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特集論文

Tongue Height, Vowel Quality and Nasality in Québec French: An Acoustic and Articulatory Study

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ケベック・フランス語における舌高，母音音色，鼻音性 —音響的，調音的研究—

SUMMARY: This paper employs ultrasound and nasometric instruments in a variable-rate reading task to examine regressive nasalization in Québec French. We measure tongue height according to nasality of context, as well as percent nasality (via an energy-based ratio formula) and vowel duration. Results show high degrees of nasalization for high vowels and certain mid vowels for the group as a whole, and that certain speakers increase the nasal salience of mid and/or high vowels, while others modulate tongue height to undo displacement of the percepts of vowel height as the result of nasal coupling.

Key words: vowel nasality, coarticulation, ultrasound, nasometry, Québec French

1. Introduction

Previous phonetic studies have long recognized the difference between language-specific aspects of production which must be planned, and those which arise due to more universal, physiological constraints. This distinction can be readily observed in prosodically prominent positions and/or in more careful or slower speech, and furthermore may be obscured outside of these conditions (see Solé 2007 and references therein). Gauging the phonological competence of speakers, then, is likely to require more than superficial data when it comes to phonetically skewed phenomena.

Nasality in French provides a fertile testing ground for these themes, in addition to being a subject which, despite extensive phonetic study, still presents important gaps in our understanding. For one, vowel nasality in French is contrastive, and in both the pedagogical and general linguistic literature (e.g., Fagyal et al. 2006, Tranel 1987, Valdman 1993) the oral-nasal distinction among vowels is purported to be maintained in coarticulatory settings. That is, vowel nasalization—which we momentarily defined simply as the passage of a lexically oral vowel to its nasal counterpart—is deemed not to apply next to, and especially not before nasal consonants.

This characterization of French, however, does not entirely concur with the phonetic literature. While most studies show negligible rates of nasalization on low and mid vowels (see §2.1 for references), high vowels are often more nasal in coarticulatory settings, at times exceeding 50% nasal. However, once the majority of phonetic parameters relating vowel height and nasality are considered, it becomes clear that high vowels are most susceptible to spontaneous nasalization. Furthermore, being the shortest of peripheral vowels, any degree of mechanical coarticulation has the potential to occupy a larger percentage of a high vowel than that of other vowel heights. It is thus relevant to the question at hand whether the elevated rates of nasalization reported on high vowels in French constitute a language-specific property of French, or are merely reflective of more universal, and therefore not prescribed, constraints on the vocal apparatus. This paper examines Québec French (*henceforth*, QF) in particular because of several factors. First, the phonetic implementation of contrastive nasal vowels in QF is known to be more gradual than that of European French varieties (Delvaux 2006, van Reenen 1986). Second, contextual nasalization in QF is reported to be higher than that in European French varieties (e.g., Tranel 1987).

With this background in mind, this study examines

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regressive nasalization in QF as spoken in Montreal, in light of the distinction between controlled and mechanical properties of production. In particular, we attempt to disentangle the obscuring effects of vowel height and duration in a bi-methodological experiment. Namely, we use nasometric and ultrasound instruments in a variable rate reading task along the lines of Solé (1992). The former instrument allows us to record the acoustic signal emanating from the nasal cavity relatively separately from that of the oral cavity. As such, we may quantify vowel nasality acoustically and examine this value for a given vowel quality as a function of overall vowel duration.

The application of ultrasound tongue imaging (*henceforth*, UTI) is a less direct way to address the question of nasal coupling, but potentially provides a nuanced look into the acoustic results. UTI is rarely used to examine gestures directly in relation to nasal coupling. However, it has been employed in previous studies to determine the configuration of intraoral articulators during the production of nasal or nasalized vowels (e.g., Delvaux 2006). More generally, Carignan et al. (2011) and Carignan (2014) show that tongue movement, among other gestures, may be manipulated either to increase the salience of nasality (in the case of French nasal vowels) or to reverse the effects of nasal coupling on a vowel's F1, effectively restoring its height in formant space (in the case of American English nasalized /i/). Further, in the absence of contradictory evidence, it is possible that F1 manipulation by intraoral articulators may be deployed to diminish the percepts of nasality itself, in the case of only slightly nasalized vowels, though a more rigorous analysis of the influence of duration is required to take shed light on this issue.

The investigated articulatory-acoustic link we address in the current article is the following: tongue height is universally proportionate to the concept of vowel height and inversely proportionate to F1. Meanwhile, all other things being equal, nasal coupling raises the F1 of high vowels (lowering them in formant space, i.e., the traditional vowel trapeze) and lowers the F1 of low and potentially mid vowels (raising them in formant space). Tongue lowering of high vowels before nasal consonants would then have the same effect as nasal coupling of these same vowels, thus increasing the salience of nasality. This effect would inversely be attained on low and mid vowels via tongue raising. Meanwhile, the opposite effects (tongue raising on high vowels and lowering on low and mid vowels) would have the effect of either restoring that vowel's height, if nasal, or, as we weakly hypothesize, negating the effects of unwanted nasalization, if marginally or merely mechanically nasalized. These relationships are more thoroughly explored in §5.1.

With regards to the current experiment, we predict that, as in European French, high vowels in QF will remain strongly nasal in pre-nasal contexts as a function of duration. Meanwhile, mid and low vowels should show either much lower rates of nasalization in this same context, or their nasality should decline sharply as they increase in length. We also make several hypotheses concerning the link between tongue height and nasality, along the lines of Cariginan (2014). First, we do not expect vowels which are uniformly low in nasality (regardless of duration) to demonstrate significant lingual movements whose acoustic consequences go in the same direction as those of nasal coupling, though tongue height may go in the opposite direction or may not be differentiated. We predict these vowels to be low and mid. Meanwhile, on high vowels, which we expect either to remain significantly nasal or to increase significantly in nasality with duration, we make the weak prediction that tongue gestures should go in the direction of increasing nasal salience (i.e., lowering). Given the increased perceptibility of nasal coupling on high vowels (see §2.2), we argue that only tongue body raising of shorter, more nasal high vowels, when they decrease in nasality over duration, should be indicative of HVN as a mechanical process.

Beyond the empirical contributions of this paper, the present study is innovative in a number of methodological aspects. First, multimethodological approaches such as ours are rare in the study of vowel nasality, and yet it is unclear to what extent different experimental approaches to nasality converge on the same conclusions (that is, whether a principled comparison of results of different types of instruments can be made, even within the same language). Second, our study expands the methodology of Solé (1992, 2007) to elucidate the difference between controlled and mechanical properties of speech for vowels of different heights separately (given the possibility that some may be more 'covertly' mechanical than others in their rates of nasalization).

The remainder of the paper is structured in the following way: Section 2 describes vowel nasality in French and phonetic factors which relate vowel height and nasal coupling. We also define the notions of 'controlled' and 'mechanical' nasalization. Section 3 provides the methodology of the study. We report the results in §4, at both the group and individual levels for the nasometry study, and provide a by-speaker analysis for the ultrasound results. Section 5 synthesizes and interprets these results, and in §6 we close the paper with general comments and a description of future work.

2. Background

2.1 Vowel Nasality in French

The oral vowel inventory of standard varieties of French is generally comprised of /a, ɛ, œ, ɔ, e, ø, o, i, y, u/. In most varieties of French, disparities in the distribution of the mid vowels (mid-closed generally being preferred in open syllables and mid-open being preferred in closed syllables) casts some doubt on their contrastive status; there is enough reason, however, to believe the pair is at least marginally contrastive (Stevenson and Zamuner 2017). Variants more specific to QF include a long, mid front unrounded vowel with various realizations, a back low vowel variant (especially in absolute word-final position) and lax high vowels [ɪ, ʏ, ʊ] in certain types of closed syllables (Walker 1984). These contextual variants are not further considered here.

