WHEN NASAL IS MORE THAN NASAL: THE ORAL ARTICULATION OF NASAL VOWELS IN TWO DIALECTS OF FRENCH

BY

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Abstract

I present the results of an articulatory (EMA and aerodynamic) and acoustic study of the realizations of three oral and nasal vowel pairs /a/-/ɑ̃/, /ɛ/-/ɛ̃/, and /o/-/ɔ̃/ recorded from 11 Northern Metropolitan French (NMF) and two Quebecois French (QF) female speakers in laboratory settings. Using simultaneous acoustic and articulatory information related to the lingual and labial articulations, I investigated how the oral/nasal vowel distinction is manifested with regard to differences in lingual and labial articulatory configuration, for each of these vowel pairs and in both of these respective dialects. Based on previous research, I expected to find evidence that all nasal vowels are produced with at least some change in lingual and labial articulatory configuration compared to their oral vowel counterparts in both dialects. By studying the position and movement of the tongue and lips during the production of target oral and nasal vowels and simultaneously recording the acoustic signal, I was able to separate the effects of velo-pharyngeal coupling and oral articulatory configuration on the acoustic output of the vocal tract. I find that in both dialects, all three nasal vowels are produced with some degree of modification of the oral articulators in comparison with their oral counterparts.

With regard to the NMF dialect: for [ɛ]-[ɛ̃], in addition to velo-pharyngeal coupling, the acoustic distinction was most likely due to changes in tongue body position, with the tongue lowered and more retracted for [ɛ̃] than for [ɛ]. For [a]-[ɑ̃], in addition to velo-pharyngeal coupling, the acoustic distinction was most likely due to a combination of lingual and labial articulations, with consistent labial articulatory differences between the two vowels, as /ɑ̃/ was produced with more lip rounding and/or protrusion than /a/ across speakers. For [o]-[ɔ̃], much inter-speaker articulatory variability, but relatively little inter-speaker acoustic variability, was observed. In general, the speakers use either primarily lingual position, or a combination of lingual position and lip rounding and/or protrusion to maintain oral articulatory differences between [o] and [ɔ̃]. The articulatory and acoustic analyses suggest that, in addition to velo-pharyngeal opening, NMF speakers may employ a combination of lingual, labial, and/or passive oral articulations (i.e., "velic" constriction due to lowering the velum) in order to reach the acoustic target for [ɔ̃]. Furthermore, patterns of F1 are somewhat contradictory, as an equal N of speakers show either no difference or higher F1 for [ɔ̃]. However, the most common pattern is a lower F1 for [ɔ̃] compared to [o] (seven of 11 speakers). Similarly, nine of 11 speakers' renditions of the target words indicate a lower F2 for [ɔ̃] compared to [o]. I found evidence of a counter-clockwise chain shift in the realizations of the three nasal vowels. However, I found evidence that the oral articulatory contributions

to this chain shift are different for the three vowels: for [ɛ̃], it is due primarily to a lower, retracted tongue position; for [ɑ̃] it is due primarily to tongue retraction and lip rounding; and for [ɔ̃], it is due primarily to a speaker-specific combination of tongue retraction and/or lip rounding. With regard to the QF dialect, I observed a lingual diphthong production of [ɛ̃] and a labial diphthong production of [ɔ̃], and I found evidence pointing to the existence of a nasal coda in the realization of [ɛ̃]. I did not find strong indications of a clockwise chain shift in the realizations of the three nasal vowels as produced by the two QF speakers in this study.

Inter-speaker variation in oral articulation and the dispersion of the NMF vowels in the acoustic space suggests variable but acoustically equivalent speaker strategies in the production of nasal vowels in NMF that I propose to interpret in terms of motor equivalence. Specifically, the results suggest that a similar acoustic dispersion is maintained across speakers within a given dialect, although speakers may use different lingual and labial configurations—in conjunction with velo-pharyngeal coupling—in order to achieve a particular acoustic goal. This inter-speaker variation may help explain partially contradictory findings observed across previous studies: various studies have observed different results with regard to tongue position for [ɑ̃] compared to [a] and for [ɔ̃] compared to [o]; I propose that these differences are due to inter-speaker variation with regard to how these nasal vowels are articulated, rather than due to differences in methodology between these studies. An important finding from the articulatory results of this study is that, in general, the oral articulatory differences for the nasal vowels in NMF compared to their oral counterparts are predicted to result in modifications to the frequencies of both F1 and F2 which are also predicted to result from velo-pharyngeal coupling (i.e., centralization of the vowel space along the F1 dimension and lowering of F2 for non-back vowels). In light of these results, I propose that the oral articulations of the nasal vowels in NMF might have evolved over time to enhance and reinforce the formant-frequency-related acoustic effects of nasalization. Although I do not observe this same pattern for the realizations of the nasal vowels in QF, I suggest that dynamic oral articulations and nasal coda production contribute to the distinctive nasality of the nasal vowels in the dialect instead. Moreover, with regard to NMF, I posit that the F1-lowering due to velo-pharyngeal coupling was likely a catalyst for the onset of a push chain shift in the realization of the nasal vowels, a nasal vowel shift that should be regarded as a continually evolving phenomenon, given the realizations observed in this study. Specifically, I observe that /ɛ̃/ is realized as [ɐ̃], that /ɑ̃/ is realized as [ɔ̞̃], and that /ɔ̃/ is realized as [õ̝]. Given the discrepancies between the traditional IPA transcriptions used for these three vowels and the realizations observed here, I offer the transcriptions [ɐ̃]-[ɔ̞̃]-[õ̝] as possible revisions to the IPA transcriptions used for the respective nasal vowels in NMF.

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Introduction

Chapter 1

Sound representation and the language of study

1.1 Speech sounds: Articulatory or acoustic goal?

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 the source of these sounds. Spoken human language cannot exist without speech articulation. But are articulatory gestures themselves the goal of speech utterances? In other words, does a speaker articulate a sound with the goal of her interlocutor perceiving the articulatory source itself? On the one hand, there are 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 and Mattingly, 1985)) or via direct perception ("direct realist" theory of speech perception (Fowler, 1986, 1989, 1990, 1991)). On the other hand, there is evidence that articulations co-vary because their acoustic effects enhance one another (Diehl and Kluender, 1989; Diehl and Walsh, 1989; Kluender et al., 1988) or are integrated components of a single perceptual object[1](Diehl et al., 1991b; Kingston et al., 1990; Kingston, 1991, 1992; Ohala, 1996).

Arguments for the former view (i.e., that representations of speech sounds and objects of speech perception are articulatory) include the claim that speech—like other evolutionary advantages—depends on biological capacities which have evolved to respond to real-world phenomena which are significant to the organism and its survival. Specific to humans and speech, these phenomena are the phonetic units of speech, the primitives of which are the articulations of the speech organs themselves. As Liberman (1993) puts it, these articulatory gestures are "the ultimate constituents of language." Arguments for the latter view (i.e., that representations of speech sounds and objects of speech perception are acoustic) include evidence suggesting that speakers can maintain the integrity of an acoustic signal even in the face of articulatory perturbation (Abbs and Gracco, 1984; Lindblom et al., 1979; Löfqvist, 1990) and that speakers sometimes employ one articulatory strategy in order to compensate for the acoustic effect of another in natural language

[1] A "perceptual object" is to be understood here as anything that we attend to when we perceive an object or an event. For example, with regard to seeing a coffee cup, the perceptual object could be considered to be the cup itself, or it could be considered to be the light which is reflected off the cup and enters through one's pupil. In a similar fashion, with regard to hearing a speech sound, the perceptual object could be considered to be the speech articulators themselves (i.e., the object of speech perception is articulatory), or it could considered to be the acoustic output of the articulors (i.e., the object of speech perception is auditory/acoustic).

(Arai, 2004; Carignan et al., 2011). The results which will be presented in the current study provide strong support for the view that the goal of speech acts is acoustic, not articulatory. Specifically, I will present evidence which suggests that speakers of French use idiosyncratic articulatory strategies in order to reach a distinctive acoustic goal, and that the oral articulations of nasal vowels might have, in some cases, evolved in order to reinforce the acoustic effects of nasalization itself.

1.2 Northern Metropolitan French and Quebecois French

According to France's Ministère des Affaires Étrangères (2013), French is an official language in 29 countries, second only to English in this respect. It is ranked the sixth most widely spoken language in the world, the second most widely spoken language in Europe, and it is estimated that there are over 148 million people in the world who speak French fluently and use it on a daily basis. The French language has played an important role in world history as an international vehicular language, and is still a *lingua franca* in many parts of the world. It has been considered a language of prestige and learnedness, and it remains one of the most popular choices for second language learners, world-wide. With such a widespread and considerable international and historic presence, it is no wonder that French has been a popular subject of linguistic study for many decades. However, it is because of its widespread presence and dialectal differentiation that "French" comes in many different varieties. It is important to differentiate the French spoken in France, from that spoken in Switzerland, from that spoken in Algeria, from that spoken in Canada, etc. When studying linguistic phenomena in the French language, one must first specify which variety or varieties of French are the focus of study. In this dissertation thesis, I will focus on the acoustics and oral articulation of nasal vowels in two geographically and phonetically distinct dialects of French: *Northern Metropolitan French* (henceforth, NMF) and *Quebecois French* (henceforth, QF).

1.2.1 Historical developments and separation

French is a Romance language, meaning that its linguistic roots can be traced back to Latin. Knowledge of the diachronic path from Latin to modern French is crucial to understanding the formation of nasal vowels in French as well as how they are articulated, as I will illustrate in this study.

Gaul, part of the Roman Empire under provincial rule for more than 500 years, consisted of an area now occupied by modern-day France, Belgium, Luxembourg, western Switzerland, and western Germany. After the fall of the Roman Empire, the Germanic-speaking Franks conquered the majority of this area in the 5th and 6th centuries[2]. The

[2] It should be emphasized that the Franks were just one of several Germanic tribes moving into the territory of Gaul. The Burgundians settled in what is now the Franco-Provençal area, and the Visigoths, in part of the Languedoc region. However, the influence of these other Germanic varieties on the Romance language spoken in those regions is still a matter of considerable debate.

Franks settled mainly north of the Loire River, leading to cultural and linguistic influences in northern Gaul. In southern Gaul, however, the Frankish presence was relatively minor compared to the north, and pre-existing cultural and linguistic Roman influence therefore remained in the south (James, 1982; Sampson, 1999). This northern–southern separation led to a linguistic isogloss, with the recognition of the dialects in the north as one main linguistic subgroup, and those in the south as another. In the north, the dialects of the more innovative linguistic variety of Gallo-Romance during this time period are known as *langue d'oïl*, while the dialects of the more conservative linguistic variety of the south are known as *langue d'oc* (named after the two forms for the word *oui* 'yes', *oïl* and *oc*, in their respective northern and southern linguistic varieties). This geographic, political, cultural, and—most importantly—linguistic division led to a difference in the formation and evolution of the nasal vowel systems in language varieties of these two areas.

In the 13th century, the south was conquered by the north during the Albigensian Crusade, which gave way to a loss of the political division between the two regions. The arising centralized influence of the Paris-based monarchy in the north brought with it the linguistic influence of their *langue d'oïl* dialect, *Francien*. This northern dialect slowly, but surely, became the linguistic standard for both the *langue d'oïl* and *langue d'oc* regions. The French settlers who came to various parts of Quebec in the 17th century were mainly from the northern/north-western provinces of France. Following Morin (2002, p. 41), three of these stand out in particular: "Poitou-Aunis-Saintonge (31,5% des pionniers ['pioneers']), Normandie-Perche (24,9%) et Île-de-France-Beauce-Brie (20,1%)." Although other sources identify a larger dialect area, comprising Brittany, Anjou, Vendée, and the Loire Valley (Ball, 1997, p. 108), there is a general agreement that the immediate surroundings of Paris have provided a lot of settlers, and that all provinces were part of the *langue d'oïl* dialect region. Thus, being from the northern, north-western dialect areas of present-day France, these settlers—in all likelihood—brought with them a wide-spread regional spoken standard (or *koiné*) that had shared roots with NMF in modern-day France (Gendron, 2007, p. 3–36). As Morin (2002, p. 42) argues[3],

> "*[...] cette [Quebecois French] prononciation dérive essentiellement des usages parisiens—plutôt populaires—à laquelle se sont néanmoins superposées des particularitéés issues d'usages d'autres régions.*"

> '[...] this [Quebecois French] pronunciation stems essentially from Parisian varieties—popular ones, for the most part—to which, nevertheless, characteristics stemming from other regional varieties were added.' (*my translation*)

[3] Following Gendron (2007) and Morin (2002), it should be noted that NMF/QF contact history seems to have had two distinct phases:

1. Between the end of the 17th century and the French Revolution, when none of the multiple travelers to French Canada (current Quebec) reported that QF pronunciation was different from everyday spoken French of Île-de-France.
2. Between the Revolution and the first half of the 19th century, when NMF (and not QF) diverged from the old, wide-spread regional pronunciation patterns that continued in Quebec.

According to Sampson (1999, pp/. 83–84) (and discussed in further detail in 8.3), the nasal vowel system at this time was most likely reduced to four phonemic nasal vowels, with the following phonetic qualities: [ɛ̃], [ỹ] (which was most likely transitioning to a lower realization of high-mid [ø̃]), [ɑ̃] (or possibly a more fronted [ã], for some speakers), and a range of realizations for [õ]-[ɔ̃]. Abbé de Dangeau, in his review of French at the end of the 17th century, claims the existence (or, perhaps, the *re-emergence*, as the case may be; see 8.3) of a fifth nasal vowel: the high front [ĩ]. However, Sampson (1999, p. 82) contends that this high front nasal vowel was confined to the prefix *in-*/*im-* found in learned words, based on the following commentary on this vowel by Abbé de Dangeau:

> "*La troisième voyelle sourde, qui est* in*, s'exprime par* in*; mais dans notre langue, nous n'avons ce son de* in *que dans le commencement des mots, comme dans* ingrat, infidèle*: par-tout ailleurs les lettres* in *ont le son de* en*, seconde voyelle sourde, comme je viens de le dire.*" (de Dangeau, 1694)

> 'The third "dull" vowel, *in*, is expressed by [the letters] *in*; but in our language, we only have this sound *in* at the beginning of words, as in *ingrat*, *infidèle*: in every other case the letters *in* have the sound *en*, the second "dull" vowel, as I have just noted.' (*my translation*)

Cosériu (1994, p. 15) finds similar evidence for this fifth vowel, [ĩ], in writings by de Regnier-Desmarais (*Grammaire*, 1706), de Buffier (*Grammaire française*, 1709) and—to a certain extent, and with reservation—de Restaut (*Principes*, 1730). However, he contends as well that the existence of this fifth vowel is certainly disputed and that, at any rate, it was widely recognized that the nasal vowel system of French very likely only contained four vowels from 1730 onward.

In the end, it is most reasonable to assume that this system of four phonemic nasal vowels (i.e., [ɛ̃], [ø̃], [ɑ̃], [õ]/[ɔ̃]) was produced by settlers from the *langue d'oïl* region of France who came to Quebec in the 17th century. We will see in the following section how this now 400-year-old nasal vowel system has since evolved into two distinctive manifestations during the time period which has followed this geographic separation; we will also observe how this distinction is realized with regard to the number of phonemic category distinctions, as well as with regard to the phonetic qualities of the individual vowels in the respective systems.

1.2.2 Nasal vowel systems in modern NMF and QF

Nasal vowel system in modern NMF

It would be both prudent and appropriate, at this juncture, to provide a working definition of the dialect which will be referred to in this study as modern *Northern Metropolitan French*[4]. The term NMF is used in this work as an umbrella

[4] The term "metropolitan" is used in the existing literature with somewhat variable definitions. In general, there are three meanings used for this term:

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 so-called *Oïl* (north) and *Oc* (south) dialect areas "from east to west approximately at the 45th parallel (Grenoble to Bordeaux)" (Wardhaugh, 2006, p. 136)[5]. In comparison with southern varieties of French, NMF possesses many distinctive phonetic and phonological characteristics, such as:

- post-tonic vowel reduction (non-realization) of word-final schwas),
- a phonemic high-mid/low-mid vowel distinction in open syllables,
- relatively strong cases of vowel harmony (Carignan and Fagyal, 2010; Fagyal et al., 2002; Nguyen and Fagyal, 2008), and
- a tendency for phrase-final stress.

In comparison with southern varieties of French, it does not contain such characteristics as:

- a post-vocalic nasal consonant in nasal vowels,
- clear realizations of the nasal vowel /œ̃/ (see discussion below), or
- realizations of post-tonic (word-final) schwa.

Descriptions of the contemporary nasal vowel system of NMF (Fagyal et al., 2006; Fougeron and Smith, 1999; Hansen, 1998, *inter alia)* posit either four phonemic vowels ([ɛ̃], [œ̃], [ɑ̃], [ɔ̃]) or three phonemic vowels ([ɛ̃], [ɑ̃], [ɔ̃]), with a preference for the three-vowel system for at least the past 40 years (Malécot and Lindsay, 1976, *inter alia)*. As summarized in Hansen (2012), the contemporary nasal vowel system of the NMF dialects most likely contain only three vowels, which are traditionally transcribed with the following IPA symbols: [ɛ̃], [ɑ̃], [ɔ̃]. The vowel [œ̃], which had lowered from the [ø̃] of the 17th century, has since merged with its unrounded counterpart, [ɛ̃]. The disappearance of this fourth vowel from the system is most likely due to both lexical and phonetic factors. With regard to lexical factors, /œ̃/ has a low functional load in French compared to /ɑ̃/ (highest among the four nasal vowels), /ɔ̃/ (second highest), and /ɛ̃/ (second lowest) (Chavasse, 1948; Delattre, 1965; Hess, 1975; Lafon, 1961; Valdman, 1976). Using

1. varieties spoken in dense urban areas, as opposed to rural areas; this is the way in which the term is used, e.g., by:
   (a) Armstrong and Pooley (2010, pp. 17, 59, 68–69),
   (b) Jamin (2005, p. 43), and
   (c) Pooley (2009, p. 66): "Metropolitan French is used in this chapter to refer to inhabitants of urban areas who are technically French, in contradiction to those who are of Maghrebian or other ethnic origin."
2. 'mainland' v. 'overseas' varieties, given the fact that French has expanded to other areas around the world; see Fagyal et al. (2006, p. 33)
3. 'standard' v. 'non-standard' varieties, by conflation of meanings 1 and 2, because the 'urban' and 'mainland' varieties tend to have greater prestige in the Western world than rural, overseas varieties.

[5] It should be noted that this 'line' should be perceived, rather, as an arc with endpoints at Grenoble and Bordeaux. The exact dividing line between the *langue d'oïl* and *langue d'oc* regions was the object of much linguistic and political debate in the late 19th century: e.g., Paris (1888) and Meyer (1877) (unity of all French dialects) versus Tourtoulon and Bringuier (1876) (distinctiveness of dialects).

results from both written and spoken corpora studies, Hansen (1998, p. 75) summarizes the relative frequencies of the appearance of these nasal vowels in the respective corpora; this summary is reproduced in Table 1.1, with my addition of the relative percentage of each nasal vowel out of the total frequency for all four nasal vowels in each corpus. It is clear from these lexical frequencies that the relative use of words containing the vowel /œ̃/ is very low (~5-7% of the occurrence of all nasal vowels). Valdman (1976, p. 66) claims for the vowels /ɛ̃/, /ɑ̃/, and /ɔ̃/, that "their potential lexical frequency would range in the thousands". In comparison, the vowel /œ̃/ appears in only ~20 words (not counting proper nouns) in the *Petit Larousse* dictionary (cited by Valdman (1976, p. 66)). With regard to phonetic factors, the acoustic distinction between the rounded [œ̃] and its unrounded counterpart [ɛ̃] is relatively slight (especially compared to the other nasal vowels in the system), and the acoustic effects of nasalization (see the first part of 2.1.1) on this particular vowel pair—as well as the perceptual ramifications of these acoustic effects (see the second part of 2.1.1)—is such that it is predicted that these two phonemes might easily be confused perceptually (see 8.3 for further discussion).

Table 1.1: Percentages of lexical frequency of NMF nasal vowels occurring in corpora from Hansen (1998, p. 75), and relative percentage of each nasal vowel compared to total frequency of all nasal vowels in each corpus.

	Chavasse (1948)		Lafon (1961)		Delattre (1965)		Hess (1975)		Valdman (1976)	
	Freq.(%)	Rel.%	Freq.(%)	Rel.%	Freq.(%)	Rel.%	Freq.(%)	Rel.%	Freq.(%)	Rel.%
/ɑ̃/	2.0	39.22	3.3	45.83	3.20	50.87	3.4	49.28	3.5	47.3
/ɔ̃/	1.7	33.33	2.0	27.78	1.62	25.76	2.0	28.99	2.2	29.73
/ɛ̃/	1.1	21.57	1.4	19.44	1.03	16.38	1.1	15.94	1.2	16.22
/œ̃/	0.3	5.88	0.5	6.94	0.44	7	0.4	5.8	0.5	6.76
Total:	5.1	100	7.2	99.99	6.29	100.01	6.9	100.01	7.4	100.01

With the combination of both lexical and phonetic influences deterring the preservation of the nasal vowel /œ̃/, it would be of little surprise to find that it has merged with /ɛ̃/ in the NMF dialect. Indeed, it has long been observed that this is the case in NMF (possibly, since the beginning of the 19th century; see Hansen (1998, pp. 91–111)), and that this merger has continued to progress over time (Hansen, 2001a, 2012; Malécot and Lindsay, 1976). There is some evidence provided by Bothorel et al. (1986) which suggests that—for those speakers who continue to maintain a distinction between /œ̃/ and /ɛ̃/—the two vowels are articulated slightly differently with regard to lingual and/or labial configuration. However, these articulatory distinctions are not consistent across the four speakers in the study and, as Coveney (2001, p. 109) suggests, these differences may be due to co-articulation with neighboring words, since this level of phonetic context was not controlled in the study. Nevertheless, it is clear that, whether or not the merger is yet complete, the vowel /œ̃/ in the NMF dialect is in the midst of disappearing in favor of [ɛ̃]. As (Hansen, 2012, p. 160) puts it, "the /œ̃/-/ɛ̃/ distinction is either very subtle, or non-existent, according to speaker, but it is not without traces in current young Parisian speech[6]." If it is still there, it only has trace value rather than a phonemic or allophonic

[6] "Parisian speech" is a subset of NMF.

presence.

Many descriptions have been written about the phonetic characteristics of the remaining three nasal vowels—/ɛ̃/, /ɑ̃/, and /ɔ̃/—and I will provide a brief overview here. Details concerning results from articulatory studies on NMF nasal vowel production can be found in 2.1.2 (lingual articulation) and 2.1.3 (labial articulation). With regard to the phonetic realization of /ɛ̃/, it has been described as being more open and posterior than the IPA symbol <ɛ> suggests: a realization more akin to [æ̃]. This sound change is considered a fairly recent one (since the 20th century), however some linguists—like Hansen (1998, p. 120), for example—argue that it may have started sometime in the 16th-18th centuries, referencing orthographic examples such as *bian* for *bien* 'well', *rian* for *rien* 'nothing', etc., in *Dictionnaire des rimes françoises*, written by the grammarian Tabourot in 1587, mocking the speech of Parisian speakers:

> "*Et bian bian, ie varron si monsieur le Doyan qui a tant de moyan, ayme les citoyans, et si, à la coustume des ancians, il leur baillera rian.*"
>
> "*Et bien bien, je verrai si monsieur le Doyen qui a tant de moyens, aime les citoyens, et si, à la coutume des anciens, il leur baillera rien.*" (*modern French translation and orthography*)
>
> 'Well well, I'll see if the Dean, who has so many resources, loves the citizens, and if, in accordance with the customs of the elders, he will give them nothing.' (*my translation*)

Whether or not the opening and retraction of /ɛ̃/ began as early as the 16th century, it is clear that this sound change was well underway by, at the very least, the first half of the 20th century (Dauzat, 1930; Fouché, 1935; Straka, 1952). Articulatory evidence (see 2.1.2) shows that [ɛ̃] is produced with a lowered, retracted tongue position compared to [ɛ]. Walter (1994) studied the speech of two generations of Parisian speakers at the end of the 20th century. She found that the older generation produced /ɛ̃/ as [æ̃], while the younger generation produced three different allophones: [æ̃], [ɑ̃], [ɔ̃]. In perception experiments involving acoustic gating of [ɛ̃], [ɑ̃], and [ɔ̃] in NMF, both Amelot (2004) and Montagu (2004) found that the "non-nasalized" initial temporal portion of [ɛ̃] was perceived by native speakers as a lower and more posterior oral vowel: that is, [a], or even [ɑ]. In fact, Montagu (2004) found identification of [a] in 99.4% of the identification answers. Both authors give a possible interpretation of this result: the lingual articulation of /ɛ̃/ is, indeed, lower and more retracted than the symbol <ɛ> suggests.

With regard to the phonetic realization of /ɑ̃/, it has been described as more closed, and possibly with a more rounded labial articulation, than the IPA symbol <ɑ> suggests: a realization more akin to [ɒ̃] or [ɔ̃]. Articulatory evidence (see 2.1.2 and 2.1.3) suggest that [ɑ̃] is produced with a retracted, and possibly lower tongue position, with more rounded labial articulation, compared to [a]. It is possible that this sound change has also been in effect since the 17th century, with orthographic examples from the time period such as *oncor* for *encore* 'again' and *avon que* for *avant que* 'before' (Straka, 1981, p. 184), although this early date is not uncontroversial (cf. Lodge (1996); Hansen

(1998, p. 112)). At any rate, there is evidence which suggests that the realization of /ɑ̃/ has been changing since at least the 18^{th} and 19^{th} centuries (Léon, 1992; Mettas, 1979; Straka, 1981; Valdman, 1976). Walter (1994) found that the older generation in her study produced /ɑ̃/ as an unrounded [ɑ̃], while the younger generation produced a rounded [ɒ̃]. Montagu (2004) found that the non-nasalized initial temporal portion of [ɑ̃] was perceived as oral [ɔ] in 88.1% of the identification answers in her study.

With regard to the phonetic realization of /ɔ̃/, there are some contradictory descriptions in the literature. It has been described by some as being a more open realization than the IPA symbol <ɔ> suggests, more akin to [ɑ̃]; it has been described by others as being a closed realization, more akin to [õ]. With regard to the former claim (i.e., /ɔ̃/ being realized more open), the following conclusions have been reached, based on impressionistic (perceptual) coding:

- Péretz-Juillard (1985) found an intermediate [ɔ̃/ɑ̃] in 9 cases of 20 children recorded in 1979.
- Fónagy (1989) identified a possible partial merger between /ɑ̃/ and /ɔ̃/, with an apparent bidirectional movement between the two vowels (i.e., some cases of /ɑ̃/ realized as more closed, and some cases of /ɔ̃/ realized as more open).
- Surveying the written forms from children, Malderez (1991) observed a few cases of evidence suggesting similar results to those from Fónagy (1989): *an* written to represent /ɔ̃/ and *on* written to represent /ɑ̃/.

With regard to the latter claim (i.e., /ɔ̃/ being realized as more closed):

- In his work on the phonology and morphology of French, Valdman (1976) claims that /ɑ̃/ is realized as [ɔ̃] and that /ɔ̃/ is realized as [õ].
- Mettas (1973, 1979), studying the pronunciation of young Parisian women, posits that /ɔ̃/ has a very high realization in stressed position, towards that of [ũ].
- Walter (1994) found that the older generation in her study produced /ɔ̃/ as a closed [õ], while the younger generation produced a very closed [õ̝].
- Hansen (2001a, 2012, p. 159) describes /ɔ̃/ as being realized as a more closed and more rounded [õ].
- Montagu (2004) found that the non-nasalized initial temporal portion of [ɔ̃] was perceived as oral [o] in 90.6% of the identification answers in her study.
- Some articulatory evidence (see 2.1.2 and 2.1.3) suggests that [ɔ̃] is produced with a more retracted tongue position compared to [o], though there is variation between studies. All studies observe a more rounded labial articulation for [ɔ̃] compared to [o]. These articulations are suggestive of a closed realization for /ɔ̃/.

Although there may be some disagreement in the literature with regard to the realization of /ɔ̃/ in NMF, I am inclined to prefer using the latter description (i.e., /ɔ̃/ realized as [õ]) as a point of departure for this study for three reasons. Firstly, there seems to be, generally, more evidence to support this description. Secondly, the realization of /ɔ̃/ as [ɑ̃] would cause wide-spread perceptual confusion between minimal pairs containing the /ɑ̃/-/ɔ̃/ distinction; this does not seem to be the case in NMF. Thirdly, the realization of /ɔ̃/ as [õ] follows a structural characteristic of the NMF nasal vowel system known as a "chain shift" which has been described by many researchers (see 2.2.3 for a discussion of nasal vowel chain shifts in NMF and QF). Assuming the realization of /ɔ̃/ as [õ] in NMF, we find three realizations of the nasal vowels /ɛ̃/, /ɑ̃/, and /ɔ̃/ in the NMF dialect which are quite different than the traditional IPA transcriptions suggest: [æ̃], [ɒ̃], and [õ], respectively. Figure 1.1 provides a summary of this description of the NMF nasal vowel system.

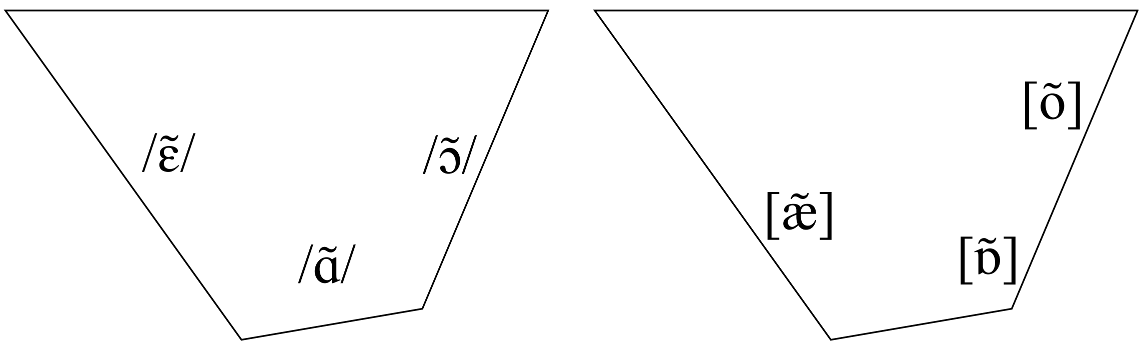


Figure 1.1: IPA transcription (left) and phonetic realization according to descriptions (right) of NMF vowel space.

Nasal vowel system in modern QF

The term Northern Metropolitan French is contrasted to another umbrella term, *Quebecois French*, used in this work very broadly to refer to the local varieties spoken broadly around Lake Saint-Jacques, south of Waswanipi and Ouje-Bougoumou[7]. In comparison with the NMF dialect, QF contains such phonetic and phonological characteristics as:

- a four-phoneme nasal vowel system (including /œ̃/),
- oral and nasal vowel diphthongs,
- affricates (via the process of assibilation: assimilation to a following front high vowel or front glide), and
- the laxing of the high tense vowels /i, y, u/ to their respective lax forms /ɪ, ʏ, ʊ/ in stressed, closed syllables (preceding any consonant but /v/, /z/, /ʒ/, or /ʁ/).

[7] Note that the use of the terms *Northern Metropolitan French* and *Quebecois French* is a methodological choice, stressing the difference between European vs. North American varieties and, as such, it is distinct from other terminological choices that are equally frequent is the sociophonetics literature.

As mentioned above, the QF nasal vowel system contains all four phonemes which were present in the *langue d'oïl* dialect of the French settlers who came to Quebec in the 17th century, including /œ̃/ (which has since merged with /ɛ̃/ in the NMF dialect, as previously described). There are not as many available descriptions of the phonetic realizations of the QF nasal vowels as there are for the NMF nasal vowels, but I will summarize some of the descriptions that do exist[8]. Results from articulatory studies on QF nasal vowel production can be found in 2.2.2. In general, it seems that the realizations of the nasal vowels in QF are somewhat less certain, and somewhat more complex, than those of the nasal vowels in NMF.

