Journal of Phonetics 46 (2014) 23–33

Contents lists available at ScienceDirect

Journal of Phonetics

journal homepage: www.elsevier.com/locate/phonetics

An acoustic and articulatory examination of the “oral” in “nasal”: The oral articulations of French nasal vowels are not arbitrary

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A R T I C L E I N F O

Article history:
Received 9 October 2013
Received in revised form
23 May 2014
Accepted 29 May 2014
Available online 1 July 2014

Keywords:
Articulation
Acoustics
EMA
Vowel nasalization
French

A B S T R A C T

This study includes results of an articulatory (electromagnetic articulography, i.e. EMA) and acoustic study of the realizations of three oral–nasal vowel pairs /a/–/ɑ̃/, /ɛ/–/ɛ̃/, and /o/–/ɔ̃/ recorded from 12 Northern Metropolitan French (NMF) female speakers in laboratory settings. By studying the position of the tongue and the lips during the production of target oral and nasal vowels and simultaneously recording the acoustic signal, the predicted effects of velo-pharyngeal (VP) coupling on the acoustic output of the vocal tract can be separated from those due to oral articulatory configuration in a qualitative manner. Based on the previous research, all nasal vowels were expected to be produced with at least some change in lingual and labial articulatory configurations compared to their oral vowel counterparts. Evidence is observed which suggests that many of the oral articulatory configurations of NMF nasal vowels enhance the acoustic effect of VP coupling on F1 and F2 frequencies. Moreover, evidence is observed that the oral articulatory strategies used to produce the oral/nasal vowel distinction are idiosyncratic, but that, nevertheless, speakers produce a similar acoustic output. These results are discussed in the light of motor equivalence as well as the view that the goal of speech acts is acoustic, not articulatory.

1. Introduction

Perkell (1997, p. 333) defines articulatory processes as “[a]rticulatory forces and movements that implement the conversion of linguistic messages into sound.” At the basis of speech sounds, we find the articulatory phenomena which are their source. Spoken human language cannot exist without speech articulation. But are articulatory gestures themselves the goal of speech utterances? There are some theories which contend that listeners ultimately perceive information about the speech articulators themselves, either via reconstruction from the acoustic signal (“motor theory of speech perception”; Liberman & Mattingly, 1985) or via direct perception (“direct realist” theory of speech perception; Fowler, 1989, 1991). However, there is other evidence that articulations co-vary because their acoustic effects enhance one another (Diehl & Kluender, 1989; Diehl & Walsh, 1989; Kluender, Diehl, & Wright, 1988) or are integrated components of perceptual objects, i.e. the objects we attend to when we perceive speech (Diehl, Walsh, & Kluender, 1991; Kingston, 1992; Ohala, 1996).

1.1. Vowel nasalization

Vowel nasalization, due to the combination of multiple articulators involved, is particularly relevant to this issue. Nasal vowels, by definition, are characterized by some degree of coupling of the nasal cavity to the oral cavity via an opening of the velo-pharyngeal (VP) port, otherwise referred to as VP coupling, a lowering of the velum or, more generally, “nasalization”. As with all vowel sounds, formant frequency differences between oral and nasal vowels are especially important for deducing the vocal tract's oro-pharyngeal shape. For oral vowels, a rough estimation of oro-pharyngeal tract shape can be deduced from the formant structure of the acoustic signal that emanates from the tract (Iskarous, 2010), and the predictions for formant changes associated with changes in the

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http://dx.doi.org/10.1016/j.wocn.2014.05.001

Table 1
Summary of results from previous articulatory research on NMF nasal vowel production.

Study	[ɛ̃] vs. [ɛ]		[ɑ̃] vs. [a]/[ɑ]		[ɔ̃] vs. [o]/[ɔ]	
	Lingual	Labial	Lingual	Labial	Lingual	Labial
Straka (1965)	Lower, retracted		Lower, retracted	Rounded		Rounded
Brichler-Labaeye (1970)	Lower, retracted	*N/A*	Lower	*N/A*		*N/A*
Zerling (1984)	Retracted		Retracted	Protruded	Retracted	Rounded
Bothorel et al. (1986)	*Not conclusive*	More open, less spread	Higher, retracted	Protruded	Advanced	Rounded
Montagu (2002)	*N/A*	*N/A*	*N/A*	Rounded, protruded	*N/A*	Rounded, retracted
Delvaux et al. (2002)	Lower, retracted		Lower, retracted	Rounded	Higher, retracted	Rounded
Delvaux (2014)	Lower, retracted		Lower, retracted	Rounded	Retracted	Rounded

oro-pharyngeal shape are relatively straightforward (Johnson, 2003, p. 113; Stevens, 2000, pp. 257–303): tongue raising is correlated with a decrease in F1, while tongue lowering is correlated with an increase in F1; tongue retraction is correlated with a decrease in F2, while tongue advancement is correlated with an increase in F2; a constriction in the lower pharynx is correlated with an increase in F1, while an expansion is correlated with a decrease in F1; lip rounding and/or protrusion is correlated with a decrease in all formants.

For nasal vowels, the shape of the oro-pharyngeal tract is obscured by the acoustic effects of VP coupling. Aside from non-frequency-related changes such as an increase in formant bandwidths and a decrease in sound pressure (Stevens, 2000), these effects include a number of changes to formant frequencies. VP coupling is predicted to result in a centralization of the vowel space along the F1-dimension: an increase in F1 for high vowels and a decrease in F1 for low vowels (Diehl, Kluender, Walsh, & Parker, 1991; Feng & Castelli, 1996; Fujimura & Lindqvist, 1971; Serrurier & Badin, 2008). Centralization of the vowel space along the F2-dimension is also likely under the effects of VP coupling, but the specific predictions are less straightforward. While a decrease in F2 is expected for non-back vowels (Delvaux, 2009; Feng & Castelli, 1996; Serrurier & Badin, 2008), there is a potential increase in F2 for back vowels (Wright, 1986). However, 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 (Shosted, 2006, p. 52), for which the predicted result is a decrease in F2. This consequence of VP coupling is especially relevant for (mid-)high back vowels, for which the raised retracted tongue dorsum creates an even greater constriction with the lowered velum. Thus, VP coupling is expected to result in a decrease in F2 for non-back vowels, although the prediction for (mid-)high back vowels is unclear.

Although formant analysis applied to the acoustics of nasal sounds is possible—and, moreover, is included as an analysis in the current study—it is challenging to predict the formant-frequency-related effects of VP coupling, since the acoustic transfer functions of the oral and nasal tracts are conflated in the acoustic signal. Nevertheless, the oro-pharyngeal shape of nasal vowels has remained of considerable interest to articulatory and acoustic phoneticians. Knowledge of the oro-pharyngeal shape of nasal vowels has implications for both diachronic and synchronic studies of language. There is evidence for interplay between the perceived acoustic effects of nasalization and the shape of the vocal tract as nasal vowels develop and change diachronically (Beddor, 1982; Beddor, Krakow, & Goldstein, 1986; Hajek, 1997; Krakow, Beddor, & Goldstein, 1988; Sampson, 1999). Krakow et al. (1988, p. 1146) observed that the F1 variation inherent in nasalization is similar to acoustic changes associated with tongue height and jaw position, and demonstrate (along with Beddor et al., 1986) that the acoustic modifications associated with increased VP aperture can be perceived as changes in oral tract shape. Delvaux (2009) shows that F2 lowering alone—which is typically modulated via changes in horizontal tongue position and labial articulation—may help trigger the percept of nasality in French.