These vowels contrast with the series of nasal vowels traditionally transcribed /ɑ̃, ɛ̃, ɔ̃, œ̃/, the last of which is undergoing a merger with its unrounded counterpart in many European varieties (e.g., Tranel 1987) but is maintained in Canadian varieties (Walker 1984). The quality of these latter four vowels in contemporary speech diverges from these transcriptions and depends on both dialect and type of evidence (namely, acoustic vs. articulatory). In general, European French nasal vowels have undergone a counterclockwise shift (e.g., Zerling 1984), while the shift is clockwise in QF (Dumas 1987, Walker 1984). In consequence, what are standardly known as /ɑ̃, ɛ̃/ are closer to [æ̃, ẽ] in QF in open syllables, according to Walker's (1984) still somewhat broad transcription; /ɔ̃, œ̃/ are not different according to him. Nasal vowels in QF are also subject to contextual variation according to syllable type, in that diphthongization applies to nasal vowels in closed syllables and, less often, in pretonic position, leading to variants [ɑ̃w̃, ɛ̃j̃, ɔ̃w̃, œ̃ɥ̃] (Walker 1984).

European and Québec French are distinguished also by the temporal implementation of nasal coupling itself on the series of nasal vowels. Though European French does demonstrate some delay in the onset of nasality (Basset et al. 2001, Cohn 1990, Delvaux et al. 2008, Montagu 2007), this delay is more pronounced in QF, particularly in the mid-front series (Delvaux 2006). Van Reenen (1982) notes using a proprietary formula that vowel nasality in both varieties is maximally 7%, with a markedly more gradual rise in QF. Based on aerodynamic and imaging (lip tracing and ultrasound) data, Delvaux (2006, p. 385) proposes [æɛẽʲ̃, ɔ̃õ, œ̃ø̃ʷ̃] as the narrow phonetic realization of /ɛ̃, ɔ̃, œ̃/ in open syllables (the low vowel [æ̃], or /ɑ̃/, showing little diphthongization), and [aãʷ̃] for the low vowel in closed syllables. See §3.1 for an explanation of the symbols used in the rest of the paper.

Regardless of the dialect, oral and nasal vowels contrast in French in word-final position and internal open syllables followed by non-nasal consonants. In general, nasal vowels may not precede nasal consonants, with a few well-defined exceptions. In addition, a general restriction holds on native vocabulary that nasal consonants may not appear in pre-consonantal position, unless as a result of the non-realization of a schwa, as in *savonn(e)rie* 'soap factory'. Word-final nasal consonants are regularly permitted, and final VN sequences may alternate with full nasal vowels in verb conjugation and gender agreement in adjectives (e.g., *bon* [bɔ̃] 'good (m.)', *bonne* [bɔn] 'good (f.)').

Though normatively and pedagogically speaking, French maintains its oral-nasal contrast, phonetic studies on contextual nasalization in multiple varieties show small to significant degrees of nasalization, which necessarily differentiates vowel types. Progressive nasalization is more pervasive than regressive nasalization (e.g., Delvaux et al. 2008, Rochet and Rochet 1991). Meanwhile, most studies agree that high vowels are most nasalized before nasal consonants (Basset et al. 2001, Delvaux et al. 2008, Rochet and Rochet 1991, Spears 2006), the vowel /i/ being over 50% nasal in the latter two studies. Note that Rochet and Rochet (1991) concerns Canadian French, while the variety of the others is Northern (i.e., non-meridional) European French.

Two counterexamples to the observed tendencies exist: First, in Clumeck's (1976) nasographic study, which measures nasality via detection of a light source situated in the nasal cavities by a sensor just beneath the velum, low vowels are most nasalized than mid and, in turn, high. This may, in fact, be attributable to articulatory confounds (see §2.2), namely that the velum is already lower on these vowels. Meanwhile, Montagu's (2007) nasometric study, the same type employed here, also finds low vowels to be the most nasalized. However, given that nasal poles on /i/, for instance, appear in the 1000–2000 Hz range, while those of low vowels appear around 500 Hz (Pruthi 2007), it is possible that her use of a high-pass filter of 600 Hz biased the results towards low vowel nasalization.

2.2 Vowel Height and Nasality

Nasal coupling is achieved by a passive lowering of the velum, which allows air to egress through the nasal cavities via the velopharyngeal port (VP). In the case of nasal (ized) vowels, the oral cavity remains unblocked, resulting in a bifurcated system. These physical correlates of nasality, namely, VP opening as a function of velic displacement and the aerodynamic requirements of this bifurcated system, overlap with those of vowel height. As such, certain vowel types are more susceptible to nasal coupling than others. In this section, we look first at the evidence favouring high vowel nasalization, coming mainly from acoustic, aerodynamic and perceptual phonetics. We then look at the interplay among vowel height, duration, and nasality which may favour low vowels over high.

Acoustic modeling studies find that the effect of any degree of VP opening will have larger effects on high vowels than on low vowels (Bell-Berti and Baer 1983, Feng and Castelli 1996, House and Stevens 1956, Maeda 1993, Pruthi 2007). House and Stevens attribute this to the lower F1 values of high vowels being more susceptible to amplitude decrease and bandwidth increase (both general acoustic indicators of nasality) by their nasal transfer function. Meanwhile, the other authors cited argue that the appearance of nasal poles in the spectral valley between F1 and F2 allows for a "large domain for validation of nasality" (Feng and Castelli 1996, p. 3701). In comparison, the first nasal pole of low vowels appears beneath the F1, the former approaching and dampening the latter as VP opening increases. Regardless of the reason evoked, all these studies find low vowels require much more nasal coupling, if not near-maximal amounts, to achieve sufficient spectral change.

A similar effect of height holds on the minimal aerodynamic requirements for nasal coupling. High vowels necessarily have smaller areas of intraoral air and thus higher pressure than mid and low vowels. As such, only a small VP opening is theoretically necessary to divert air through the nasal cavities (Hajek 1997), which is supported in experimental findings on vowels in pre-nasal contexts (Al-Bamerni 1983, Lubker and Moll 1965, McDonald and Baker 1951). All in all, high vowels require comparatively little velic displacement in order to be nasalized.

Intrinsic velic height, which is proportionate to vowel height—that is, being lowest on low vowels and highest on high (Henderson 1984)—provides an apparent counterexample but, in fact, argues largely for the same relation illustrated above. According to the largely abandoned "opening hypothesis," nasal coupling is achieved on low vowels with minimal effort because of the already low position of the velum associated with them. While low vowels in non-nasal contexts are indeed known to be pronounced with a slightly open velopharyngeal port (Al-Bamerni 1983, Bell-Berti 1973, Clumeck 1976, Fritzell 1969, Hiroto et al. 1963), actual nasal coupling is negligible for the acoustic and aerodynamic reasons cited earlier. Perceptual studies do find that without any nasal coupling, low vowels are judged as more nasal than high (Ali et al. 1971, Brito 1975, House and Stevens 1956, Lintz and Sherman 1961, Maeda 1982). However, once nasal coupling begins, low vowels in Maeda (1982) require nearly three times the degree of nasal coupling to match the high vowels, which are immediately judged as nasal; this effect is found in numerous perceptual studies (e.g., Abramson et al. 1981, Benguerel and Lafargue 1981, Carney and Sherman 1971, Hawkins and Stevens 1985, House and Stevens 1956, Kingston and Macmillan 1995, Macmillan et al. 1999, Stevens et al. 1987). In sum, rather than suggesting spontaneity of nasalization, the low velic position of low vowels may instead indicate shifting of the oral-nasal threshold (Ohala 1975, pp. 299–301), or rather that the velum is intentionally raised higher during high oral vowels to prevent undesirable nasal coupling (Bell-Berti 1993, p. 69).

When the independent interactions of vowel length with both vowel height and nasality are taken into consideration, a different pattern emerges, wherein low vowels may be favoured for nasalization. First, whether in experimental findings (see Hajek and Maeda 2000 and Toivonen et al. 2015 for references), in notions of intrinsic length (e.g., Catford 1977, Gussenhoven 2007, Lehiste 1970, Maddieson 1997) or in phonological constructs like sonority-based markedness (de Lacy 2006), low vowels are the most prominent. Meanwhile, vowel nasality has both a diachronic (Hajek 1997) and synchronic affinity for longer vowels. Not only are contrastive nasal vowels on average longer than their oral counterparts in numerous languages (see Greenberg et al. 1978, Ruhlen 1975 for references), but also increased vowel duration aids perception of nasality (e.g., Lahiri and Marslen-Wilson 1991, Lintz and Sherman 1961, Whalen and Beddor 1989). Taken together, ample evidence exists for a competing parameter giving preference to low nasal vowels (Hajek and Maeda 2000).