In a manual created to "*corriger les fautes d'articulation*" ('correct errors in articulation') related to the pronunciation of the sounds in Canadian French, Gendron (1968) claims that the position of the tongue for [ɛ̃] is nearly the same as for the oral [ɛ], though *very slightly* higher; however, in his earlier work, he states that the production of /ɛ̃/ "*donne* [. . .] *l'impression d'être prononcée très en avant*" ('gives [. . .] the impression of being pronounced very [far] forward'), but that it is not quite as high or forward as [ẽ] (Gendron, 1966, p. 99). He also states that [ɛ̃] has a tendency to be denasalized, especially in stressed position. No mention is given in either work to a diphthongized realization of /ɛ̃/. Walker (1984) describes /ɛ̃/ as being realized as [ẽ] in stressed, open syllables, which differs slightly from the earlier descriptions by Gendron (1966, 1968), in that it is higher and more forward.

With regard to the realization of /ɑ̃/, Gendron (1966, p. 98) claims that it "*produit l'impression d'être formée en avant de la bouche*" ('gives the impression of being produced in the front of the mouth'). Later, in his 1968 work (p. 76), he states plainly that /ɑ̃/ is realized with the same tongue position as for the anterior oral [a], but that it is "poorly nasalized" (i.e., denasalized). Walker (1984) describes /ɑ̃/ as being realized as [æ̃] in stressed, open syllables, which differs slightly from the earlier descriptions by Gendron, in that it is higher and more forward.

With regard to the realization of /ɔ̃/, Gendron (1968, p. 101) states that it is often realized similarly to [ɑ̃] as a result of unrounding of the lips, but that this pronunciation is "faulty" (*un défaut*). Gendron (1966, p. 100) posits that /ɔ̃/ is realized with the some tongue position as oral [ɔ], but that it sounds to be more open than the [ɔ̃] of NMF. He also claims that [ɔ̃] is more nasalized than either [ɑ̃] or [ɛ̃], but that it is nevertheless less nasalized than its NMF counterpart. Walker (1984) notes no difference in the realization of /ɔ̃/ with regard to the IPA symbol used: he posits that it is realized as [ɔ̃].

Gendron (1966, p. 100) claims that /œ̃/ practically does not exist any longer in Canadian French: like for the NMF dialect, it has merged with /ɛ̃/ as a result of unrounding of the lips. However, in 1968, he does not mention the loss of /œ̃/ in the dialect, and describes the realization of /œ̃/ as having the same lingual and labial configurations

[8]In the literature that is summarized here, the term "Canadian French" (*français canadien*) is sometimes used for what I have labeled "Quebecois French". However, the dialect of Canadian French that is described in these works is that which is spoken in urban areas of the Quebec province. Therefore, the term "Canadian French" used in these works seems to be the same dialect that I term "Quebecois French". I will stay faithful to the terms used in the original works where those terms apply, but I here inform the reader that the two terms should be considered synonymous for the purposes of the current research.

as oral /œ/. Walker (1984) notes no difference in the realization of /œ̃/ with regard to the IP symbol used: he posits that it is realized as [œ̃]. He also claims that diphthongization is a variable (but infrequent) feature of nasal vowels in closed syllables, or in pretonic position. For these diphthong variants, the oral articulatory adjustments are manifested not in the nucleus, but rather in the offglide. Thus, according to Walker (1984), /ɛ̃, œ̃, ɑ̃, ɔ̃/ are realized as either the monophthongs [ẽ, œ̃, æ̃, ɔ̃] or their respective diphthongs [ɛ̃ʲ, œ̃ᶣ, ɑ̃ʷ, ɔ̃ʷ] in the QF dialect.

Although there is not complete agreement with regard to the descriptions of the realizations of the QF nasal vowels, there are some general conclusions that we can draw. Similarly to the nasal vowels of NMF, we find descriptions of three realizations of the nasal vowels /ɛ̃/, /ɑ̃/, and /ɔ̃/ in the QF dialect which are quite different than the traditional IPA transcriptions suggest: [ẽ]/[ɛ̞̃], [æ̃]/[ã], and [ɔ̝̃]/[ɑ̞̃], respectively. All of the descriptions for QF presented here claim that /œ̃/ is realized as [œ̃]. Figure 1.2 provides a summary of this description of the QF nasal vowel system.

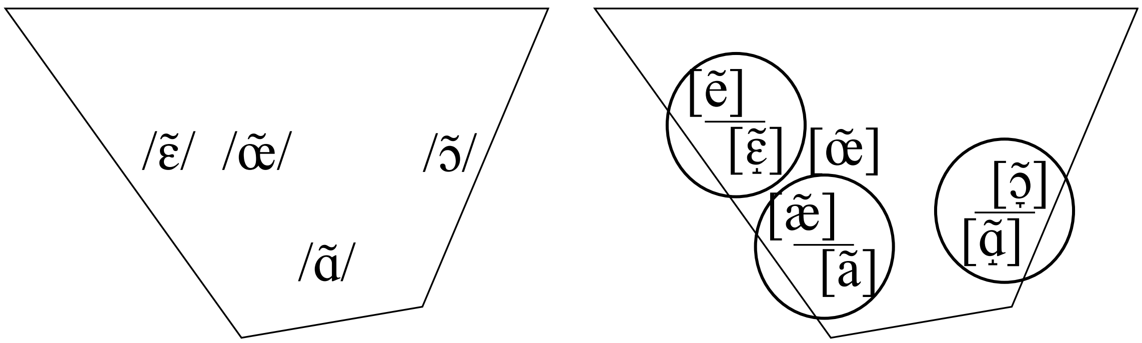


Figure 1.2: IPA transcription (left) and phonetic realization according to descriptions (right) of QF vowel space.

In the following chapter, I will outline the acoustic and perceptual characteristics of vowel nasalization, as well as how some of these characteristics can interact both with one another and with the acoustic and perceptual characteristics of oral articulations. I will also summarize the research that has previously been performed on both the acoustic and oral articulatory realizations of contemporary NMF and QF. Together with the history of the dialectal separation which I have presented in this chapter, I will show (in the following chapter, as well as throughout the rest of this study) how the contemporary realizations of the nasal vowels in these two French dialects may have been influenced—at least in part—by inherent characteristics of nasalization itself.

Chapter 2

Sources of variability in vowel nasalization

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 port, otherwise referred to as a lowering of the velum. This coupling modifies the acoustic output of the vowel production by introducing an additional spectral resonant pattern to that of the oral cavity. Aside from the so-called velic opening hypothesis (Al-Bamerni, 1983; Bell-Berti, 1993; Clumeck, 1976; Chen and Wang, 1975; Hajek, 1997; Hombert, 1987; Ohala, 1975; Ruhlen, 1973; Shosted, 2003), in much of the literature on vowel nasalization, oral and nasal vowel congeners (e.g. [i] and [ĩ]) are often compared as if the only substantive physical difference between the two is coupling between the velo-pharyngeal and oral tracts (Morais-Barbosa, 1962; Narang and Becker, 1971; Paradis and Prunet, 2000). In other words, it is often assumed that nasal vowels are produced with the same lingual and labial configurations as their oral vowel counterparts. Even in the acoustic modeling literature, when vocal tract transfer functions are used to compute the differences between oral and nasal vowels (Feng and Castelli, 1996; Pruthi et al., 2007, *inter alia*), the inputs to the model typically differ only in the degree of nasal-oral coupling. Thus, such a model of vowel nasalization assumes that the velum lowers, allowing air to pass through the nasal cavity, but that all other oral articulators maintain the same configuration. In the description of nasal or nasalized vowels[1], as well as in related phonological analyses, the assumption that these vowels differ from their oral congeners only in terms of nasal-oral coupling is perhaps too simple. Recent work suggests that lingual position may vary under nasal and oral conditions, potentially compensating for the size and shape of the nasal cavity (Carignan et al., 2011; Engwall et al., 2006; Rong and Kuehn, 2010; Shosted et al., 2012a).

The acoustic effects of vowel nasalization have been widely studied (see 2.1.1), although complete consensus has not yet been reached as to the essential acoustic characteristics of vowel nasalization (Delattre, 1954; Fant, 1960; Feng and Castelli, 1996; Hawkins and Stevens, 1985; Maeda, 1993; Pruthi et al., 2007). One reason is probably technical: acoustics captured using a microphone positioned at a speaker's lips will capture a signal in which the acoustic effects of the oral articulatory configurations are indeterminate, since both oral and nasal sound pressures are combined.

[1] I follow Beddor (1993); Dixit et al. (1987); Ohala (1999); Stevens (1998) in using the term *nasal* to describe phonologically contrastive sets of vowels in languages like French, Hindi, and Portuguese. Ladefoged (2005, p. 200) uses the term differently, to describe sounds in which air escapes from only the nose, and uses *nasalized* to describe sounds in which air escapes from both the nose and the mouth. In contrast, I use *nasalized* to describe sounds in which air escapes from both the nose and the mouth, but for which the presence of this additional airflow (via the nose) is contextual (i.e., due to co-articulation with an adjacent nasal consonant) and does not constitute a phonological difference in a language (e.g., contextually nasalized vowels in English).

Without knowing the precise velo-pharyngeal aperture and the complex nasal geometry of the speaker, sorting out the velo-pharyngeal and nasal transfer functions from the oro-pharyngeal transfer function may be an intractable problem. Another reason for the absence of agreement on the nature of vowel nasalization is likely due to the fact that there may be more variation in how nasal vowels can be, and are produced than has been previously assumed (Arai, 2004; Carignan et al., 2011; Engwall et al., 2006; Shosted et al., 2012a; Zerling, 1984, *inter alia*). Arai (2004) and Carignan et al. (2011), for example, observed that phonetically co-articulated nasalized oral vowels in English are produced with different lingual articulation than oral vowels without contextual nasal co-articulation. Shosted et al. (2012a) have found lingual and labial articulatory differences between the oral and nasal vowels of Hindi, as well as evidence of a clockwise chain shift in the realizations of the nasal vowels. Given this variation, looking for a handful of invariant, essential characteristics therefore might not be the best way to investigate the nature of nasality. How nasal vowels are produced can be different from language to language (Beddor and Strange, 1982; Hajek, 1997; Henderson, 1984; Schourup, 1973), male speaker to female speaker (Engwall et al., 2006; Maeda, 1993), and dialect to dialect (Delvaux et al., 2008; Durand, 1988; Engwall et al., 2006; Teston and Demolin, 1997; Walker, 1984).

2.1 Phonetic variability

2.1.1 Effects of vowel nasalization

Acoustic effects of vowel nasalization

The acoustic changes associated with nasalization have drawn considerable attention (Chen, 1973, 1975; Delattre, 1954; Fant, 1960; Feng and Castelli, 1996; Fujimura, 1961; Fujimura and Lindqvist, 1971; Hawkins and Stevens, 1985; House and Stevens, 1956; Kataoka et al., 2001; Lonchamp, 1979; Maeda, 1982, 1993; Pruthi et al., 2007; Stevens et al., 1987). Once the nasal cavity is coupled to the oro-pharyngeal tube, its large surface area and soft tissues reduce energy and increase bandwidths in low frequencies, resulting in the reduced global prominence of F1 (Stevens, 1998, p. 193). Variation in the nasalization-induced modulation of F1 is observed due to the interaction of the oral transfer function with extra pole-zero pairs (Maeda, 1993). These pole-zero pairs arise due to coupling between the oral tract, nasal tract, and maxillary and sphenoidal sinuses. Asymmetry in the nasal passages is another source of extra pole-zero pairs (Engwall et al., 2006; Serrurier and Badin, 2008; Stevens, 1998).

The coupling of the nasal and oro-pharyngeal tracts significantly alters the low-frequency domain of the sound spectrum (Hawkins and Stevens, 1985; Kataoka et al., 2001; Pruthi et al., 2007). According to a model based on sweep-tone measurements of vocal tract output, “all formants of a nasalized vowel shift monotonically upwards” with increased velo-pharyngeal opening (Fujimura and Lindqvist, 1971, p. 552). F1-lowering may result from the nasalization of low vowels, but only when the degree of nasalization is sufficient to introduce a high-amplitude nasal formant (Diehl et al., 1991a). Thus, moderately nasalized low vowels as well as moderately or heavily nasalized non-low vowels will manifest a raised F1, while heavily nasalized low vowels (such as phonemic low nasal vowels) may manifest a lowered F1. However, F1 frequency is most typically modulated independently of velo-pharyngeal opening (VPO): F1 frequency is determined mostly by the vertical position of the tongue in the oral cavity, but is also known to be modulated by changes to the aperture of the pharynx (Perkell and Nelson, 1985; Stevens, 1998, *inter alia*). Using a speech model based on data from MRI and CT scans, Serrurier and Badin (2008) observed the individual influence of velic lowering on the acoustic vowel space for the corner vowels [a, i, u]. They found that the acoustic space was centralized along both the F1 and F2 dimensions, reducing F1 range from around 260-700 Hz for "pure oral" vowels (from glottis to lips) to around 370-510 Hz for "pure nasopharyngeal" vowels (from glottis to nostrils), and reducing F2 range from around 600-2350 Hz to around 950-1150 Hz. These results are broadly consistent with earlier model simulations performed by Feng and Castelli (1996), who observed frequency lowering along both the F1 and F2 dimensions in an analog model of velo-pharyngeal coupling[2].

Because of the interaction between the acoustic poles and zeros associated with the nasal tract, and the poles associated with the oral tract, spectral center of gravity (COG) is perhaps a more reliable and informative characteristic of the acoustic effect of velo-pharyngeal coupling on the spectra energy surrounding the frequency region of F1 of the oral tract transfer function. Spectral COG can be considered as the average of amplitude in a given frequency range. For example, given two acoustic poles of the same amplitude, the COG of the spectral region including both poles will be half-way between the two poles (i.e. the average of the two poles). However, given one pole of an amplitude and second pole of a lesser amplitude, the COG of the spectral region including both poles will be between the two poles, but closer to the pole with the greater amplitude. A graphical paradigm of spectral COG is given in Figure 2.1[3]. The relevance of COG for vowel nasalization involves the interaction of the first pole associated with the oral tract with the first pole associated with the nasal tract.

Since the size and shape of the nasal tract is not modified during speech like the oral tract is, the frequency of the poles associated with the nasal tract transfer function are not expected to change between vowels with different oral articulatory configurations. Therefore, the F1 COG will differ depending upon whether the first pole associated with the nasal tract (the so-called 'nasal formant') has a higher or lower frequency than the first pole associated with the oral tract. For oral vowel articulatory configurations yielding high F1, additional nasal coupling is known to lower the COG in the F1 region ("vowel raising") due to frequency of the first nasal formant being lower than the F1 of the oral tract. Conversely, for oral vowel articulatory configurations yielding low F1, additional nasal coupling is known to

[2] In this study, I will refer to changes to the frequencies of F1 and F2 which are due to velo-pharyngeal coupling as "formant-frequency-related" acoustic effects, generally, and "F1-related" and "F2-related" acoustic effects, specifically.

[3] Modified from Feth & Krishnamurthy, available at: http://www.cse.ohio-state.edu/pnl/WCA/files/Feth.ppt

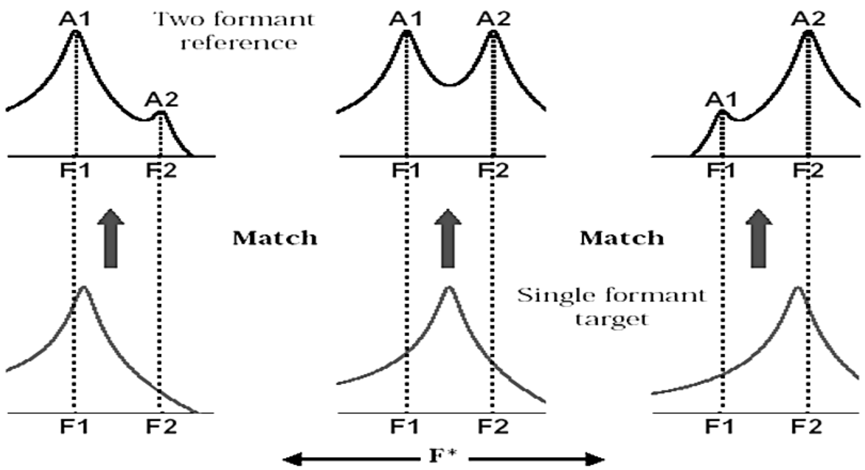


Figure 2.1: Examples of spectral center of gravity (COG).

raise the COG in the F1 region ("vowel lowering") due to the frequency of the first nasal formant being higher than the F1 of the oral tract. In this way, one of the acoustic effects of velo-pharyngeal coupling on the acoustic vowel space is a centralization along the F1 COG dimension: high vowels are lowered and low vowels are raised under the influence of nasalization.

Perception of vowel nasalization

The perceptual impact of nasalization has been studied in great depth, as well (Beddor et al., 1986; Beddor and Hawkins, 1990; Hawkins and Stevens, 1985; Huffman, 1990; Kataoka et al., 2001; Maeda, 1993). Ito et al. (2001) argue that spectral shape, not just formant frequency, is necessary for reliable oral vowel perception. This is arguably the case for nasal vowels, as well. Indeed, Beddor and Hawkins (1990, p. 2684) find that vowel quality, especially height, is determined by both the frequency of prominent low-frequency harmonics and their energy fall-off for synthetically nasalized vowels. The lowest pole associated with the nasal transfer function perceptually merges with the lowest pole of the oro-pharyngeal transfer function (Maeda, 1993). As a result, the spectra of nasal vowels are considered less distinct than those of their oral counterparts. Nasal vowels have been judged to be more similar to each other than oral vowels (Bond, 1975; Butcher, 1976; Mohr and Wang, 1968). Kataoka et al. (2001, p. 2181) find a strong correlation between the perception of hypernasality and increased amplitude in the spectrum of the band that lies between F1 and F2, as well as lowered amplitude of the band surrounding F2. Maeda (1993) considers a flattening of the spectrum in the region between F1 and F2 to be associated with the perception of synthesized vowel nasalization. Hawkins and Stevens (1985, p. 1562) generally support the notion that, by broadening and flattening the prominence that occurs near the first formant, a synthetic oral vowel can be made to sound nasal.

The centralization of the acoustic vowel space along the F1 COG dimension (see 2.1.1) has a perceptual correlate, as well. In the same way that the presence of one spectral formant near the frequency region of another spectral formant will shift the COG in this region, two spectral formants whose respective frequencies are within 3.5 Bark will be perceived as one weighted average between the two peaks (Beddor et al., 1986; Chistovich and Lublinskaya, 1979). Since the frequency of the perceived F1 may or may not be the same as the F1 produced by the oral transfer function, I refer to the perceived F1 of a vowel (oral or nasalized) as F1′ (after Carignan et al. (2011)). In cases where F1 is high (for low vowels like /a/) the effect of nasalization is to lower F1′; in cases where F1 is low (for high vowels like /i/) the effect is to raise F1′. Krakow et al. (1988, p. 1146) observe that the F1′ variation inherent in nasalization is similar to acoustic changes associated with tongue height and jaw position. For example, a relative increase in F1′ may be attributed to either a lowered tongue/jaw position or an increase in nasal coupling (especially for high vowels), and a decrease in F1′ may be attributed to either a raised tongue/jaw position or an increase in nasal coupling (for low vowels). In this way F1′ can be considered to be the perceptual equivalent of the spectral F1 COG.

Because there are (at least) two articulatory mechanisms which can independently modulate F1 COG and, thus, F1′, it may be possible for listeners to confuse these mechanisms when attending to nasal vowel quality. Indeed, Wright (1975, 1986) found that listeners can misperceive nasalization in terms of vowel height. Specifically he observed that nasalized [ĩ] was perceived as lower and further back than oral [i] while nasalized [ã] was perceived as higher than oral [a] Wright (1986, p. 54–55). Hawkins and Stevens (1985, p. 1573) found that, when nasality was perceptually ambiguous along a continuum of [o-õ], listeners seemed to make judgments of nasality based on differences in vowel height. Beddor et al. (1986); Krakow et al. (1988) demonstrate that the acoustic modifications associated with increased velo-pharyngeal aperture can indeed be attributed to changes in oral tract shape, though only for non-contextually nasalized vowels. They argue that misinterpretation of nasalization in terms of oral articulatory configuration arises exclusively when nasalization is “inappropriate”, e.g. when nasal coupling is excessive (phonetically inappropriate) or when nasalization appears without a conditioning environment (phonologically inappropriate) (Beddor et al., 1986, p. 214). However, by taking into account response bias effects, Kingston and Macmillan (1995); Macmillan et al. (1999) found that for (heavily) nasalized mid vowels, the acoustic dimensions of nasalization and F1 mutually enhance in the perceptual domain, whether the vowel is isolated, followed by an oral consonant, or followed by a nasal consonant.

It is less clear whether F2, most typically modulated by forward–backward movement of the tongue body (Stevens, 1998, p. 203), has a strong effect on the percept of nasality. Front (high F2) vowels are more often perceived as nasalized, though the effects are often weak or limited to only a few vowels (Bream, 1968; House and Stevens, 1956; Lintz and Sherman, 1961; Maeda, 1982, 1989). Conversely, Delvaux (2009) shows that F2 lowering alone may help trigger the percept of nasality in French.

2.1.2 Previous findings: Lingual articulation

Most of the previous work on the oral articulation of nasal vowels in French involves qualitative descriptions using cineradiographic images (Bothorel et al., 1986; Brichler-Labaeye, 1970; Straka, 1965; Zerling, 1984). These early articulatory studies had somewhat conflicting results, perhaps due to inter-speaker variation and relatively low speaker and repetition *N*s in each study. However, these seminal studies provide important articulatory evidence that oral and nasal vowel congeners in French do not share the same oral articulatory configurations. More recent studies involve MRI data and larger repetition *N*, adding to the growing understanding of the oral articulation of nasal vowels in French (Delvaux et al., 2002; Engwall et al., 2006). ø With regard to the lingual articulation of nasal [ɛ̃] and oral [ɛ] (see 2.1.3 for previous findings on labial articulation), Zerling (1984) describes [ɛ̃] as more retracted than [ɛ], but with the same tongue height. Brichler-Labaeye (1970), on the other hand, describe [ɛ̃] as being produced with a lower tongue position than [ɛ]. X-ray schemas from Straka (1965) show [ɛ̃] as produced with a very low tongue position, nearly as low as for the oral vowel [a]; the schemas also suggest that [ɛ̃] is produced with a much more retracted tongue position than for the oral counterpart [ɛ]. MRI evidence from Delvaux et al. (2002) and Engwall et al. (2006) suggest that the four Belgian French speakers studied[4] produce [ɛ̃] with both a lower and more retracted tongue position than for [ɛ][5]. Indeed, many accounts of French vowel articulation, even very early accounts, make the claim that [ɛ̃] is realized as lower than [ɛ] (Armstrong, 1932; Battye and Hintze, 1992; Brichler-Labaeye, 1970; Carton, 1974; Léon, 1992; MacCarthy, 1975; Zerling, 1984). However, the tracings from Bothorel et al. (1986) of two male and two female NMF speakers suggest that this may not always be the case. The first male speaker produces [ɛ̃] with a lower tongue position than [ɛ], whereas the second male speaker has a tongue articulation which is more bunched, in that the body of the tongue is at the same height but the blade and root are lower, and somewhat retracted for the latter speaker. For the female speakers, one had almost no change in tongue articulation at all, while the other had an advanced tongue root for [ɛ̃], causing a raised tongue blade when compared to the oral [ɛ]. However, there are two matters of importance to note from Bothorel et al. (1986)'s findings: firstly, although the speakers are said to have spoken Standard French during the recording session in Strasbourg, France, where the influence of the Germanic substrate in spoken French cannot be excluded. Secondly, the two female speakers, who did not have the same lingual articulation as the males, produced the nasal vowel [ɛ̃] with a smaller labial aperture (i.e. lips more closed and less spread) than oral [ɛ]. This difference was, importantly, greater for the two females than for the males. This suggests the possibility of interplay between the secondary articulators for the production of nasal vowels.

With regard to the lingual articulation of nasal [ɑ̃] and oral [a]/[ɑ], some of the previous research suggests that [ɑ̃] is lower and more retracted than its oral counterpart, though the differences are less marked than those between

[4]The same four speakers—two males and two females—were used in both Delvaux et al. (2002) and Engwall et al. (2006), though the research focus, experimental design, data collection protocol, and analysis protocol were different in the two studies.

[5]Generally, Engwall et al. (2006) find that three of the four speakers tend to retract the tongue more for *all* of the nasal vowels compared to their oral counterparts.

[ɛ̃] and [ɛ] (Brichler-Labaeye, 1970; Delvaux et al., 2002; Engwall et al., 2006). The x-ray schemas from Straka (1965) suggest that [ɑ̃] may be produced with a slightly lower tongue position than [ɑ], and is clearly more retracted; additionally, [ɑ̃] is clearly lower and more retracted than [a]. Zerling (1984), who studied [ɑ] rather than [a] as an oral counterpart to [ɑ̃], observed that the tongue body was slightly more retracted during the productions of the nasal vowels [ɑ̃] than during the production of their oral counterparts [ɑ]. Delvaux et al. (2002) find that [ɑ̃] is "somewhat" lower than [a], and also more retracted. Other research suggests that, while lingual retraction of [ɑ̃] compared with [a] is fairly consistent, a lowered tongue position may not be as consistent. Findings from Bothorel et al. (1986) suggest, rather, that [ɑ̃] is more closed than its oral counterpart [a].

With regard to the lingual articulation of nasal [ɔ̃] and oral [o]/[ɔ], [ɔ̃] is sometimes described as having a more retracted tongue position than its oral counterpart (Delvaux et al., 2002; Zerling, 1984), although findings of lingual retraction are not always consistent (Bothorel et al., 1986). The x-ray schemas provided by Straka (1965) suggest that [ɔ̃] has the same lingual position as the oral [ɔ], but with a labial articulation which is closer to that of [o] than of [ɔ]. Zerling (1984) observed that the tongue body for the two speakers studied was slightly more retracted during the production of [ɔ̃] than during the production of [ɔ]. However, the tracings in Bothorel et al. (1986) suggest that three of the four speakers have a more retracted tongue body for the articulation of [ɔ] than for that of [ɔ̃], which is in direct contradistinction to the findings by Zerling (1984). Delvaux et al. (2002) found more consistent labial differences between [ɔ̃] and [ɔ], but do note that [ɔ̃] manifests a more retracted, and sometimes higher tongue position than [ɔ] for female speakers, but that lingual position is the same between the two vowels for the male speakers. It is not clear whether these differences between the findings of previous studies are due to different methodologies used, to inter-speaker differences in the oral articulation of /ɔ̃/, to the possible variability in the realization of this vowel suggested by the disparate claims regarding the realization of /ɔ̃/ in NMF (summarized in 1.2.2), or to some combination of all three factors.

With regard to the lingual articulation of the rounded pair [œ̃] and [œ], only one of the four speakers from Bothorel et al. (1986) produced a discernible difference between the two vowels, having a lower tongue position for [œ̃] than for [œ]. Findings from Brichler-Labaeye (1970); Delvaux et al. (2002) suggest that, like for the unrounded pair [ɛ̃]-[ɛ], the rounded front nasal [œ̃] is produced with a lower and more retracted tongue position than [œ], though these differences are much less pronounced than for [ɛ̃]-[ɛ] (see 1.2.2 and 4.2 for further discussion on nasal vowel [œ̃], as well as its context within the current research).

I would like to note here work performed by Montagu (2007), which is not articulatory in nature, but which involves a rather innovative way of using acoustics to infer the oral articulation of the nasal vowels in NMF. In this work, she uses indications of the temporal onset of nasalization in the acoustic signal to determine the so-called *Nasal Onset Time* (NOT) of the nasal vowels (i.e., the portion of the vowel from the vowel onset to the temporal moment at which which nasalization begins). With the understanding that the lowering of the velum will cause acoustic modifications which cannot be teased apart from the acoustic characteristics of the oral tract function, she measures the average formant values during the NOT. The minimum NOT observed across speakers and vowel types was found to be 30 ms, which is the NOT window which was used for the formant analysis. The assumption underlying this methodology is that the formant values at this portion of the vowel will accurately represent the configuration of the oral articulators before nasalization begins and, by extension, that these formant values will be unaffected by the formant-frequency-related acoustic effects of velo-pharyngeal coupling. Using this methodology, she interprets the results of the formant analysis in the following ways (pp. 173–174):

- ɛ̃ is produced with a lower, more retracted tongue position than [ɛ],
- ɑ̃ is produced with a higher, more retracted tongue position than [a], and
- ɔ̃ is produced with the same lingual position as [o].

She concludes from her observations that the oral articulatory configurations of the nasal vowels in NMF are not accurately described by the IPA symbols traditionally used to represent them. There are, however, a number of assumptions which seem to be implicit in this methodology; therefore, the results should be interpreted cautiously. The assumptions are the following:

1. The precise moment of the lowering of the velum can accurately be determined from the acoustic signal.
2. The oral articulatory targets of the nasal vowel production are reached before the velum lowers.
3. The "underlying" composition of a nasal vowel is V + N (*à la*, e.g., Paradis and Prunet (2000)), and these two phonological/articulatory constituents can be separated and analyzed distinctly.

2.1.3 Previous findings: Labial articulation

Bothorel et al. (1986) found that many of the oral articulatory differences observed between oral and nasal vowel pairs occurred in adjustments to labial, not lingual configuration, even with regard to the unrounded vowel pair [ɛ̃]-[ɛ]. The distance between the lips was greater for [ɛ] than for [ɛ̃] for all speakers, though this difference was more pronounced for the female speakers than the male speakers. Furthermore, all of the speakers produced [ɛ] with more spread lips than [ɛ̃].

With regard to the labial articulation of [ɑ̃] and [a]/[ɑ], nasal [ɑ̃] has generally been observed to be more rounded than its oral counterpart (Bothorel et al., 1986; Delvaux et al., 2002; Montagu, 2002; Zerling, 1984). Zerling (1984) observed that the most significant differences with regard to oral articulation were found, in fact, in labial configuration: both speakers' lips were more protruded for the production of [ɑ̃] than for the production of the corresponding oral [ɑ][6]. Bothorel et al. (1986) also observed more lip protrusion for [ɑ̃] than for [a], Delvaux et al. (2002) observed more lip rounding for [ɑ̃] than for [a], and Montagu (2002) observed smaller labial aperture and greater labial protrusion for [ɑ̃] than for [a]. The x-ray schemas from Straka (1965), on the other hand, suggest that [ɑ̃] is produced with the same labial configuration as [ɑ], but that both vowels are produced with a more rounded labial configuration than [a].

With regard to the labial articulation of [ɔ̃] and [o]/[ɔ], Zerling (1984) observed that in the articulation of [ɔ̃] the lips are strongly rounded, much more so than for [ɔ], and to a degree comparable to the rounding gesture for [o]. Similarly, the x-ray schemas provided by Straka (1965) suggest that [ɔ̃] has a labial articulation which is closer to that of [o] than of [ɔ]. These labial gestures are also observed by Bothorel et al. (1986) and in the static and real-time MRI data provided by Delvaux et al. (2002); Engwall et al. (2006). Montagu (2002) observed smaller labial aperture, but less labial protrusion, for [ɔ̃] than for [o]. Zerling (1984) found that, for oral [ɔ] and nasal [ɔ̃], three of the four speakers produced the nasal vowel with more lip protrusion than the oral vowel, and the fourth, a slightly higher jaw position for the nasal vowel (and, thus, more protrusion as well). With regard to rounding, the two female speakers—as well as one of the male speakers, to a lesser extent—displayed more constricted lip rounding for [ɔ̃] than for [ɔ].

With reference to the labial findings by Zerling (1984) and Bothorel et al. (1986) for [ɑ̃]-[ɑ] and [ɔ̃]-[ɔ], Maeda (1993) posits that the reason for these observed gestural enhancements is the lowering of F1, which, as a result, would be expected to match the antiformant frequency of the nasal tract transfer function, since the high F1 of [ɑ] (700 Hz) would necessitate a nearly maximum degree of nasal coupling in order for the vowel to be perceived as nasal. Using a two-tube model of velo-pharyngeal coupling, Maeda calculated the effect of lip protrusion with an area function appropriate for the production of [ɑ]. The observed result was that as little as 2 cm additional lengthening of the lip section was sufficient to lower F1 from 664 Hz to 580 Hz, and F2 from 1240 Hz to 1140 Hz. With this additional oral tube length, only a small amount of velo-pharyngeal coupling, about 0.4 cm^2, would be needed in order to weaken the F1 peak and thus to flatten the spectrum in the low-frequency region, resulting in the percept of nasality (Maeda, 1993, p. 164). However, this is the opposite of what Engwall et al. (2006) claim regarding the acoustic effect of nasalization, since they posit that the gestural enhancements observed in the production of the French nasal vowels are used in order to separate the antiformant from F1 instead of bringing them together, as Maeda posits.