1.2. Nasal vowels in Northern Metropolitan French

The current study focuses on the oral articulatory configurations of nasal vowels in Northern Metropolitan French (henceforth, NMF[1]). One of the reasons for investigating NMF, specifically, is that the three nasal vowel systems /ɛ̃–ɑ̃–ɔ̃/ of modern NMF is said to be undergoing a "push chain shift" (Fónagy, 1989; Hansen, 2001; Maddieson, 1984; Malderez, 1991; Walker, 1984). 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. Interestingly, a number of the acoustic changes involved in this change shift are the same as those which are predicted by VP coupling: the retraction of /ɛ̃/ (a non-back vowel) is consistent with predictions of F2-lowering due to VP coupling; the raising of /ɑ̃/ (a low vowel) is consistent with predictions of F1-lowering due to VP coupling; however, the raising of /ɔ̃/ is not consistent with predictions of the acoustic effect of VP coupling on F1, since /ɔ̃/ is not a low vowel. Understanding the specific oral articulatory configurations involved in the manifestation of this chain shift might help clarify possible causes of the shift, in addition to developing the knowledge of how multiple articulations co-vary in the production of vowel nasalization in NMF.

[1] The term NMF is used here as an umbrella term to refer to European varieties of French spoken by people born and raised in France, north of the main dialectal isogloss separating France into the so-called *Oïl* (north) and *Oc* (south) dialect areas.

Most of the previous work on the oral articulation of nasal vowels in French involves qualitative descriptions of X-ray or cineradiographic images (Bothorel, Simon, Wioland, & Zerling, 1986; Brichler-Labaeye, 1970; Straka, 1965; Zerling, 1984). These seminal articulatory studies had somewhat conflicting results, perhaps due to relatively low speaker and repetition numbers in each study. More recent studies involve labial videos (Montagu, 2002) and MRI (Delvaux, Metens, & Soquet, 2002; Delvaux, 2014, results reported in Delvaux, 2012) and larger repetition numbers, adding to the growing understanding of the oral articulation of nasal vowels in French. All the previous studies included between two and four speakers. The results are summarized in Table 1.

There are some notable differences between these studies which make drawing conclusive interpretations somewhat problematic. Firstly, some studies compare [ɑ̃] and [ɔ̃] to [ɑ] and [ɔ], respectively, while others compare them to [a] and [o], respectively. Secondly, while most of these studies involve NMF, others involve speakers of Alsatian French (Bothorel et al., 1986) and Belgian French (Delvaux et al., 2002; Delvaux, 2014), although the authors state that these speakers were "without regional accent" (Bothorel et al., 1986, p. 3) or that the variety studied "is close to standard Parisian French" (Delvaux et al., 2002, p. 582). These inter-study differences notwithstanding, we are able to draw some general conclusions about the oral articulation of the three nasal vowels [ɛ̃, ɑ̃, ɔ̃], as compared to their oral congeners [ɛ, a, o], in NMF:

- [ɛ̃] is produced with a more retracted and lower tongue position than [ɛ]. There is not much evidence suggesting any difference in labial articulation between the two vowels. There is a small amount of cross-study variation regarding these oral articulatory configurations.
- [ɑ̃] is produced with a more retracted, and possibly lower tongue position than [a]. Additionally, [ɑ̃] is produced with more protruded and/or rounded labial articulation than [a]. There is a moderate amount of cross-study variation regarding these oral articulatory configurations.
- [ɔ̃] is, possibly, produced with a more retracted and higher tongue position than [o]. Additionally, [ɔ̃] is produced with more rounded labial articulation than [o]. There is a moderate-to-large amount of cross-study variation regarding these oral articulatory configurations.

The current study expands the previous research through the use of electromagnetic articulography, commonly referred to as "EMA", which tracks the position of electromagnetic sensors adhered to flesh points. The goal of this research is to study the positions of lingual and labial articulators and to simultaneously measure acoustic parameters which are known to be correlated with changes in lingual and labial configurations. These articulatory and acoustic parameters will be compared between productions of oral–nasal congeners. In this way, qualitative inferences can be made about which acoustic effects might be due to observed oral configurations and which ones might be due to VP coupling.

2. Material and methods

The participants in this study were all female native speakers of NMF. The decision to use only females was to reduce variation in formant frequencies due to vocal tract size, as well as to control for differences that have been observed between male and female speakers with regard to the articulation of nasal vowels (Engwall, Delvaux, & Metens, 2006). In total, 13 NMF speakers were recorded, although the data from one speaker (S07) were removed due to sensor position tracking errors. Thus, the data from 12 speakers are presented here. The word list contained 18 French lexical items, mostly monosyllabic, of the syllable types /CV/ where C is a voiceless stop and V is a target vowel. The word list was balanced for place of articulation (/p, t, k/) and target vowel (/a, ɑ̃, ɛ, ɛ̃, o, ɔ̃/). Minor changes were made to the word list throughout the course of the study, due to recommendations made by native speakers. The word lists are provided in Tables Tables A1–A3 in Appendix A. Each word appeared in the carrier phrase *Il retape* X *parfois* (He retypes *X* sometimes), where *X* is the target word, and the phrases were presented to the speakers on a computer screen. There were 10 internally randomized blocks of the word list, resulting in a total of 180 tokens, with 10 repetitions per word.

For this research, the productions of [ɛ̃,ɑ̃,ɔ̃] are compared to those of their respective oral counterparts [ɛ,a,o]. The IPA transcriptions [ɛ̃,ɑ̃,ɔ̃] are conventional for the French phonetics literature (Fougeron & Smith, 1999), although it is not clear that they are intended to represent the synchronic oral articulation of these vowels. Rather, these transcriptions seem to be based on historical underlying forms, or possibly even notations for the French phonetics literature which are influenced by the normativity which was once imposed by the French educational system. The situation is further complicated by the fact that [ɑ] and [ɔ] rarely—never, for some speakers—appear in open syllables in modern NMF (Fougeron & Smith, 1999, pp. 78–79). Therefore, [ɑ] and [ɔ] should not be used as oral counterparts 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 (Fougeron & Smith, 1999, p. 78). With these considerations in mind, [ɛ, a, o] were chosen to compare with [ɛ̃,ɑ̃,ɔ̃].