2.3 Mechanical vs. Controlled Nasalization

Given the phonetic factors interacting with vowel nasality, not to mention the relative imprecision (Shelton et al. 1970) and slowness (e.g., Bell-Berti 1993) of the velum, the question naturally arises how to distinguish intentional (viz. controlled) and accidental (viz. mechanical) nasalization. This is especially the case in high vowels, which tend to be shorter, meaning imperfect alignment may occupy a more significant portion of a vowel already more nasalized with slighter effort.

To counter this, we employ three strategies: First, in the acoustic part of the study, intra-phoneme (as well as intra-speaker) normalization is performed. Oral and nasal energy values of pre-nasal tokens are effectively evaluated against those of tokens of the same vowel as a whole, including non-nasal settings. Second, we employ the insights of Solé (1992, 2007), which compares nasalization rates over speech rates (or duration as reflected by speech rate). Roughly speaking, she finds that the nasal phase of mechanically nasalized vowels in continental Spanish remains fairly constant in its duration as overall vowel duration increases; in other words, the nasalized percentage of the vowel decreases. Meanwhile, the opposite holds in American English: nasal phase duration increases with overall duration, its percentage remaining relatively constant. She argues the latter to be indicative of controlled nasalization. We expand this methodology to examine individual vowel qualities.

Finally, our bimethodological (nasometric+ultrasonic) approach allows us to examine the effect of tongue height according to the presence or absence of a following nasal consonant, again separately for individual vowel qualities. Intraoral gestures may either heighten the salience of nasal coupling or counteract it. Namely, French speakers use tongue body position to distinguish oral-nasal pairs; in particular, the tongue tends to be less advanced in [ã, ɛ̃, ɔ̃] and lower in the first two, in comparison with their oral counterparts (Carignan 2014 and references therein). These gestures, among others, serve to emphasize the effects nasal coupling has on their first two formants. Meanwhile, American English speakers raise the tongue body on pre-nasal /i/, which Carignan et al. (2011) argue serves to counteract F1-raising associated with nasal coupling of high vowels.

It is our hypothesis that if high vowels are highly nasal *only* at shorter durations, and thus likely mechanically nasalized, tongue body raising at shorter durations may serve to counteract both easily implemented and easily perceived nasal coupling. Meanwhile, if nasalization is indeed mechanical, we may expect neutral tongue body (no increase of salience) or lowered tongue body (increase of salience) on pre-nasal high vowels. As non-high vowels are likely to be less significantly nasalized, we make no particular predictions about the relationship between percent nasality and tongue body displacement, though again, some mitigation of nasal coupling may hold at shorter and/or more nasalized tokens (in which case both vowel height and anteriority must be taken into consideration).

3. Methodology

3.1 Experimental Set-up

Ten native speakers of QF (7 women, 3 men; age range 19 to 28, mean=23.3) were recruited to participate in the study. All speakers had at least begun university and grew up in the greater Montreal area. Given this profile of young, educated, metropolitan speakers, as well as the formal, laboratory setting of the experiment, we assume the variety represented here corresponds to a neutral, standard dialect of QF. Members of the research team possessing QF as their native language reported no peculiarities or important divergences in the participants' data. Finally, no participants reported any diagnosed language or auditory impairments, nor did any claim to be suffering of allergies or diseases affecting the nasal cavities at the time of recording. The current paper presents data from speakers 3, 4, 5, 6 and, in the case of the ultrasound results 7. (See §4.2 for an explanation.)

A reading list of French expressions was created for the first task of this experiment. Phonemic oral targets consisted of the 7 oral vowel categories of French, roughly corresponding to /a, e, ø, o, i, y, u/. Lax vowels were not differentiated because of syllabic constraints on their distribution; thus, a label such as /e/, for instance, may refer to [e] or [ɛ]. Abstracting away from the phonetic variation in contrastive nasal vowels in QF (see §2.1), nasal targets consisted of the 4 categories /ã/ (low), /ẽ/ (mid front unrounded), /õ/ (mid back rounded) and /ø̃/ (mid front rounded). These targets were placed into various contexts according to the phonotactic limitations of French, namely (a) oral vowels in non-nasal settings (_CV, _#, _C#), (b) oral vowels in nasal settings (_NV, _N#) and (c) nasal vowels in non-nasal settings (_CV, _#), where 'C'=a non-nasal consonant and '#'=a word boundary. Examples for each are provided in Table 1 for low vowels with orthographic and broad transcription for standard QF. The vowel and nasal consonant, where applicable, are bolded and

Table 1 Reading list structure, with low vowel examples.

Nasality	*Context*	*Expression*	*Translation*
Oral	_NV	des c**am**arades [de.k**a.m**a.ʁad]	'friends'
Oral	_N#	la f**emm**e pressée [la.f**am**.pʁe.se]	'the rushed woman'
Oral	_CV	ce par**a**dis perdu [sə.pa.ʁ**a**.d^{z}i.pɛʁ.d^{z}y]	'this lost paradise'
Oral	_#	des pap**a** poules [de.pa.p**a**.pʊl]	'father hens'
Oral	_C#	des vis**a**ges pâles [de.vi.z**a**ʒ.pã^{w}l]	'pale faces'
Nasal	_CV	la s**an**té publique [la.s**ã**.te.py.blɪk]	'public health'
Nasal	_#	des ag**ents** terribles [de.za.ʒ**ã**.te.ʁɪb]	'terrible agents'

underlined in both. Standard syllable boundaries are separated by a period in the phonetic transcription. The design included both simple and complex onsets in the adjective-initial syllable in _N# types; this was coded for separately but is not represented in the table.

This design yielded 56 target-context sequences per reading list. Each participant read this list in a randomized order 2 or 3 times (depending on time constraints) at a self-directed, normal speaking rate. An expanded list including words from the previous task was created for a second task. Participants were asked to read a randomized version this list first at a slower rate than usual, taking care to string together syllables. Participants then read the list, newly randomized, at a faster than usual, though still comprehensible, rate. Participants were asked to direct these paces themselves, and feedback was given when necessary.

An unfortunate effect of certain restrictions imposed on the creation of the stimuli (especially avoidance of low-frequency words and incomprehensible expressions) is that word length and flanking consonants could not be controlled. We do not anticipate an effect of word length in the variable-rate task, seeing as target syllables are either initial (in the open syllable condition) or final (closed syllables). These factors may be investigated and eliminated, if need be, in future work.

3.2 Data Acquisition

3.2.1 Ultrasound Tongue Imaging (UTI)

UTI data were registered for five (near) monolingual speakers of Montreal French using an MC4 convex ultrasound transducer with a 20 mm radius and the Articulate Assistant Advanced (*henceforth*, AAA) software package. The ultrasound probe was placed between the chin and neck/throat of each subject in order to produce a midsagittal image of the tongue surface. The probe was held in place using a custom-designed helmet. Subjects were asked to drink water for the initial task in order to approximate the hard palate, alveolar ridge and teeth. Baselines were established for the different vowels by asking the subjects to repeat the vowels in isolation (i.e., with no flanking consonants, which may motivate contextual effects).

To segment the data, sound files were uploaded to Praat and imported back into the AAA software package for spline segmentation, where an automatic tracking function was employed to trace the tongue contours. Tongue profiles were visually inspected and corrected by hand if warranted. In order to avoid effects of place of articulation of the surrounding consonants, only the stable centre (25% in from the left and right margins of the vowel) of the vowel was extracted. Forty-two polar x–y coordinates corresponding to the contours at different superimposed grid points were converted to cartesian coordinates and exported to a matrix for further processing.