The differences between [œ] and [œ̃] with regard to labial articulation include a large amount of inter-speaker variation. In research performed by Bothorel et al. (1986), Speaker 1 showed very slightly more protrusion for [œ] than for [œ̃], and identical lip aperture. Speaker 2 showed slightly more protrusion for [œ] than for [œ̃], but with very open labial aperture for [œ] and relatively spread lips for [œ̃]. Speaker 3 showed no difference in lip protrusion, but more rounding for [œ] than for [œ̃]. Speaker 4 showed slightly more protrusion and more rounding for [œ than for

[6]Given that [ɑ] is described as more rounded than [a], it can reasonably be assumed that differences in labial aperture would have been even more pronounced for the pair [ɑ̃]-[a], had the oral vowel [a] been included in Zerling (1984).

[œ̃]. Findings by Delvaux et al. (2002) suggest that [œ̃] may be more rounded than [œ], but this difference is less clear than for other vowel pairs.

2.2 Other sources of variability

2.2.1 Inter-speaker differences

Recent articulatory evidence suggests that the degree of velo-pharyngeal coupling for nasal vowel production may be variable between speakers, and may in fact depend upon an individual speaker's physical morphology (Delvaux et al., 2008; Engwall et al., 2006). Delvaux et al. (2008) found that, in the context of co-articulatory nasalization (i.e. NV, NṼ, and NVN items), the proportional nasal flow of nasal [ɛ̃] was not significantly different from that of its oral counterpart [ɛ], suggesting that there may not be a difference in the degree of velo-pharyngeal coupling[7] during the production of these two vowels in a co-articulatory nasal environment. How, then, are listeners able to distinguish a nasal vowel from its oral congener without being able to rely upon the acoustic consequences of velo-pharyngeal coupling normally ascribed to nasal/oral vowel distinction? The authors propose that the nasal vowel [ɛ̃] is distinguished from the oral vowel [ɛ] in this context not by velo-pharyngeal coupling, but by differences in lingual articulation: the acoustic effect of the more open and less fronted lingual position associated with [ɛ̃] compared to [ɛ] have been shown to enhance perception of nasality for French listeners especially in nasal context (Delvaux et al., 2004; Delvaux, 2009, see 2.1.1 and 2.1.2).

Similarly, using MRI images of the three-dimensional oral and nasal tracts and cross-sectional areas of the velo-pharyngeal port, Engwall et al. (2006) found that there was almost no difference in the area of the velo-pharyngeal opening between the productions of [ɛ̃] and [ɛ] for one of the four speakers studied. The authors posited that changes in the oral cavity could be made for [ɛ̃] in the absence of velo-pharyngeal coupling in order to maintain its distinction from [ɛ]. Generally, they found that the four speakers used one of three strategies to produce a phonemic nasal vowel: (1) create a relatively large degree of velo-pharyngeal coupling while maintaining the lingual and labial articulations of the corresponding oral vowel; (2) create a relatively small degree of velo-pharyngeal coupling while also making significant changes in the oral articulation; or (3) create an intermediate degree of velo-pharyngeal coupling while also making an intermediate degree of change in the oral articulation. Importantly, this articulatory variability seemed to be related to differences in nasal tract morphology. The subject with the shortest nasal tract was found to make larger changes than the other three subjects in both oral articulatory configuration and velo-pharyngeal coupling. The two

[7] It is important to note that proportional nasal flow is an indirect measure of nasalization, and in some cases it cannot reliably be used to make inferences about the degree of velo-pharyngeal coupling. For example, increased oral impedance due to a raised tongue body causes proportional nasal flow to be greater for /i/ than /a/, since more air is shunted through the nasal cavity; however, velo-pharyngeal coupling has been shown to be greater for /a/ than for /i/, possibly due the muscular connection of *palatoglossus* between the anterior surface of the soft palate and the sides of the tongue dorsum; see (Al-Bamerni, 1983; Amelot, 2004; Bell-Berti, 1993; Clumeck, 1976; Chen and Wang, 1975; Hajek, 1997; Hombert, 1987; Ohala, 1975; Ruhlen, 1973; Shosted, 2003).

subjects with relatively longer nasal tracts either combined a large degree of velo-pharyngeal coupling with little to no change in oral articulation, or a small degree of velo-pharyngeal coupling with greater change in oral articulatory configuration. The fourth subject seemed to employ an intermediate strategy of combining relatively smaller degrees of velo-pharyngeal coupling with relatively smaller changes in oral articulation. Additionally, it was found that the female speakers manifested larger differences in oral articulation than the male speakers, and that the female speakers also had shorter nasal tracts than the male speakers.

These findings suggest that at least some of the oral articulatory strategies observed in nasal vowel production may, in fact, be intentional *compensatory* strategies. In other words, for those speakers whose nasal tracts are not long enough to provide acoustic effects which are significant enough to maintain the phonemic distinction of nasality, changes to the articulatory configuration of the tongue and lips may be employed which will further alter the acoustic output (see 2.3 for discussion on “motor equivalence”). This also suggests that some of the variation observed between previous studies on the articulation of nasal vowels in French may, in fact, be due to inter-speaker differences in articulation.

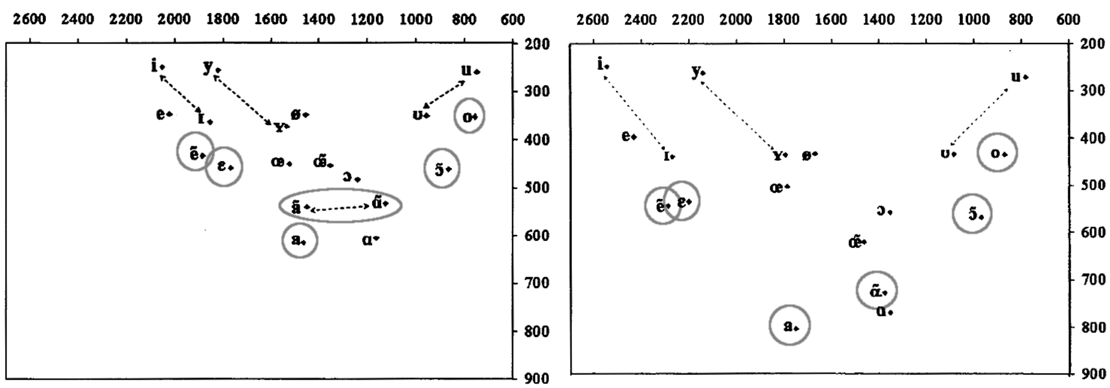
2.2.2 Dialectal differences: NMF and QF

Compared to previous work performed on nasal vowel articulation in NMF, our current understanding of the articulation of the vowel system of the QF dialect is relatively modest. There are some descriptions of the phonetic realizations of nasal vowels in QF (Gendron, 1966, 1968; Walker, 1984), some acoustic data (Martin, 2002), and some articulatory data (Charbonneau, 1971; Delvaux, 2006). The descriptions have already been detailed in 1.2.2, but will be briefly summarized here. Gendron (1966, 1968) suggests that /ɛ̃/ is realized as slightly more forward and slightly more closed than [ɛ], although not as forward and closed as [ẽ]. He claims that /ɑ̃/ is realized with the same tongue position as [a] (thus, [ã]), and that /ɔ̃/ is often realized as [ɑ̃]. Walker (1984) describes /ɛ̃/ and /ɑ̃/ as being realized as [ẽ] and [æ̃], respectively, in stressed, open syllables. He notes no change in articulation for /œ̃/ and /ɔ̃/, being realized as [œ̃] and [ɔ̃], respectively. He also claims that diphthongization is a variable (but infrequent) feature of nasal vowels in closed syllables, or in pretonic position. For these diphthong variants, the oral articulatory adjustments manifested in the realizations of the monophthong nasal variants are realized not in the nucleus, but rather in the offglide. Thus, according to Walker (1984), /ɛ̃, œ̃, ɑ̃, ɔ̃/ are realized as either the monophthongs [ẽ, œ̃, æ̃, ɔ̃] or their respective diphthongs [ɛ̃ʲ, œ̃ᶣ, ɑ̃ʷ, ɔ̃ʷ] in the QF dialect.

Using acoustic evidence from six male and six female speakers[8], Martin (2002) describes the nasal vowels in QF with regard to their F1 and F2 frequencies. The acoustic figures for the male and female speakers’ productions are replicated in subfigures 2.2a (males) and 2.2b (females); the nasal vowels and their oral counterparts relevant

[8] The speakers in Martin (2002) were students at l’Université de Laval, between 20 and 25 years old. Three speakers were from Quebec, three were from Lac Saint-Jean, two were from Bas-Saint-Laurent, two were from Sherbrooke, one was from Côte-Nord, and one was from Montreal.

to this study are highlighted with gray circles/ellipses. According to both the acoustic figures and Martin (2002)'s descriptions: [ẽ] is anterior and closed, and [œ̃] is central, as described by Walker (1984). However, according to formant space figures, the acoustic space for [ẽ] is much closer to that of [ɛ] than to that of [e] for males, and it is nearly the same as [ɛ] for females, with no difference in F1 between [ẽ] and [ɛ] and very little difference in F2. No commentary is given for [ɔ̃], but according to the formant space figures, [ɔ̃] clearly manifests a lower F2 than [ɔ], and a higher F1 and higher F2 than [o]. With regard to the acoustic realization of [ɑ̃], Martin (2002)'s acoustic results seem to be contrary to Walker (1984) description. Specifically, there is very little F2 variation for the female speakers, with the primary realization being [ɑ̃]. On the other hand, the male speakers manifest more F2 variation, with a clear variant [ã] which manifests a lower F1 than [a], but with no difference in F2. Nevertheless, even this fronted variant [ã] is in contradistinction to Walker (1984)'s description of the realization of /ɑ̃/ as a very fronted, and possibly raised, [æ̃]. Concerning diphthongization, Martin (2002) confirms that the nasal vowels are indeed diphthongized in the acoustic space, but it seems that these diphthongs can exist in open syllables as well as closed syllables, contra Walker (1984). However, the phonetic realization of these diphthongs are different than those described in Walker (1984): they are described by Martin as [ᵃẽ, ᵓõ, ᵅœ̃, ãᵓ].



(a) QF acoustic space (males).

(b) QF acoustic space (females).

Figure 2.2: Figures of QF acoustic space from Martin (2002, p. 84). F2 frequency (Hz) is displayed on *x*-axis, and F1 frequency (Hz) is displayed on *y*-axis.

With regard to articulatory research on QF nasal vowel production, there has been some important work performed, albeit relatively little (Charbonneau, 1971; Delvaux, 2006). Charbonneau (1971) used tracings of X-ray images to describe the articulation of QF nasal vowels by two male speakers. He found that, in general, the QF nasal vowels are "much more closed" than those of NMF (p. 294). He states clearly that /ɛ̃/ is realized with a tongue height between [ɛ] and [e], that /œ̃/ is realized with a tongue height between [ø] and [y], and that /ɑ̃/ is realized with a higher tongue position than the anterior [a]. More precisely, with regard to /ɛ̃/-/ɛ/, /œ̃/-/œ/, and /ɑ̃/-/ɑ/, he states that every nasal vowel is realized with a higher tongue position than its oral counterpart, but with no difference in horizontal tongue position.

With regard to /ɔ̃/-/ɔ/, there are some seemingly contradictory statements. On the one hand, Charbonneau states that /ɔ̃/ is realized with a vertical tongue position between [ɛ] and [a]; this would be a relatively low realization for /ɔ̃/ (i.e., [ɔ̞̃] or [ɒ̝̃]). On the other hand, he states elsewhere that /ɔ̃/ is realized with approximately the same tongue height as [ɔ], but is very slightly more retracted. Overall, the precise lingual articulation of [ɔ̃] in QF is unclear from Charbonneau (1971)'s data and description, but it seems likely that it is a slightly lowered and retracted tongue position compared to [ɔ]. Finally, Charbonneau (1971, p. 298) states that the Quebec speakers from urban areas (especially those from the Montreal region[9]) have not merged /œ̃/ with /ɛ̃/, but maintain the lip rounding which distinguishes the former from the latter. This is contrary to the description of QF nasal vowels by Gendron (1966), but in agreement with those by Gendron (1968) and Walker (1984).

With regard to diphthongized realizations, Charbonneau (1971, pp. 297–300) only makes reference to a diphthong variant of the nasal vowel /ɛ̃/ in open syllables, but to diphthong variants of all four nasals /ɛ̃/, /ɑ̃/, /ɔ̃/, and /œ̃/ in closed syllables. Concerning the diphthong realization of /ɛ̃/ in both open and closed syllables, he states that it is "very closed" and "strongly nasalized" in its final [temporal] portion, claiming that it is sometimes confused with [e] to the French (i.e., of France) ear (p. 298). However, he does not specify the dynamic articulatory characteristics of the diphthong variant of this, or any of the other nasal vowels.

Finally, with regard to the temporal extent of velo-pharyngeal coupling, Charbonneau (1971, p. 297) states that the QF nasal vowels in his study are composed of an oral segment, a nasalized segment, a nasal segment, and a variable nasal consonant segment. He states (p. 297; quoting Straka (1955, p. 246)) that, when this nasal consonant occurs, it could be a:

> "*reste de l'ancien [n] ou [m] ou le début de la consonne subséquente qui a été... nasalisée accidentellement par la voyelle nasale à la fin de laquelle le voile du palais ne s'est pas relevé à temps.*"
>
> 'remainder of the old [n] or [m] or the beginning of the following consonant which was... accidentally nasalized by the nasal vowel, at the end of which the velum wasn't raised in time.' (*my translation*)

More recently, Delvaux (2006) used synchronized ultrasound, video, and nasal airflow data to simultaneously monitor lingual articulation, labial articulation, and the timing of velo-pharyngeal opening, for five speakers of QF[10]. However, the research is concentrated on the articulation of the nasal vowels themselves, and not on the articulatory differences between the nasal vowels and their oral counterparts; thus, conclusions regarding oral-nasal articulatory differences cannot be drawn from this work in the same way as for Charbonneau (1971). With regard to aerodynamics, she finds evidence for denasalization or delayed nasalization of the nasal vowels. This phenomenon is observed for all vowels, but is greatest for [ɛ̃]. With regard to oral articulation, Delvaux finds that diphthongized variants of the

[9] Given the wording here, the reader is led to believe that Charbonneau is making anecdotal reference beyond the two speakers in his study.
[10] Delvaux does not specify where in Quebec these five speakers are from, only that they are "*québécois*".

nasal vowels can exist in open syllables as well as closed syllables, which is in (at least, partial) contradistinction to descriptions from Gendron (1966, 1968); Walker (1984); however, she notes that the diphthongization is less apparent in open syllable context. Ultrasound lingual traces are provided for one speaker's production of the open syllable nonce word forms /pɛ̃/, /pœ̃/, /pɑ̃/, and /pɔ̃/, and the articulatory manifestations of the vowels are described in the following ways:

- /ɛ̃/ manifests the greatest articulatory change throughout the production of the vowel, with the tongue moving forward and toward the palate, resulting in [æɛẽʲ̃].
- Less dynamic articulation is noted for the realization of /ɔ̃/: rounding of the lips and a slight retraction of the tongue, resulting in [ɔ̃õ].
- Raising and fronting of rounded /œ̃/, similar to its unrounded counterpart /ɛ̃/, is noted: [œ̃ø̃ʷ̃].
- Finally diphthongization in the realization of /ɑ̃/ was slight, and only found in the closed syllable /ɑ̃s/, and was only produced by 4 out 5 speakers: [aɑ̃ʷ̃s].

In summary, the articulatory evidence provided by Charbonneau (1971) and Delvaux (2006) support—in part—descriptions of QF nasal vowels by Gendron (1966, 1968) and Walker (1984), and acoustic evidence by Martin (2002), though there are some discrepancies. Specifically, both Charbonneau (1971) and Delvaux (2006) found evidence of fronting and/or raising of /ɛ̃/, resulting in (through inference) [ɛ̃ẽ] (Charbonneau, 1971) or [æɛẽʲ̃] (Delvaux, 2006); this vowel is described as [ẽ] by both Walker (1984) and Martin (2002), though Gendron (1966) claims that it is not quite as far forward/high as [ẽ]. Although Walker (1984) claims that diphthongization of the nasal vowels does not occur in open, stressed syllables, evidence of diphthongized variants in both open and closed syllables is observed by both Charbonneau (1971) (for the production of /ɛ̃/) and Delvaux (2006) (for the production of /ɛ̃/, /œ̃/, and /ɔ̃/). With regard to the realization of /ɑ̃/, neither Charbonneau (1971) nor Delvaux (2006) find evidence for the more fronted tongue position [ã] described by Gendron (1966) or [æ̃] described by Walker (1984); these articulatory results partially support the acoustic evidence presented by Martin (2002), who found some evidence for a variant of a more advanced tongue position as [ã] for males (though not for females), but no evidence of [æ̃] for any of the speakers. The slight tongue retraction and rounded labial configuration for the realization of /ɔ̃/ observed by Delvaux (2006), resulting in [ɔ̃õ], and the tongue raising/retraction observed by Charbonneau (1971), resulting in [ɑ̃ɔ̃], support the descriptions provided by Walker (1984) and Martin (2002) for a diphthong realization of this vowel. However, as was found for the diphthong realization of /ɛ̃/, the slight dynamic articulation [ɔ̃õ] observed by Delvaux (2006) was evidenced in an open, stressed syllable, contra Walker (1984).

2.2.3 Nasal vowel chain shifts

One of the reasons for the decision to investigate in this study the articulation of nasal vowels in NMF and QF, specifically, is that the nasal vowel *systems* themselves are reported to manifest in drastically different ways in the two dialects (Maddieson, 1984; Fónagy, 1989; Malderez, 1991; Hansen, 2001b; Walker, 1984, *inter alia*; see 1.2.2 for a general description). Specifically, the two nasal vowel systems are said to be undergoing a “chain shift”, but in opposing directions. A chain shift happens when the realization of one phoneme in a system is altered diachronically to such an extent that it nears the realization of another phoneme in the system (Hock, 1991, pp. 156–157). If, when this occurs, the realization of another phoneme (or multiple phonemes) in the system is then modified in turn, this interaction is referred to as a chain shift. There are two types of chain shifts: “push” chains and “pull” chains. When the initiating phoneme encroaches upon the space of the realization of another phoneme, causing the latter phoneme to “be pushed” and manifested with a different realization in order to avoid a category merger, this is known as a push chain. When the initiating phoneme leaves a space in the system which is then occupied by another which is “pulled” into the space where the initiating phoneme was previously realized, this is known as a pull chain. When applied to the whole vowel quadrilateral, nasal vowel subsystems can undergo chain shifts in, broadly, two directions: counter-clockwise and clockwise throughout the vowel space, respectively. These chain shift directions—as concerns the realizations of /ɛ̃/, /ɑ̃/, and /ɔ̃/—are shown in Figure 2.3 (after Fagyal et al. (2006)). Nasalization, as argued above, imposes unique acoustic modifications on vowels (see 2.1.1). For this reason, I will not discuss or consider in any specific way Labov’s well-known three principles of chain-shifting (Labov, 1994)[11], since it may be the case that nasal vowels act differently than oral vowels as part of chain shifts, with regard to their tendencies for directional movement in the vowel space. In any case, this discourse is outside the scope of the current study.

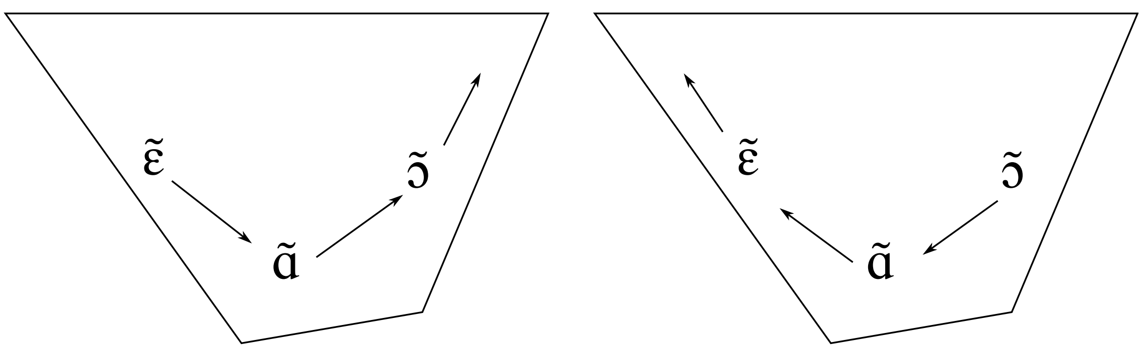


Figure 2.3: Counter-clockwise (left) and clockwise (right) nasal vowel chain shifts.

[11]These principles are:

1. Long vowels rise.
2. Short vowels and nuclei of upgliding diphthongs fall.
3. Back vowels move to the front.

In order to demonstrate how these chain shifts are manifested in NMF and QF, we will compare the combined results from lingual articulatory research in these two dialects. A summary of the previous findings on the lingual articulation of nasal vowels in NMF and QF are given in Table 2.1[12]. With regard to NMF, taking the results of the different Northern dialects together, the general articulatory tendencies are as follows. /ɛ̃/ is lowered and retracted (realized possibly as [æ̃], nearing the space of [ɑ̃]). There is some cross-study variation for the articulation of /ɑ̃/, but it seems that /ɑ̃/, in turn, is retracted, and possibly lower, with lip rounding and/or protrusion (realized possibly as [ɒ̃], nearing the space of [ɔ̃]). There is much more cross-study variation for the articulation of /ɔ̃/, but it seems that /ɔ̃/ is retracted, in turn, and possibly higher, with lip rounding (realized possibly as [õ]). This is an example of a *counter-clockwise* chain shift, as demonstrated in the left-most image in Figure 2.3.

Table 2.1: Summary of results from previous articulatory research on French nasal vowel production.

Dialect	[ɛ̃] v. [ɛ]		[ɑ̃] v. [a]		[ɔ̃] v. [o]	
	Lingual	Labial	Lingual	Labial	Lingual	Labial
Northern Metropolitan French Straka (1965)	lower, retracted		lower, retracted	rounded		rounded
Northern Metropolitan French Brichler-Labaeye (1970)	lower, retracted	*N/A*	lower	*N/A*		*N/A*
Northern Metropolitan French Zerling (1984)	retracted		retracted	protruded	retracted	rounded
Northern Metropolitan French Montagu (2002)	*N/A*	*N/A*	*N/A*	rounded, protruded	*N/A*	rounded, retracted
Alsatian French Bothorel et al. (1986)	*not conclusive*	more open, less spread	higher, retracted	protruded	advanced	rounded
Belgian French Delvaux et al. (2002)	lower, retracted		lower, retracted	rounded	higher, retracted	rounded
Quebecois French Charbonneau (1971)	higher, raising		higher		lowered, retracted	
Quebecois French Delvaux (2006)	raising, fronting				slight retraction	rounded

With regard to QF, the nasal vowel sub-system of QF has been described by Walker (1984, p. 82) as undergoing a *clockwise* chain shift (right-most image in Figure 2.3)[13]. However, the acoustic evidence shown in Martin (2002) and, especially, the articulatory evidence provided by Charbonneau (1971) and Delvaux (2006) does not fully support this claim. What is clear from both the descriptions and the articulatory evidence reported previously in the literature is that the lingual realization of /ɛ̃/ is fronted and raised, which would be consistent with the diachronic change associated with a clockwise chain shift. However, since there is little consistent evidence of a fronted lingual position associated with realization of /ɑ̃/, this fronting of /ɛ̃/ to [ẽ] may not be caused by the realization of /ɑ̃/ advancing upon the space of

[12] Labial results from Brichler-Labaeye (1970) and lingual results from Montagu (2002) are listed as '*N/A*' in the table, since these articulations were not measured in the respective studies. Additionally, labial results for the production of /ɛ̃/-/ɛ/ from Montagu (2002) are listed as '*N/A*', since this vowel pair was not studied.

[13] Acoustic and articulatory evidence for a clockwise chain shift in the realizations of nasal vowels has recently been found for Hindi, as well (Shosted et al., 2012a).

[ɛ̃]. Furthermore, the fronting and raising of /ɛ̃/ is *dynamic*, as evidenced by articulatory evidence: [ɛ̃ẽ] (Charbonneau, 1971) or even [æɛẽʲ̃] (Delvaux, 2006). Therefore, it is unclear whether the advanced, higher tongue position is a result of a systematic, diachronic change in the same manner as the nasal vowel system in NMF. Indeed, the results from Delvaux (2006) suggest that it is only the latter part of the dynamic articulation which is fronted and raised (i.e. [–ẽʲ̃]), whereas the beginning portion of the dynamic articulation actually arises from the lower articulatory space of [æ] (i.e. [æɛ–]), near the articulatory location of the fronted [æ̃] articulation of /ɑ̃/ claimed by Walker (1984). However, as previously mentioned, neither Charbonneau (1971), nor Delvaux (2006), nor Martin (2002) find consistent evidence for the more fronted tongue position [æ̃] described by Walker (1984), which does not support the claim for a clockwise chain shift. Finally, the acoustic evidence from Martin (2002) does clearly suggest a realization of [ɔ̃] rather than [õ]. Since [ɔ̃] is somewhat near the acoustic space of [ɑ̃], a fronting of /ɑ̃/ to either [ã] or [æ̃] would be consistent with a chain shift in the realization of QF nasal vowels. However, given the lack of either articulatory or acoustic evidence for a more fronted realization of /ɑ̃/ across speakers in Charbonneau (1971), Delvaux (2006), and Martin (2002), it is not clear that the lowered realization of [ɔ̃] is evidence which necessarily supports a clockwise chain shift.

2.3 Articulatory enhancement and attenuation of nasalization

It has been argued that phonetic realizations of the same phonemic vowel can be produced using many different configurations of the individual articulators (Maeda, 1990, p. 132). The numerous degrees of freedom in such a system might be constrained by covariation in articulatory position (Lindblom, 1990; Noteboom and Eefting, 1992). This covariation, compensation, or inter-articulatory coordination is also known as “motor equivalence” (Abbs, 1986; Hughes and Abbs, 1976; MacNeilage, 1970; Perkell et al., 1993) and is supported in part by studies suggesting that speakers can maintain the integrity of an acoustic signal even in the face of articulatory perturbation (Abbs and Gracco, 1984; Löfqvist, 1990, *inter alia*) and that speakers sometimes employ one articulatory strategy in order to compensate for the acoustic effect of another in natural language (Arai, 2004; Carignan et al., 2011). While each gesture arguably has a unique acoustic consequence, some gestures (even at distant points in the vocal tract) have similar acoustic consequences and thus may combine to synergistically enhance a particular acoustic property (Diehl and Kluender, 1989; Diehl et al., 1991a, 2001; Kingston and Diehl, 1994; Kluender, 1994; Parker et al., 1986). In addition to basic articulatory and acoustic information, speakers may store in memory information about how to enhance the contrasts between sounds (Keyser and Stevens, 2006); it is reasonable that speakers even store information about how to compensate for “contextual perturbation”, arising from the phonetic environment (Ohala, 1993b, p. 245).

In 2.1.1 it was established that one of the acoustic effects of velo-pharyngeal coupling is a centralization of the vowel space along the F1 dimension: nasalized high vowels are lowered in the acoustic space and nasalized low vowels are raised in the acoustic space. Moreover, one of the perceptual effects of velo-pharyngeal coupling is a centralization of the vowel space along the F1′ dimension: nasalized high vowels are perceived as lower and nasalized low vowels are perceived as higher. In the light of motor equivalence, where multiple articulatory configurations can result in the same acoustic manifestation, we can view the relation between the acoustic centralization of the vowel space along the F1/F1′ dimension and lingual centralization of the "articulatory space" in terms of articulatory *enhancement* and *attenuation* of nasalization. For example, nasalization of /i/ will result in a raised F1/F1′ when compared to a non-nasalized [i]; a lowered tongue position for the production of [i] will also result in a raised F1/F1′ when compared to a non-lowered [i]. Thus, a lowered tongue position for the production of a nasalized [ĩ] can be considered an *enhancement* of the F1-related acoustic effect of nasalization. Conversely, a raised tongue position (which will lower F1/F1′) for the production of nasalized [ĩ] can be considered an *attenuation* of the F1-related acoustic effect of nasalization, an articulation whose acoustic effect (lowering F1/F1′) reduces or works against the F1-related acoustic effect of velo-pharyngeal coupling (raising F1/F1′). Contrariwise, articulatory enhancement and attenuation of the F1/F1′ centralization of vowel nasalization would work in the opposite manner: a raised tongue position for nasalized low vowels (lowering F1/F1′) can be considered to be an enhancement of nasalization (lowering F1/F1′), while a lowered tongue position for nasalized low vowels (raising F1/F1′) can be considered an attenuation of nasalization (lowering F1/F1′).

Articulatory enhancement/attenuation of vowel nasalization has the potential to lead to different consequences for the phonemic status of vowel nasalization depending upon whether the language in question has vowel nasality as a phonemic or a phonetic characteristic. Table 2.2 displays a schematic representation of these possibilities.

Table 2.2: Schematic representation of possible articulatory enhancement or attenuation for vowel systems with, respectively, phonemic or phonetic vowel nasalization.

	Enhancement	Attenuation
Phonemic	Maintain phonemic distinction	Phonemic merger
Phonetic	Phonemic split	Resist phonemic distinction

In a language where vowel nasality is phonemic (like French), an articulatory enhancement of the acoustic centralization of a particular nasal vowel can help maintain the phonemic distinction of a nasal vowel and its oral congener. For example, if [i] and [ĩ] are phonemically distinct in a language, a lowered tongue position for the production of [ĩ] (which is predicted to raise F1/F1′) is likely to enhance the raising of F1/F1′ caused by velo-pharyngeal coupling, and could help maintain the phonemic distinction between [i] and [ĩ]. Conversely, an articulatory attenuation of the acoustic centralization of a particular nasal vowel could eventually lead to a phonemic merger. For example, if [i] and [ĩ] are phonemically distinct in a language, a raised tongue position for the production of [ĩ] (which is predicted to lower F1/F1′) is likely to attenuate the raising of F1/F1′ caused by velo-pharyngeal coupling, and the F1/F1′ of both [i] and [ĩ] could be brought into the same frequency range. With the variation of this acoustic (and perceptual) variable minimized, phonemic merger of these two vowels can be argued to have a greater likelihood to occur[14].

On the other hand, in a language where nasality is a phonetic characteristic of vowels (like English), the possible phonemic ramifications of articulatory enhancement and attenuation of vowel nasalization are predicted to be very different. For example, if [i] and [ĩ] are allophones in a language (due to the presence or absence of co-articulatory nasalization), a lowered tongue position for the production of [ĩ] (which is predicted to raise F1/F1′) is likely to enhance the raising of F1/F1′ caused by velo-pharyngeal coupling, which could eventually lead to a phonemic split of the two vowels—of course, depending on multiple other factors—due to the even greater acoustic (and perceptual) separation than that caused by velo-pharyngeal coupling alone. Conversely, a raised tongue position for the production of [ĩ] (which is predicted to lower F1/F1′) is likely to attenuate the raising of F1/F1′ caused by velo-pharyngeal coupling, and the F1/F1′ of both [i] and [ĩ] could be brought into the same frequency range. This articulatory attenuation of the formant-frequency-related acoustic effects of vowel nasalization could, then, help resist the phonemic split of the oral vowel and its nasal congener. Articulatory evidence suggests that speakers of American English do, indeed, modify the vertical position of the tongue during the production of phonetically nasalized vowels in a way which attenuates the change of F1/F1′ caused by velo-pharyngeal coupling, possibly as a way of compensating for this acoustic effect (Arai, 2004; Carignan et al., 2011)[15].