The methodology for this study involves simultaneously recorded articulatory and acoustic measures (see Carignan, 2013 for more details). Simultaneously collected articulatory and acoustic measures, as well as articulatory data for a relatively large number of speakers, are novel in research on the oral articulation of NMF nasal vowels. The articulatory signals were recorded using electromagnetic articulography systems made by Carstens Medizinelektronik GmbH: the three-dimension AG500 Electromagnetic Articulograph, located in the Speech Dynamics Laboratory in the Beckman Institute at the University of Illinois at Urbana-Champaign, and the two-dimension AG200 Electromagnetic Midsagittal Articulograph, located at Grenoble Images Parole Signal Automatique

(GIPSA-lab) at l'Université Stendhal-Grenoble 3, in Grenoble, France. Speakers S01–S03 were recorded at Illinois, and speakers S04–S13 were recorded at GIPSA-lab.

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,[2] with a sensor at the midpoint between these two. The sensors adhered to these three flesh points were used for measuring positions related to the tongue tip (TT), tongue midpoint (TM), and tongue back (TB). Additionally, two sensors were placed on the lips: one on the vermilion border of the upper lip (UL), and the other one on the vermilion border of the lower lip (LL), in order to measure the degree of labial aperture and lip protrusion. Measurements of the superior–inferior displacement (z-dimension for AG500 and y-dimension for AG200; for the sake of simplicity, superior–inferior displacement for both systems will be referred to as the y-dimension) and anterior–posterior displacement (x-dimension for both AG500 and AG200) of each sensor were used to infer the vertical position and the horizontal position of these five flesh points during the experiment.

At the University of Illinois, the acoustic signal was recorded using a Countryman Isomax E6 directional microphone positioned approximately 4–5 cm from the corner of the mouth. The low metal mass of the Isomax E6 allows for use within the EMA cube without introducing sensor tracking error due to spurious electromagnetic interference. The signal gain was modulated using an M-Audio Fast Track Pro preamplifier to an appropriate level where the signal would not clip during the recording session. At GIPSA-lab, the acoustic signal was recorded with a stand-mounted AKG C 1000 S condenser microphone positioned 18–20 cm from the mouth. The microphone was aligned with the sagittal plane of the speaker's head, lowered approximately 15 cm from the transverse plane, and pointed diagonally upwards toward the speaker's mouth. After having performed experimental trials, the research engineer at GIPSA-lab had determined that this positioning avoided sensor tracking error caused by electromagnetic interference from the metal body of the microphone. Target vowels were segmented manually using the acoustic signal, after Shosted, Carignan, and Rong (2012).

2.1. Measures

2.1.1. Acoustic measures

F1 and F2 values were calculated and logged for the midpoint of each vowel. Formant frequencies were measured using Praat 5.1.33 with the default settings for most variables: the predicted number of formants was set to 5, with a window length of 25 ms, and pre-emphasis from 50 Hz. However, in order to minimize error in formant recognition, the maximum formant value was set to one of the two different values, depending upon whether a given vowel was one of the anterior-most three vowels or one of the posterior-most three vowels (determined post-hoc, via visual inspection of the vowel space). Consequently, the maximum formant for /a/, /ɛ/, and /ɛ̃/ (three anterior-most vowels) was set to 5500 Hz, and the maximum formant for /ɑ̃/, /o/, and /ɔ̃/ (three posterior-most vowels) was set to 5000 Hz. This method of using two different maximum formant values reduced the majority of errors, while remaining errors were corrected manually in the following way: after plotting formant values for each vowel category, clear outliers were double-checked against the spectrogram and/or spectral slice for the given token, and spectrally informed modifications were made if needed.

2.1.2. Articulatory measures

The articulatory data were measured and analyzed using both native and custom-written functions in Matlab 7.14. All lingual measures dealt with the superior–inferior dimension (e.g., "TM_y") and the anterior–posterior dimension (e.g., "TB_x") of the lingual sensors TT, TM, and TB, as previously explained. Labial measures involved the anterior–posterior dimension of the UL ("UL_x") and LL ("LL_x") sensors, as well as the Euclidean distance between the UL and LL sensors ("Dist."). UL_x and LL_x are used to infer the degree of labial protrusion, while Dist. is used to infer the degree of labial aperture.[3] All lingual and labial measures were calculated and logged for the midpoint of each vowel, in order to correspond with the formant measures.

2.1.3. Statistical analyses

Statistical analyses were performed on the acoustic and articulatory measures using one-way ANOVA tests in R 2.11.1. In each analysis, the experimental measure (e.g., TM_x value, and F1 frequency) was the dependent variable and vowel nasality (oral/nasal) was the independent variable. For each measure, and for each speaker, three ANOVA tests were performed (i.e. one ANOVA model for each vowel pair). Thus, the results for the acoustic and articulatory measures are the differences in measure values between nasal vowels and their oral vowel congeners (i.e. [ɑ̃] vs. [a], [ɛ̃] vs. [ɛ], and [ɔ̃] vs. [o]) for each speaker.

In order to observe the general pattern of the relationships between the six vowels in the acoustic space, each speaker's F1 and F2 values were normalized using Lobanov z-score calculation and plotted in Fig. 1.[4] Linear mixed-effects (LME) models (Baayen, Davidson, & Bates, 2008; Gueorguieva & Krystal, 2004; Pinheiro, Bates, DebRoy, Sarkar, & Team, 2011) were performed for each oral–nasal vowel pair using the *lmer* function in the *lme4* package in R. In each LME model, formant z-score was used as the

[2] One potential disadvantage of using EMA for this research (as opposed to, e.g., X-ray or MRI) is the difficulty in placing a sensor sufficiently posterior on the tongue to properly assess tongue back height, especially for (mid-)high nasal vowels, for which the velum is lowered at the same place where tongue height should be measured.

[3] The UL data for S03 were removed due to sensor position tracking errors, so only the LL_x measure can be used for labial analysis for this speaker. Therefore, the UL_x and Dist. measures for this speaker are labeled as "N/A" in Table 7, below.

[4] Ellipses represent the distribution of each vowel category, where the radius is calculated using the *qf* function in R: sqrt(2$_*$qf(0.75, 2, N−1)) (Evanini, Rosenfelder, & Fruehwald, 2012).

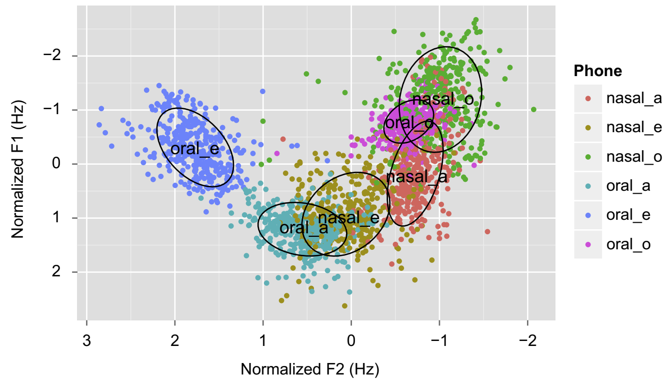

Fig. 1. Lobanov *z*-score normalized F1 and F2 values for all speakers. Vowel labels are plotted at the median intersects for each vowel category.

dependent variable, vowel nasality as a fixed effect, and speaker and block (i.e. repetition) as random effects. In total, six LME tests were performed: two sets of formant *z*-scores $\times$ three vowel pairs.