3.2.2 Nasometry

Acoustic data were gathered with a pre-calibrated Glottal Enterprises NAS-1 SEP Clinic nasometer, a hand-held device which consists of two equally spaced microphones and one of three separator plates (small, medium or large). Each participant was matched with the best-fitting plate, according to the width of their upper lip. When the nasometer is held to the face, the separator plate enters into contact with the philtrum, blocking the signals between the nasal and oral microphones. Though the angle itself is not crucial, participants were instructed to hold the nasometer at an angle approximately 10 degrees from perpendicular, as suggested by the nasometer manual. Participants were instructed to avoid passing from one angle to another extreme. Recordings were performed in Praat at a sampling frequency of 44.1 kHz in stereo, where each channel corresponded to one of the microphones (i.e., nasal microphone=left channel, oral microphone=right).

3.3 Data annotation and Processing

3.3.1 Ultrasound Tongue Imaging (UTI)

After data for the forty-two x,y coordinates were exported from the AAA software package an extrapolation method called kriging was performed. Kriging was preferred over cubic or b-spline extrapolation in order to avoid kinking of the spline at the tongue root region, a common by-product of cubic or b-spline smoothing methods. An example of this kinking is illustrated with the vowel /ø/ from our data in Figure 1. Tongue tip position is on the right side of the image. Additionally, given certain assumptions on the priors, interpolative kriging has been shown to provide the best linear unbiased prediction of a curve given a sampling of points (Parthasarathy, Stone and Prince 2003).

For this study, we created our own Python implementation of the smoothing method presented in Parthasarathy, Stone and Prince (2003). The algorithm requires the choice of a covariance function as well as a model for the noise in the measured data. In our implementation of their algorithm we chose the same covariance function, $k(x_a, x_b)=||x_a-x_b||^2 \ln||x_a-x_b||^2$, used in Parthasarathy Stone and Prince (2003) for our data points. We also share their assumption that the noise in our measurements is white (and, to be clear, zero-mean) noise with a variance of 10 mm^2. The final function generated for each curve is the sum of a linear function of the covariance of any input x with an affine function of the same x. An example of the output of our kriging method for a vowel /a/ in the different pre-nasal and non-pre-nasal contexts is illustrated in Figure 2.

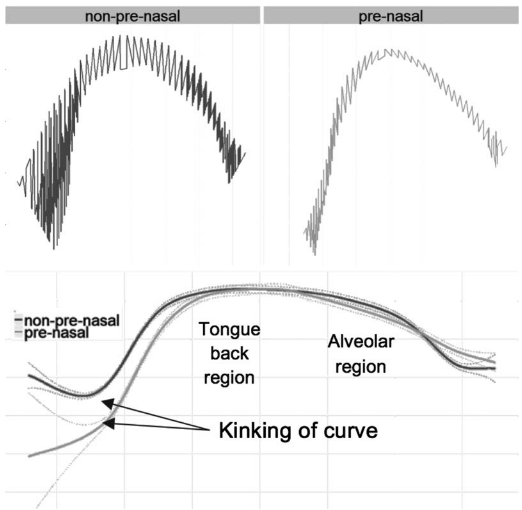

Figure 1 Raw data before smoothing (top panels) and a b-spline smoothing method (bottom panel) interpolating the raw data points, which caused the curve to kink at the tongue root region.

3.2.2 Nasometry

The nasometric recordings were automatically segmented by WebMAUS (Schiel 1999, Kisler et al. 2017) with standard French settings, and the resulting textgrids were manually inspected and corrected by two independent judges skilled in phonetic segmentation. Both the spectrogram and the stereo waveforms were consulted for this process. Vowel boundaries in prenasal settings were best determined by the presence vs. absence of periodic waves in the oral channel. The oral and nasal channels were then split, and energy readings of vowel targets were taken over intervals of 5 milliseconds within each channel. Vowel duration was also extracted.

Max-min normalization was applied to raw energy readings, again within channel, speaker and target. Finally, these readings were fed into the Differential Energy Ratio (DER) equation. This formula is similar to other ratio-based formulae such as nasalance (Fletcher 1976) or its precursor TONAR (Fletcher and Bishop 1970), with the added advantage that it may take into account rapid changes in energy differences (Dow 2016). The DER expresses vowel nasality as the ratio of predominantly nasal energy to total energy. First, differential energy is calculated at each point by subtracting nasal energy (y) from oral energy (x).

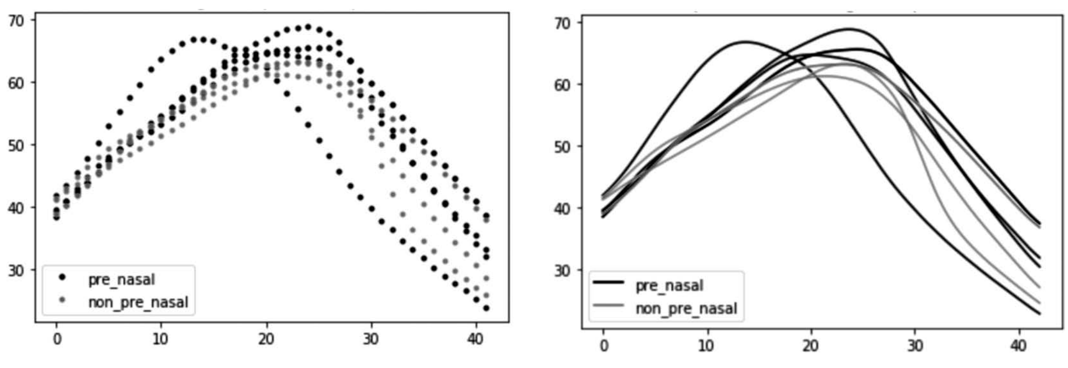

Figure 2 Plots of y data points as extracted to forty points along the x axis (left panel), vs. interpolation of points (right panel) using described kriging method, tongue tip position on the left.

$$DER = \frac{\mid \sum_i \min(x_i - y_i, 0) \mid}{\mid \sum_i \min(x_i - y_i, 0) \mid + \sum_i \max(x_i - y_i, 0)}$$

Figure 3 Differential Energy Ratio (DER). x_i, y_i**=oral and nasal energy, at a given point.**

An arbitrary threshold of nasality is set at zero, that is, where the two are equal. Positive values are considered thus predominantly oral, which are summed to provide the prominence of the oral phase. Meanwhile, the absolute value of the sum of negative values (therefore predominantly nasal) provides the prominence of the nasal phase. The ratio of the nasal phase energy to total energy, multiplied by 100, returns the DER, whose formula is provided in Figure 3.

3.3 Statistical Analysis

3.3.1 UTI: Functional Data ANOVA (FANOVA)

As there is no empirically tested and consensually agreed upon method in the literature to pool UTI data across speakers, we limit our analysis here to a by-speaker analysis of tongue height. For the by-speaker statistical analyses, forty-two x,y coordinates corresponding to the individual tongue curves were exported into a matrix and analyzed using a functional test of variance (henceforth FANOVA). FANOVA were preferred over other non-parametric methods used to make inferences regarding the effects of different categorical factors on the tongue curve, such as spline ANOVA(SSANOVA) due to the fact that FANOVA generates an F- ratio that can be used to derive an adjusted partial p-value calculated from permutation tests using the integrated Bartlett's test statistic $B^I_{D^k}$ (see Pini et al. (2019) for a full explanation of the algorithms). This facilitates the interpretation of significance for any given region of the tongue.

The model we used was an adapted version in Python of the multi-aspect local inference for functional data method outlined in Pini et al. (2019). Means were calculated for each of the forty-two x,y coordinates for the tongue contour for a specific vowel in one of two conditions: pre-nasal and non-pre-nasal. Thus, the functional inference method adopted here seeks a solution to a two-population test, whereby the model's objective is to make inferences on the regions of the tongue contour that serve to reject the null hypothesis that the tongue contours for the two test conditions belong to the same group.

For our model, three intervals corresponding to tongue front (TF), tongue mid (TM) and tongue back (TB) were defined. The TF interval (points 7–14 of the forty-two x,y coordinates for each contour) is defined for each subject as the interval just behind the teeth and ending right behind the alveolar ridge. The TM interval (points 8–21 of the forty-two x,y coordinations for each contour) is defined as the region between the alveolar ridge and soft palate. The TB region is delimited as the backmost part of the tongue region (points 22–28 of the forty-two x,y coordinates for each contour). For the latter interval (TB) samples of each speaker repeating [k] were used to approximate the tongue back region, since no physical landmark in the vocal tract was visible with which to define the region. These intervals were maintained for all speakers, though, due to placement of the ultrasound probe for two speakers, the order is reversed from left to right in the images since the ultrasound probe for two of the speakers was placed in the opposite direction[1]. An example of these intervals is illustrated in the following Figure 4. Tongue tip position is on the left side of the figure.