Enhancement may have occurred in the history of languages that presently have phonemic nasal vowels, resulting in an articulatory centralization of the vowel space (Beddor, 1982; Hajek, 1997; Sampson, 1999). Height centralization is well-documented typologically for phonemic nasal vowels: in a variety of languages, under the influence of nasalization, high vowels are transcribed as lower and low vowels are transcribed as higher (Beddor, 1982, p. 91–104). Take, for example, the lowering of [i] in the evolution of the word *vinum* 'wine' from Latin (where oral [i] and nasal [n] are heterosyllabic), to Old French (OF; where [ĩ] is phonetically nasalized via regressive assimilation to the tautosyllabic [n]), to Northern Metropolitan French (NMF; where "i" is retained in the orthography, but the realization of the fully phonemic nasal vowel is lower in the vowel space) (Sampson, 1999):

[14] Of course, such a merger would be mitigated by other factors (e.g., nasalization is not only driven by changes in F1/F1′, but also formant amplitude, formant bandwidth, acoustic zeros, etc., discussed in 2.1.1), but I contend that the overlap of F1/F1′ in two adjacent vowel spaces would be a contributing factor if a merger were to occur.

[15] It is important to note that none of these articulatory/acoustic effects exert a deterministic influence on vowel systems. Sound change is a complex phenomenon where multiple factors play a role. None of these scenarios do, therefore, suggest that sound change related to nasalization is teleological. The combinatory possibilities outlined in Table 2.2 and detailed in this section represent a summary of potential outcomes of enhancement/attenuation of nasalization in various vowel systems.

Latin		OF		NMF
vinum [w**i**num]	⇒	*vin* [v**ĩ**n]	⇒	*vin* [v**ɛ̃**]

It is likely that this articulatory centralization of the vowel space, which is an enhancement of the acoustic centralization of nasalization, is more than mere coincidence. Given the perceptual confusion between F1′ change due to velo-pharyngeal coupling with F1′ change due to lingual configuration described in 2.1.1 (Beddor et al., 1986; Krakow et al., 1988), it is likely that there is a tendency for the acoustic centralization of the vowel space due to nasalization to be misperceived as an *articulatory* centralization, and to be produced as such by subsequent generations, thus leading to a centralization of lingual height as vowel nasalization becomes phonologized in a language (Ohala, 1975, 1981, 1993a,b, 1996).

2.4 Acoustic ambiguity: The many-to-one problem

Nasal vowels typify speech production's classic "many-to-one problem": situations where a variety of articulations may each result in a comparable acoustic output. For example, a lowered F1 frequency observed in [ã] (with respect to oral [a]) may be due to nasal coupling, to tongue raising, to lip rounding, to lip protrusion, to pharyngeal expansion, or to some combination of these articulations. Accurately describing the acoustic-articulatory mapping of nasal vowels is challenging because VPO, tongue position, labial configuration, pharyngeal constriction/expansion, and even velic lowering influence acoustic spectra and their perception in overlapping ways.

If the degree of VPO is known or estimated, acoustic models of nasalization (Feng and Castelli, 1996; Maeda, 1993; Pruthi et al., 2007; Rong and Kuehn, 2010) may help disambiguate oral articulation and VPO. While VPO can be estimated using a variety of techniques (Rong et al., 2011; Baken and Orlikoff, 2000, ch. 11), the acoustic consequences of nasalization also depend on measures of nasal tract geometry, which are even more difficult to assess than VPO itself (Dang and Honda, 1996; Engwall et al., 2006; Pruthi et al., 2007). Another approach is to physically measure the configuration of the oral articulators during the production of oral and nasal vowel congeners while simultaneously recording the acoustic output. The conflation of the effects of these articulations in the acoustic signal creates an ambiguity which makes inferring the articulatory configurations from the acoustics an intractable problem. However, simultaneous acquisition of articulatory and acoustic signals can disambiguate this ambiguity. Multiple articulations call for multiple articulatory methodologies in order to tease apart the relative articulatory contributions to the acoustic signal, an approach which I investigate in this study.

Chapter 3

Research Questions and Hypotheses

3.1 Summary of previous research

The previous findings for articulatory research on NMF nasal vowels compared to their oral counterparts, as described in 2.1.2 and 2.1.3, can be summarized as shown in Table 3.1. If we assume that the oral articulation of the nasal vowels in the Alsatian and Belgian French varieties can be generalized to NMF[1], the oral articulation of the three nasal vowels [ɛ̃, ɑ̃, ɔ̃], as compared to their oral congeners [ɛ, a, o], are as follows for NMF:

- [ɛ̃] is produced with a more retracted, and possibly lower tongue position than [ɛ]. There is not much evidence suggesting that there is 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.

With regard to QF, given that the research question in Delvaux (2006) involved describing the oral articulatory configurations of the nasal vowels, and not the *differences* in oral articulatory configurations between the nasal vowels and their oral congeners, it would be problematic to use the articulatory evidence from that study to infer such differences in the same way as for NMF in Table 3.1. However, we can use the articulatory evidence from Charbonneau

[1] Bothorel et al. (1986); Delvaux et al. (2002); Engwall et al. (2006) seem to consider these generalizations reasonable, mentioning no difference between the dialects in their respective studies and NMF. Bothorel et al. (1986, p. 3) state simply that the Alsatian speakers were "without regional accent". Delvaux et al. (2002) and Engwall et al. (2006) do not comment on any differences between Belgian French and NMF, but Delvaux et al. (2008, p. 582) state that "middle-class Belgian French is close to standard Parisian French", detailing some of the differences between the two dialects (p. 583), which do not seem to pose an issue for the comparison of oral and nasal vowels. However, I recognize that the dialectal variation in the French-speaking world—even within Europe—is clearly an important factor, and that these generalizations should certainly be considered with moderation.

Table 3.1: Summary of results from previous articulatory research on NMF nasal vowel production.

Dialect	[ɛ̃] v. [ɛ]		[ɑ̃] v. [a]		[ɔ̃] v. [o]	
	Lingual	Labial	Lingual	Labial	Lingual	Labial
Northern Metropolitan French Straka (1965)	lower, retracted		lower, retracted	rounded		rounded
Northern Metropolitan French Brichler-Labaeye (1970)	lower, retracted	*N/A*	lower	*N/A*		*N/A*
Northern Metropolitan French Zerling (1984)	retracted		retracted	protruded	retracted	rounded
Northern Metropolitan French Montagu (2002)	*N/A*	*N/A*	*N/A*	rounded, protruded	*N/A*	rounded, retracted
Alsatian French Bothorel et al. (1986)	*not conclusive*	more open, less spread	higher, retracted	protruded	advanced	rounded
Belgian French Delvaux et al. (2002)	lower, retracted		lower, retracted	rounded	higher, retracted	rounded

(1971) (summarized in Table 3.2), as well the acoustic evidence from Martin (2002) to infer the articulatory differences in the production of QF nasal vowels. The relative differences in F1 and F2 frequency of the three nasal vowels [ɛ̃, ɑ̃, ɔ̃], as compared to their oral congeners [ɛ, a, o] are given in Table 3.3. Combining the articulatory evidence with the acoustic evidence used to infer lingual position, the lingual configuration of the three nasal vowels [ɛ̃, ɑ̃, ɔ̃], as compared to their oral congeners [ɛ, a, o], are as follows for QF:

- [ɛ̃] is produced with a slightly higher and slightly more advanced tongue position than [ɛ], for males; [ɛ̃] is produced with a slightly more advanced tongue position than [ɛ], for females.

- [ɑ̃] is produced with a higher and more retracted (with inter-speaker variability) tongue position than [a], for males; [ɑ̃] is produced with a higher and slightly retracted tongue position than [a], for females.

- [ɔ̃] is produced with a lower and more retracted tongue position than [o], for both males and females.

Table 3.2: Summary of results from previous articulatory research by Charbonneau (1971) on QF nasal vowel production.

Dialect	[ɛ̃] v. [ɛ]		[ɑ̃] v. [ɑ]		[ɔ̃] v. [ɔ]	
	Lingual	Labial	Lingual	Labial	Lingual	Labial
Quebecois French: males Charbonneau (1971)	higher		higher		lowered, retracted	

Table 3.3: Summary of results from acoustic research by Martin (2002) on QF nasal vowel production.

Dialect	[ɛ̃] v. [ɛ]		[ɑ̃] v. [a]		[ɔ̃] v. [o]	
	F1	F2	F1	F2	F1	F2
Quebecois French: males Martin (2002)	lower	higher	lower	lower (*variable*)	higher	higher
Quebecois French: females Martin (2002)		higher	lower	lower	higher	higher

3.2 Research questions and hypotheses

As shown in 2, and summarized above in 3.1, research has previously been performed on the differences in oral articulatory configurations of nasal vowels and their oral vowel counterparts in both NMF and QF. What is missing from the current research on nasal vowel production in French, however, is an analysis of the articulatory configurations of nasal vowels and their oral vowel counterparts, as well as the acoustic manifestations of these configurations, and if possible for a relatively large speaker population, in both of these French dialects; meeting this need is the aim of this dissertation study.

I will use electromagnetic articulography (EMA) to observe lingual and labial articulatory configurations, aerodynamic equipment to verify the presence or absence of velo-pharyngeal coupling[2], and a microphone to measure the acoustic signal, after Carignan et al. (2011); Shosted et al. (2012a). EMA has a number of advantages in articulatory speech research. Firstly, the data collected is automatically quantified (in either mm or cm, depending on the particular EMA system used), avoiding the need to create a method of quantifying signals in a meaningful way. For this reason, EMA provides an advantage over other articulatory methodologies such as ultrasound or MRI, with which static and/or dynamic structures need to be first located, then quantified, in order to perform statistical analyses. Secondly, EMA is both relatively unobtrusive and insensitive to non-metal equipment and low-mass metal equipment. For this reason, EMA allows for simultaneous use of a non-metal aerodynamic mask to be placed on the nose for measuring nasal airflow, and a low-mass metal head-mount microphone for measuring acoustics. Using a methodology like MRI, on the other hand, would pose difficulty for additional equipment to be included in the methodology, for fear of causing harm to the speaker and/or the equipment, and because of electromagnetic noise introduced to the MRI signal. Thirdly, EMA is a silent-running system, which allows for the simultaneous acquisition of high-fidelity acoustic recording. MRI, on the other hand, produces large amounts of physical noise which is recorded by the microphone; therefore,

[2]The inclusion of aerodynamic equipment was due to the fact that the current study is a part of a larger research program, which includes investigation of the oral articulation of nasal and nasalized vowels in American English (Carignan et al., 2011), Hindi (Shosted et al., 2012a), French (the current study), and Brazilian Portuguese. It was desirable to maintain the same methodology across all of the experiments in this program, therefore measurements of nasal airflow were included in the current study. However, since the research questions investigated here do not necessitate nasal airflow measures, the airflow data will not be presented in this dissertation, except for as one of the evidences given in 7.6 for the presence of a nasal coda consonant in QF.

even with current noise-cancellation technology, reliable formant tracking in the acoustic signal is prohibitively difficult. Taking the above points into consideration, EMA technology is likely an appropriate methodology for measuring oral articulation within the constraints of the research questions for this study.

By studying the position and movement of the tongue and lips during oral and nasal vowels, while simultaneously recording the acoustic signal, we are able to separate the effects of VPO and oral articulations on the acoustic output of the vocal tract. Accordingly, we can predict four types of differences between oral/nasal vowel pairs in which the nasal vowel manifests (after Shosted et al. (2012a)):

- (Type-I): No acoustic or oral articulatory difference (with respect to the oral vowel).
- (Type-II): Oral articulatory difference with no acoustic difference.
- (Type-III): Acoustic difference with no articulatory difference.
- (Type-IV): Both articulatory and acoustic differences.

There are a number of hypotheses which will be tested in this study. Previous research has revealed acoustic differences between the nasal vowels [ɛ̃, ɑ̃, ɔ̃] and the oral vowels [ɛ, a, o] in both NMF and QF. If nasal vowels and their oral counterparts differ solely with respect to the presence or absence of velo-pharyngeal coupling, then I predict to find evidence for only Type III differences in the current study. If nasal vowels and their oral counterparts differ primarily with respect to the configurations of the oral articulators, then I predict to find evidence for only Type IV differences. If, however, the differences between nasal vowels and their oral counterparts are due to a combination of velo-pharyngeal coupling and change in oral articulatory configurations, then I predict to find evidence of both Type III and Type IV differences.

I digress for a moment to clarify the IPA transcriptions of the nasal vowels used in this study. The IPA transcriptions for [ɛ̃, ɑ̃, ɔ̃] and [ɛ, a, o] are conventional for the French phonetics literature (Fougeron and Smith, 1999). It is not clear, however, that these transcriptions are intended to represent the synchronic oral articulation of these vowels (see 1.2.2 for discussion on the IPA symbols and the realizations of these vowels). It is not clear, either, that these transcriptions are intended to be a normative teaching tool for modern, synchronic pronunciation. For example, the use of the symbol <ɔ> does not necessarily imply that the mid back nasal vowel [ɔ̃] is, or should be articulated with a lower tongue position than the mid back oral vowel [o], nor does the use of the symbol <ɛ> imply that the mid front nasal vowel [ɛ̃] is, or should be articulated with the same lingual position as the mid front oral vowel [ɛ]. Instead, the transcriptions of the nasal vowels 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 (i.e., imposed normative pronunciation). The situation is further complicated by the fact that [ɑ] and [ɔ] rarely—never, for some speakers—appear in open syllables in modern NMF. Therefore, [ɑ] and [ɔ] should not be 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 and Smith, 1999, p. 78). With these factors considered, I will start out by using the traditional IPA transcriptions for the nasal vowels [ɛ̃, ɑ̃, ɔ̃] to compare to their respective oral counterparts [ɛ, a, o], and I will make suggestions on how to adapt phonetic symbols currently used in both dialects of French to the acoustic/articulatory realities suggested by this study.

With regard to the NMF dialect, based on the findings from previous studies, I predict to observe the following differences in oral articulatory configurations of the nasal vowels [ɛ̃, ɑ̃, ɔ̃] compared to their oral counterparts [ɛ, a, o]:

- [ɛ̃] will be produced with a lower (observed in 3/5 studies), more retracted (observed in 4/5 studies) tongue position than [ɛ]. There will be no differences in labial articulation (observed in 3/4 studies) between [ɛ̃] and [ɛ].

- [ɑ̃] will be produced with a lower (observed in 3/5 studies), more retracted (observed in 4/5 studies) tongue position than [a]. [ɑ̃] will also be produced with a more rounded and/or protruded (observed in 5/5 studies) labial configuration than [a].

- [ɔ̃] will be produced with no difference in tongue height (observed in 4/5 studies) and no difference in horizontal tongue position (observed in 2/5 studies). [ɔ̃] will also be produced with a more rounded and/or protruded (observed in 5/5 studies) labial articulation than [o].

With regard to the QF dialect, my predictions for oral articulation of the nasal vowels with respect to the oral vowels are based on acoustic evidence from Martin (2002) for female speakers and articulatory evidence from Charbonneau (1971). My predictions of dynamic articulation of the nasal vowels is based on articulatory evidence from Delvaux (2006). I predict to observe the following differences in oral articulatory configurations of the nasal vowels [ɛ̃, ɑ̃, ɔ̃] compared to their oral counterparts [ɛ, a, o], and the following dynamic articulations:

- At the midpoint of the vowel, [ɛ̃] will be produced with a more advanced, and possibly higher tongue position than [ɛ]. The dynamic lingual articulation will be rising and fronting from the beginning to the end of the vowel production.

- At the midpoint of the vowel, [ɑ̃] will be produced with a higher, more retracted tongue position than [a]. No dynamic articulation will be manifested in the open syllable condition used in this study.

- At the midpoint of the vowel, [ɔ̃] will be produced with a lower tongue position than [o]; results for horizontal tongue position are conflicting and, therefore, a prediction cannot easily be made. However, the dynamic lingual articulation will be slight retraction, and the dynamic labial articulation will be increased rounding, from the beginning to the end of the vowel production.

Additionally, the large speaker population in the current study will allow for investigation of the cross-study variation observed in previous research on NMF. This variation is summarized thus:

- Some evidence suggests that [ɛ̃] is produced with a more retracted and lower tongue position than [ɛ], while other evidence suggest only a more retracted tongue position. Additionally, some evidence suggests a more open, less spread labial articulation for [ɛ̃] compared to [ɛ], while other evidence does not.

- Some evidence suggests that [ɑ̃] is produced with a lower tongue position than [a]; some evidence suggests a more retracted tongue position; some evidence suggests both a lowered and more retracted tongue position; some evidence suggests a *higher* and more retracted tongue position. Additionally, some evidence suggests a more protruded labial articulation for [ɑ̃] compared to [a]; some evidence suggests a more rounded labial articulation; some evidence suggests both a more protruded and more rounded labial articulation.

- Some evidence suggests no difference in lingual position for [ɔ̃] compared to [o]; some evidence suggests a more retracted tongue position; some evidence suggests a more advanced tongue position; some evidence suggests a higher and more retracted tongue position.

Given that the speaker populations are between 1 and 4 for all of these previous studies except for one Montagu (2002), it is difficult to ascertain whether this variation is due to difference across studies (e.g. methodologies, types of measures, etc.) or to differences between individual speakers. If, with a relatively large speaker population in the NMF dialect, I find inter-speaker uniformity in the oral articulatory configurations used to produce the nasal–oral distinction and uniformity in the acoustic realizations, I can surmise that the cross-study variation summarized above is due to differences across studies. If I find inter-speaker variation in the oral articulatory configurations which is similar to this cross-study variation, but with relatively little corresponding variation in the acoustic realizations, I can conclude that the cross-study variation is not due to differences across studies, but rather to inter-speaker variation in the oral articulation of the nasal vowels. If I find inter-speaker variation in both the oral articulatory configurations and the acoustic realizations, I can conclude that the cross-study variation is due to variability in the realizations of the nasal vowels in the NMF dialect.

Methodology

Chapter 4

Experimental Design

4.1 Speakers

The participants in this study were all female native speakers of NMF or QF. 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 (see 2.2.1). Specifically, the observations from Engwall et al. (2006) suggest that female speakers, who generally have a shorter nasal tract than male speakers, make use of greater oral articulatory differences in the oral–nasal vowel distinction compared to male speakers. Therefore, if oral articulatory modifications are to be observed, they are predicted to be observed for the nasal vowel productions of female speakers more likely than for the nasal vowel productions of male speakers. In total, 13 NMF speakers and two QF speakers were recorded.

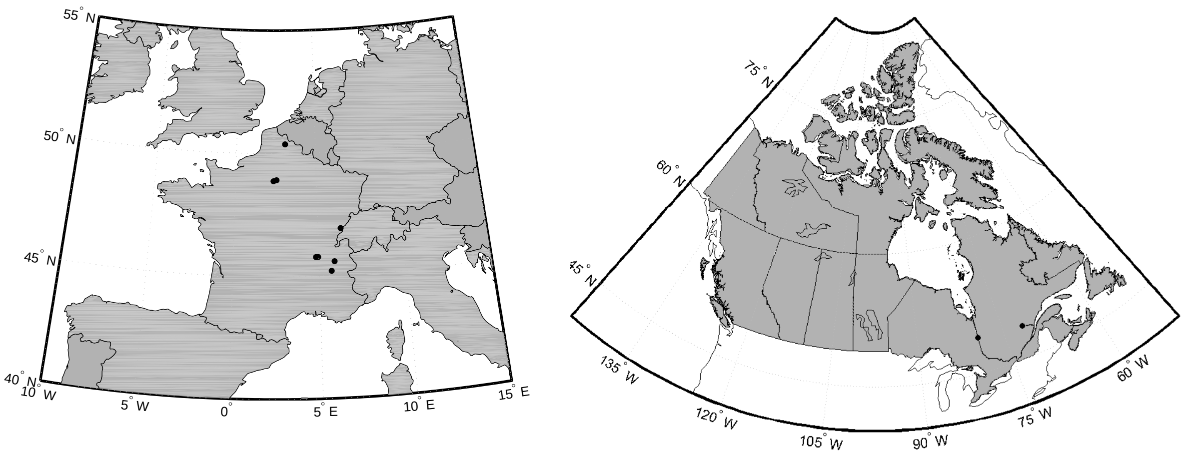
The sociolinguistic background information of the speakers are given in Appendix B, including age, place of birth, and parents' origins[1]. This background information can be summarized as follows:

- For the "Northern Metropolitan French" dialect, native speakers were selected who are from urban areas of the central/northern region of France, as defined in 1.2.2: north of the Aquitaine–Midi–Languedoc–Provence southern line. The NMF speakers' origins are denoted in subfigure 4.1a. The mean geographic coordinates of these origins is $47°13'$ N, $4°31'$ E, with a standard deviation of $2°4'$ latitude (229.8 km), and $1°31'$ longitude (168.6 km). This average geographic location is 51.6 km west of Dijon, France. Additionally, the speakers selected were relatively young adults from urban areas, in order to minimize rural dialect biases. The NMF speakers' age range is from 20-40 years, with an average age of 26.3 years and a median age of 25 years.

- For the "Quebecois French" dialect, native speakers were selected who are from the Quebec province in Canada, as defined in 1.2.2. The QF speakers' origins are denoted in subfigure 4.1b. The mean geographic coordinates of these origins is $48°45'$ N, $75°34'$ E, with a standard deviation of $0°17'$ latitude (31.5 km), and $5°31'$ longitude (613.4 km). This average geographic location is 120 km northwest of the Gouin Reservoir in Quebec, Canada.

[1]Two of the NMF speakers (NMF02 and NMF03) could not be contacted for this information, which is the reason for the exclusion of their background information. However, the selection criteria for NMF02 and NMF03 were the same as for the other NMF speakers.

Additionally, the speakers selected were relatively young adults from urban areas, in order to minimize rural dialect biases. The QF speakers' age range is from 26-31 years, with average and median ages of 28.5 years[2].



(a) Speaker map of France.

(b) Speaker map of Canada.

Figure 4.1: Country maps, with speaker origins identified by black dots (nine NMF speakers and two QF speakers).

By adhering to these sociolectal controls, I am confident that the speakers selected for this study are representative of female speakers from their respective NMF and QF dialects.

Three NMF speakers were recorded at the University of Illinois (i.e. speakers NMF01-03). An additional 10 NMF speakers were recorded at GIPSA-lab, at l'Université Stendhal-Grenoble 3 (i.e. speakers NMF04-13). However, two speakers—NMF07 and NMF10—were removed from data analysis due to ubiquitous EMA sensor location tracking errors. Both QF speakers were recorded at the University of Illinois (i.e. speakers QF01-02). In total, data from 11 NMF speakers and 2 QF speakers are analyzed and discussed in the current study.

4.2 Word list

The original word list ("word list A" in Appendix A) used at the inception of this dissertation study was a subset of the word used in Delvaux et al. (2008). The word list A consists of 84 French lexical items, the majority of which are monosyllabic, with the target vowel in an open syllable. Each word contains either one of the oral vowels /ɛ/, /a/ or /o/, or one of the nasal vowels /ɛ̃/, /ɑ̃/ or /ɔ̃/, as a nucleus, and either /p/, /b/, /t/, /d/, /k/, /g/, /f/, /v/, /s/, /z/, /ʃ/, /ʒ/, /ʀ/ or /l/ as an onset consonant. 16 of the words are bisyllabic, since monosyllabic lexical items could not be found

[2] Since I was only able to gather data from relatively few QF speakers compared to number of NMF speakers featured in this study, it should be made clear that the extent to which the results for these two QF speakers can be generalized to all of QF should be considered in relative moderation. Moreover, as is the case in France, the QF dialect is not necessarily uniform throughout all of the Quebec province; possible geographical/dialectal variation variability may be evidenced in the results of this study, and the interpretations that will eventually be made from the results should be taken with appropriate moderation.

for certain consonant-nucleus combinations (e.g., [kɛ̃]). However, for these bisyllabic words, the target vowel is in the second of the two syllables, and therefore will receive word-level stress during a natural production, as is the case for the vowels in all of the monosyllabic words. This word list was used for the first speaker recorded (QF01). Three blocks of these 84 words were used for recordings made with word list A, with internal randomization for each block. The randomization scheme was changed for each participant, avoiding ordering effects. Thus, there are a total of 252 tokens, with 3 repetitions per target word, allowing for 42 comparisons of each oral-nasal pair in word list A (i.e. 42 separate instances of each of the corresponding vowel pairs: /ɛ/-/ɛ̃/, /o/-/ɔ̃/, and /a/-/ɑ̃/).

The word list used for speakers QF02 and NMF01 ("word list B") is a subset of word list A which includes only voiceless stop onset consonants /p, t, k/. This decision was made due to aerodynamic considerations: the onset of nasalization will change depending upon what type of onset consonant precedes the target vowel. Liquids, voiced stops, and even fricatives have been found to be subject to anticipatory nasalization (Shosted, 2009), rendering the task of determining the onset of nasalization a difficult one. Word list B, therefore, contains 18 words. 10 blocks of the 18 words were used for recordings made with word list B, with internal randomization for each block. The randomization scheme was changed for each participant, avoiding ordering effects. Thus, there are a total of 180 tokens, allowing for 30 comparisons of each oral-nasal pair in word list B.

The word list used for speakers NMF02 and NMF03 ("word list C") contains three modifications from word list B, two for the vowel /a/ and one for the vowel /ɛ/. The word *pas* 'step' was changed to *papa* 'daddy' for the syllable /pa/, the word *cas* 'case' was changed to *caca* 'poop' for the syllable /ka/, and the word *quai* 'platform' was changed to *paquet* 'package' for the syllable /kɛ/. This decision was made after the preliminary examination for this dissertation study, where a member of the committee[3] mentioned that some speakers (especially QF speakers) may pronounce the word *pas* as [pɑ] instead of [pa], the word *cas* as [kɑ] instead of [ka], and the word *quai* as [ke] instead of [kɛ].

The word list used for speakers NMF04-NMF13 ("word list D") contains three modifications from word list C, all for the vowel /ɛ/. The word *paix* 'peace' was changed to *Pepsi* 'Pepsi' for the syllable /pɛ/, the word *tait* '(it) keeps quiet' was changed to *taie* 'cover', and the word *paquet* 'package' was changed to *cepstral* 'cepstral (analysis)' for the syllable /kɛ/. This decision was made after a presentation of the results from speakers QF01-QF02 and NMF01-NMF03 at GIPSA-lab in Grenoble, France (October 3, 2011), where several members of the audience mentioned that some speakers may pronounce the word *paix* as [pe] instead of [pɛ], and the word *paquet* as [pake] instead of [pakɛ]. Also, *taie* was deemed preferable to *tait* for lexical reasons, given that it would seem more natural for a noun to appear in the carrier phrase than a verb. To ensure that word-level stress was placed on the first syllable for the bisyllabic words *Pepsi* and *cepstral*, where the target vowel appears in the first syllable, the target syllable appeared in capital letters on the screen (i.e. "Il retape PEPsi parfois" and "Il retape CEPstral parfois", using the carrier phrase described

[3] Annie Tremblay (p.c., August 19, 2010)

below). In addition, the speakers were instructed during preparation for the experiment to place regular, natural stress on the first, and not the last syllable for these words. Example pronunciations for each type of stress placement were given to the speaker, and the speaker repeated in turn. The experimenter monitored pronunciation throughout the experiment, and confirmed that natural stress was placed on the target syllable.

Each word was inserted into the carrier phrase *Il retape* X *parfois* ('He retypes *X* sometimes'), where 'X' is the target word (after Carignan and Fagyal (2010)). The choice for this particular phrase is due to the occurrence of the phoneme /p/ at both the left and right edges of the target word. This particular sound is desirable at these locations for two reasons:

1. Since tongue articulation during the production of the target vowels is a main focus in this study, a bilabial consonant is needed at both edges of the target word in order to reduce possible progressive or regressive lingual co-articulation from affecting the articulation of the target vowel. The use of a bilabial consonant, therefore, will help ensure that such co-articulation will not be a factor, given that no lingual gesture is predicted to be associated with the production of the bilabial consonant.

2. If a nasal vowel were to be followed by a voiced consonant, it is likely that determining the end of nasalization would be difficult, since segmentation of the vowel was determined by voicing in the acoustic wave form. Additionally, it has been found that carryover nasal co-articulation from a nasal vowel is more extensive preceding voiced consonants than voiceless consonants (Delvaux et al., 2008), and would further exacerbate the problem of determining the temporal extent of nasalization.

The inclusion of different places of articulation for the onset consonants in the target words (or in the target syllable in the bisyllabic words) serves as a control for possible biased acoustic and articulatory effects of progressive co-articulation on the target vowel from the production of any particular consonant. In this way, the descriptive analysis of the target vowels will be one that is both robust in the nature of the characteristics described (i.e. not biased), as well as close as possible to a description of these vowels as they are produced in natural speech (i.e. speech which necessarily includes a variety of consonant types).

Given that the QF dialect maintains a distinction between four possible nasal vowels (/ɑ̃/, /ɔ̃/, /ɛ̃/ and /œ̃/), a word should be given here about the decision to exclude /œ̃/ from this study. As discussed in detail in 1.2.2, it has been found that the phonetic differences between the two front nasal vowels /ɛ̃/ and /œ̃/ have been neutralized in the NMF dialect, in favor of the phonemic representation of /ɛ̃/ (Malécot and Lindsay, 1976, *inter alia)*. In other dialects—QF, in particular—the phonetic distinction between these two phonemes remains intact (Walker, 1984, *inter alia)*. However, even in the QF dialect where this distinction is maintained, it has a very low lexical functional load, since there are few minimal pairs which are formed using the /ɛ̃/-/œ̃/ contrast. Given the fact that NMF does not have this four-way distinction and that this distinction has a low lexical functional load in both NMF and QF, only words containing a nasal vowel which would be pronounced as /ɛ̃/ in both dialects have been included in the word list, and none which could be pronounced as /œ̃/ in either dialect. In this way, a direct comparison can be made across dialects of the vowel /ɛ̃/, since this vowel, unlike /œ̃/, is represented both phonemically and phonetically in both the NMF and QF dialects researched in this study.

4.3 Procedures

For recording sessions occurring at the University of Illinois, the carrier phrases were presented to the speaker as a series of slides in Microsoft PowerPoint on a laptop computer. The phrases were in white text, set against a 50% gray background, in order to minimize strain on the speaker's eyes due to reading repetitions in high-contrast slides. The speaker had a brief training session before the experiment, explaining the task, asking the speaker to read at a normal volume and at a normal rate, and allowing opportunity for the speaker to read a few practice phrases in order to familiarize them with both the task and with speaking in a normal rate while having the EMA sensors adhered to their tongue and lips. The speaker's performance in the task was monitored by one of the experimenters (myself), and the speaker was asked to repeat token phrases which were produced erroneously. Erroneous phrases occurred very rarely (one or two times per speaker session).

For recording sessions occurring at GIPSA-lab, the carrier phrases were presented to the speaker one block at a time. The phrases were in black text, set against a white background, in two columns. For each block, the speaker was instructed to read from top to bottom on the screen, reading first the phrase in the first column, then the phrase in the second column, for each row on the screen. In this way, the randomization scheme for each block was preserved. The speaker had a brief training session before the experiment, explaining the task, asking the speaker to read at a normal volume and at a normal rate, and allowing opportunity for the speaker to read a few practice phrases in order to familiarize them to both the task and to speaking in a normal rate while having the EMA sensors adhered to their tongue and lips. The speaker's performance in the task was monitored by one of the experimenters (myself), and the speaker was asked to repeat token phrases which were produced erroneously. Erroneous phrases occurred very rarely (one or two times per speaker session).

Chapter 5

Equipment and Measures

The methodology for this study involves simultaneously recorded articulatory, aerodynamic, and acoustic measurements. The articulatory signals were recorded using electromagnetic articulometry systems made by Carstens Medizinelektronik GmbH[1]: the three-dimension AG500 Electromagnetic Articulograph (EMA) (Carignan et al., 2011; Parrell et al., 2010; Shosted et al., 2012a; Wang et al., 2009; Wu and Shih, 2010), 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 (EMMA) (Arai, 2004; D'Imperio et al., 2007; Tasko et al., 2007; Lieshout et al., 2007), located at Grenoble Institut de Paroles et Science Acoustique (GIPSA-lab) at l'Université Stendhal-Grenoble 3, in Grenoble, France. The aerodynamic signals were recorded using systems which measure differential nasal air pressure (calibrated as flow): a Matlab-based data acquisition system involving hardware made by Biopac[2] and National Instruments[3] at the University of Illinois (Carignan et al., 2011; Shosted et al., 2012a), and the EVA2 portable workstation[4] at GIPSA-lab (Demolin, 2011; Ghio and Teston, 2004).