Consideration was given to the use of LME models in the statistical analysis of the articulatory data, as well. By using LME models on the articulatory data in the same manner as described above for the acoustic data, the statistical analysis would incorporate the data from all the speakers and treat any differences between the speakers as a random occurrence. However, since part of the goal of the current study is to help clarify the cross-study variation observed in previous articulatory research (see Section 1.2), it would be undesirable to integrate all the articulatory data from the speakers, since doing so would mask possible inter-speaker variation.[5] Thus, taking these issues into account, the decision was made to analyze the articulatory data for each speaker separately as outlined above.

3. Results

3.1. Acoustic results

The acoustic space of the 12 speakers' productions of the six vowels, using individual F1 and F2 *z*-scores, is plotted in Fig. 1. Results for the linear hypotheses of oral–nasal vowel counterparts belonging to the same distribution are provided in Tables 2 and 3 for F1 and F2 *z*-scores, respectively.

The results for the LME models reveal significant differences for all three vowel pairs in both the F1 and F2 dimensions. Specifically, [ɑ̃] is realized with a lower F1 and lower F2 than [a], [ɛ̃] is realized with a higher F1 and lower F2 than [ɛ], and [ɔ̃] is realized with a lower F1 and lower F2 than [o].

The results for the separate one-way ANOVAs with F1 and F2 as independent variables are provided in Table 4. With regard to the acoustic distinction between [ɑ̃] and [a], the results are consistent for all 12 speakers: [ɑ̃] is realized with a lower F1 and lower F2 than [a]. With regard to the acoustic distinction between [ɛ̃] and [ɛ], the results are consistent for all 12 speakers: [ɛ̃] is realized with a higher F1 and lower F2 than [ɛ]. With regard to the acoustic distinction between [ɔ̃] and [o], there is some inter-speaker variability. With regard to the realization of [ɔ̃] compared to [o], the results are the following:

- 7 speakers: lower F1, lower F2.
- 2 speakers: no difference in F1, lower F2.
- 1 speaker: lower F1, no difference in F2.
- 1 speaker: higher F1, lower F2.
- 1 speaker: higher F1, no difference in F2.

An interesting result is that for all but two instances (S06's and S13's productions of the vowel pair [o]–[ɔ̃]), all three nasal vowels are realized with a lower F2 than their oral counterparts, for all 12 speakers. The implications of this finding will be discussed in Section 4.

3.2. Lingual articulation results

The results for the one-way ANOVAs with superior–inferior displacement as the independent variable are provided in Table 5. Although the results for F1 are generally consistent across speakers, the results for tongue height are not, with the exception of the vowel pair [ɛ] and [ɛ̃]: a higher F1 for [ɛ̃] was observed for all 12 speakers, and [ɛ̃] is universally realized with some evidence of a lower tongue position (predicted to raise F1) than [ɛ]. With regard to [ɑ̃] vs. [a], a lower F1 for [ɑ̃] was observed for all 12 speakers, whereas very few speakers manifest a higher tongue position (predicted to lower F1) for [ɑ̃] vs. [a]. With regard to [ɔ̃] vs. [o], a lower F1 for [ɔ̃] was observed for the majority of speakers (8/12), whereas only two speakers (S03 and S12) manifest a higher tongue body

[5] I would like to thank Cécile Fougeron for her valuable input regarding this decision.

Table 2
Linear mixed effects model results for F_1 *z-scores* (model F1 z-score ~ Nasality).

Linear hypotheses	Estimate	Std Err	*t*-value
[a]–[ɑ̃] = 0	1.08323	0.04072	26.604
[ɛ]–[ɛ̃] = 0	−1.20768	0.03670	−32.91
[o]–[ɔ̃] = 0	0.37426	0.03662	10.22

Table 3
Linear mixed effects model results for F_2 *z-scores* (model F2 z-score ~ Nasality).

Linear hypotheses	Estimate	Std Err	*t*-value
[a]–[ɑ̃] = 0	1.28771	0.02104	61.19
[ɛ]–[ɛ̃] = 0	1.73001	0.02448	70.66
[o]–[ɔ̃] = 0	0.33651	0.02175	15.47

Table 4
Results of one-way ANOVA tests with nasality (oral/nasal) as a dependent variable, and F1 (Hz) and F2 (Hz) as independent variables. Formant values for oral vowels are on the left in each column; formant values for nasal vowels are on the right. Light gray cells denote significant differences for which the nasal vowel formant value is lower than that of its oral congener; dark gray cells denote significant differences for which the nasal vowel formant value is higher.

Speaker	[a]–[ɑ̃]		[ɛ]–[ɛ̃]		[o]–[ɔ̃]	
	F1	F2	F1	F2	F1	F2
S01	947–704 $F(1,58)=49$***	1741–936 $F(1,58)=454$***	457–1005 $F(1,58)=2695$***	2578–1550 $F(1,58)=928$***	438–420	922–697 $F(1,58)=125$***
S02	831–673 $F(1,57)=61$***	1584–974 $F(1,57)=715$***	658–829 $F(1,57)=94$***	1959–1268 $F(1,57)=584$***	594–502 $F(1,58)=11$**	1005–789 $F(1,58)=46$***
S03	845–788 $F(1,58)=50$***	1625–1047 $F(1,58)=402$***	706–925 $F(1,58)=151$***	2090–1400 $F(1,58)=306$***	594–420 $F(1,58)=81$***	970–746 $F(1,58)=117$***
S04	806–727 $F(1,58)=44$***	1427–891 $F(1,58)=379$***	546–801 $F(1,58)=384$***	2163–1139 $F(1,58)=5690$***	415–302 $F(1,58)=72$***	974–705 $F(1,58)=493$***
S05	885–635 $F(1,56)=155$***	1641–983 $F(1,56)=650$***	644–799 $F(1,58)=114$***	2223–1542 $F(1,58)=1432$***	511–470 $F(1,58)=5$*	1010–729 $F(1,58)=190$***
S06	799–694 $F(1,58)=168$***	1537–1065 $F(1,58)=299$***	533–782 $F(1,58)=578$***	2397–1384 $F(1,58)=1247$***	555–609 $F(1,58)=42$***	1074–1092
S08	802–651 $F(1,58)=258$***	1566–1036 $F(1,58)=471$***	601–758 $F(1,58)=165$***	2128–1334 $F(1,58)=1055$***	467–503 $F(1,58)=8$**	963–789 $F(1,58)=115$***
S09	737–575 $F(1,58)=265$***	1614–972 $F(1,58)=194$***	522–622 $F(1,58)=99$***	2175–1382 $F(1,58)=352$***	515–520	1050–783 $F(1,58)=13$***
S10	692–510 $F(1,58)=151$***	1603–885 $F(1,58)=932$***	552–617 $F(1,58)=18$***	1855–1238 $F(1,58)=262$***	509–431 $F(1,58)=28$***	1085–989 $F(1,58)=5$*
S11	704–526 $F(1,58)=37$***	1583–911 $F(1,58)=558$***	563–597 $F(1,58)=4$*	1936–1173 $F(1,58)=518$***	462–308 $F(1,58)=318$***	1037–891 $F(1,58)=46$***
S12	796–690 $F(1,58)=19$***	1480–958 $F(1,58)=174$***	547–751 $F(1,58)=184$***	2205–1326 $F(1,58)=287$***	530–451 $F(1,58)=53$***	1051–990 $F(1,58)=4$*
S13	860–627 $F(1,58)=41$***	1452–962 $F(1,58)=322$***	582–775 $F(1,58)=36$***	2231–1368 $F(1,58)=183$***	432–348 $F(1,58)=12$***	907–923