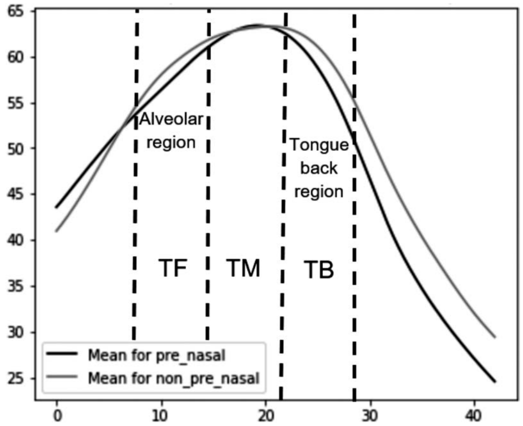

Figure 4 Means of interpolated curves for pre-nasal and non-pre-nasal contexts for /ø/. Dashed vertical lines delimit intervals dividing the tongue contour into tongue front (TF), tongue mid (TM) and tongue back (TB). The x axis represents the horizontal dimension along 42 equidistant points, while the y axis represents vertical position of the tongue in millimeters from the x coordinate.

For our analysis FANOVA were performed for a single factor 'context' with two levels: non-pre-nasal and pre-nasal. Within these two contexts (non-pre-nasal and pre-nasal), there were three different levels used to address more microscopic differences based phonetic context. However, for the current article only main effects for the pre-nasal/non-pre-nasal contexts

Table 2 Test statistics for each vowel and speaker. Adjusted partial *p*-values are given for the interval in which the tongue reached its maximum height, indicated in parentheses to the right[2)].

	Speaker 3	Speaker 4	Speaker 5	Speaker 6	Speaker 7
a	—	F(0.36), $p=0.60$ (TM), ns	F(1.82), $p=0.02$ (TM)*	F(0.80), $p=0.01$ (TM)**	—
e	F(4.39), $p=0.007$ (TM)*	F(4.02), $p<0.001$ ***	F(8.51), $p=0.03$ (TM)*	F(14.87), $p=0.02$ (TM)*	F(17.88), $p=0.05$ (TM)*
ø	F(8.73), $p=0.02$ (TM)*	F(1.60), $p=0.07$ (TM), ns	F(8.90), $p=0.02$ (TM)*	F(84.53), $p=0.03$ (TM)*	F(15.72), $p=0.06$ (TM), ns
o	F(4.57), $p=0.001$ (TB)***	F(37.42), $p<0.001$ (TB)***	F(28.16), $p=0.003$ (TB)*	F(62.31), $p=0.004$ (TB)**	F(13.37), $p=0.008$ (TB)**
u	F(58.44), $p=0.001$ (TB)***	F(6.59), $p=0.05$ (TB)*	F(58.90), $p=0.006$ (TB)**	F(11.79), $p=0.006$ (TB)**	F(1.04), $p=0.36$ (TB), ns
i	F(8.85), $p=0.01$ (TF)**	F(12.80), $p=0.04$ (TF)*	F(5.93), $p=0.04$ (TF)**	F(8.14), $p=0.04$ (TF)*	F(0.50), $p=0.05$ (TF)*
y	F(13.03), $p=0.03$ (TF)*	F(2.07), $p=0.007$ (TF)**	F(65.03), $p<0.001$ (TF)***	F(2.05), $p=0.06$ (TF), ns	F(15.79), $p=0.06$ (TF), ns

will be considered. Pair-wise comparisons of the different sub-levels will be addressed in future articles. The three levels are as follows: non-pre-nasal: V_#, V_C#, V_CV; pre-nasal: V_N#, V_NV, V_N#CL (where 'CL' =oral consonant+liquid sequence).

3.3.2 Acoustic Data: Statistical Models

To explore individual sub-systems, we performed linear regressions within individual speakers to determine nasality based on vowel duration and height, with an interaction between the two. Vowel height was used instead of individual targets due to an insufficient number of observations for certain targets. Given that speaker 4's low vowel behaved unlike that of the other speakers, and that the mid vowel category behaved more uniformly among speakers, the latter height was chosen as the reference level. Finally, as individual speakers' DER values were strongly negatively skewed, these readings were log-transformed for all speakers, with an added constant of 0.001, to avoid log(0).

4. Results

4.1 UTI: By-speaker FANOVA Analysis

In this section, we address the results of the UTI portion of the study addressing the relationship between tongue height in pre-nasal and non-pre-nasal contexts. We begin with the ground-level results for each speaker and then offer a maximum tongue height analysis for each speaker and vowel.

Speaker 3 showed significant effects for maximum tongue height between the pre-nasal and non-pre-nasal contexts for all vowels (as shown in Table 2), but the direction of the effects was not consistent. Maximum tongue height for pre-nasal vowels (as shown in Table 3) were only higher than their non-pre-nasal correlates for /o, u, y, i/. Results for the remaining vowels, /e, ø/ (/a/ was discarded for this speaker, as denoted by the '-' in Tables 2 and 3, due to a technical flaw during recording which is still being addressed), showed the opposite direction (i.e., maximum tongue height was higher in the non-pre-nasal context). Speaker 4 (see Table 2) showed similar results in that maximum tongue heights for /u/ and /y/ in the pre-nasal context were significantly higher than in the non-pre-nasal context (see Table 3). Additionally, /a/ in the pre-nasal context also showed higher tongue height maxima than in the non-pre-nasal context (see Table 3). For /u/, there is little difference in maximum tongue height between the pre-nasal and non-pre-nasal contexts, but results of the FANOVA (see Table 2) showed significant differences for the TB interval between the two contexts. For Speaker 5, maximum tongue height for the pre-nasal context was only (marginally) higher for the vowel /o/ (see Table 3), all other vowels showed the opposite direction. Results for Speaker 6 (see Table 3) show higher mean maximum tongue heights for vowels in the non-pre-nasal context than for pre-nasal vowels except for

Table 3 Mean maximum tongue height for each speaker (Sp), vowel and context (pre-nasal and non-pre-nasal).

	Pre-nasal							Non-pre-nasal						
Sp	a	e	ø	o	u	y	i	a	e	ø	o	u	y	i
3	—	67.58	67.0	75.33	81.42	73.13	63.83	—	72.43	72.88	74.30	77.84	67.88	63.14
4	61.70	63.60	62.14	69.31	71.48	72.15	66.47	60.50	65.28	69.64	71.71	71.33	65.08	71.91
5	65.80	63.18	64.32	64.93	60.73	63.65	67.50	66.50	64.58	66.01	64.34	64.84	63.94	69.03
6	74.57	72.77	75.20	74.86	80.82	77.79	75.60	76.74	73.41	75.75	76.83	82.15	73.98	76.99
7	—	56.49	67.33	61.02	75.80	66.09	67.11	—	70.76	66.48	75.67	74.46	71.29	75.67

/y/, which is significantly higher than in the non-pre-nasal context. The vowels /ø/ and /u/ (as with Speaker 3, /a/ was discarded for Speaker 7, as denoted by the '-d' in Tables 2 and 3, due to a technical flaw during recording which is still being addressed) for Speaker 7 were the only vowels where maximum tongue height was higher in the pre-nasal context (see Table 3), though the differences were not significant (see Table 2). These results are consistent with the pooled data analysis offered in the previous section.

Table 2 reports the results of the FANOVA analyses for each speaker, vowel and context for the interval in question. To recall, the tongue contours were divided into three regions corresponding to the tongue front (TF), tongue mid (TM) and tongue back (TB). The specific interval for which the test statistics were obtained appears in parentheses beside the adjusted partial *p*-value. For each speaker and vowel, the F-statistc along with the calculated adjusted partial *p*-value (with significance codes) are provided. Shading indicates a significant effect for which the pre-nasal context showed the higher mean maximum tongue height. Otherwise, if a significant effect obtains, the pre-nasal context showed the lower mean maximum tongue height, or a non-significant relation held.

