral articulatory configurations observed here which are predicted to enhance the VP-induced lowering of F1 for [ɑ̃], traditionally claimed to be due to VP coupling alone.

The F1 frequency of [ɛ]—a relatively high vowel[4] with a relatively low F1 frequency—is predicted to rise under the effects of nasalization due to centralization along the F1 dimension. Additionally, [ɛ̃] manifested larger OC AAA (interpreted as a lower tongue position) than [ɛ], which is also predicted to result in a higher F1 for [ɛ̃] compared to [ɛ]. Furthermore, [ɛ̃] manifested smaller LP AAA than [ɛ], which is also predicted to result in a higher F1 for [ɛ̃] compared to [ɛ]. Therefore, there are at least two oral articulatory configurations observed here which are predicted to enhance the VP-induced raising of F1 for [ɛ̃], traditionally claimed to be due to VP coupling alone.

There are (at least) three articulatory variables which are predicted to change the F2 frequency of nasal and nasalized vowels: VP coupling, tongue backness, and labial aperture. VP coupling is predicted to lower F2 frequency for all vowels. Tongue backness lowers F2 frequency, as well. Finally, labial constriction also lowers formant frequencies, as mentioned earlier. We posit an additional articulatory mechanism which is predicted to change the F2 frequency of nasal vowels. The lowering of the soft palate creates a 'velic' constriction (with the velum lowering towards the tongue dorsum rather than the tongue dorsum rising towards the velum [40, p. 52]). Shosted *et al.* argue that this articulation also lowers F2 [10, p. 462]. We regard this as a secondary but significant acoustic effect of nasalization, one that has perhaps been overlooked in the literature until recently. The acoustic–perceptual outcome of VP opening is most often considered in terms of the contributions of the nasal cavity and sinuses. However, the lowered velum itself creates a constriction in the oropharyngeal tube that also affects the acoustics. Moreover, the ubiquitously lower MP AAA values for the nasal vowels compared to their oral congeners suggest that tongue retraction is also used to enhance the acoustic effects of nasalization for the nasal vowels of NMF.

Based on the findings of Serrurier and Badin [17] and Feng and Castelli [18], it is hypothesized that F2 lowers for all of the nasal vowels studied here. Additionally, all nasal vowels were observed to manifest a smaller MP AAA (interpreted as a more retracted tongue position) than their oral congeners, an articulation which is also predicted to result in a lower F2 for the nasal vowels. Moreover, the lowering of the velum during VP coupling creates a velic constriction and is also predicted to result in a lower F2 for the nasal vowels. Therefore, there are at least two oral articulatory configurations which are predicted to enhance the VP-induced lowering of F2 that is increasingly observed in the literature [17, 23].

6. Conclusion

We present real-time MRI evidence suggesting that both lingual and pharyngeal configurations may be systematically employed to enhance the acoustic effect of VP coupling in the production of NMF nasal vowels. This supports and extends the hypothesis that the acoustic characteristics of nasalization can be attained by a family of speech gestures that include, but are not limited to, the opening of the VP port.

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[4] In fact, [ɛ] manifests the lowest OC AAA (interpreted as the highest tongue position) among the vowels studied here.

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