* Significance level $p<0.05$.
** Significance level $p<0.01$.
*** Significance level $p<0.001$.

position (predicted to lower F1) for [ɔ̃] vs. [o]. On the contrary, the majority of speakers produce [ɔ̃] with a lower tongue position (predicted to raise F1) compared to [o].

The results for the one-way ANOVAs with anterior–posterior displacement as the independent variable are provided in Table 6. Compared with the results for F1 and tongue height, the results for tongue retraction are more consistent with the results for F2. It was observed in Section 3.1 that, for all but two instances, all three nasal vowels were realized with a lower F2 than their oral vowel congeners for all the speakers. With regard to horizontal tongue position, for all 12 speakers' productions of [ɛ̃] vs. [ɛ], and for 11/12 speakers' productions of [ɑ̃] vs. [a], the nasal vowels are produced with a more retracted tongue position (predicted to lower F2) than their respective oral counterparts. The results for [ɔ̃] vs. [o] are not as consistent: 10/12 speakers' productions of [ɔ̃] vs. [o] are realized with a lower F2, whereas only six of these 10 speakers manifest any evidence of lingual retraction for [ɔ̃] compared to [o].

3.3. Labial articulation results

The results for the one-way ANOVAs with lip protrusion (UL_x,LL_x) and labial aperture (Dist.) as independent variables are provided in Table 7. With regard to the labial articulation of [ɑ̃] compared to [a], there is a small amount of inter-speaker variability. For 11/12

Table 5
Results of one-way ANOVA tests with nasality (oral/nasal) as a dependent variable, and superior–inferior dimension EMA values for TT_y, TM_y and TB_y as independent variables. Light gray cells denote significant differences for which a given sensor is lower for the nasal vowel than for its oral congener; dark gray cells denote significant differences for which the sensor is higher for the nasal vowel.

Speaker	[a]–[ɑ̃]			[ɛ]–[ɛ̃]			[o]–[ɔ̃]		
	TT_y	TM_y	TB_y	TT_y	TM_y	TB_y	TT_y	TM_y	TB_y
S01	$F(1,48)=13^{***}$	$F(1,47)=97^{***}$	$F(1,49)=17^{***}$	$F(1,52)=41^{***}$	$F(1,52)=224^{***}$	$F(1,52)=529^{***}$		$F(1,50)=85^{***}$	$F(1,52)=154^{***}$
S02			$F(1,55)=6^{*}$		$F(1,54)=31^{***}$	$F(1,56)=17^{***}$			
S03		$F(1,58)=6^{*}$	$F(1,55)=14^{***}$		$F(1,58)=12^{**}$	$F(1,56)=28^{***}$	$F(1,56)=67^{***}$	$F(1,57)=35^{***}$	
S04		$F(1,58)=8^{**}$	$F(1,58)=14^{***}$	$F(1,58)=211^{***}$	$F(1,58)=293^{***}$	$F(1,58)=18^{***}$		$F(1,58)=62^{***}$	$F(1,58)=194^{***}$
S05	$F(1,56)=18^{***}$	$F(1,56)=25^{***}$				$F(1,58)=15^{***}$		$F(1,58)=17^{***}$	$F(1,58)=93^{***}$
S06	$F(1,58)=8^{**}$		$F(1,58)=10^{**}$	$F(1,58)=304^{***}$	$F(1,58)=11^{**}$		$F(1,58)=33^{***}$	$F(1,58)=17^{***}$	$F(1,58)=4^{*}$
S08				$F(1,58)=22^{***}$	$F(1,58)=32^{***}$				$F(1,58)=18^{***}$
S09	$F(1,58)=6^{*}$	$F(1,58)=11^{**}$		$F(1,58)=25^{***}$	$F(1,58)=62^{***}$	$F(1,58)=10^{**}$		$F(1,58)=10^{**}$	$F(1,58)=17^{***}$
S10	$F(1,58)=78^{***}$	$F(1,58)=50^{***}$		$F(1,58)=20^{***}$	$F(1,58)=80^{***}$	$F(1,58)=10^{**}$		$F(1,58)=9^{**}$	$F(1,58)=7^{**}$
S11	$F(1,58)=8^{**}$				$F(1,58)=23^{***}$	$F(1,58)=10^{**}$	$F(1,58)=26^{***}$		$F(1,58)=26^{***}$
S12	$F(1,58)=17^{***}$	$F(1,58)=6^{*}$	$F(1,58)=10^{**}$		$F(1,58)=35^{***}$		$F(1,58)=6^{*}$	$F(1,58)=10^{**}$	$F(1,58)=5^{*}$
S13			$F(1,58)=7^{**}$	$F(1,58)=42^{***}$	$F(1,58)=139^{***}$	$F(1,58)=6^{*}$		$F(1,58)=9^{**}$	$F(1,58)=22^{***}$

* Significance level $p<0.05$.
** Significance level $p<0.01$.
*** Significance level $p<0.001$.

speakers, [ɑ̃] is produced with greater labial protrusion than [a]. For six of these 11 speakers, this protrusion is accompanied by smaller labial aperture; for another four speakers (disregarding S03, for whom Dist. could not be calculated), it is not. For one speaker, only a smaller labial aperture differentiates [ɑ̃] from [a], without any evidence of labial protrusion. Taken together, these observations suggest that [ɑ̃] is realized with greater lip rounding than [a] by all 12 speakers, but that the articulatory strategy for producing this rounding is different between speakers (i.e. some employ greater labial protrusion, some employ smaller labial aperture, and some employ both). With regard to [ɛ̃] vs. [ɛ], no clear inter-speaker pattern can be observed, suggesting that, while labial differences may be observed for a given speaker's production of these two vowels, there is no consistent labial articulatory difference for [ɛ̃] compared to [ɛ], overall. With regard to [ɔ̃] vs. [o], there is also much inter-speaker variability. The majority of the speakers (8/12) produce [ɔ̃] with a smaller labial aperture than [o]. However, five speakers produce [ɔ̃] with evidence of more retracted lips than [o], suggesting that [o] is produced with greater lip protrusion than [ɔ̃] for these speakers. 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.