Mean maximum tongue heights for each speaker, vowel and context are provided in Table 3. Figure 5 plots the means for maximum tongue height for each speaker and vowel.

To summarize our results, only speakers 3 and 4 showed significant tongue height raising in pre-nasal contexts (with the exception of /i/ for speaker 4). Otherwise, tongue height was either insignificant between contexts or was generally lower in pre-nasal contexts, regardless of vowel height. We synthesize these results with the nasometric results presented in the next section.

4.2 Nasometric Results

An initial examination of oral vowels in non-nasal settings suggested error in the handling of the nasometer in the second task of speaker 7. Specifically, the oral vowels from her slower reading task were near ceiling-rate in nasality. A visual examination of her recordings confirmed that the oral and nasal channels in this task are technically different but near-identical, whereas the two should normally be quite distinct. This is highly suggestive of insufficient contact between the nasometer plate and her upper lip. Since it could not be determined with certitude at which point this error was introduced, this speaker's data are excluded from all nasometric results. They are still present in the ultrasound results, as these data are not affected by this error. All in all, 1,027 vowels from speakers 3, 4, 5 and 6 are analyzed here.

4.2.1 Group Results

Contrastive nasal vowels for all speakers range from 74.77% nasal in the case of /ã/ to 95.52% in the case of /õ/, while non-high oral vowels in non-nasal contexts demonstrate average DER values no higher than 1.7%, in the case of /ø/. High vowels have comparatively slightly elevated DER averages at 4.07%, 8.65% and 10.26% for /u, y, i/, respectively. A closer investigation of these vowels by context show higher averages in absolute word-final position (/i/=24.57%, /y/=33.94%, /u/=11.13%), versus these same vowels in final syllables closed by voiced fricatives and sonorants, with a maximum nasality of 0.52% for /u/. While the latter context is not favourable to high vowel lenition in QF, the former is (Cedergren and Simoneau 1985), with a scale going in the same direction, that is, /u/ lenition being more common than that of /i/, which is in turn more common than that of /y/ (Gendron 1966). Pre-nasal position is not favourable to high vowel lenition (other than potential laxing) in these same studies. Anecdotally, high vowel devoicing was fairly common in

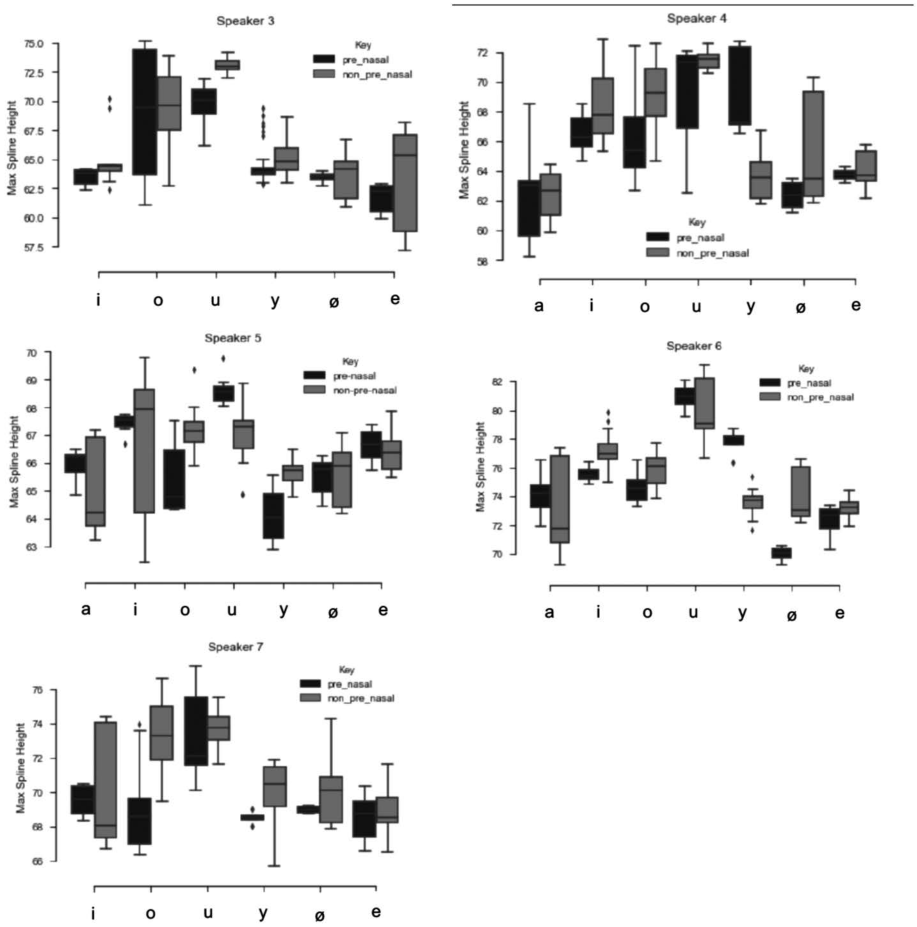

Figure 5　Boxplots for maximum spline height (y axis) of individual vowels (x axis) by speaker.

the data, especially in the word-final vowel /u/ of *époux* 'husband', due to the preceding voiceless stop. The failure of nasometry to account for voiceless segments is well known (e.g., Audibert and Amelot 2011). As the uncharacteristically low oral energy of such segments sometimes dips beneath that of their also low nasal energy, falsely nasal values are fed into ratio-based formulae. Pre-nasal high vowels do not follow this profile; rather, they show typical to slightly diminished rates of oral energy and high rates of nasal energy. The high DER averages of certain oral /i, u/ vowels in the controls do not thus invalidate their high readings in pre-nasal settings. In the future, devoiced vowels may be identified and discarded, and stimuli must avoid voiceless onsets before high vowels.

Meanwhile, the group-level acoustic data for pre-nasal vowels show predictably higher rates of nasality. The low vowel /a/ is on average 44.67% nasal, and in the mid vowels, /e, ø, o/ are 65.83%, 43.9% and 63.56% nasal, respectively. Finally, the high vowels /i, y, u/ are on average 70.42%, 72.38% and 54.73% nasal, respectively.

4.2.2　Individual Results

An initial investigation into inter-speaker reveals a high degree of variation with respect to individual vowels' nasality. Table 4 presents the mean and standard deviation of nasality of pre-nasal vowels by speaker.

The vowels /a, e, ø/ present particularly large ranges, and speakers 4 and 5 are generally have higher rates of nasality than 3 and 6. The intra-speaker and intra-phoneme variance evidenced from the standard deviation numbers can be explained in part by vowel duration. Figure 6 plots, for each individual vowel, nasality (x-axis) vs. duration (y-axis), with colour differentiating speakers. Coloured lines (also differentiated by line-type) indicate the linear smoothed conditional means of

Table 4 Mean nasality in DER (‘*M*’) and standard deviation (‘*sd*’) of pre-nasal vowels by speaker.