5.1 Equipment

5.1.1 Acoustics

At the University of Illinois, the acoustic signal was recorded using a Countryman Isomax E6 directional microphone[5] 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[6]

[1] http://www.articulograph.de
[2] http://www.biopac.com
[3] http://www.ni.com
[4] http://www.sqlab.fr
[5] http://www.countryman.com
[6] http://www.akg.com

positioned 18-20 cm from the mouth. The microphone was aligned with the sagittal plane of the speaker's head, lowered approximately 15 cm slightly from the transverse plane, and pointed diagonally upwards toward the speaker's mouth. After having performed experimental trials, the laboratory technician at GIPSA-lab, Christophe Savariaux[7], determined that this positioning avoided sensor tracking error caused by spurious electromagnetic interference from the metal body of the microphone.

5.1.2 University of Illinois: Carstens AG500 EMA

Five speakers from this study (QF01-02, NMF01-03) were recorded at the University of Illinois. The equipment used for measuring lingual and labial articulation at this research location was the AG500 Electromagnetic Articulograph (EMA; henceforth, AG500). The AG500 system creates a controlled electromagnetic environment inside of a large Plexiglas cube with internal dimensions of 56.5×52.7×50.8 cm. AC electric current runs through six electromagnetic coil emitters (henceforth, "emitters"), each at a specific frequency. The emitters are located along the periphery of the cube. When small electromagnetic coil receivers (henceforth, "sensors") are introduced to the magnetic field, the position of each sensor can be inferred by the potential difference (voltage) registered by the sensor for each of the six frequencies produced via electromagnetic induction. The amplitudes of these voltages relating to the six frequencies are recorded by a central computer. Given the constant rate of electromagnetic amplitude decay ($\frac{1}{r^2}$, where $r =$ the radius of the magnetic field around the emitter), the AG500 can calculate the relative distance of each sensor from each of the six emitters. Using these six emitters, the AG500 can calculate five dimensions of information related to the position and rotation of each sensor: *x*-dimension (forward–backward), *y*-dimension (left–right), *z*-dimension (upward–downward), pitch, and yaw. The AG500 can record the relative positions of up to 12 sensors in a three-dimensional space at a sampling rate of 200 Hz. The AG500 can be used for speech production research by gluing the sensors to the speech articulators and then tracking their relative positions in three dimensions. The glue used for the current study is Histoacryl tissue adhesive (TissueSeal LLC, Ann Arbor MI).

Three sensors were adhered along the midsagittal line of tongue at even intervals. Using a surgical pen, three marks were made on the lingual midline in the following way:

1. The speaker was instructed to protrude her tongue. Using non-latex gloves and a dental gauze pad, the experimenter pulled the tongue forward as far as possible and placed a mark as far back as could be reached with relative ease to the experimenter and comfort to the speaker. This mark was used as a guide to adhere the tongue back sensor.

2. Using a small flexible ruler, the experimenter placed a mark at 1 cm from the tip of the tongue. This mark was used as a guide to adhere the tongue tip sensor.

[7] http://www.gipsa-lab.grenoble-inp.fr/ christophe.savariaux

3. Using the ruler to measure the distance between the TB and TT marks, the experimenter placed a mark halfway between the two marks. This final mark was used as a guide to adhere the tongue midpoint sensor.

The sensors adhered to these three positions were used for measuring correlated positions of the tongue tip ("TT"), tongue midpoint ("TM"), and tongue back ("TB"). Measurements of the *z*-dimension (upward–downward displacement) and *x*-dimension (forward–backward displacement) of each sensor are used to infer the vertical position and horizontal position, respectively, of these three points of the tongue during the experiment. Additionally, four sensors were placed around the mouth: two sensors at each corner of the mouth, one on the vermilion border of the upper lip ("UL"), and one on the vermilion border of the lower lip ("LL"), in order to measure the degree of labial aperture (as inferred from the area measurement of the polygon created from these four sensors, and from the euclidean distance between the UL and LL sensors) and lip protrusion (as inferred from the *x*-dimension of the UL and LL sensors); see 5.2.2 for a detailed description of these measures.

Each speaker was situated near the center of the cube, in order to obtain the most reliable position calculations of the sensors. In order to correct for movements of the head within the cube, three addition sensors were used: one sensor was placed on the bridge of the nose, and two on the posterior zygomatic arch in front of the left and right tragi. The skin at these three locations remains relatively unperturbed during speech production; therefore, the sensors at these locations were used as points of reference in order to determine the measurements for tongue and lip movement relative to the position of the head. The tongue and lip movement data were corrected for head movement using the native Carstens software.

5.1.3 GIPSA-lab: Carstens AG200 EMMA

10 speakers from this study (NMF04-13) were recorded at GIPSA-lab. The equipment used for measuring lingual and labial articulation at this research location was the AG200 Electromagnetic Midsagittal Articulograph (EMMA; henceforth, AG200).

The AG200 system is the predecessor to the AG500 system and, as such, works in a similar way as the AG500. Instead of using six electromagnetic coil emitters to measure five dimension of sensor information, the AG200 uses three emitters to measure two dimensions of sensor information: *x*-dimension (forward–backward), *y*-dimension (upward–downward). The three emitters are located along the periphery of a Plexiglas "helmet" structure which is placed over and around the speaker's head, and secured in place. As with the AG500, the AG200 can record the relative positions of up to 12 sensors at a sampling rate of 200 Hz, albeit in a two-dimensional space instead of a three-dimensional space.

Three sensors were adhered along the midsagittal line of the tongue at even intervals, following the same protocol described above in 5.1.2 for AG500 tongue sensor placement. The sensors adhered to these three positions were used for measuring correlated positions of TT, TM, and TB. Measurements of the *y*-dimension (upward–downward displacement) and *x*-dimension (forward–backward displacement) of each sensor are used to infer the vertical position and horizontal position, respectively, of these three points of the tongue during the experiment. Additionally, two sensors were placed on the vermilion border of the upper lip (UL) and on the vermilion border of the lower lip (LL), in order to measure the degree of labial aperture (as inferred from euclidean distance between the UL and LL sensors) and lip protrusion (as inferred from the *x*-dimension of the UL and LL sensors); see 5.2.2 for a detailed description of these measures. Two additional sensors were adhered to the nose bridge and between the maxillary central and lateral incisors, to use for head correction.

Since the AG200 calculates sensor positions in two dimensions instead of three, variation in the position of the sensors along the coronal plane (left–right), as well as the sensor orientation, can lead to sensor tracking error. Therefore, great care was taken to adhere the sensors as close to the sagittal plane as possible, and to align the rotation of the sensor with the sagittal plane. Signal RMS was monitored for each sensor channel before and during the experimental procedure to help ensure that sensor tracking error did not occur, and sensors which manifested higher-than-acceptable signal RMS were repositioned and/or replaced if needed before the experiment continued.

5.1.4 University of Illinois: Aerodynamic system

In order to measure nasal air pressure (calibrated as flow) at the University of Illinois, the subject wore a Glottal Respironics nasal CPAP mask which creates a seal around the nose (Carignan et al., 2011; Shosted et al., 2012a). A 3 m length of 4 mm internal-diameter tubing was connected to a venting outlet in the mask on one side and a Biopac TSD160D high-flow pressure transducer on the other side. The voltage output of the transducer, when amplified by the connected Biopac DA100C differential bridge amplifier and passed to a Krohn-Hite 3360 analog filter, primarily as an anti-aliasing filter (10 kHz low-pass). The final filtered signal is routed through a National Instruments BNC-2110 shielded BNC block connector which allows serial connection to a National Instruments PCI-6013 data acquisition (DAQ) board installed in a Windows XP computer. This DAQ board converts the analog voltage signal to a digital signal to be recorded in Matlab in real-time.

During the recording of the experiment, the Matlab function which records the pressure data is set to record the entire session in one sweep. This is done in order to allow for time synchronization with both the EMA position data and the acoustic data. The process of the synchronization method is explained in 5.1.7.

5.1.5 GIPSA-lab: Aerodynamic system

The EVA2 (Evaluation Vocale Assistée, SQLab) system was used to measure nasal air pressure (calibrated as flow) at GIPSA-lab. The subject wore a silicon mask around the nose, and two tubes were connected to venting outlets in the mask on one side and the pneumotacograph of the EVA2 system on the other side. The following explanation of the details of the EVA2 system is adapted from Demolin (2011); Ghio and Teston (2004).

The pneumotacograph used in the EVA2 system contains a stainless steel wire mesh with a 200 μm diameter and a step of mesh of 250 μm. The wire mesh is reduced in size (to 30 mm diameter and 20 mm length) to optimize its response time and linearity in all articulatory contexts. The differential pressure transducers used (Data Instrument DCXL) are able to measure flow on the order of 1 $\frac{cm^3}{s}$. The resistance of the grid is 10 Pa by $\frac{dm^3}{s}$ (i.e., $\frac{litre}{s}$). This represents approximately 1% of the intra oral pressure of a normal subject, which does not disturb the normal operation of the vocal tract. Resistance was selected for a level of saturation of the sensor to the value of 10 $\frac{dm^3}{s}$ in forced breathing, which represents dynamics of 60 dB. To reduce the non-linear effects of measurement caused by aerodynamic turbulences produced during speech, the pressure tap is made in 8 points of the circumference of the measurement pipe and a grid of tranquillization (of negligible resistance) is laid out in front of the pressure taps. The sensor itself is made of a synthetic material, Polyacetal, which has a very good resistance to sterilization and UV.

5.1.6 Equipment synchronization

Equipment synchronization: University of Illinois

The Sybox-Opto4 unit included with the AG500 system provides time synchronization of AG500 position data with acoustic data. This synchronization is performed automatically with the native Carstens recording software, using a positive voltage pulse at the beginning of each sweep and a negative voltage pulse at the end of each sweep. Following the synchronization method used in Carignan et al. (2011); Shosted et al. (2012a), the signal carrying these pulses was split and re-duplicated using a BNC y-cable, so that the pulses were also recorded in Matlab simultaneously with nasal air pressure measurements at a resolution of 1 kHz. A custom Matlab script was used to identify the time points of these pulses by comparing the amplitude of each sample point with that of the preceding point. When the absolute value of the amplitude differential crossed a user-controlled threshold, the time point was recorded. Since the pulse has a sharp rise time, this method ensures that only one point of each pulse is recorded (i.e. the first sample following the pulse onset). The resolution of the pulse signal is 200 Hz, resulting in a margin of error of 5 ms in the temporal accuracy of the recording of the time point of each pulse. An additional Matlab script was used to segment the nasal air pressure signal between each pair of pulses. Each segment was compared with the segmented files of the EMA data for analysis.

Equipment synchronization: GIPSA-lab

Synchronization of the acoustic, articulatory, and aerodynamic data was accomplished with a different protocol for the recordings performed at GIPSA-lab. Instead of synchronizing the data for recordings of individual carrier phrases, synchronization was performed on blocks of phrases. Recordings of block data were initiated and stopped manually for both the AG200 and EVA2 systems. These manual controls were performed at two separate computer stations, one located outside the sound booth (experimenter 2, controlling the AG200) and one located inside the sound booth (experimenter 1, controlling the EVA2). Therefore, two experimenters were needed to initiate and stop these recordings manually for the respective systems; communication between the experimenters was, thus, necessary to ensure proper synchronization. Using an electronic device which created an electronic pulse along with a simultaneous audio pulse which was played on a speaker located inside the sound booth, the synchronization method protocol included the following steps, in the following temporal order:

1. Experimenter 1 (EVA2 station) initiates aerodynamic recording from inside the booth, and gives a verbal acknowledgment of initiation to experimenter 2 (AG200 station).

2. Experimenter 2 initiates AG200 and audio recording systems from outside the sound booth.

3. Experimenter 2 sends synchronization pulse, which is recorded by the AG200, EVA2, and audio systems. Audio cue of synchronization pulse is also audible from inside the sound booth.

4. Speaker reads the block of phrases which is visible on the computer screen in front of her.

5. After speaker finishes reading the block of phrases, experimenter 2 sends synchronization pulse, which is recorded by the AG200, EVA2, and audio systems.

6. Experimenters 1 and 2 manually stop recording on the EVA2, AG200, and audio systems.

Using these synchronization pulses in the respective AG200, EVA2, and audio signals, synchronization and segmentation of the 10 individual blocks was performed automatically in Matlab.

Acoustic annotation of the segments of the target word was performed manually, according to the following protocol: The first annotation point was set at the beginning of the vowel, specified as the beginning of periodicity in the acoustic signal. The second annotation point was set at the end of the vowel, specified as the last acoustic period to cross a threshold of 20% of the maximum amplitude of the vowel, after Shosted et al. (2012a). The third and final annotation point was set at the end of the closure of the following /p/, (from the word *parfois* in the carrier phrase, or the coda /p/ in *PEPsi* and *CEPstral* for the data recorded at GIPSA-lab), defined as the onset of frication in the audio signal caused by the burst release of the voiceless /p/ consonant. The annotation of the audio data obtained at the University of Illinois was performed by myself. The annotation of the audio data obtained at GIPSA-lab was performed by an undergraduate assistant whom I hired and trained[8].

[8]The funding for this assistant was made possible thanks to the NSF Grant #1121780 to Ryan Shosted (PI), Christopher Carignan and Zsuzsanna Fagyal (Co-PIs).

5.1.7 Calibration

Calibration: University of Illinois

One of the advantages of using the methodological design which has been created for this research is that both systems can be independently calibrated. The AG500 uses proprietary calibration hardware and software created by Carstens. Twelve sensors are calibrated together as a set, and all sensors in a set are recalibrated when one or more sensors need to be replaced due to wear. Three machined calibration “magazines”, each of which holds four sensors, are used to calibrate the set of 12 sensors. Each magazine has four 90° notched grooves which hold the sensors in place. The user places the flat side of each sensor in its respective groove, aligned with the appropriate wall of the groove, and tightens the sensors in place via plastic arms which secure the placement and orientation of the four sensors. Once all 12 sensors are secured in the three magazines, the magazines are mounted to a machined cylinder and plate device known as a “circal”. The placement of the sensors on the circal suspends them in the exact center of the EMA cube, and the AG500 rotates the circal 360°. During this rotation, the location and rotational position of each sensor with relation to the six emitters in the cube is recorded in a calibration session file. The AG500 system later uses this information to calculate the position of the sensors during an experimental recording session. The calibration session file can be used multiple times with the same set of sensors, until the sensor set requires recalibration.

The aerodynamic system is calibrated before each recording session, i.e., for each speaker. The method of calibration involves a plaster mold which I fabricated to fit the nasal CPAP mask. Once the mask is in place, the mold creates an airtight seal, with the exception of a rubber tube which extends through the back of the plaster mold into the mask itself. Using a tapered rubber plug, this tube allows for an airtight insertion of a smaller tube which is connected to a Boxer 7004 high performance gas pump. The pump generates an outflow of 1033 $\frac{ml}{s}$ and an inflow of -1033 $\frac{ml}{s}$ with a pause (0 $\frac{ml}{s}$) between pulses. Two calibration recordings are made in Matlab: one positive flow recording from the outflow end, and one negative flow recording from the inflow end. Each recording has a duration of 5 seconds. The averages of each positive flow peak, each negative flow peak, and each period of null flow are used as the calibration values for the recording session.

Calibration: GIPSA-lab

Like the AG500, the AG200 uses proprietary calibration hardware and software created by Carstens. Four sensors are calibrated together as a set; therefore, three sets of sensors (i.e. 12 sensors) are calibrated for a given session. The sensors are placed through a tube inside a cylindrical calibration magazine and pulled through holes in the side of the magazine. The magazine has four 90° notched grooves which hold the sensors in place. The user places the flat side of each sensor in its respective groove, aligned with the appropriate wall of the groove, and secures the placement and orientation of the four sensors sensor in place with an adhesive strip. The magazine with the four secured sensors is attached to a pulley wheel on a stand; the user turns this wheel during the calibration recording process, and the location and rotational position of each sensor with relation to the six emitters in the cube is recorded in a calibration session file. The process is repeated two additional times for the rest of the 12 sensors. The AG200 system later uses this information to calculate the position of the sensors during an experimental recording session. The calibration session file can be used multiple times with the same set of sensors, until the sensor set requires recalibration.

The AG200 data were also shifted and rotated with reference to the occlusal plane (i.e. "bite plane") using custom Matlab scripts[9]. In order to perform this transformation, the position and angel of the speaker's bite plane first needed to be determined, which was done according to the following protocol: after the experimental data were recorded, two of the sensors were removed and adhered to a piece of clear plastic at a pre-determined interval. The experimenter placed this plastic into the speaker's mouth, aligning both sensors with the midsagittal plane. The speaker was then instructed to bite down lightly, while the experimenter adjusted the horizontal position of the plastic until the front-most sensor was aligned with the front edge of the upper incisors. A short recording of the position and rotation of these sensors was then made. The process was repeated a second time, and the recording which yielded the smallest standard deviation for the RMS of both sensors was chosen for use in the final bite plane transformation. The experimental data were then shifted in the *y*-dimension (upward–downward) and rotated with respect to this bite plane recording, a process which was performed automatically with the custom Matlab scripts.

With regard to the aerodynamic calibration, the EVA2 pressure sensors have two scales, 40 and 200 hPa, and are calibrated by a precision electronic manometer. The manometer is a THOMMEN type HM28, scale 0-300 hPa, 0.05% FS class within which pressure is generated by a hand precision pump. The zero-baseline of the calibrated signal was verified at the beginning of every session before placing the nasal mask on the speaker (i.e., when only atmospheric load was present at the sensor). Corrections to the zero-baseline were made as needed before the mask was placed on the speaker.

5.2 Measures

5.2.1 Acoustic measures

Formant Measurement

Formant frequencies were measured using Praat 5.1.33[10] with the default settings for most variables: the predicted number of formants was set to 5, with a window length of 25ms, and pre-emphasis from 50 Hz. However, in order to

[9] I would like to thank Christophe Savariaux and Phil Hoole, who created and modified these scripts, and who have allowed me to use them to process these AG200 data.

[10] http://www.praat.org

minimize error in formant recognition, the maximum formant value was set to one of 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. Specifically, 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. Additionally, formant values in Hertz were converted to perceptually more relevant Bark values using Traunmuller (1997)'s formula for the vowel dispersion measurement, detailed below.

Vowel midpoint formant values and average formant values were calculated and logged with reference to the segmentation boundaries outlined in 5.1.6 using a custom Praat script. F1 and F2 values were calculated at the midpoint between the vowel onset and offset, and F1 and F2 values were also averaged across the duration of the vowel and logged. Dynamic acoustic measures for the QF dialect were performed in order to investigate the acoustic characteristics of vowel diphthongization. As for the dynamic articulatory measures described in 5.2.2, the dynamic acoustic measures were obtained by first temporally segmenting the vowel into evenly divided $\frac{1}{3}$ portions. Then, F1 and F2 values were calculated and logged for the midpoint of each portion, as well as for the average of each portion, as explained below.

Dynamic acoustic measurements of Quebecois French vowels

Dynamic formant measures for the QF dialect were performed in order to investigate the acoustic characteristics of vowel diphthongization. These dynamic measures were obtained by first temporally segmenting the vowel into evenly divided $\frac{1}{3}$ portions: from the start of the vowel to $\frac{1}{3}$ of the temporal extent of the vowel, from $\frac{1}{3}$ of the temporal extent of the vowel to $\frac{2}{3}$ of the temporal extent of the vowel, and from $\frac{2}{3}$ of the temporal extent of the vowel to the end of the vowel. Then, the acoustic measures outlined above were performed on each portion: average formant values were calculated for each of the three portions, and formant values were calculated at the midpoint of each of the three portions.

Vowel Dispersion

Vowel dispersion measurements are given in Table 5.1, calculated using vowel average and vowel midpoint formant values measured as described above. The vowel dispersion of each speaker's acoustic space was calculated according to Clopper and Pierrehumbert (2008) in the following way. The mean F1 and F2 for each of the six vowel categories were calculated and logged as six separate pairs of formant values ([$F1_1$, $F2_1$]…[$F1_6$, $F2_6$]). The mean F1 and F2 of all of the six vowel categories was calculated and logged as the centroid of the entire vowel space ([$F1_\Sigma$, $F2_\Sigma$]). The euclidean distance between each vowel category mean and this centroid were calculated and logged. Finally, the vowel dispersion measurement was calculated as the mean of these six euclidean distances. In this way, a larger value (in either Hertz or Bark) in Table 5.1 can be interpreted as a more widely dispersed vowel space, and a smaller value can be interpreted as a more contracted vowel space.

Table 5.1: Vowel dispersion measurements.

Speaker	Average (Hertz)	Midpoint (Hertz)	Average (Bark)	Midpoint (Bark)
NMF01	612.53	625.87	3.14	3.22
NMF02	342.48	366.95	1.8	1.95
NMF03	389.3	417.99	2.1	2.28
NMF04	412.17	436.27	2.32	2.53
NMF05	448.68	463.21	2.31	2.41
NMF06	345.82	350.36	1.69	1.7
NMF08	386.3	392.03	2.03	2.07
NMF09	401.75	428.88	2.01	2.2
NMF11	341.26	352.15	1.83	1.87
NMF12	329.75	343.94	1.74	1.84
NMF13	402.62	422.8	2.22	2.35
QF01	454.79	467.98	2.25	2.3
QF02	500.84	508.83	2.28	2.32

5.2.2 Articulatory measures

The data were measured and analyzed using both native and custom-written functions in Matlab 7.14 (2012a)[11]. All lingual measures dealt with the inferior–superior dimension (*z*-dimension for AG500 and *y*-dimension for AG200) and forward–backward dimension (*x*-dimension for both AG500 and AG200) of the lingual sensors TT, TM, and TB. The sensor positions at the vowel midpoint (“midpoint”), and the average positions of during the vowel (“average”), with reference to the segmentation boundaries outlined in 5.1.6, were logged using simple arithmetic functions. There were different midpoint and average lip measurements used for this study, depending on whether the data was collected with the AG500 system or the AG200 system. For the AG500 data, two different labial aperture measures were used: first, by measuring the area of the polynomial calculated by the (x, z) coordinates of the four sensors placed around the mouth (“aperture”, in the results tables in 6.3 and 7.3); second, by measuring the euclidean distance between the UL and LL sensors (“distance”, in the results tables in 6.3 and 7.3), according to the following formula:

$$d(x, z) = \sqrt{(x_1 - x_2)^2 + (z_1 - z_2)^2} \tag{5.1}$$

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

where UL has coordinates (x_1, z_1) and LL has coordinates (x_2, z_2). In this way, the two labial aperture measurements are comparable: one which takes into account the whole area of the labial opening as inferred by the four sensors placed around the mouth, and the other which takes into account the distance between the upper lip and lower lip as an inference of labial aperture. Midpoint and average *x*-dimension values for the UL and LL sensors were logged as inferences of lip protrusion. For the AG200 data, the same labial measures described above for AG500 data were used, except for the exclusion of the "aperture" measure, for which the calculation required four sensors. The AG200 system, which calculates sensor position in the midsagittal plane, cannot be used to measure labial aperture in this way. Therefore, while labial aperture using the AG500 data is analyzed using both the aperture and distance measures described here, the cross-speaker comparisons of labial aperture (i.e., data collected from both the AG500 and AG200 systems) are performed using only the UL/LL euclidean distance measure.

Sensor errors were located by plotting the trajectories of each vowel in each onset condition, and then manually selecting any possible outliers after visual inspection of the trajectories. The sweep numbers of these possible outliers were determined using a custom Matlab function. The data for these sweeps were then checked visually against the acoustic and aerodynamic signals to see if any sensor errors did indeed occur in the region of the vowel. Confirmed errors were then logged, and removed from the dataset prior to analysis and plotting. Because EMA sensors may manifest errors independently of one another, it was only necessary to exclude tokens when the variable being measured was influenced by a particular sensor error. For example, if the TM sensor was judged to function properly but the TT sensor was not, it was necessary to exclude measurements relating to the TT but not the TM.

Dynamic articulatory measurements of Quebecois French vowels

Dynamic lingual and labial measures for the QF dialect were performed in order to investigate the oral articulatory characteristics of vowel diphthongization. These dynamic measures were obtained by first temporally segmenting the vowel into evenly divided $\frac{1}{3}$ portions: from the start of the vowel to $\frac{1}{3}$ of the temporal extent of the vowel, from $\frac{1}{3}$ of the temporal extent of the vowel to $\frac{2}{3}$ of the temporal extent of the vowel, and from $\frac{2}{3}$ of the temporal extent of the vowel to the end of the vowel. Then, the articulatory measures outlined above were performed on each portion. Average measurements were calculated by simply taking the mean value of the samples in each of these three parts, and these mean values were logged as average measurements. Measurements were also calculated at the midpoint of each third portion. If a given portion contained an odd number of samples, the value of the middle sample was logged as the midpoint measurement for that portion; if the given portion contained an even number of samples, the average of the two middle samples was calculated and logged as the midpoint measurement.

5.3 Statistical analysis

Once tokens with relevant errors had been excluded from the dataset, statistical analyses were performed on the articulatory and acoustic measures using one-way ANOVA tests in R 2.11.1[12]. The data were separated in two ways before they were submitted to the ANOVA tests. Firstly, while the AG500 system allows for head-correction within a single session, we have not yet been able to implement a system for normalizing differences between speakers (e.g. differences in height and placement in the cube; additionally, differences in oral morphology may be intractable). For this reason, the data for each speaker were analyzed separately. Secondly, because it is assumed *a priori* that lingual configuration will inherently be different for vowels which differ with respect to their location in the vowel space, it was necessary to separate the dataset by vowel quality before statistical analysis. These data reductions resulted in 6 separate ANOVA tests for each articulatory and acoustic measure: 2 measurement modes (vowel midpoint, vowel average) x 3 vowel pairs ([a]-[ɑ̃], [ɛ]-[ɛ̃], [o]-[ɔ̃]). In each analysis, the experimental measure (e.g. average TM *x*-dimension value, midpoint F1 frequency, etc.) was the dependent variable and vowel nasality (oral / nasal) was the predictor variable. In this way, the results for the articulatory and acoustic measures are the differences in measure values between nasal vowels and their oral vowel congeners (i.e., [a] v. [ɑ̃], [ɛ] v. [ɛ̃], and [o] v. [ɔ̃]) for each individual speaker.

Consideration was given to the use of linear mixed-effects (LME) models in the statistical analysis of this data (Baayen et al., 2008; Gueorguieva and Krystal, 2004; Pinheiro et al., 2011). The LME model considered would treat the experimental measure as the dependent variable, vowel nasality as a fixed effect, and speaker and block (i.e., repetition) as random effects. By using LME models to observe the interaction between the measures and vowel nasality, the statistical analysis would incorporate the data from all of the speakers of a given dialect, 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 research, and to determine of this variation is possibly due to inter-speaker variation (see 3.2), it is not, in fact, desirable for the purposes of the current research to integrate all of the data from the speakers within a dialect, since doing so would mask any inter-speaker variation that might otherwise be observable[13]. Thus, taking these issues into account, the decision was made to analysis the data for each speaker separately as outlined above.

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

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

Results

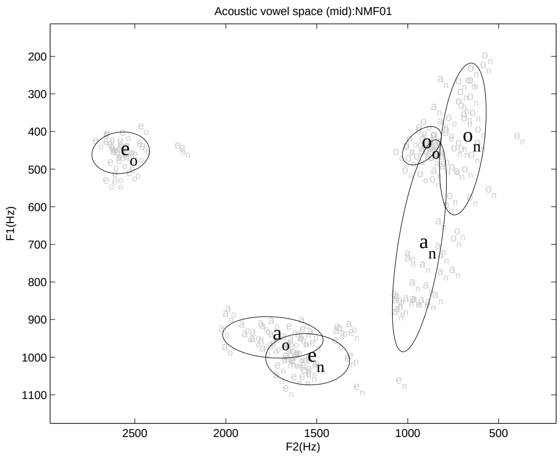
Chapter 6

Northern Metropolitan French

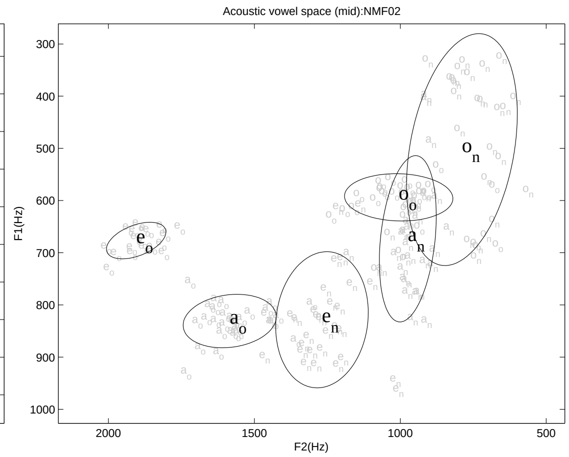
6.1 Northern Metropolitan French: Acoustic results

Because the formant-frequency-related acoustic effects which are due to velo-pharyngeal coupling cannot be teased apart from those which are due to oral articulation by analyzing the acoustic signal alone, it is reasonable to first analyze the acoustic signal before comparing the acoustic output to oral articulatory configurations. In this way, it will be possible to determine which acoustic differences between oral and nasal congeners can be explained by oral articulatory configurations and which acoustic differences cannot.

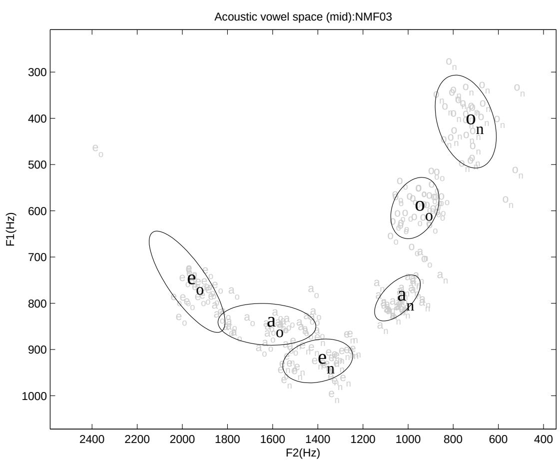
Plots of F1 and F2—as measured at the vowel midpoint—are given in Figures 6.1 and 6.2. These figures clearly confirm the existence of a counter-clockwise shift in the acoustic manifestations of the nasal vowels of NMF explained in 2.2.3. Specifically, [ɛ̃] manifests a relatively high F1 and low F2 (in fact, F2 is lower for nasal [ɛ̃] than for oral [a]); [ɑ̃], in turn, manifests a relatively low F2 and, possibly, low F1; and [ɔ̃], in turn, manifests a relatively low F1 and low F2. These results will be discussed further in 6.4.