4. Discussion

Taking into consideration the results for the lingual and labial articulatory differences of the vowel pairs studied here, as well as the corresponding acoustic output, we can observe that, whereas the acoustic differences between vowel pairs are generally the same across speakers (with some inter-speaker variation for the vowel pair [o]–[ɔ̃]), the articulatory sources of these acoustic differences are not the same for all speakers. The most consistent articulatory-acoustic mapping is for the vowel pair [ɛ]–[ɛ̃]: the lower, more retracted tongue position for [ɛ̃] compared to [ɛ] is predicted to yield a higher F1 and lower F2 for the nasal vowel compared to its oral congener; these acoustic differences are, indeed, observed for all 12 speakers. Moreover, VP coupling is predicted to lower F2 for non-back vowels. Thus, the lower F2 observed for [ɛ̃] compared to [ɛ] is also predicted by the effect of nasalization on [ɛ̃]. This suggests that lingual articulation enhances the acoustic effect of nasalization on F2 for [ɛ̃] vs. [ɛ].

The interpretation of the vowel pair [a]–[ɑ̃] is less straightforward. On the one hand, 11/12 speakers produce [ɑ̃] with a more retracted tongue position than [a]; this articulation is predicted to lower F2, an acoustic realization that is observed for all 12 speakers. On the other hand, very few speakers manifest any evidence of a raised tongue position for [ɑ̃], an articulation which is predicted to lower F1; nevertheless, all 12 speakers manifest a lowered F1 for [ɑ̃] vs. [a]. However, [ɑ̃] is produced with greater lip protrusion and/or smaller labial aperture than [a] by all 12 speakers, articulatory configurations which are predicted to lower both F1 and F2. In this case, labial articulation may help account for observed acoustic realizations that lingual articulation cannot. Moreover, VP coupling is predicted to lower both F1 and F2 for low, non-back vowels. Thus, the lower F1 and F2 observed for [ɑ̃] compared to [a] is also predicted by the effect of nasalization on [ɑ̃]. This suggests that horizontal lingual position and labial articulation enhance the acoustic effect of nasalization on F1 and F2 for [ɑ̃] vs. [a].

The vowel pair [o]–[ɔ̃] manifests the most discrepancies between the oral articulations employed by the speakers and the corresponding acoustic output. Although there are inter-speaker differences, the acoustic pattern for the majority of the speakers is for [ɔ̃] to be realized with a lower F1 and lower F2 compared to [o]; using speaker as a random effect, the LME models performed on normalized formant values reveal that this is indeed the general pattern. However, there are relatively few speakers who produce [ɔ̃] with a higher more retracted tongue position compared to [o], a lingual articulation which would account for the observed acoustic output. In fact, the majority of speakers produce [ɔ̃] with a *lower* tongue position than [o], a lingual configuration which is predicted to

Table 6
Results of one-way ANOVA tests with nasality (oral/nasal) as a dependent variable, and anterior–posterior dimension EMA values for TT_x, TM_x and TB_x as independent variables. Light gray cells denote significant differences for which a given sensor is more posterior for the nasal vowel than for its oral congener; dark gray cells denote significant differences for which the sensor is more anterior for the nasal vowel.

Speaker	[a]–[ɑ̃]			[ɛ]–[ɛ̃]			[o]–[ɔ̃]		
	TT_x	TM_x	TB_x	TT_x	TM_x	TB_x	TT_x	TM_x	TB_x
S01	$F(1,48)=67^{***}$	$F(1,47)=90^{***}$	$F(1,49)=84^{***}$	$F(1,52)=75^{***}$	$F(1,52)=26^{***}$	$F(1,52)=290^{***}$	$F(1,53)=6^{*}$		$F(1,52)=15^{***}$
S02				$F(1,56)=5^{*}$	$F(1,54)=35^{***}$				$F(1,56)=5^{*}$
S03	$F(1,58)=48^{***}$	$F(1,58)=131^{***}$	$F(1,55)=85^{***}$	$F(1,58)=148^{***}$	$F(1,58)=180^{***}$	$F(1,56)=103^{***}$	$F(1,56)=15^{***}$	$F(1,57)=11^{**}$	
S04	$F(1,58)=87^{***}$	$F(1,58)=99^{***}$	$F(1,58)=130^{***}$	$F(1,58)=216^{***}$	$F(1,58)=213^{***}$	$F(1,58)=337^{***}$		$F(1,58)=63^{***}$	$F(1,58)=81^{***}$
S05		$F(1,56)=789^{***}$	$F(1,56)=7^{***}$	$F(1,58)=42^{***}$		$F(1,58)=137^{***}$		$F(1,58)=14^{***}$	
S06	$F(1,58)=38^{***}$	$F(1,58)=23^{***}$	$F(1,58)=50^{***}$	$F(1,58)=195^{***}$	$F(1,58)=71^{***}$	$F(1,58)=160^{***}$			
S08	$F(1,58)=28^{***}$	$F(1,58)=27^{***}$	$F(1,58)=29^{***}$	$F(1,58)=164^{***}$	$F(1,58)=55^{***}$	$F(1,58)=54^{***}$		$F(1,58)=10^{**}$	$F(1,58)=14^{***}$
S09	$F(1,58)=20^{***}$	$F(1,58)=35^{***}$	$F(1,58)=18^{***}$	$F(1,58)=31^{***}$	$F(1,58)=15^{***}$	$F(1,58)=8^{**}$		$F(1,58)=7^{**}$	
S10	$F(1,58)=46^{***}$	$F(1,58)=24^{***}$	$F(1,58)=13^{***}$	$F(1,58)=46^{***}$	$F(1,58)=24^{***}$	$F(1,58)=13^{***}$		$F(1,58)=9^{**}$	$F(1,58)=7^{*}$
S11	$F(1,58)=13^{***}$	$F(1,58)=11^{**}$	$F(1,58)=10^{**}$	$F(1,58)=88^{***}$	$F(1,58)=59^{***}$	$F(1,58)=53^{***}$	$F(1,58)=7^{*}$		
S12	$F(1,58)=27^{***}$	$F(1,58)=66^{***}$	$F(1,58)=71^{***}$	$F(1,58)=33^{***}$	$F(1,58)=23^{***}$	$F(1,58)=18^{***}$	$F(1,58)=5^{*}$	$F(1,58)=36^{***}$	$F(1,58)=39^{***}$
S13	$F(1,58)=31^{***}$	$F(1,58)=12^{***}$	$F(1,58)=8^{**}$	$F(1,58)=40^{***}$	$F(1,58)=17^{***}$	$F(1,58)=7^{*}$			

* Significance level $p<0.05$.
** Significance level $p<0.01$.
*** Significance level $p<0.001$.

Table 7
Results of one-way ANOVA tests with nasality (oral/nasal) as a dependent variable, and labial measures described in Section 2.1.2 as independent variables. Light gray cells denote significant differences for which a given measure is smaller for the nasal vowel than for its oral congener; dark gray cells denote significant differences for which the measure is larger for the nasal vowel.