	/a/		/e/		/ø/		/o/		/i/		/y/		/u/	
	M	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*	*M*	*sd*
3	12.77	7.9	47.26	38.26	13.25	13.66	61.19	28.31	69.12	37.99	63.68	40.94	48.99	39.71
4	76.37	32.49	79.33	30.18	68.48	35.58	76.57	31.76	78.93	30.82	66.5	39	42.84	37.89
5	56.22	35.39	92.39	17.89	45.31	35.99	62.99	36.72	84.53	27.4	83.85	32.18	73.84	29.94
6	25.25	30.83	5.86	5.32	47.24	44.1	47.65	28.47	40.47	37.72	77.33	31.5	54.93	40.44

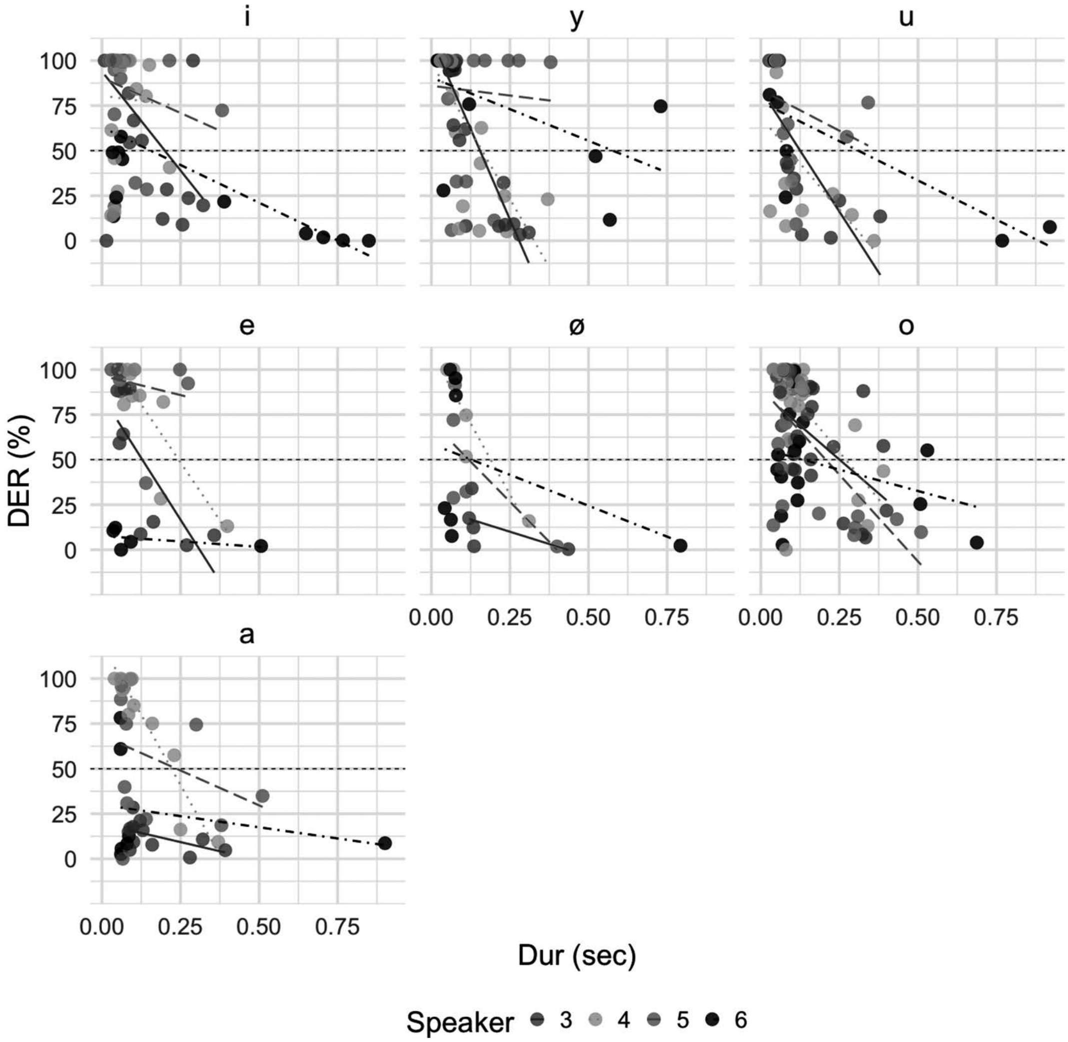

Figure 6 Nasality of pre-nasal vowels vs. their duration.

that set of observations. A dashed black line indicates 50% nasality.

Many vowels for many speakers tend to be low in nasality at their longer realizations, whether they are highly nasal at their shortest durations or low in nasality to start with. Cases in which speakers appear to agree in the end are /a, ø/. Such is the case also for vowel /e/ for all speakers but speaker 5. The vowel /o/ presents a greater degree of variation and a greater concentration of highly nasal vowels at shorter durations. Meanwhile, among high vowels, speakers 4 and 5 appear to maintain /i/-nasalization and, more arguably, /y/-nasalization as well. The data suggest nasalization of /u/ only in speaker 5's data. The above data, however, must be taken with a grain of salt, as extremely long vowels are relatively few in number and may as such unduly bias visual inspection of the results. For this reason, we turn to individual speaker height regressions.

No height category proved statistically significant in nasality for speaker 3, nor was the interaction between duration and any height category significant. Duration as a main predictor did have a significant effect of reducing nasality ($p<0.01$). The overall model was significant ($F(5,103)=5.92$, $p<0.001$) with a fit of $R^2=0.22$. Speaker 4's regression found no significant effects, whether main or interaction. The overall model was significant ($F(5,105)=5.42$, $p<0.001$) with a fit of $R^2=0.21$. Like speaker 3, speaker 5's model found duration as a main effect to significantly lower nasality ($p<0.001$). Low vowels were found as significantly less nasal than the mid reference level ($p<0.001$), but not high vowels ($p=0.33$). Duration had a positive, significant effect on the nasality of high vowels ($p<0.05$), and curiously enough, on that of low vowels as well ($p<0.01$). The overall model was significant ($F(5,104)=4.72$, $p<0.001$) with a fit of $R^2=0.18$. Finally, in speaker 6's model, high vowels' nasality was significantly higher than that of mid vowels ($p<0.05$) but fell significantly with duration ($p<0.05$). No other significant effects were found. The overall model was significant ($F(5,63)=6.27$, $p<0.001$) with a fit of $R^2=0.33$.

These models, like the descriptive statistics above, must be taken with caution. Even within speakers, height groups do not always behave homogenously. Additionally, even within height groups, token numbers are still not very robust, and though the models are all significant, they do not explain much of the variation present in each individual.

5. Discussion

In this section, we synthesize the individual results from the two instruments used in the experiment, namely UTI (ultrasound) and nasometric. We then offer an interpretation of these results. Before we begin, though, we must remind the reader of how we establish nasalization as controlled, as well as how we envisage the communication of our two instruments' results.

5.1 Preliminaries

Nasalization on a pre-nasal vowel, whether mechanical or controlled, cannot be established by the UTI evidence alone. However, an isolated effect of tongue height difference (between contexts) can be inferred from this evidence. That is, we acknowledge significant tongue raising in a given context as having an effect of lowering that vowel's F1, and vice-versa (i.e., tongue lowering raises F1). We say 'an isolated effect' explicitly for the reason that other, unmeasured articulators may additionally manipulate the F1. As such, these effects are merely hypothesized and must later be compared against formant measurements. In addition, though only the stable centre of vowels were measured in the ultrasound data, flanking consonants were not controlled for in the stimuli. As such, longer-distance effects of consonant-vowel coarticulation cannot be entirely rejected, though enough variety is present in all types of conditions that we do not anticipate undue influence to have occurred in any one environment.

The interpretation of these hypothesized formant changes depends, for one, on vowel height. The reader is reminded that nasal coupling centralizes F1 along the height dimension; that is, the F1 of high nasalized vowels is (all things being equal) raised, effectively lowering it in the vowel space, while that of low, and arguably mid, is lowered, raising it in the vowel space. Generally speaking, articulatory effects may either go in the same or the opposite direction as the height-specific effects of nasal coupling. These are the following: tongue raising of high nasalized vowels goes against the effects of nasal coupling, while tongue lowering goes in the same direction. Inversely, tongue raising of low and mid vowels goes in the same direction as nasal coupling, while tongue lowering goes in the opposite direction. We will abstract away from this difference to call any relationship going in the same sense as *unidirectional* and that going in the opposite sense as *bidirectional*.

The interpretation of the synthesized results depends equally on the nasometric results. As we have seen, there is evidence for truly nasalized (controlled) vowels, 'covertly' oral vowels (i.e., mechanically nasalized) and truly oral vowels. A unidirectional relationship of truly nasal vowels is the clearest case: we propose here that speakers are increasing the nasal salience of these vowels. In the case of mechanical nasalization, an overall unidirectional relationship is inconclusive. We would expect this effect to interact with the nasality-duration cline, and we can only speculate that additional intraoral gestures would conspire to avoid

Table 5 Interpretation of UTI results according to nasometric results, with reference to specific height effects. 'H'=high vowels, 'L'=low, 'M'=mid. 'T' refers to the relevant area of the tongue.