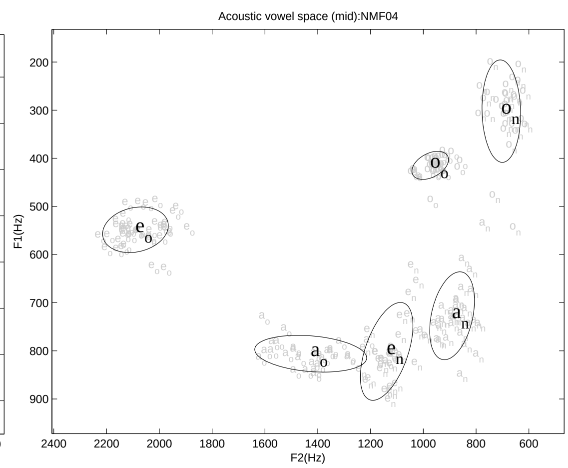
(a) Speaker NMF01 acoustic space



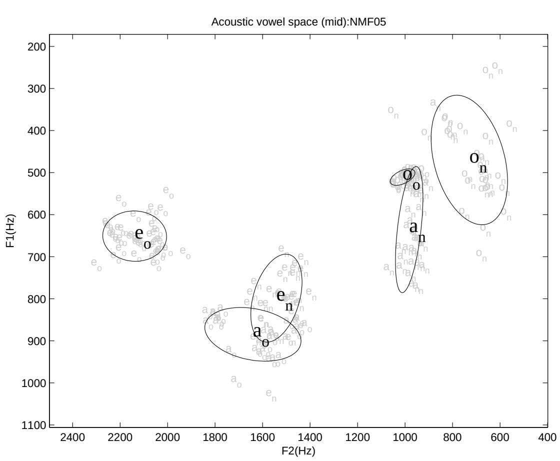
(b) Speaker NMF02 acoustic space



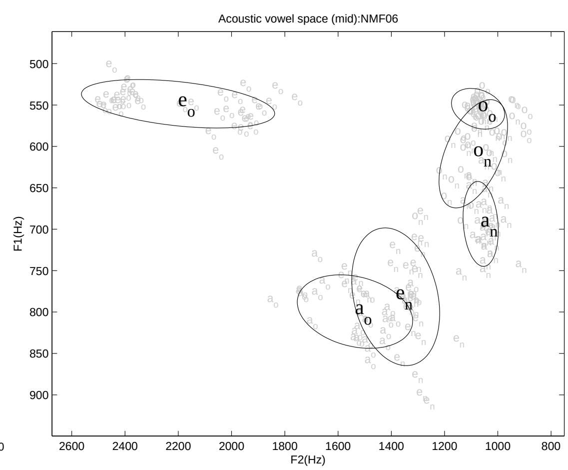
(c) Speaker NMF03 acoustic space



(d) Speaker NMF04 acoustic space

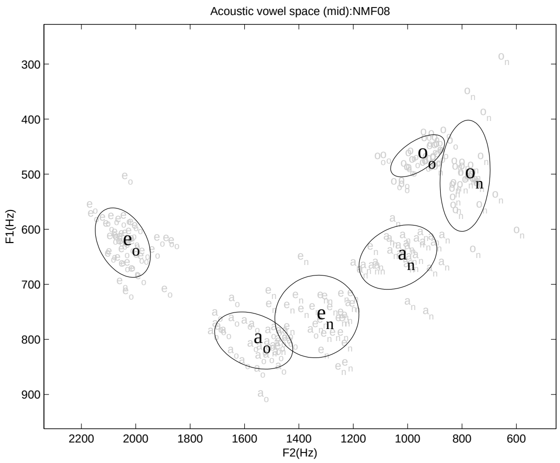


(e) Speaker NMF05 acoustic space

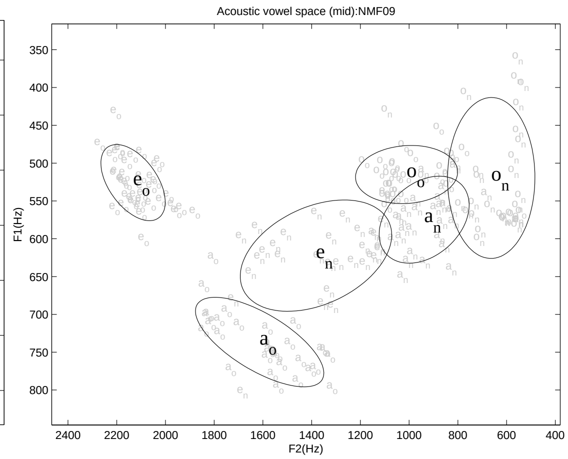


(f) Speaker NMF06 acoustic space

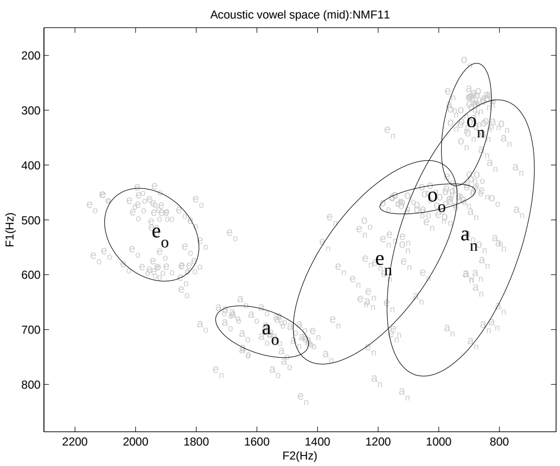
Figure 6.1: Acoustic space for speakers NMF01-NMF06. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



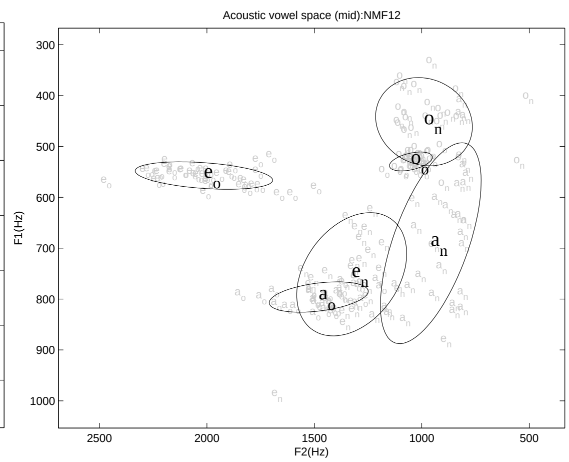
(a) Speaker NMF08 acoustic space



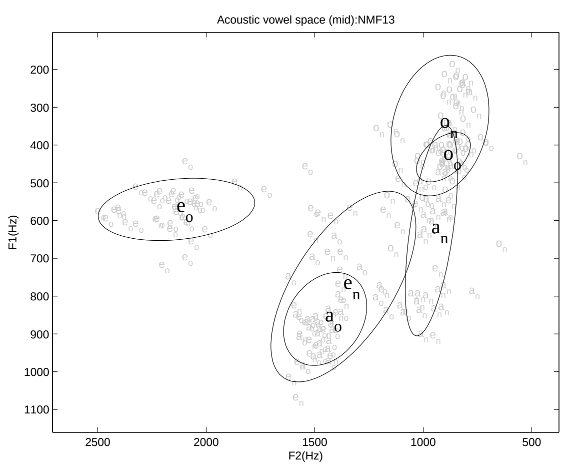
(b) Speaker NMF09 acoustic space



(c) Speaker NMF11 acoustic space



(d) Speaker NMF12 acoustic space



(e) Speaker NMF13 acoustic space

Figure 6.2: Acoustic space for speakers NMF08-NMF13. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

The results for the one-way ANOVAs with F1 and F2 as independent variables are provided in Table 6.1. The formant values for a given vowel pair are displayed in their relevant cell, with the formant value for the oral vowel on the left and the formant value for its nasal congener on the right. Table cells with measures which yield no significant difference are filled white. Cells with measures which yield a significant difference ($p < 0.05$) are filled in one of two shades of gray: cells which are highlighted in light gray correspond to a significant difference where the formant value for the nasal vowel is significantly *lower* than the value for its oral congener (e.g., F2 of [ɑ̃] < F2 of [a]), and cells which are highlighted in dark gray correspond to a significant difference where the formant value for the nasal vowel is significantly *higher* than the value for its oral congener (e.g., F1 of [ɛ̃] > F1 of [ɛ]).

Table 6.1: Results of one-way ANOVA tests for NMF speakers, with nasality (oral/nasal) as a dependent variable, and F1 (Hz) and F2(Hz) as independent variables. Significance level: $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$.

Speaker		[a]-[ã]		[ɛ]-[ɛ̃]		[o]-[ɔ̃]	
		Midpoint	Average	Midpoint	Average	Midpoint	Average
NMF01	F1	947–704 $F(1, 58) = 49***$	924–678 $F(1, 58) = 153***$	457–1005 $F(1, 58) = 2695***$	456–992 $F(1, 58) = 2408***$	438–420	436–420
	F2	1741–936 $F(1, 58) = 454***$	1720–928 $F(1, 58) = 493***$	2578–1550 $F(1, 58) = 928***$	2555–1562 $F(1, 58) = 911***$	922–697 $F(1, 58) = 125***$	925–729 $F(1, 58) = 41***$
NMF02	F1	831–704 $F(1, 58) = 12***$	812–676 $F(1, 58) = 16***$	658–829 $F(1, 57) = 94***$	642–800 $F(1, 57) = 117***$	594–502 $F(1, 58) = 11**$	584–507 $F(1, 58) = 9**$
	F2	1584–1023 $F(1, 58) = 108***$	1589–1041 $F(1, 58) = 108***$	1959–1268 $F(1, 57) = 584***$	1948–1278 $F(1, 57) = 620***$	1005–789 $F(1, 58) = 46***$	1015–908 $F(1, 58) = 7*$
NMF03	F1	845–788 $F(1, 58) = 50***$	841–776 $F(1, 58) = 60***$	706–925 $F(1, 58) = 151***$	703–905 $F(1, 58) = 138***$	594–420 $F(1, 58) = 81***$	594–432 $F(1, 58) = 84***$
	F2	1625–1047 $F(1, 58) = 402***$	1625–1046 $F(1, 58) = 434***$	2090–1400 $F(1, 58) = 306***$	2084–1401 $F(1, 58) = 309***$	970–746 $F(1, 58) = 117***$	971–916
NMF04	F1	806–727 $F(1, 58) = 44***$	784–683 $F(1, 58) = 92***$	541–801 $F(1, 58) = 365***$	535–744 $F(1, 58) = 203***$	415–302 $F(1, 58) = 72***$	420–350 $F(1, 58) = 50***$
	F2	1427–891 $F(1, 58) = 379***$	1430–904 $F(1, 58) = 426***$	2061–1139 $F(1, 58) = 2689***$	2055–1147 $F(1, 58) = 2376***$	974–705 $F(1, 58) = 493***$	969–745 $F(1, 58) = 329***$
NMF05	F1	885–635 $F(1, 56) = 155***$	871–638 $F(1, 56) = 269***$	644–799 $F(1, 58) = 109***$	639–794 $F(1, 58) = 96***$	511–470 $F(1, 58) = 5*$	512–489
	F2	1641–983 $F(1, 56) = 650***$	1636–1004 $F(1, 56) = 666***$	2128–1542 $F(1, 58) = 720***$	2118–1558 $F(1, 58) = 686***$	1010–729 $F(1, 58) = 190***$	1016–777 $F(1, 58) = 179***$
NMF06	F1	799–694 $F(1, 58) = 168***$	780–709 $F(1, 58) = 74***$	551–782 $F(1, 57) = 451***$	550–794 $F(1, 57) = 504***$	555–609 $F(1, 58) = 42***$	552–608 $F(1, 58) = 47***$
	F2	1537–1065 $F(1, 58) = 299***$	1531–1068 $F(1, 58) = 278***$	2134–1384 $F(1, 57) = 251***$	2105–1399 $F(1, 57) = 297***$	1074–1092	1074–1074
NMF08	F1	802–651 $F(1, 58) = 258***$	790–649 $F(1, 58) = 237***$	624–758 $F(1, 58) = 129***$	621–749 $F(1, 58) = 131***$	467–503 $F(1, 58) = 8**$	463–501 $F(1, 58) = 13***$
	F2	1566–1036 $F(1, 58) = 471***$	1569–1045 $F(1, 58) = 493***$	2037–1334 $F(1, 58) = 954***$	2037–1338 $F(1, 58) = 911***$	963–789 $F(1, 58) = 115***$	966–811 $F(1, 58) = 65***$
NMF09	F1	737–575 $F(1, 58) = 265***$	718–573 $F(1, 58) = 263***$	520–622 $F(1, 58) = 90***$	517–617 $F(1, 58) = 98***$	515–520	504–512
	F2	1614–972 $F(1, 58) = 194***$	1609–952 $F(1, 58) = 320***$	2154–1382 $F(1, 58) = 388***$	2148–1375 $F(1, 58) = 426***$	1050–783 $F(1, 58) = 13***$	1012–894 $F(1, 58) = 5*$
NMF11	F1	704–533 $F(1, 58) = 31***$	694–535 $F(1, 58) = 84***$	509–577 $F(1, 58) = 8**$	505–575 $F(1, 58) = 15***$	462–326 $F(1, 58) = 95***$	464–312 $F(1, 58) = 493***$
	F2	1583–928 $F(1, 58) = 358***$	1568–958 $F(1, 58) = 518***$	1966–1210 $F(1, 58) = 422***$	1956–1247 $F(1, 58) = 465***$	1037–909 $F(1, 58) = 36***$	1034–921 $F(1, 58) = 34***$
NMF12	F1	796–690 $F(1, 58) = 19***$	784–647 $F(1, 58) = 87***$	557–751 $F(1, 58) = 168***$	554–687 $F(1, 58) = 193***$	530–451 $F(1, 58) = 53***$	521–439 $F(1, 58) = 82***$
	F2	1480–958 $F(1, 58) = 174***$	1476–995 $F(1, 58) = 242***$	1991–1326 $F(1, 58) = 160***$	1988–1300 $F(1, 58) = 180***$	1051–990 $F(1, 58) = 4*$	1052–966 $F(1, 58) = 18***$
NMF13	F1	860–627 $F(1, 58) = 41***$	837–643 $F(1, 58) = 56***$	565–775 $F(1, 58) = 43***$	560–753 $F(1, 58) = 68***$	432–348 $F(1, 58) = 12***$	432–364 $F(1, 58) = 13***$
	F2	1452–962 $F(1, 58) = 322***$	1463–1021 $F(1, 58) = 272***$	2135–1368 $F(1, 58) = 173***$	2111–1374 $F(1, 58) = 255***$	907–923	913–950

6.1.1 Northern Metropolitan French: Formant analysis of [a]-[ɑ̃]

The acoustic results for [a] v. [ɑ̃] are universally consistent for all of the 11 NMF speakers: nasal [ɑ̃] has both a lower F1 and a lower F2 compared to oral [a]. The acoustic difference for [ɑ̃] compared to [a] can be summarized as:

All speakers manifest a **lower F1**, and a **lower F2**: F1 ↓ F2 ↓

Averaged across speakers, the differences are as follows: F1 of [ɑ̃] is, on average, 153 Hz (1.41 Bark) lower than F1 of [a] for vowel-midpoint measurements, and 148 Hz (1.35 Bark) lower for vowel-average measurements. F2 is, on average, 586 Hz (5.64 Bark) lower for vowel-midpoint measurements, and 569 Hz (5.5 Bark) lower for vowel-average measurements.

Given these acoustic differences, the lingual position for nasal [ɑ̃] is predicted to be higher (i.e., resulting in a lower F1) and more retracted (i.e., resulting in a lower F2) compared to oral [a]. However, the acoustic centralization under the influence of nasalization (see 2.1.1) predicts that [a], which is a low vowel with a relatively high F1, will manifest a lower F1 when nasalized. Furthermore, modeling work by Feng and Castelli (1996); Serrurier and Badin (2008) predicts a lowering for F2 under the effect of nasalization for all of the vowels in the current study, which would be particularly apparent for the nasalization of a relatively fronted vowel like [a]. Therefore, a higher and more retracted lingual position for [ɑ̃] compared with [a]—which would be predicted by the lower F1 and F2 observed here for all of the speakers—may not be observed in the articulatory data, after all: the lowered F1 and F2 observed in the acoustic signal may be due, rather, to the formant-frequency-related acoustic effects of velo-pharyngeal coupling, which are also predicted to result in a lower F1 and lower F2 for [ɑ̃] v. [a].

Given the inter-speaker uniformity with regard to the acoustic difference between [a] and [ɑ̃], I do not predict to observe any inter-speaker differences with regard to the lingual and labial articulations of these two vowels: the inter-speaker oral articulatory configurations for [a] v. [ɑ̃] are predicted to be uniform, as are the inter-speaker acoustic manifestations observed here. In other words, there is no inter-speaker variation observed in the acoustics of [a] v. [ɑ̃]; thus, I predict to find no inter-speaker variation in the oral articulatory configuration of [a] v. [ɑ̃].

6.1.2 Northern Metropolitan French: Formant analysis of [ɛ]-[ɛ̃]

The acoustic results for [ɛ] v. [ɛ̃] are also universally consistent for all of the 11 NMF speakers: nasal [ɛ̃] has a higher F1, but a lower F2, compared to [ɛ]. The acoustic difference for [ɛ̃] compared to [ɛ] can be summarized as:

All speakers manifest a **higher F1**, and a **lower F2**: F1 ↑ F2 ↓

Averaged across speakers, the differences are as follows: F1 of [ɛ̃] is, on average, 208 Hz (2.05 Bark) higher than F1 of [ɛ] for vowel-midpoint measurements, and 193 Hz (1.88 Bark) higher for vowel-average measurements. F2 is, on average, 757 Hz (6.94 Bark) lower for vowel-midpoint measurements, and 739 Hz (6.81 Bark) lower for vowel-average measurements.

Given these acoustic differences, the lingual position for nasal [ɛ̃] is predicted to be lower (i.e., resulting in a higher F1) and more retracted (i.e., resulting in a lower F2) compared to oral [ɛ]. The effect of acoustic centralization under the influence of nasalization does not provide an immediately clear prediction for the realization of F1 for [ɛ̃] compared to the F1 of [ɛ], since [ɛ] is a mid-vowel (i.e., already relatively centralized, especially in these NMF acoustic results). With regard to F2, the frequency is predicted to lower under the effect of nasalization for all vowels in this study, which would be particularly apparent for the nasalization of a relatively fronted vowel like [ɛ] (indeed, [ɛ] is the most fronted vowel in this data set for the NMF dialect). Therefore, a lowered tongue position for [ɛ̃] compared with [ɛ] is predicted to be observed in the articulatory data, since it is not clear that the higher F1 for [ɛ̃] which is observed here would be predicted by the F1-related acoustic effect of velo-pharyngeal coupling. However, a retracted tongue position for [ɛ̃] compared with [ɛ]—which would be predicted to lower F2—may not be observed in the articulatory data: the lower F2 observed in the acoustic signal may be due, rather, to the F2-related acoustic effect of velo-pharyngeal coupling, which predicts a lower F2 for [ɛ̃] v. [ɛ].

Given the inter-speaker uniformity with regard to the acoustic difference between [ɛ] and [ɛ̃], I do not predict to observe any inter-speaker differences with regard to the lingual and labial articulations of these two vowels: the inter-speaker oral articulatory configurations for [ɛ] v. [ɛ̃] are predicted to be uniform, as are the inter-speaker acoustic manifestations observed here. In other words, there is no inter-speaker variation observed in the acoustics of [ɛ] v. [ɛ̃]; thus, I predict to find no inter-speaker variation in the oral articulatory configuration of [ɛ] v. [ɛ̃].

6.1.3 Northern Metropolitan French: Formant analysis of [o]-[ɔ̃]

Unlike the acoustic results for [a]-[ɑ̃] and [ɛ]-[ɛ̃], the acoustic results for [o] v. [ɔ̃] are not universally consistent across all of the NMF speakers. In fact, there is a large degree of inter-speaker variation with regard to differences in the acoustic manifestation of these two vowels. The most consistent acoustic distinction between [o] and [ɔ̃] is a lowered F1 and F2 for [ɔ̃] compared to its oral counterpart [o]. However, only six of the 11 speakers manifest this particular acoustic distinction for vowel-midpoint measurements, and only four of these six speakers manifest this distinction when using data averaged across the entire vowel. Since measurements at the vowel midpoint are predicted to be less affected by co-articulation with the surrounding consonants, I will outline the inter-speaker variation with regard to the formant measurements made at the vowel midpoint only, for the sake of simplicity. With regard to the realization of [ɔ̃] compared to [o]:

6 speakers manifest a **lower F1**, and a **lower F2**:	F1 ↓	F2 ↓
2 speakers manifest no difference in F1, and a **lower F2**:		F2 ↓

1 speaker manifests a **lower F1**, and no difference in F2: F1 ↓

1 speaker manifests a **higher F1**, and a **lower F2**: F1 ↑ F2 ↓

1 speaker manifests a **higher F1**, and no difference in F2: F1 ↑

In addition to the inter-speaker variation, the absolute differences in formant frequencies between [o] and [õ] are not as great as they are for the other two vowel pairs. For the 6 speakers who manifest a lower F1 and a lower F2 for [õ] compared to [o], the differences are as follows: F1 of [õ] is, on average, 106 Hz (0.84 Bark) lower than F1 of [o] for vowel-midpoint measurements, and F2 is 197 Hz (1.91 Bark) lower for vowel-midpoint measurements. For the two speakers who manifest a *higher* F1 value for [õ] compared to [o] (compared to the other 9 speakers, who manifest either a lower F1 value or no difference in F1), the differences are relatively small: F1 of [õ] is, on average, only 45 Hz (0.07 Bark) higher than F1 of [o] for vowel-midpoint measurements.

Similarly to [ɛ]-[ɛ̃], the effect of acoustic centralization under the influence of nasalization does not provide an immediately clear prediction for the realization of F1 for [õ] compared to the F1 of [o], since [o] is a mid-vowel (i.e., already relatively centralized). However, since [o] is a relatively high mid-vowel in these NMF acoustic results, F1 is predicted to raise slightly under the influence of nasalization. The effect of velo-pharyngeal coupling on F2 frequency is not completely clear, either, since [o] is a back vowel, which already has a relatively low F2. Therefore, lingual predictions must be made on a case-by-case basis, with the following predictions for individual speakers based on the acoustic realizations of their productions of [o]-[õ]:

- Speakers NMF02, NMF03, NMF04, NMF05, NMF11, and NMF12 will produce [õ] with a higher, more retracted tongue position than [o].
- Speakers NMF01 and NMF09 will produce [õ] with a more retracted tongue position than [o], with no difference in tongue height.
- Speaker NMF13 will produce [õ] with a higher tongue position than [o], with no difference in horizontal tongue position.
- Speaker NMF08 will produce [õ] with a lower, more retracted tongue position than [o].
- Speaker NMF06 will produce [õ] with a lower tongue position than [o], with no difference in horizontal tongue position.

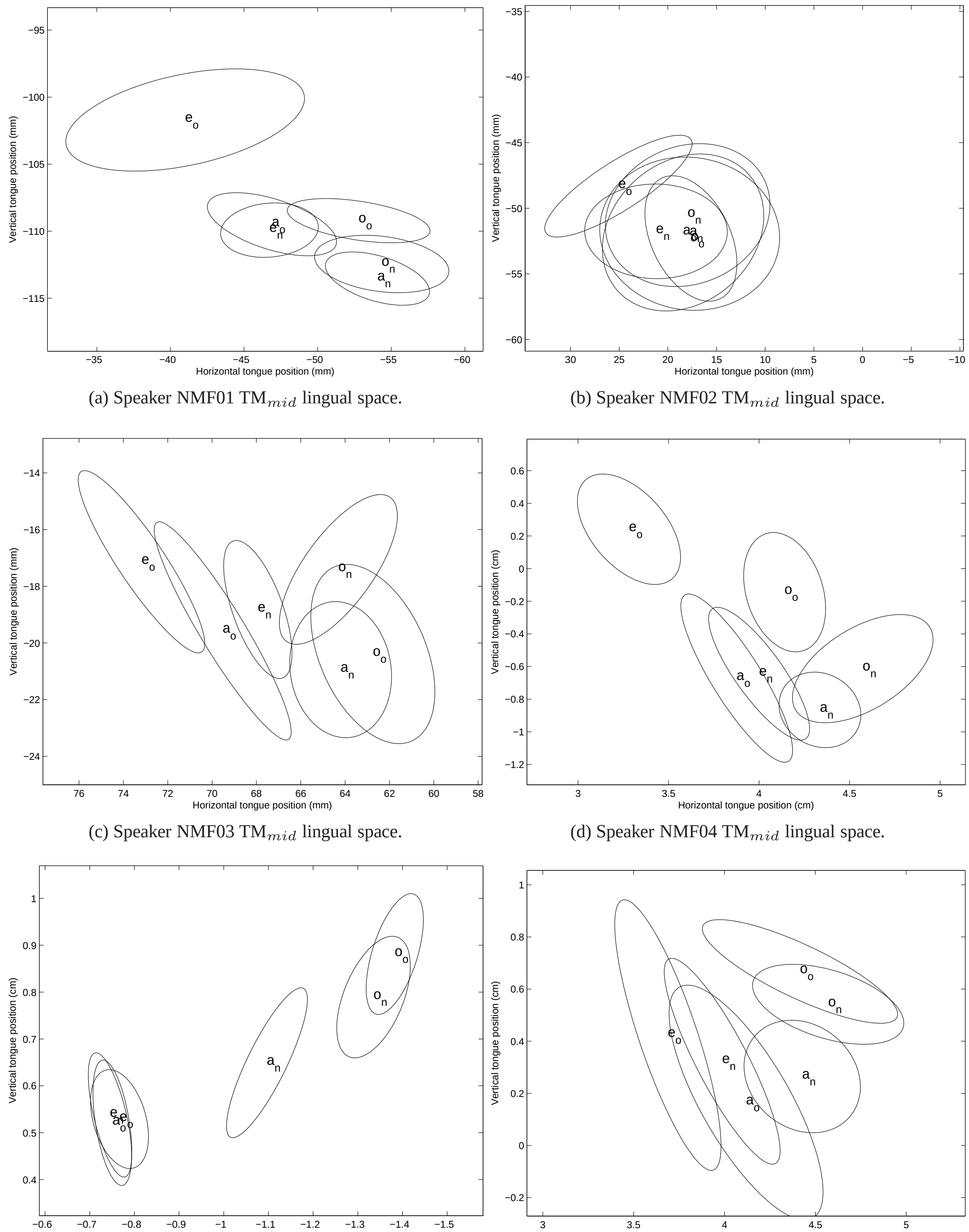
6.2 Northern Metropolitan French: Lingual articulation

6.2.1 Northern Metropolitan French: Lingual articulation summary

Plots of *x*-dimension and *y*-dimension (*z*-dimension for AG500 data) TM sensor values measured at the midpoint of the vowels are displayed in Figures 6.3 and 6.4. Observation of these plots reveals that, in general, the position of the midpoint of the tongue can account for some of the acoustic dispersion observed in 6.1, but not all. The results for the one-way ANOVAs with *y*-dimension values (vertical tongue position) of the TT, TM, and TB sensors as the independent variable are provided in Tables 6.2 and 6.3. The results for the one-way ANOVAs with *x*-dimension values (horizontal tongue position) as the independent variable are provided in Tables 6.4 and 6.5. Table cells with measures which yield no significant difference are colored white. Cells with measures which yield a significant difference ($p < 0.05$) are highlighted in one of two shades of gray: cells which are highlighted in light gray correspond to a significant difference where the sensor value for the nasal vowel is significantly *lower* than the value for its oral congener (i.e., lower tongue position for *y*-dimension values, and more retracted tongue position for *x*-dimension values), and cells which are highlighted in dark gray correspond to a significant difference where the sensor value for the nasal vowel is significantly *higher* than the value for its oral congener (i.e., higher tongue position for *y*-dimension values, and more advanced tongue position for *x*-dimension values)[1].

[1] A word should be given here about the relatively large degree of overlap in the lingual space for speakers NMF02 and NMF13. This overlap does not seem to be due to EMA sensor tracking error, since I do not find clear evidence of errors manifested in the data. Therefore, I would like to make a few comments regarding the relatively small degree of distinction between vowels with regard to lingual position:

1. Although there is a large degree of overlap there are, nevertheless, significant differences in lingual position between the oral and nasal vowel congeners. I would predict significant differences between all of the six vowels with regard to lingual dispersion, as well, but that question is outside the scope of the current study.
2. It may be the case that the configurations of other oral articulators (e.g., lips, pharynx) are used to help create the acoustic dispersion of the vowel space observed for these two speakers. However, this question is also outside the scope of the current study.
3. In some cases, a relatively small change in articulation might cause a relatively larger change in acoustics (Perkell, 1997; Stevens, 1989). If this is the case for these speakers, dispersion that is clearly evident in the acoustic space may not be as evident in the lingual space.



(a) Speaker NMF01 TM_{mid} lingual space.

(b) Speaker NMF02 TM_{mid} lingual space.

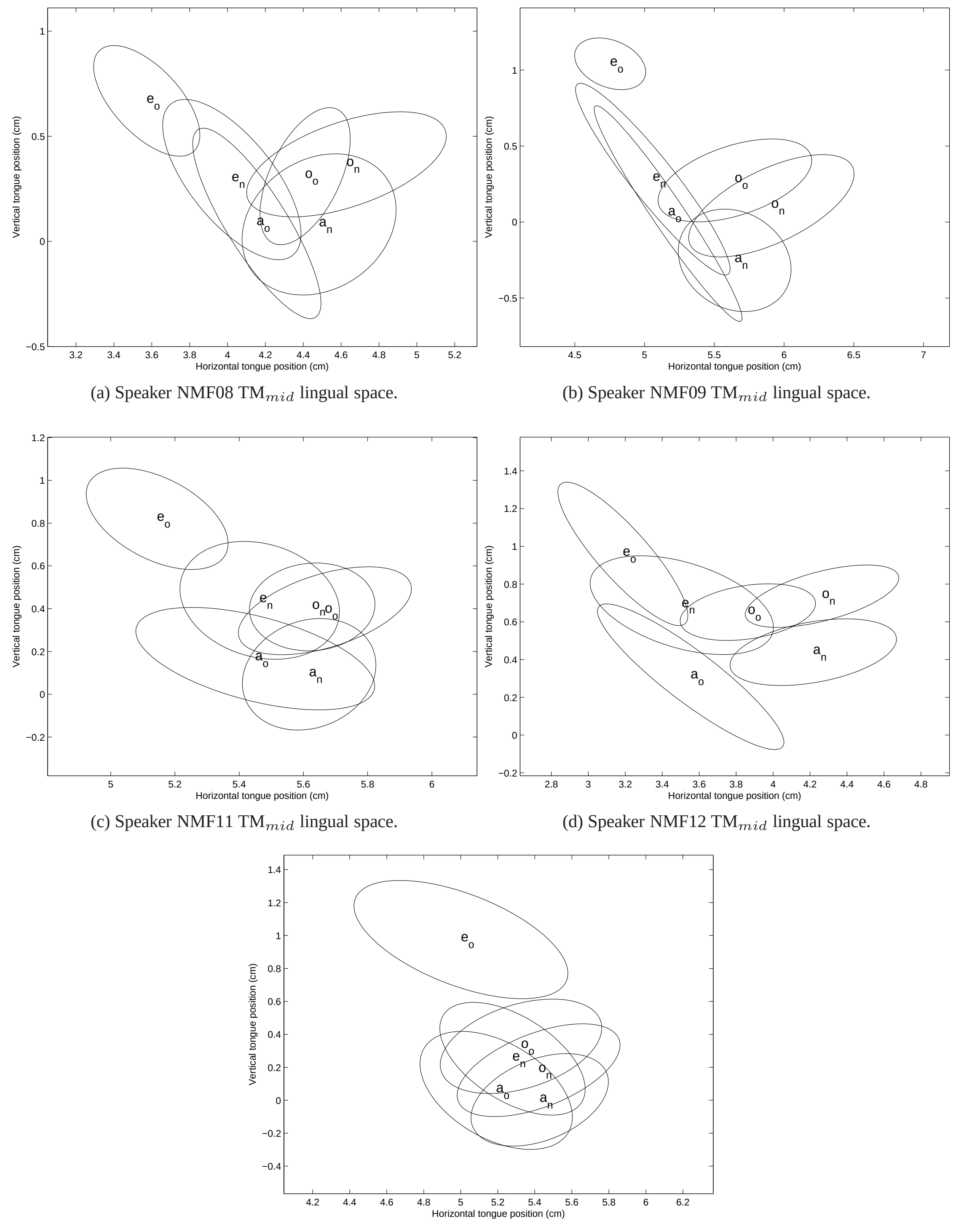
(c) Speaker NMF03 TM_{mid} lingual space.

(d) Speaker NMF04 TM_{mid} lingual space.

(e) Speaker NMF05 TM_{mid} lingual space.

(f) Speaker NMF06 TM_{mid} lingual space.

Figure 6.3: TM_{mid} lingual space for speakers NMF01-NMF06. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



(a) Speaker NMF08 TM$_{mid}$ lingual space.

(b) Speaker NMF09 TM$_{mid}$ lingual space.

(c) Speaker NMF11 TM$_{mid}$ lingual space.

(d) Speaker NMF12 TM$_{mid}$ lingual space.

(e) Speaker NMF13 TM$_{mid}$ lingual space.

Figure 6.4: TM$_{mid}$ lingual space for speakers NMF08-NMF13. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

Table 6.2: Results of one-way ANOVA tests for speakers NMF01-NMF06, with nasality (oral/nasal) as a dependent variable, and average *y*-dimension EMA values (mm) for TT, TM and TB as independent variables. Tongue articulations of nasal vowels are specified with respect to their oral congeners. Significance level: $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$.