Speaker	[a]–[ɑ̃]			[ɛ]–[ɛ̃]			[o]–[ɔ̃]		
	UL_x	LL_x	Dist.	UL_x	LL_x	Dist.	UL_x	LL_x	Dist.
S01			$F(1,58)=95^{***}$			$F(1,58)=20^{***}$			
S02	$F(1,56)=6^{*}$	$F(1,56)=206^{***}$	$F(1,56)=324^{***}$		$F(1,57)=10^{**}$	$F(1,57)=15^{***}$			$F(1,57)=9^{**}$
S03	N/A	$F(1,58)=6^{*}$	N/A	N/A		N/A	N/A	$F(1,57)=30^{***}$	N/A
S04	$F(1,58)=820^{***}$	$F(1,58)=73^{***}$		$F(1,58)=27^{***}$			$F(1,58)=9^{**}$		$F(1,58)=9^{**}$
S05	$F(1,56)=13^{***}$	$F(1,56)=595^{***}$	$F(1,56)=210^{***}$	$F(1,58)=49^{***}$			$F(1,58)=5^{*}$	$F(1,58)=13^{***}$	$F(1,58)=7^{*}$
S06	$F(1,58)=78^{***}$	$F(1,57)=47^{***}$	$F(1,57)=96^{***}$		$F(1,56)=19^{***}$	$F(1,56)=39^{***}$	$F(1,58)=5^{*}$	$F(1,57)=6^{*}$	$F(1,57)=23^{***}$
S08	$F(1,58)=58^{***}$	$F(1,58)=125^{***}$	$F(1,58)=126^{***}$		$F(1,58)=9^{**}$	$F(1,58)=21^{***}$	$F(1,58)=4^{*}$	$F(1,58)=11^{**}$	$F(1,58)=19^{***}$
S09	$F(1,58)=39^{***}$	$F(1,58)=23^{***}$	$F(1,58)=126^{***}$		$F(1,58)=4^{*}$				$F(1,58)=86^{***}$
S10	$F(1,58)=269^{***}$	$F(1,58)=348^{***}$			$F(1,58)=8^{**}$	$F(1,58)=17^{***}$			$F(1,58)=13^{***}$
S11	$F(1,58)=73^{***}$	$F(1,58)=84^{***}$	$F(1,58)=23^{***}$	$F(1,58)=11^{**}$	$F(1,58)=14^{***}$	$F(1,58)=79^{***}$		$F(1,58)=5^{*}$	$F(1,58)=35^{***}$
S12	$F(1,58)=39^{***}$	$F(1,58)=123^{***}$	$F(1,58)=299^{***}$						$F(1,58)=122^{***}$
S13	$F(1,58)=259^{***}$	$F(1,58)=318^{***}$					$F(1,58)=6^{*}$		$F(1,58)=19^{***}$

* Significance level $p<0.05$.
** Significance level $p<0.01$.
*** Significance level $p<0.001$.

raise F1; however, a higher F1 is only observed for two of the speakers who produce [ɔ̃] with a lower tongue position than [o]. Labial configuration may help explain some of these articulatory–acoustic discrepancies in some cases, since most of the speakers produce [ɔ̃] with smaller labial aperture (predicted to lower F1/F2) compared to [o]; however, other speakers produce [o] with greater lip protrusion (also predicted to lower F1/F2) compared to [ɔ̃]. For three speakers (S01, S05, S06), neither lingual nor labial configuration can account for the acoustic differences observed between [o] and [ɔ̃]. These remaining discrepancies can be summarized in the following way: F1 is lower than that can be explained by vertical tongue position and labial configuration, and F2 is lower than can be explained by horizontal tongue position and labial configuration. Moreover, these articulatory/acoustic discrepancies are not predicted by the effects of VP coupling, due to the fact that [ɔ̃] is neither a low vowel (lower F1 is not explained by VP coupling) nor a non-back vowel (lower F2 is not explained by VP coupling).

Using real-time MRI to research the articulatory differences between these oral–nasal vowel pairs as produced by three NMF speakers (separate from the 12 speakers in this study), Carignan, Shosted, Fu, Liang, and Sutton (2013) and Carignan, Shosted, Fu, Liang, and Sutton (2014) find evidence of greater lower pharyngeal constriction for [ɛ̃,ɔ̃] compared to [ɛ,o], respectively, and greater lower pharyngeal expansion for [ɑ̃] compared to [a]. As detailed in Section 1.1, a constriction in the lower pharynx is predicted to raise F1, while an expansion is predicted to lower F1. Thus, the observed pharyngeal configurations are predicted to result in a higher F1 for [ɛ̃] vs. [ɛ] and a lower F1 for [ɑ̃] vs. [a], acoustic distinctions which have indeed been observed in the current study. This suggests that pharyngealization contributes to the acoustic realization of [ɛ̃,ɑ̃] in NMF. With regard to [ɔ̃], whereas pharyngeal constriction may explain the higher F1 observed for some speakers' production of [ɔ̃] vs. [o] in the current study, the lower F1 for [ɔ̃] observed for the majority of the speakers is not consistent with the pharyngeal configuration observed in Carignan et al. (2013) and Carignan et al. (2014).

As mentioned in Section 1.1, although F2-lowering is not necessarily predicted for back vowels under the influence of nasalization, the velic constriction created by the lowering of the soft palate is predicted to lower F2 frequency, and is especially relevant for (mid-) high back vowels (such as the realization of /ɔ̃/ observed in this study), for which the raised, retracted tongue dorsum would conceivably create an even greater constriction with the lowered velum. Although this articulation may be “passive” (i.e. it is an indirect consequence of VP coupling), the result is an important acoustic effect which should not be disregarded. Further research is needed to determine how much this F2-lowering can be generalized to vowel nasalization in other languages—Shosted et al. (2012, p. 462) have observed lower F2 for non-front nasal vowels compared to their oral vowel counterparts in Hindi, for example—but based on modeling work by Serrurier and Badin (2008) and perception work by Delvaux (2009) for NMF nasal vowels, it is reasonable to consider F2-lowering due to velic lowering a factor in the results of the current study: the ubiquitously lower F2 values observed for all nasal vowels, for all speakers, suggest that this velic constriction may be a contributing factor to the acoustic manifestation of these vowels in NMF. Future research on the degree of velic constriction in the production of NMF nasal vowels would be beneficial, as well as computer simulations on how this constriction may contribute to the overall F2 realization of the NMF nasal vowel space.

Taking all these factors into consideration, it is reasonable to speculate that, regarding general acoustic and articulatory patterns, speakers use idiosyncratic combinations of the following articulations in order to create F1 and F2 frequency differences which help distinguish oral/nasal vowel pairs in NMF:

[ɑ̃] vs. [a]

- F1 distinction is due to VP coupling, lip rounding, and lower pharyngeal expansion.
- F2 distinction is due to VP coupling, lingual retraction, lip rounding, and velic lowering.