Direction	Nasalization	Interpretation
Unidirectional **H**: T raising; **L**, **M**: T lowering	Controlled Mechanical Absent	Increase of nasal salience Inconclusive Independent effects
Bidirectional **H**: T lowering; **L**, **M**: T raising	Controlled Mechanical Absent	Height adjustment Negation of nasal salience / height adjustment Independent effects

an increase in nasal salience of such vowels. Finally, any effects (unidirectional or bidirectional) of vowels which are never contextually nasalized are predicted to be independent of nasality (e.g., V–C transition).

Bidirectional effects are generally trickier. When the nasometric results suggests that such vowels are still truly nasal, it would be hazardous to claim speakers are intentionally nasalizing on one hand while actively negating those same effects at the same time. Rather, following Carignan et al. (2011), we interpret these cases as a restitution of height percepts. Another, not necessarily competing explanation is that when the vowels in question have contrastive nasal counterparts in French, speakers are implementing a covert contrast, that is, avoiding conflation of underlying and derived vowel nasality. We leave this question for future research. Finally, mechanically nasalized vowels showing bidirectional effects are potential candidates for negation of undesirable nasality, especially at faster rates, though again, the durational aspect must be considered first. Table 5 summarizes these interpretations, with specific reference to tongue height in pre-nasal contexts for each height category.

Finally, the absence of an effect may also be informative. We interpret such cases, when nasalization is either controlled or mechanical, as an acceptance on the speakers' part of nasal coupling and/or height height, or perhaps even a lack of consciousness thereof, especially in the cases of vowel heights on which nasality is more difficult to perceive. The absence of effect in truly non-nasalized vowels simply confirms speakers' avoidance of coarticulation.

5.2 Individual-level Analysis

In our synthesis of individual speakers' results, we refer to the FANOVA predictions from §4.1.1 for the articulatory side and a combination of the vowel-specific, descriptive statistics from the nasometric results as well as the more general, height-based predictions of the individual regressions presented in §4.2.2.

No controlled nasalization was predicted for speaker 3. In her descriptive results, /a, ø/ appear almost entirely oral, while the other vowels appear mechanically nasalized. In all other instances (except for /o/) in her UTI results, effects are significant and unidirectional, and are thus inconclusive according to the discussion at the beginning of this section. Only in the case of /o/ does her pre-nasal tongue raising go in the same direction as the effects of nasal coupling. The fact that her model does not predict mid-vowel nasalization is likely an unfortunate consequence of its generalization to height categories. As such, we cannot offer any clear analysis, save for the possibility that /o/-nasalization is active and emphasized in her speech.

Speaker 4 also showed insignificant effects of height and its interaction with duration, and in his descriptive results, all vowels showed signs of decreasing steeply in nasality over time, with the possible exception of /i/, though with his UTI results considered, this speaker has a bidirectional effect on this vowel. The vowels /e, o, u/ also show bidirectional effects, as well as being more likely mechanically nasalized; they may thus attest height readjustment or mitigation of nasal coupling. Finally, /y/ shows a unidirectional effect, despite appearing merely mechanically nasalized, and as such, cannot currently be accounted for.

Speaker 5 provides an interesting case study. Her low vowel was the only to show a positive, significant interaction with duration, though it was also identified as significantly less nasal than mid vowels. This speaker also showed significant tongue lowering of this vowel before nasal consonants, thus a bidirectional effect. All in all, this appears to be a candidate for the use of tongue position to negate nasalization itself; whereas otherwise we are more staunchly agnostic to the difference between this sort of analysis and the 'height restitution' analysis. As for her high vowels, duration had a positive, significant effect, and the speaker showed significant unidirectional effects on all three of these vowels. In terms of the mid vowels, /o/ showed

Table 6 Intuited relationship between UTI effects and nasometric effects, by speaker and vowel.

Type	Tokens
Increase in nasal salience	3 /o/; 5 /i, y, u/
Height adjustment	4 /i/; 5 /e/
Negation of nasal salience or height adjustment	3 /ø/; 4 /e, o, u/; 5 /a, ø/; 6 /y, u/
Inconclusive	3 /e, i, y, u/; 4 /y/; 5 /o/
Independent effects	6 /a, e, ø, o/

unidirectional effects, while /e, ø/ showed bidirectional effects. Descriptively speaking, only /e/ is a clear candidate for controlled nasalization; her tongue lowering on this vowel before nasal consonants may thus be to avoid confusion with her also nasalized /i/, as with the group. The vowel /ø/'s being mechanical with bidirectional effects again falls into the analysis of undoing differences of height and/or nasal coupling, while /o/ is inconclusive (mechanical but unidirectional).

Finally (as we cannot synthesize speaker 7's results), speaker 6 showed significant effects of nasality on high vowels but also a significant decline of her nasality, at least in comparison with mid vowels. These same vowels were either equal in tongue height between contexts (in the case of /i/) or showed bidirectional effects (in the case of /y, u/). We interpret this as a lack of controlled nasalization on such vowels. No other significant effects were found in her model, though quite curiously, unidirectional effects were found for all other vowels. On some of these vowels, nasality appeared absent even at the shortest durations. This speaker thus may have either hyperarticulated her speech, or perhaps the noted effects in the UTI results are due to independent factors not present in other speakers' data.

Table 6 summarizes this discussion by dividing speakers' individual vowels into the same 5 categories as in Table 5. For clarification 'height adjustment' refers to vowels likely controlled for nasalization but showing bidirectional effects, while 'negation of nasal salience or height adjustment' refers to mechanically nasalized vowels showing bidirectional effects. Speaker 3's /a/, speaker 4's /ø/ and speaker 6's /i/ are excluded, as no significant UTI effects were found on these vowels.

6. Conclusion

In this paper, we used ultrasound and nasometric instruments to probe regressive nasalization of individual vowel qualities in Québec French as spoken in Montreal. In the ultrasound data, we looked at tongue curves and maximum height values according to the nasality of the following context. These results informed us of whether speakers may be altering acoustic outputs either in the same or the opposite direction as that of nasal coupling, with respect to F1. In the nasometric data, we considered the relationship between nasality (as a ratio-based formula) and overall duration. This comparison informs us of whether higher rates of nasality at faster speech rates are intentional (controlled) or merely due to coarticulation (mechanical).

Ultimately, we find relatively high rates of idiosyncrasies when the ultrasound data are paired with the nasometric data. Despite the high degree of nasalization exhibited on high front vowels for the group as a whole (as predicted), only speaker 5 can be convincingly argued to increase the nasal salience of these vowels as well as of /u/. Other speakers' results are either inconclusive or potentially argue for the opposite (i.e., decrease in nasal salience).

Given that few other studies on nasal coarticulation employ multiple instrument types, even fewer (if not none) addressing the present paper's main question (that is, can we identify controlled nasalization without a vowel height confound?), we do not find this variation surprising. Even further, we recognize the need for additional measurements of both types before a satisfying synthesis can be reached. Namely, as previously discussed, tongue anteriority and pharyngeal constriction are two articulatory measurements known to be manipulated in reaction to nasal coupling. On the acoustic side, formant measurements may be important, especially in determining causal relationships within subsystems. For instance, to know if a certain nasalized vowel is raised or lowered to avoid potential confusion with another nasalized vowel, it is likely of importance to know their acoustic properties. This paper lays the foundation for this future work, showing that at least for some speakers of QF, high vowel nasalization may be a controlled property of the language.

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Notes

1) The fact that the ultrasound probe was placed in an opposite direction for some speakers does not affect the results. Results were computed by speaker. The software package AAA includes a function to automatically shift the direction of the images for this very reason. However, as results were obtained for each speaker separately, there was no methodological need that warranted the shifting of direction of the ultrasound imaging. It is for this reason that the interval regions in Figures 1, 2 and 4 are not uniform. Images for these figures were chosen due to esthetic reasons.

2) The astute reader will notice that there are significant effects in Table 4 in a given interval where there is very little difference in maximum tongue height, as illustrated in Table 5. This is due to the fact that the statistical model bases differences on both the vertical and horizontal position of the tongue contours, whereas the maximum height measure only addresses tongue height in the y dimension. Thus, there can be significant differences between contours on the x (horizontal) dimension without there being a difference in tongue height on the vertical dimension (y).

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