Speaker		[a]-[ã]		[ɛ]-[ɛ̃]		[o]-[ɔ̃]	
		Midpoint	Average	Midpoint	Average	Midpoint	Average
NMF01	TT	lower $F(1,48) = 13***$	lower $F(1,48) = 7*$	lower $F(1,52) = 41***$	lower $F(1,52) = 28***$		
	TM	lower $F(1,47) = 97***$	lower $F(1,47) = 73***$	lower $F(1,52) = 224***$	lower $F(1,52) = 219***$	lower $F(1,50) = 85***$	lower $F(1,50) = 80***$
	TB	lower $F(1,49) = 17***$	lower $F(1,49) = 11**$	lower $F(1,52) = 529***$	lower $F(1,52) = 452***$	lower $F(1,52) = 154***$	lower $F(1,52) = 173***$
NMF02	TT						
	TM			lower $F(1,54) = 31***$	lower $F(1,54) = 37***$		
	TB	higher $F(1,56) = 7**$	higher $F(1,56) = 6*$	lower $F(1,56) = 17***$	lower $F(1,56) = 18***$		
NMF03	TT					higher $F(1,56) = 67***$	higher $F(1,57) = 48***$
	TM	lower $F(1,58) = 6*$		lower $F(1,58) = 12**$	lower $F(1,58) = 10**$	higher $F(1,57) = 35***$	higher $F(1,58) = 28***$
	TB	lower $F(1,55) = 14***$	lower $F(1,55) = 10**$	lower $F(1,56) = 28***$	lower $F(1,56) = 22***$		
NMF04	TT			lower $F(1,58) = 276***$	lower $F(1,58) = 122***$		
	TM	lower $F(1,58) = 8**$	lower $F(1,58) = 7*$	lower $F(1,58) = 193***$	lower $F(1,58) = 110***$	lower $F(1,58) = 62***$	lower $F(1,58) = 51***$
	TB	higher $F(1,58) = 14***$	higher $F(1,58) = 6*$	lower $F(1,58) = 11**$	lower $F(1,58) = 5*$	lower $F(1,58) = 194***$	lower $F(1,58) = 95***$
NMF05	TT	lower $F(1,56) = 18***$	lower $F(1,56) = 16***$	lower $F(1,58) = 11**$	lower $F(1,58) = 6*$		
	TM	higher $F(1,56) = 25***$	higher $F(1,56) = 29***$			lower $F(1,58) = 17***$	lower $F(1,58) = 10**$
	TB			lower $F(1,58) = 17***$	lower $F(1,58) = 10**$	lower $F(1,58) = 93***$	lower $F(1,58) = 50***$
NMF06	TT	lower $F(1,58) = 8**$	lower $F(1,58) = 6*$	lower $F(1,57) = 79***$	lower $F(1,57) = 66***$	lower $F(1,58) = 33***$	lower $F(1,58) = 31***$
	TM					lower $F(1,58) = 17***$	lower $F(1,58) = 9**$
	TB	higher $F(1,58) = 10**$	higher $F(1,58) = 7*$	higher $F(1,57) = 6*$	higher $F(1,57) = 5*$	lower $F(1,58) = 4*$	lower $F(1,58) = 4*$

Table 6.3: Results of one-way ANOVA tests for speakers NMF08-NMF13, with nasality (oral/nasal) as a dependent variable, and average *y*-dimension EMA values (mm) for TT, TM and TB as independent variables. Tongue articulations of nasal vowels are specified with respect to their oral congeners. Significance level: $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$.

Speaker		[a]-[ã]		[ɛ]-[ɛ̃]		[o]-[ɔ̃]	
		Midpoint	Average	Midpoint	Average	Midpoint	Average
NMF08	TT			lower $F(1, 58) = 31***$	lower $F(1, 58) = 27***$		
	TM			lower $F(1, 58) = 45***$	lower $F(1, 58) = 37***$		
	TB			lower $F(1, 58) = 6*$	lower $F(1, 58) = 5*$	lower $F(1, 58) = 18***$	lower $F(1, 58) = 16***$
NMF09	TT	lower $F(1, 58) = 6*$	lower $F(1, 58) = 6*$	lower $F(1, 58) = 33***$	lower $F(1, 58) = 30***$		
	TM	lower $F(1, 58) = 11**$	lower $F(1, 58) = 10**$	lower $F(1, 58) = 93***$	lower $F(1, 58) = 91***$	lower $F(1, 58) = 10**$	lower $F(1, 58) = 13***$
	TB			lower $F(1, 58) = 12**$	lower $F(1, 58) = 12**$	lower $F(1, 58) = 17***$	lower $F(1, 58) = 22***$
NMF11	TT	lower $F(1, 58) = 8**$	lower $F(1, 58) = 6*$	lower $F(1, 57) = 34***$	lower $F(1, 58) = 32***$	higher $F(1, 58) = 26***$	higher $F(1, 58) = 22***$
	TM			lower $F(1, 57) = 73***$	lower $F(1, 58) = 59***$		
	TB			lower $F(1, 57) = 15***$	lower $F(1, 58) = 11**$	lower $F(1, 58) = 26***$	lower $F(1, 58) = 17***$
NMF12	TT	higher $F(1, 58) = 17***$	higher $F(1, 58) = 7*$	lower $F(1, 58) = 5*$		higher $F(1, 58) = 6*$	higher $F(1, 58) = 4*$
	TM	higher $F(1, 58) = 6*$		lower $F(1, 58) = 24***$	lower $F(1, 58) = 18***$	higher $F(1, 58) = 10**$	higher $F(1, 58) = 13***$
	TB	higher $F(1, 58) = 10**$	higher $F(1, 58) = 5*$			lower $F(1, 58) = 5*$	
NMF13	TT		lower $F(1, 58) = 4*$	lower $F(1, 58) = 81***$	lower $F(1, 58) = 78***$		
	TM			lower $F(1, 58) = 146***$	lower $F(1, 58) = 110***$	lower $F(1, 58) = 9**$	lower $F(1, 58) = 12**$
	TB	higher $F(1, 58) = 7**$		lower $F(1, 58) = 7*$		lower $F(1, 58) = 22***$	lower $F(1, 58) = 20***$

Table 6.4: Results of one-way ANOVA tests for speakers NMF01-NMF06, with nasality (oral/nasal) as a dependent variable, and average *x*-dimension EMA values (mm) for TT, TM and TB as independent variables. Tongue articulations of nasal vowels are specified with respect to their oral congeners. Significance level: $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$.

Speaker		[a]-[ã]		[ɛ]-[ɛ̃]		[o]-[ɔ̃]	
		Midpoint	Average	Midpoint	Average	Midpoint	Average
NMF01	TT	retracted $F(1,48) = 67***$	retracted $F(1,48) = 53***$	retracted $F(1,52) = 75***$	retracted $F(1,52) = 51***$	retracted $F(1,53) = 6*$	
	TM	retracted $F(1,47) = 90***$	retracted $F(1,47) = 64***$	retracted $F(1,52) = 26***$	retracted $F(1,52) = 25***$		
	TB	retracted $F(1,49) = 84***$	retracted $F(1,49) = 62***$	retracted $F(1,52) = 290***$	retracted $F(1,52) = 251***$	retracted $F(1,52) = 15***$	retracted $F(1,52) = 10**$
NMF02	TT			retracted $F(1,56) = 5*$	retracted $F(1,56) = 5*$		
	TM			retracted $F(1,54) = 35***$	retracted $F(1,54) = 31***$		
	TB					fronted $F(1,56) = 5*$	
NMF03	TT	retracted $F(1,58) = 48***$	retracted $F(1,58) = 37***$	retracted $F(1,58) = 148***$	retracted $F(1,58) = 106***$	fronted $F(1,56) = 15***$	fronted $F(1,57) = 12**$
	TM	retracted $F(1,58) = 131***$	retracted $F(1,58) = 105***$	retracted $F(1,58) = 180***$	retracted $F(1,58) = 141***$	fronted $F(1,57) = 11**$	fronted $F(1,58) = 8**$
	TB	retracted $F(1,55) = 85***$	retracted $F(1,55) = 74***$	retracted $F(1,56) = 103***$	retracted $F(1,56) = 75***$		
NMF04	TT	retracted $F(1,58) = 87***$	retracted $F(1,58) = 75***$	retracted $F(1,58) = 240***$	retracted $F(1,58) = 194***$		
	TM	retracted $F(1,58) = 99***$	retracted $F(1,58) = 74***$	retracted $F(1,58) = 224***$	retracted $F(1,58) = 147***$	retracted $F(1,58) = 63***$	retracted $F(1,58) = 38***$
	TB	retracted $F(1,58) = 130***$	retracted $F(1,58) = 104***$	retracted $F(1,58) = 339***$	retracted $F(1,58) = 231***$	retracted $F(1,58) = 81***$	retracted $F(1,58) = 44***$
NMF05	TT			retracted $F(1,58) = 43***$	retracted $F(1,58) = 21***$		
	TM	retracted $F(1,56) = 789***$	retracted $F(1,56) = 769***$	fronted $F(1,58) = 5*$		fronted $F(1,58) = 14***$	fronted $F(1,58) = 9**$
	TB	retracted $F(1,56) = 7**$	retracted $F(1,56) = 7*$	retracted $F(1,58) = 118***$	retracted $F(1,58) = 67***$		
NMF06	TT	retracted $F(1,58) = 38***$	retracted $F(1,58) = 25***$	retracted $F(1,57) = 87***$	retracted $F(1,57) = 65***$		
	TM	retracted $F(1,58) = 23***$	retracted $F(1,58) = 17***$	retracted $F(1,57) = 32***$	retracted $F(1,57) = 22***$		
	TB	retracted $F(1,58) = 50***$	retracted $F(1,58) = 34***$	retracted $F(1,57) = 50***$	retracted $F(1,57) = 33***$		

Table 6.5: Results of one-way ANOVA tests for speakers NMF08-NMF13, with nasality (oral/nasal) as a dependent variable, and average *x*-dimension EMA values (mm) for TT, TM and TB as independent variables. Tongue articulations of nasal vowels are specified with respect to their oral congeners. Significance level: $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$.

Speaker		[a]-[ã]		[ɛ]-[ɛ̃]		[o]-[õ]	
		Midpoint	Average	Midpoint	Average	Midpoint	Average
NMF08	TT	retracted $F(1,58) = 28***$	retracted $F(1,58) = 30***$	retracted $F(1,58) = 176***$	retracted $F(1,58) = 155***$		
	TM	retracted $F(1,58) = 27***$	retracted $F(1,58) = 27***$	retracted $F(1,58) = 66***$	retracted $F(1,58) = 52***$	retracted $F(1,58) = 10**$	retracted $F(1,58) = 8**$
	TB	retracted $F(1,58) = 29***$	retracted $F(1,58) = 30***$	retracted $F(1,58) = 62***$	retracted $F(1,58) = 52***$	retracted $F(1,58) = 14***$	retracted $F(1,58) = 11**$
NMF09	TT	retracted $F(1,58) = 20***$	retracted $F(1,58) = 18***$	retracted $F(1,58) = 34***$	retracted $F(1,58) = 28***$		
	TM	retracted $F(1,58) = 35***$	retracted $F(1,58) = 30***$	retracted $F(1,58) = 17***$	retracted $F(1,58) = 17***$	retracted $F(1,58) = 7**$	retracted $F(1,58) = 6*$
	TB	retracted $F(1,58) = 18***$	retracted $F(1,58) = 15***$	retracted $F(1,58) = 5*$	retracted $F(1,58) = 4*$		
NMF11	TT	retracted $F(1,58) = 13***$	retracted $F(1,58) = 10**$	retracted $F(1,57) = 122***$	retracted $F(1,58) = 105***$	fronted $F(1,58) = 7*$	fronted $F(1,58) = 4*$
	TM	retracted $F(1,58) = 11**$	retracted $F(1,58) = 9**$	retracted $F(1,57) = 60***$	retracted $F(1,58) = 45***$		
	TB	retracted $F(1,58) = 10**$	retracted $F(1,58) = 8**$	retracted $F(1,57) = 59***$	retracted $F(1,58) = 48***$		
NMF12	TT	retracted $F(1,58) = 27***$	retracted $F(1,58) = 23***$	retracted $F(1,58) = 24***$	retracted $F(1,58) = 18***$	retracted $F(1,58) = 5*$	
	TM	retracted $F(1,58) = 66***$	retracted $F(1,58) = 53***$	retracted $F(1,58) = 19***$	retracted $F(1,58) = 13***$	retracted $F(1,58) = 36***$	retracted $F(1,58) = 24***$
	TB	retracted $F(1,58) = 71***$	retracted $F(1,58) = 63***$	retracted $F(1,58) = 12**$	retracted $F(1,58) = 9**$	retracted $F(1,58) = 39***$	retracted $F(1,58) = 27***$
NMF13	TT	retracted $F(1,58) = 31***$	retracted $F(1,58) = 27***$	retracted $F(1,58) = 31***$	retracted $F(1,58) = 26***$		
	TM	retracted $F(1,58) = 12***$	retracted $F(1,58) = 11**$	retracted $F(1,58) = 11**$	retracted $F(1,58) = 8**$		
	TB	retracted $F(1,58) = 8**$	retracted $F(1,58) = 8**$	retracted $F(1,58) = 5*$			

6.2.2 Northern Metropolitan French: Lingual articulation of [a]-[ɑ̃]

Figures highlighting the articulatory data for the vowel pair [a]-[ɑ̃] are shown below. Plots of the TT sensor data are given in Figures 6.5 and 6.6, plots of the TM sensor data are given in Figures 6.7 and 6.8, and plots of the TB sensor data are given in Figures 6.9 and 6.10. All data provided in these figures are measurements taken at the vowel midpoint. For the vowel pair [a]-[ɑ̃], there is much discrepancy between the lingual configuration and the acoustic output: whereas all 11 speakers manifest a lower F1 and a lower F2 for [ɑ̃] compared to [a], not all speakers produce [ɑ̃] with higher and more retracted tongue position compared to [a], a lingual configuration which would account for the acoustic realizations of these two vowels. Therefore, the acoustic difference between oral [a] and its nasal counterpart [ɑ̃] cannot be explained solely by lingual configuration.

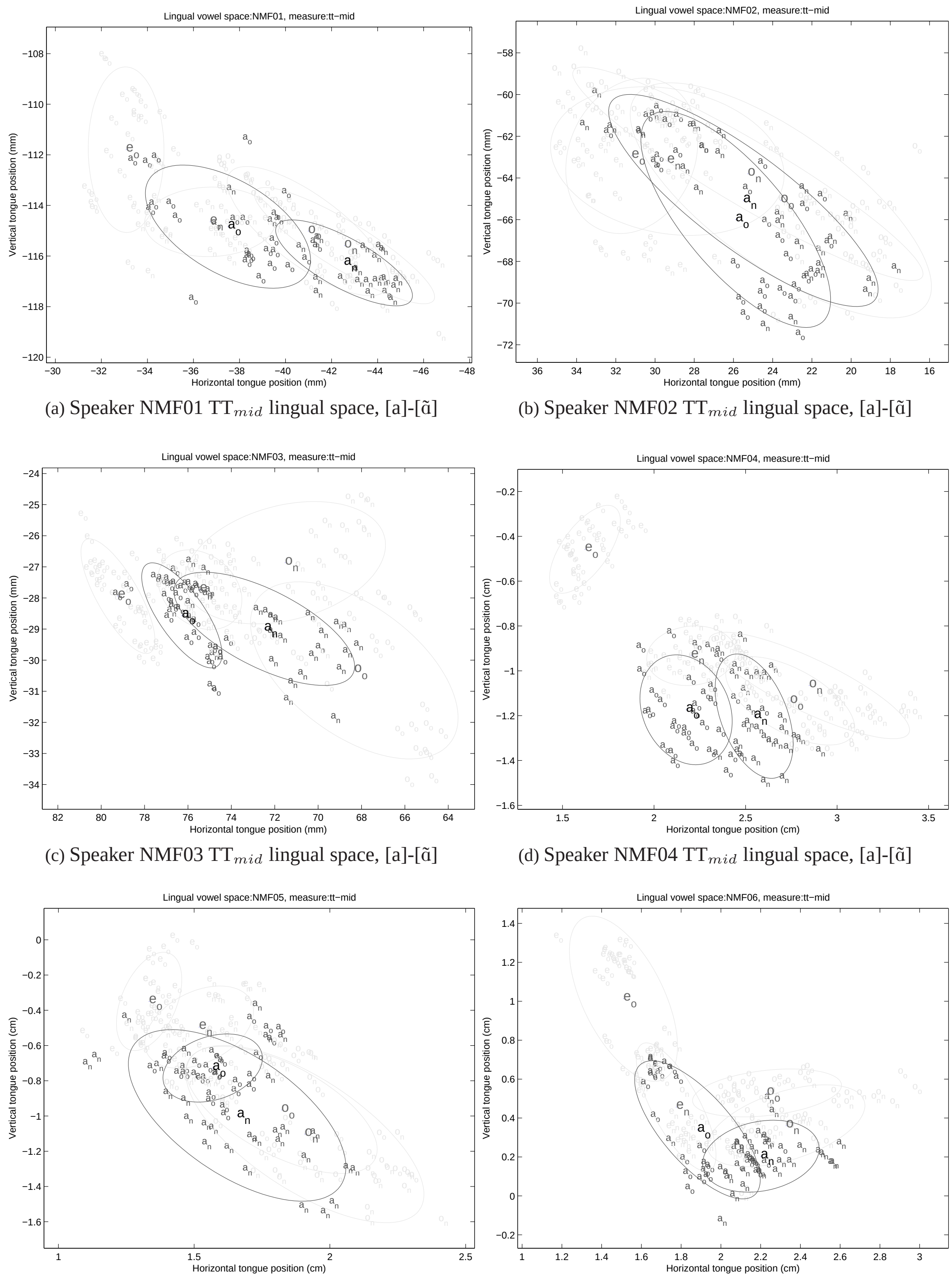
With regard to the results concerning tongue height and its relation to the results for F1, six of the 11 speakers produce [ɑ̃] with a vertical tongue position which may possibly account for its relative acoustic realization compared to [a]. One speaker (NMF12) produces [ɑ̃] with the entire tongue body raised compared to [a]: TT, TM, and TB are all higher for [ɑ̃] compared to [a]. Five speakers produce [ɑ̃] in a manner which suggests posterior bunching: for four speakers TB is higher for [ɑ̃] v. [a] (with a lower TT or TM, for two of these four speakers), and for one speaker TM is higher for [ɑ̃] v. [a] while TT is lower. For these six speakers, the raised tongue position—in whole or in part—may account for the lower F1 for [ɑ̃] compared to [a]. The predictions with regard to tongue height are, therefore, substantiated by the results for these six speakers.

However, this leaves five speakers for whom the acoustic realization of [ɑ̃] v. [a] is not predicted by their respective vertical lingual position. For three speakers (NMF01, NMF03, NMF09), the body of the tongue is lower for [ɑ̃] than for [a]: the TM and/or TB sensor are lower, without any evidence suggestive of posterior bunching. For the other two speakers (NMF08, NMF11), the body of the tongue (TM and/or TB) manifests no difference in tongue height for [ɑ̃] compared to [a], which cannot explain the lower F1 observed for [ɑ̃] v. [a].

With regard to the results concerning horizontal tongue position and its relation to the results for F2, 10 of the 11 speakers produce [ɑ̃] with a horizontal tongue position which may possibly account for its relative acoustic realization: the tongue is more retracted for [ɑ̃] v. [a], a lingual configuration which predicts the observed lower F2 for [ɑ̃] v. [a]. The predictions with regard to horizontal tongue position are, therefore, substantiated by the results for these 10 speakers. For one speaker (NMF02), however, none of the lingual sensors manifest a difference in horizontal position for [ɑ̃] compared to [a], which cannot explain the lower F2 observed for [ɑ̃] v. [a].

In summary, the following discrepancies are observed for the lingual articulation and acoustic realization of [ɑ̃] compared to [a]:

- Speakers NMF01, NMF03, and NMF09 produce [ɑ̃] with a lower tongue position than [a], yet [ɑ̃] is realized with a lower F1 than [a].



(a) Speaker NMF01 TT$_{mid}$ lingual space, [a]-[ã]

(b) Speaker NMF02 TT$_{mid}$ lingual space, [a]-[ã]

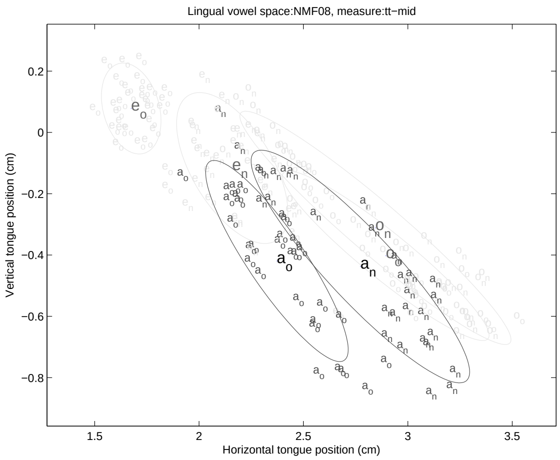
(c) Speaker NMF03 TT$_{mid}$ lingual space, [a]-[ã]

(d) Speaker NMF04 TT$_{mid}$ lingual space, [a]-[ã]

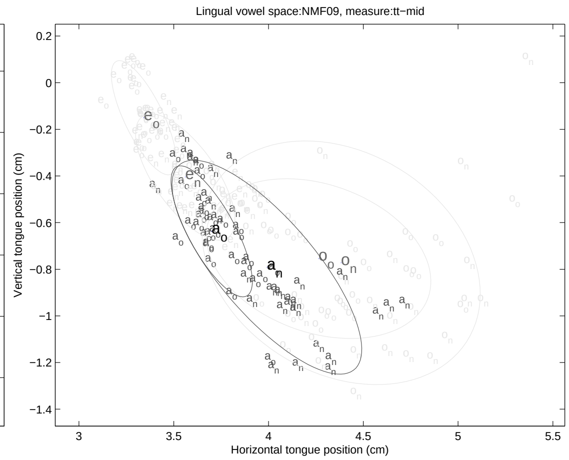
(e) Speaker NMF05 TT$_{mid}$ lingual space, [a]-[ã]

(f) Speaker NMF06 TT$_{mid}$ lingual space, [a]-[ã]

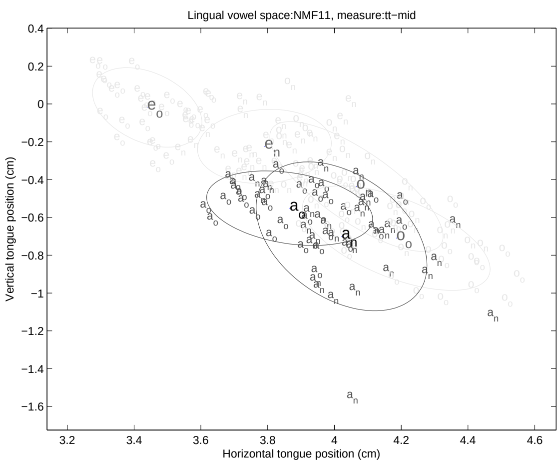
Figure 6.5: TT$_{mid}$ lingual space for speakers NMF01-NMF06, with data sets for [a]-[ã] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



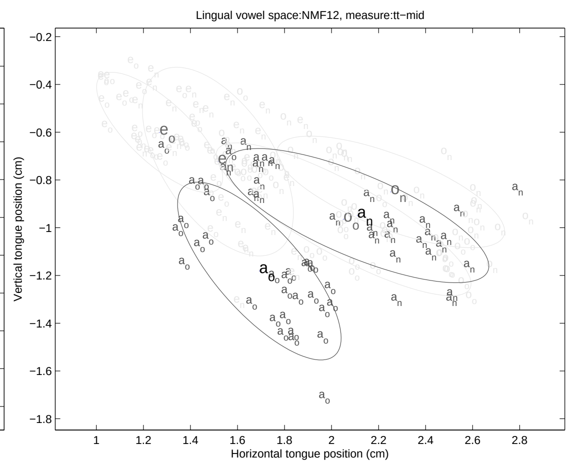
(a) Speaker NMF08 TT_{mid} lingual space, [a]-[ã]



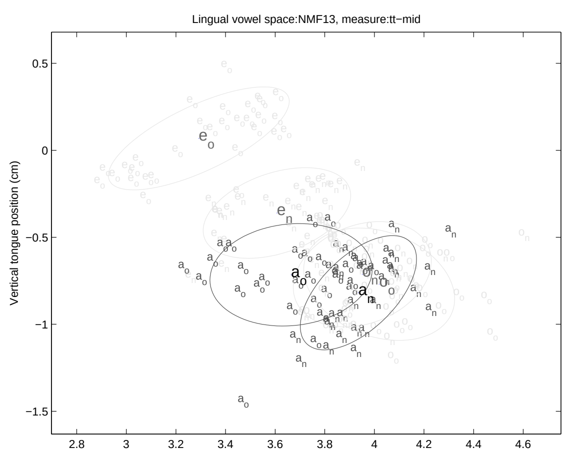
(b) Speaker NMF09 TT_{mid} lingual space, [a]-[ã]



(c) Speaker NMF11 TT_{mid} lingual space, [a]-[ã]

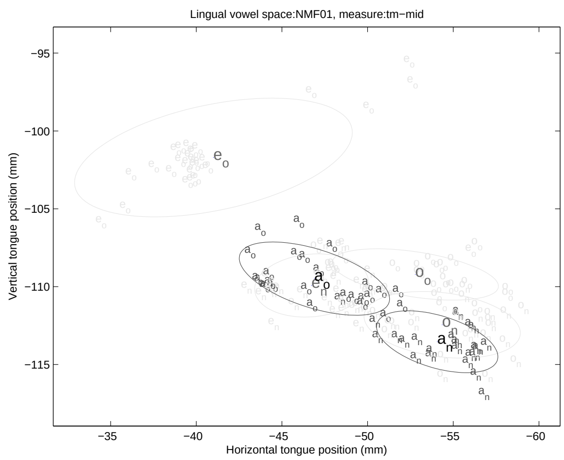


(d) Speaker NMF12 TT_{mid} lingual space, [a]-[ã]

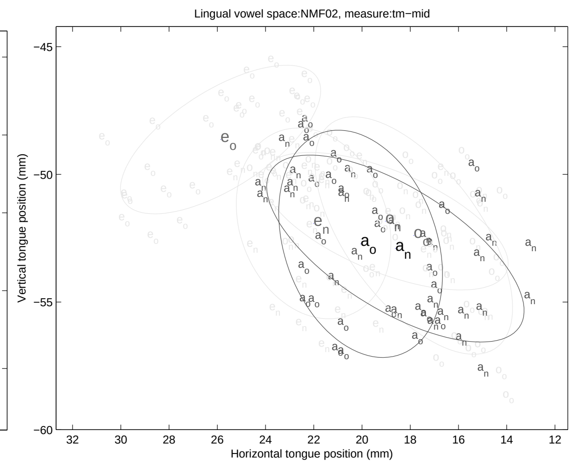


(e) Speaker NMF13 TT_{mid} lingual space, [a]-[ã]

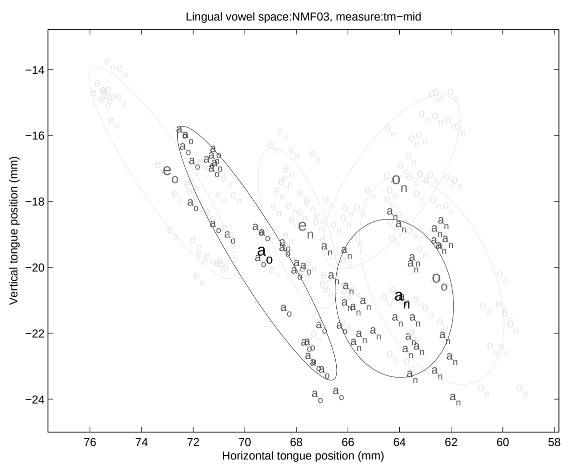
Figure 6.6: TT_{mid} lingual space for speakers NMF08-NMF13, with data sets for [a]-[ã] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



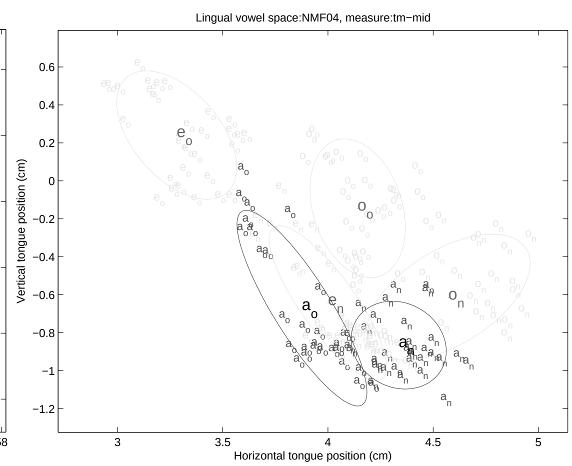
(a) Speaker NMF01 TM$_{mid}$ lingual space, [a]-[ã]



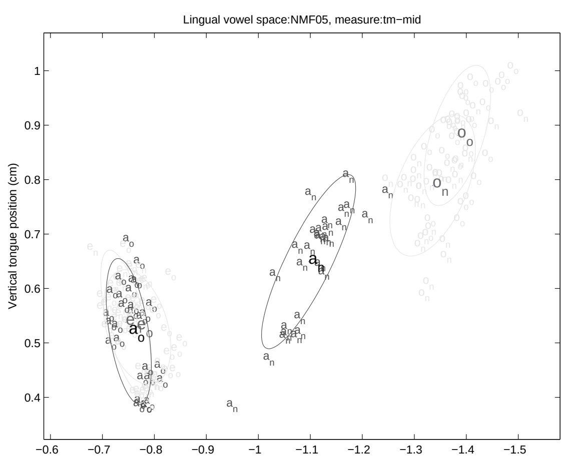
(b) Speaker NMF02 TM$_{mid}$ lingual space, [a]-[ã]



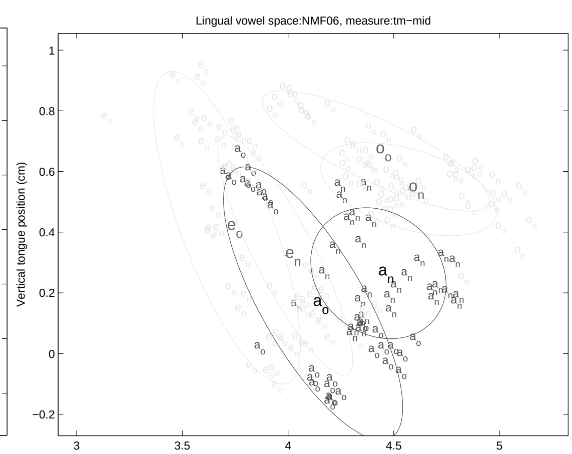
(c) Speaker NMF03 TM$_{mid}$ lingual space, [a]-[ã]



(d) Speaker NMF04 TM$_{mid}$ lingual space, [a]-[ã]

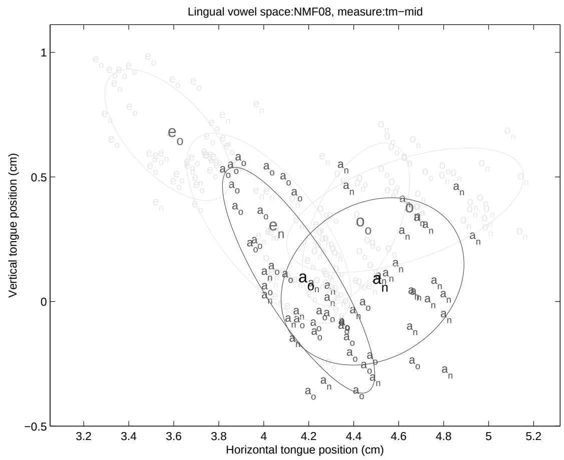


(e) Speaker NMF05 TM$_{mid}$ lingual space, [a]-[ã]