[ɛ̃] vs. [ɛ]

- F1 distinction is due to lower tongue position and lower pharyngeal constriction.
- F2 distinction is due to VP coupling, lingual retraction, and velic lowering.

[ɔ̃] vs. [o]

- F1 distinction is due to lip rounding; lower pharyngeal constriction and tongue height may also contribute to speaker-specific F1 distinction.
- F2 distinction is due to lingual retraction (speaker-dependent), lip rounding, and velic lowering.

The results from this study suggest that, generally, the acoustic realizations of these three nasal vowels (see Fig. 1) are [ɐ̃] (e.g., *pain* [pɐ̃]), [ɔ̝̃] (e.g., *paon* [pɔ̝̃]), and [õ̞] (e.g., *pont* [põ̞]), rather than the realizations which their respective conventional IPA transcriptions [ɛ̃], [ɑ̃], and [ɔ̃] imply. These results are consistent with the counter-clockwise chain shift reported for the realization of the three nasal vowel systems of NMF (see Section 1.2). The articulatory and acoustic results from this study, taken together with the predicted effects of VP coupling on the acoustic vowel space, suggest the possibility that this “pushing” of /ɛ̃/ towards the acoustic space occupied by [ɑ̃] was, perhaps, triggered by the inherent consequence of VP coupling on the acoustic realization of /ɛ̃/. Moreover, the raising of /ɑ̃/ towards the acoustic space occupied by [ɔ̃] is also consistent with the frequency-related effect of VP coupling. However, the raising of /ɔ̃/ is not consistent with the acoustic effect of VP coupling and, therefore, may simply be due to the influence of the chain shift itself (i.e. a reactionary consequence of the raising of /ɑ̃/ towards the acoustic space occupied by [ɔ̃]). This particular analysis is, of course, speculative, but regardless of whether the chain shift was indeed initiated by the acoustic effect of VP coupling, the results from the current study suggest that oral articulatory configurations are used to peripheralize the counter-clockwise movement of the nasal vowels along the acoustic space in modern NMF.

Finally, the inclusion of a relatively large number of speakers in this study reveals evidence that speakers use idiosyncratic oral articulatory strategies to reach similar acoustic outputs in order to produce the distinction between oral/nasal vowel congeners in NMF. This suggests that the articulatory differences observed between previous studies (especially with regard to the vowel pairs [a]–[ɑ̃] and [o]–[ɔ̃]) may simply be due to undersampling of the variability in the articulatory strategies employed by NMF speakers in the production of these nasal vowels, rather than to any methodological differences between these previous studies.

5. Conclusion

Nasal vowels typify speech production's classic ‘many-to-one problem’: “a case where more than one articulator configuration can be used to produce the same acoustic signal” (Hogden et al., 1996, p. 1821). The results from the current study lend support to this claim. Hughes and Abbs (1976, p. 199) define motor equivalence as “the capacity of a motor system to achieve the same end-product with considerable variation in the individual components that contribute to that output.” The notion of motor equivalence seems to be appropriate to explain the production of NMF nasal vowels: multiple articulatory variables (VP coupling and oral articulatory configurations) can produce similar effects on F1 and F2 frequencies. The articulatory evidences observed and discussed in this and related research suggest that lingual, labial, pharyngeal, and even velic articulations of the NMF nasal vowels can be interpreted as mechanisms of enhancement of nasalization, at least in terms of the acoustic effect of VP coupling on the frequencies of F1 and F2.

These results give strong support to the view that the goal of speech acts is acoustic, not articulatory (see Kingston, 1992; Kluender et al., 1988; Ohala, 1996; cf. Fowler, 1989, 1991; Liberman & Mattingly, 1985), by showing that speakers use a variety of articulatory combinations in order to achieve a similar acoustic output. If speakers perceive information about the configurations of speech articulators themselves, then we should find minimal inter-speaker variability with regard to the articulation of speech sounds, since variability in articulation would lead to variability in perception. On the other hand, if speakers perceive only acoustic information about speech sounds, and any articulatory variability is, instead, integrated into perceptual objects, then we should not be surprised to observe inter-speaker variability with regard to the articulation of speech sounds, and relatively less variability with regard to the corresponding acoustic output. The results from this study support the latter case.

Acknowledgments

Data collection was made possible with the help and expertise of Christophe Savariaux, research engineer of the Parole et Cognition department at GIPSA-lab (http://www.gipsa-lab.grenoble-inp.fr/∼christophe.savariaux)

This research was financially supported, in part, by NSF Grant #1121780 to Ryan Shosted (PI), Christopher Carignan (Co-PI), and Zsuzsanna Fagyal (Co-PI).

The acoustic and articulographic data and measures for speakers S04-S13 are publicly available on the author's website at the following address: http://www.christophercarignan.com/dissertation/database

Appendix A. Word list

The word lists A, B, and C are given in Tables A1, A2, and A3 respectively.

Table A1
Word list A (speaker S01).

Onset C	/a/	/ɑ̃/	/ɛ/	/ɛ̃/	/o/	/ɔ̃/
/p/	*pas*	*paon*	*paix*	*pain*	*pot*	*pont*
	'step'	'peacock'	'peace'	'bread'	'jar'	'bridge'
/t/	*ta*	*temps*	*tait*	*teint*	*tôt*	*thon*
	'your'	'weather'	'(it) keeps quiet'	'complexion'	'early'	'tuna'
/k/	*cas*	*quand*	*quai*	*co.quin*	*co.co*	*con*
	'case'	'when'	'platform'	'scoundrel, rascal'	'coconut'	'idiot, jerk'

Table A2
Word list B (speakers S02–03).

Onset C	/a/	/ɑ̃/	/ɛ/	/ɛ̃/	/o/	/ɔ̃/
/p/	*pa.pa*	*paon*	*paix*	*pain*	*pot*	*pont*
	'daddy'	'peacock'	'peace'	'bread'	'jar'	'bridge'
/t/	*ta*	*temps*	*tait*	*teint*	*tôt*	*thon*
	'your'	'weather'	'(it) keeps quiet'	'complexion'	'early'	'tuna'
/k/	*ca.ca*	*quand*	*pa.quet*	*co.quin*	*co.co*	*con*
	'poop'	'when'	'package'	'scoundrel, rascal'	'coconut'	'idiot, jerk'

Table A3
Word list C (speakers S04–13).

Onset C	/a/	/ɑ̃/	/ɛ/	/ɛ̃/	/o/	/ɔ̃/
/p/	*pa.pa*	*paon*	*paix*	*pain*	*pot*	*pont*
	'daddy'	'peacock'	'peace'	'bread'	'jar'	'bridge'
/t/	*ta*	*temps*	*taie*	*teint*	*tôt*	*thon*
	'your'	'weather'	'cover'	'complexion'	'early'	'tuna'
/k/	*ca.ca*	*quand*	*pa.quet*	*co.quin*	*co.co*	*con*
	'poop'	'when'	'package'	'scoundrel, rascal'	'coconut'	'idiot, jerk'

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