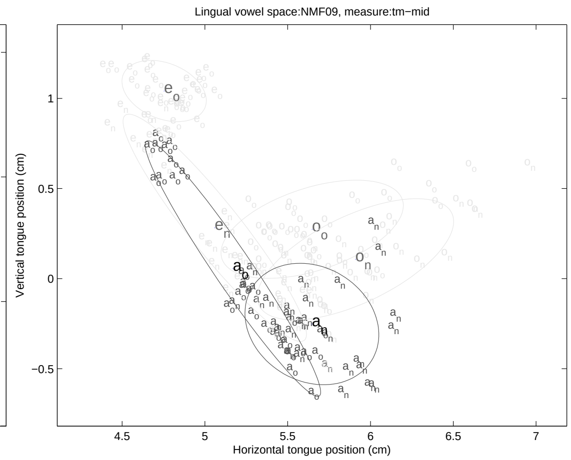


(f) Speaker NMF06 TM$_{mid}$ lingual space, [a]-[ã]

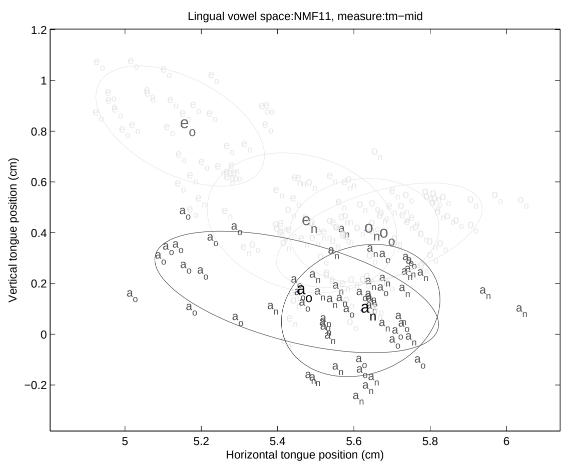
Figure 6.7: TM$_{mid}$ lingual space for speakers NMF01-NMF06, with data sets for [a]-[ã] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



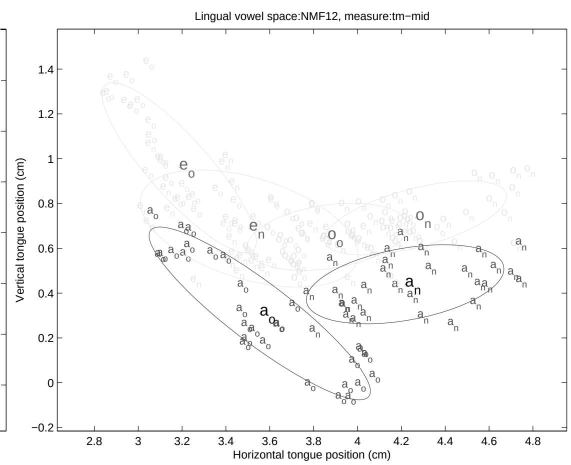
(a) Speaker NMF08 TM_{mid} lingual space, [a]-[ã]



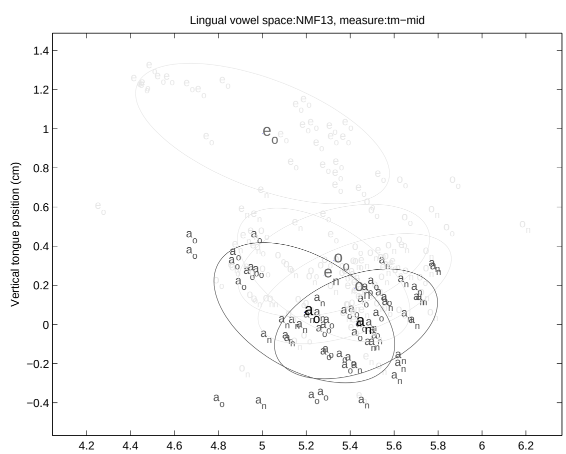
(b) Speaker NMF09 TM_{mid} lingual space, [a]-[ã]



(c) Speaker NMF11 TM_{mid} lingual space, [a]-[ã]

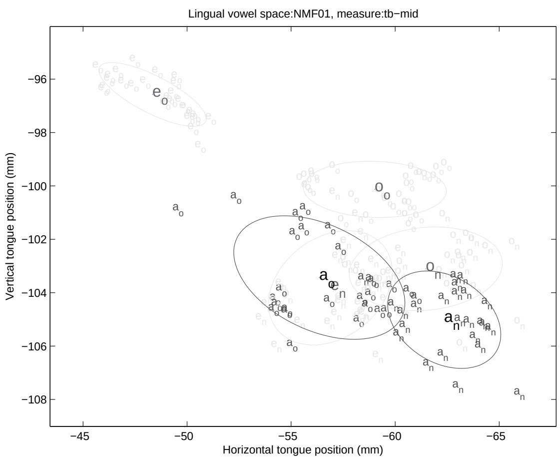


(d) Speaker NMF12 TM_{mid} lingual space, [a]-[ã]

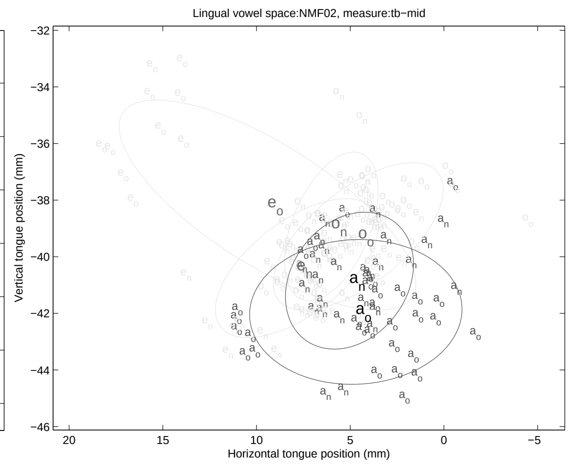


(e) Speaker NMF13 TM_{mid} lingual space, [a]-[ã]

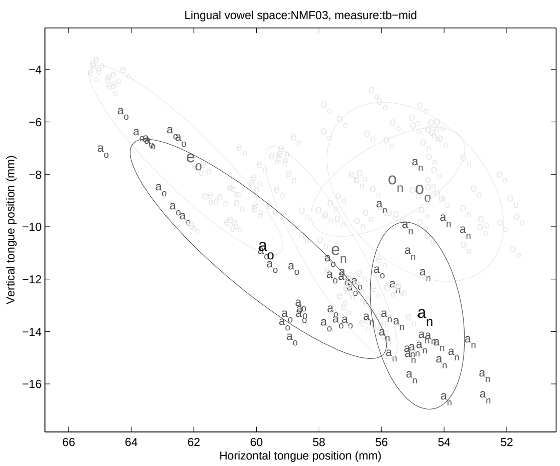
Figure 6.8: TM_{mid} lingual space for speakers NMF08-NMF13, with data sets for [a]-[ã] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



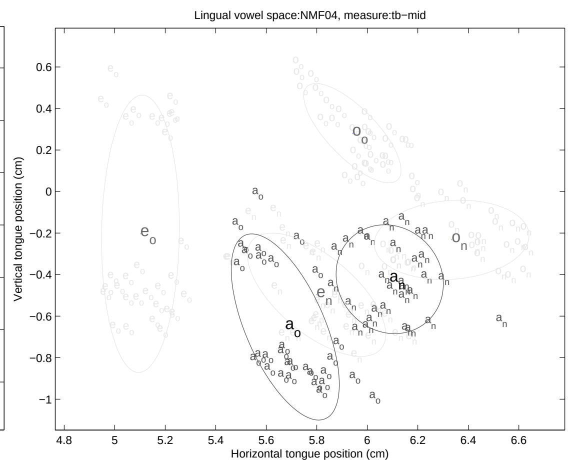
(a) Speaker NMF01 TB$_{mid}$ lingual space, [a]-[ã]



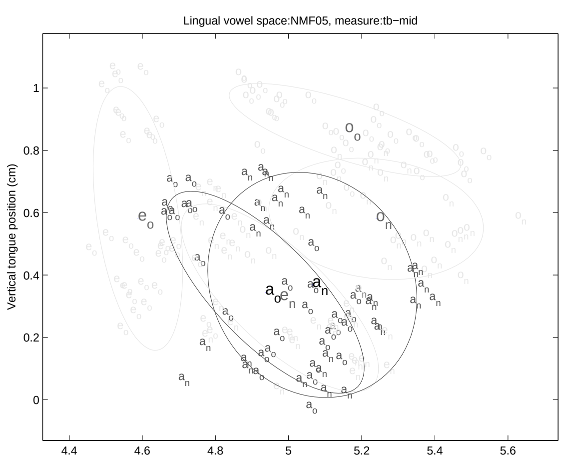
(b) Speaker NMF02 TB$_{mid}$ lingual space, [a]-[ã]



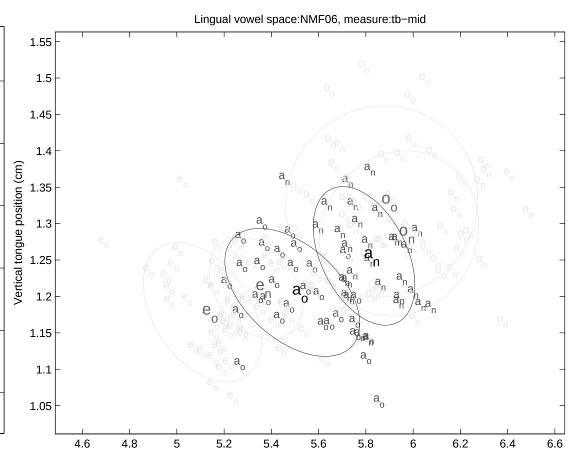
(c) Speaker NMF03 TB$_{mid}$ lingual space, [a]-[ã]



(d) Speaker NMF04 TB$_{mid}$ lingual space, [a]-[ã]

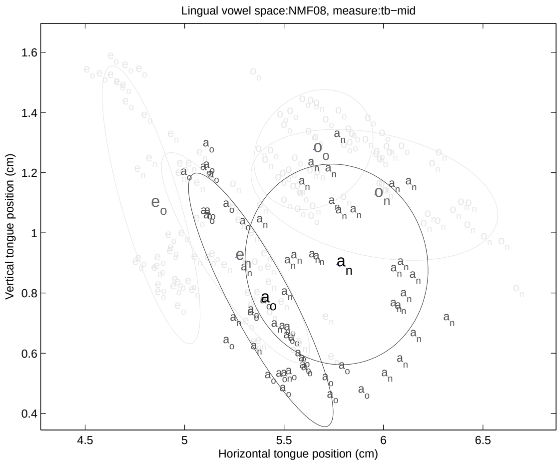


(e) Speaker NMF05 TB$_{mid}$ lingual space, [a]-[ã]

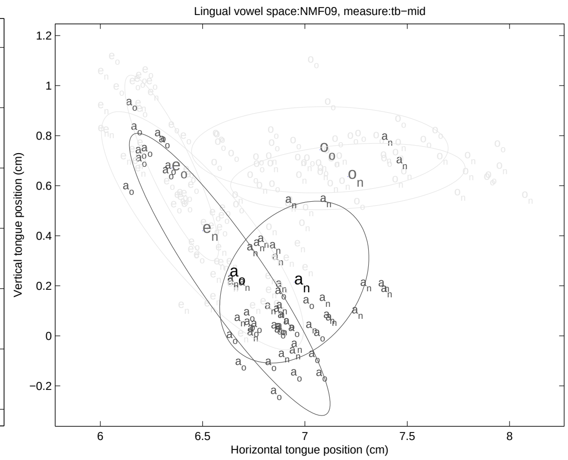


(f) Speaker NMF06 TB$_{mid}$ lingual space, [a]-[ã]

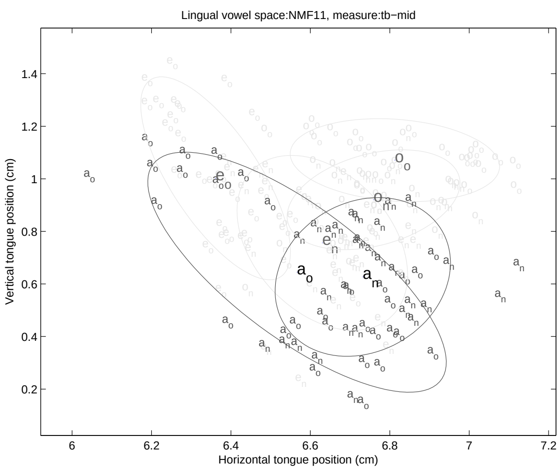
Figure 6.9: TB$_{mid}$ lingual space for speakers NMF01-NMF06, with data sets for [a]-[ã] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



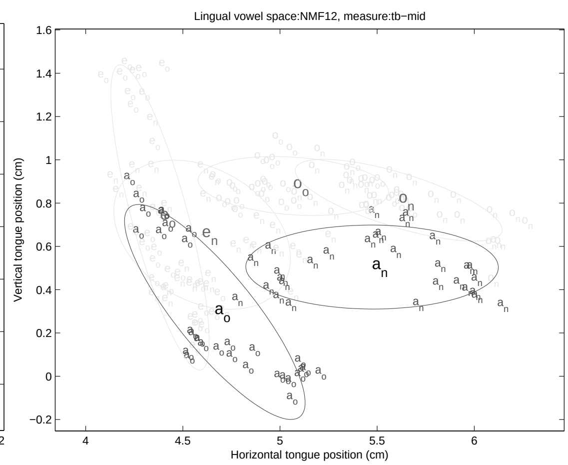
(a) Speaker NMF08 TB_{mid} lingual space, [a]-[ã]



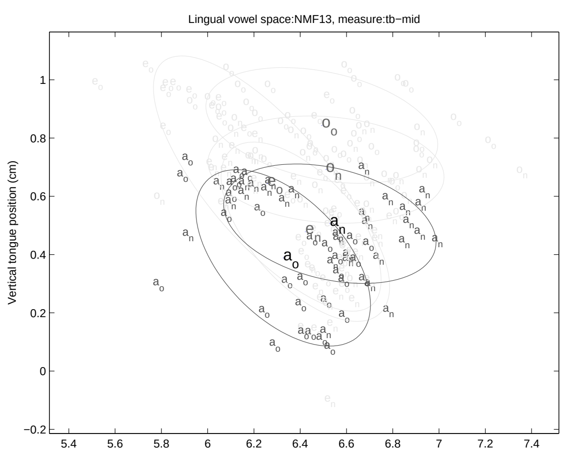
(b) Speaker NMF09 TB_{mid} lingual space, [a]-[ã]



(c) Speaker NMF11 TB_{mid} lingual space, [a]-[ã]



(d) Speaker NMF12 TB_{mid} lingual space, [a]-[ã]



(e) Speaker NMF13 TB_{mid} lingual space, [a]-[ã]

Figure 6.10: TB_{mid} lingual space for speakers NMF08-NMF13, with data sets for [a]-[ã] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

- Speakers NMF08 and NMF11 produce [ɑ̃] with the same tongue height as [a], yet [ɑ̃] is realized with a lower F1 than [a].
- Speaker NMF02 produces [ɑ̃] with the same horizontal tongue position as [a], yet [ɑ̃] is realized with a lower F2 than [a].

The discrepancies between lingual configuration and the acoustic output of the vowel pair [a]-[ɑ̃] can be summarized as follows:

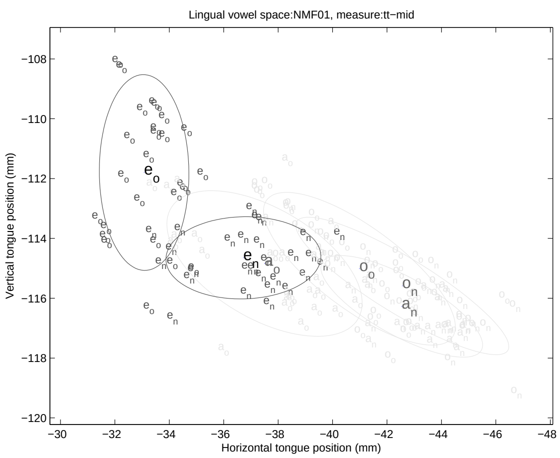
1. F1 is lower for [ɑ̃] than can be explained by tongue height alone.
   (a) F1 is lower, yet tongue is lower (predicted to raise F1).
   (b) F1 is lower, yet there is no difference in tongue height.
2. F2 is lower for [ɑ̃] than can be explained by horizontal tongue position alone.
   (a) F2 is lower, yet there is no difference in horizontal tongue position.

6.2.3 Northern Metropolitan French: Lingual articulation of [ɛ]-[ɛ̃]

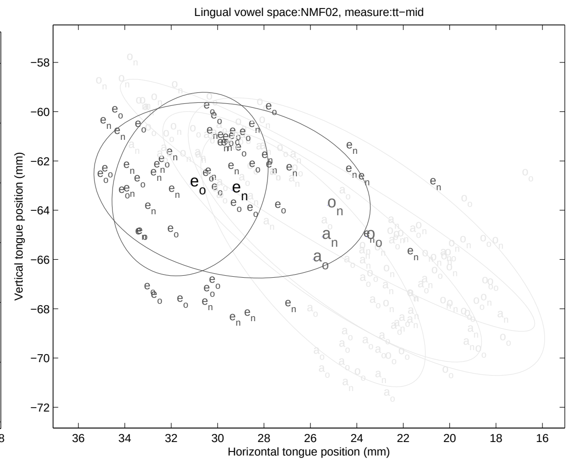
Figures highlighting the articulatory data for the vowel pair [ɛ]-[ɛ̃] are shown below. Plots of the TT sensor data are given in Figures 6.11 and 6.12, plots of the TM sensor data are given in Figures 6.13 and 6.14, and plots of the TB sensor data are given in Figures 6.15 and 6.16. All data provided in these figures are measurements taken at the vowel midpoint. For the oral/nasal vowel pair [ɛ]-[ɛ̃], there is almost no discrepancy between the lingual configuration and the acoustic output: all 11 speakers manifest a higher F1 and a lower F2 for [ɛ̃] compared to [ɛ], 10 of the 11 speakers produce [ɛ̃] with a lower tongue position compared to [ɛ], and all 11 speakers produced [ɛ̃] with a more retracted tongue position compared to [ɛ]. Therefore, the acoustic difference between oral [ɛ] and its nasal counterpart [ɛ̃] can be explained by the lingual configuration.

With regard to the results concerning tongue height and its relation to the results for F1, 10 of the 11 speakers clearly produce [ɛ̃] with a lower tongue position than [ɛ], which may explain the higher F1 for [ɛ̃] v. [ɛ] for these speakers. The predictions with regard to tongue height are, therefore, substantiated by the results for these 10 speakers. One speaker (NMF06), however, manifests a lingual configuration which is indicative of posterior bunching: TT is lower, and TB is higher for [ɛ̃], with no difference in the height of TM.

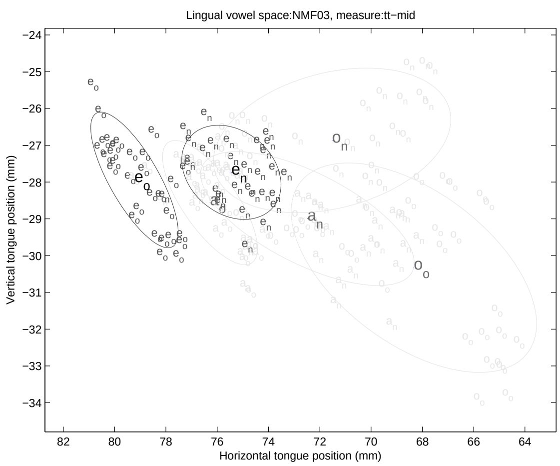
With regard to the results concerning horizontal tongue position and its relation to the results for F2, all 11 speakers produce [ɛ̃] with a more retracted tongue position than [ɛ], which may explain the lower F2 for [ɛ̃] v. [ɛ] for all of the speakers. The predictions with regard to horizontal tongue position are, therefore, substantiated by the results for all 11 speakers.



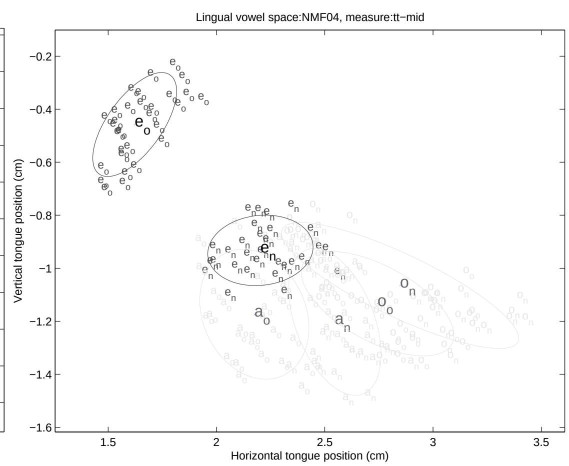
(a) Speaker NMF01 TT_{mid} lingual space, [ɛ]-[ɛ̃]



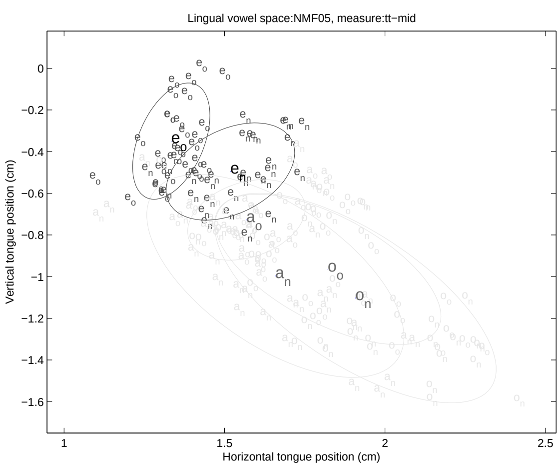
(b) Speaker NMF02 TT_{mid} lingual space, [ɛ]-[ɛ̃]



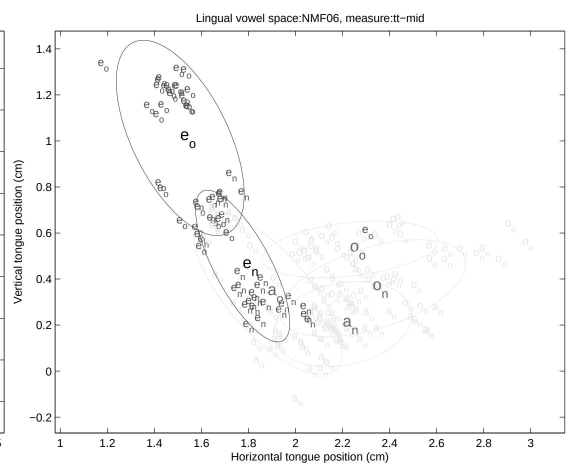
(c) Speaker NMF03 TT_{mid} lingual space, [ɛ]-[ɛ̃]



(d) Speaker NMF04 TT_{mid} lingual space, [ɛ]-[ɛ̃]

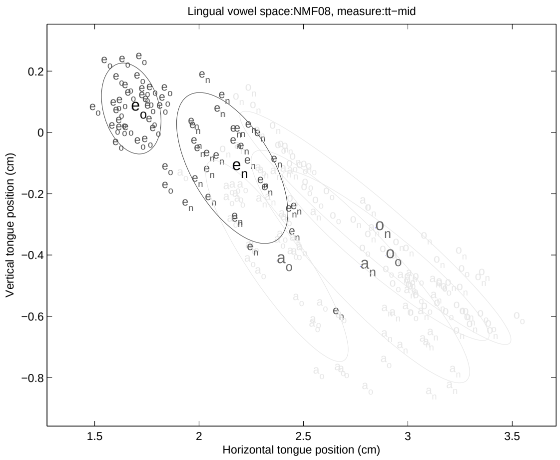


(e) Speaker NMF05 TT_{mid} lingual space, [ɛ]-[ɛ̃]

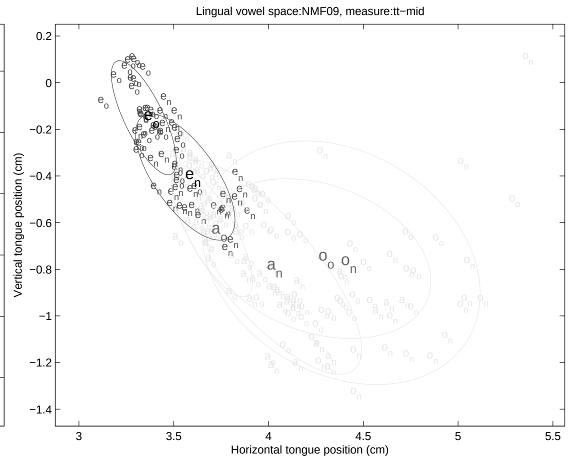


(f) Speaker NMF06 TT_{mid} lingual space, [ɛ]-[ɛ̃]

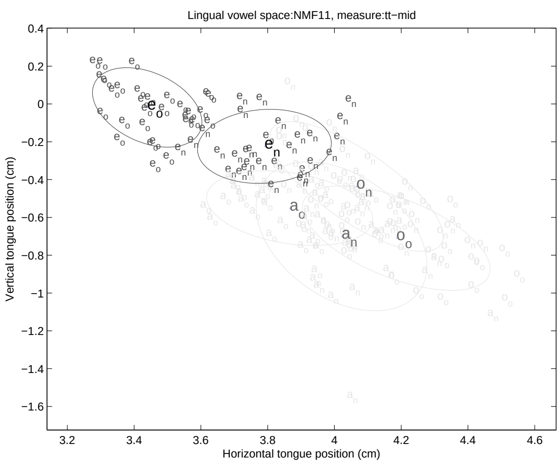
Figure 6.11: TT_{mid} lingual space for speakers NMF01-NMF06, with data sets for [ɛ]-[ɛ̃] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



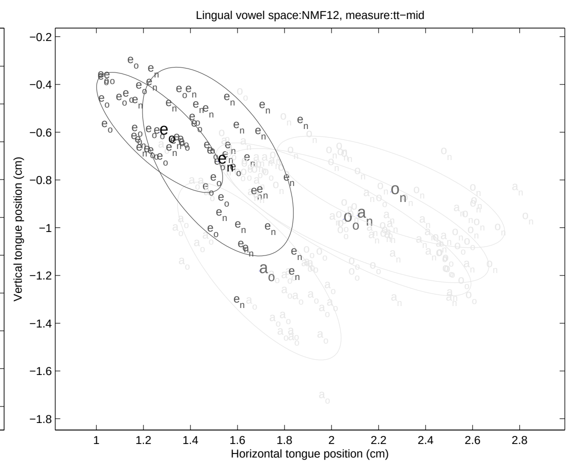
(a) Speaker NMF08 TT$_{mid}$ lingual space, [ɛ]-[ɛ̃]



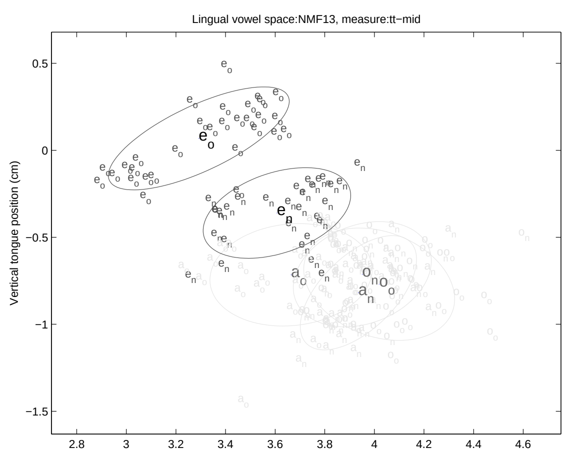
(b) Speaker NMF09 TT$_{mid}$ lingual space, [ɛ]-[ɛ̃]



(c) Speaker NMF11 TT$_{mid}$ lingual space, [ɛ]-[ɛ̃]

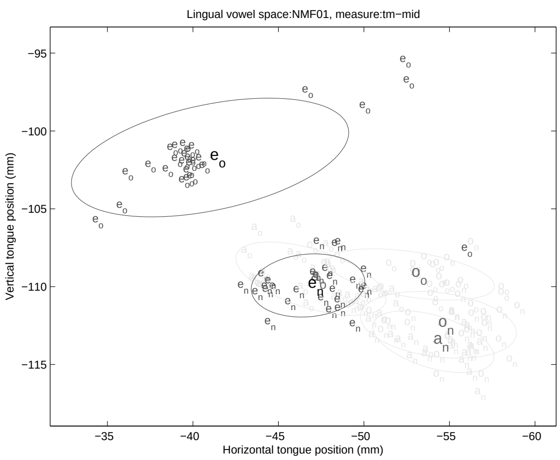


(d) Speaker NMF12 TT$_{mid}$ lingual space, [ɛ]-[ɛ̃]

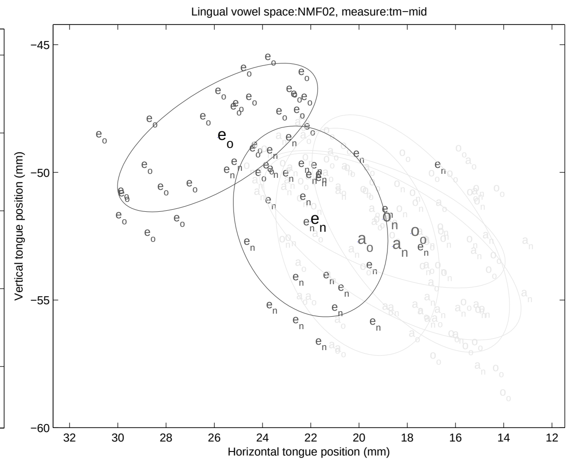


(e) Speaker NMF13 TT$_{mid}$ lingual space, [ɛ]-[ɛ̃]

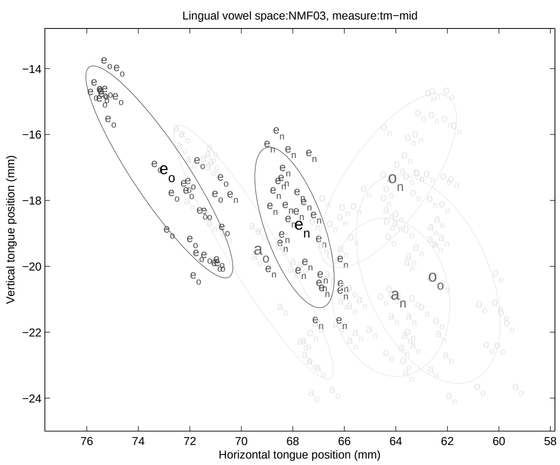
Figure 6.12: TT$_{mid}$ lingual space for speakers NMF08-NMF13, with data sets for [ɛ]-[ɛ̃] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



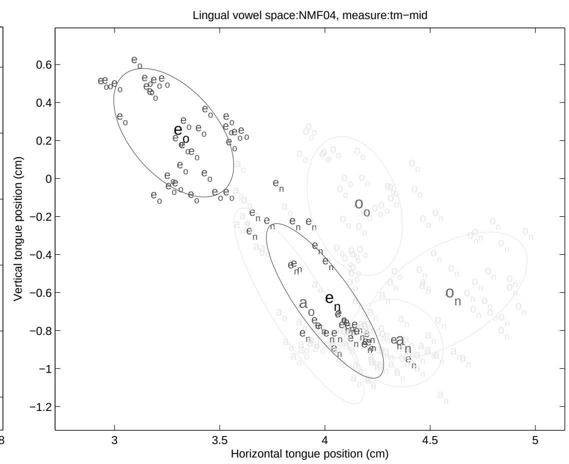
(a) Speaker NMF01 TM_{mid} lingual space, [ɛ]-[ɛ̃]



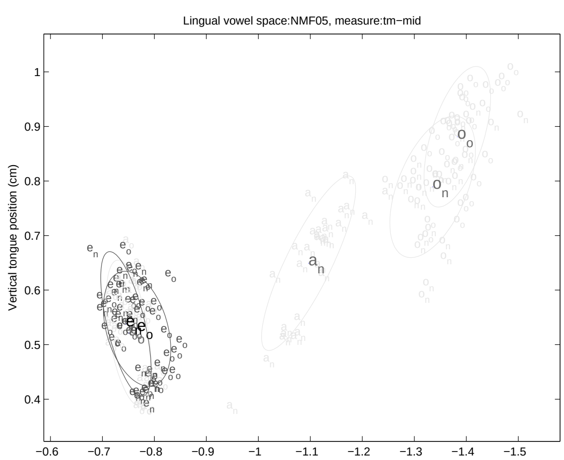
(b) Speaker NMF02 TM_{mid} lingual space, [ɛ]-[ɛ̃]



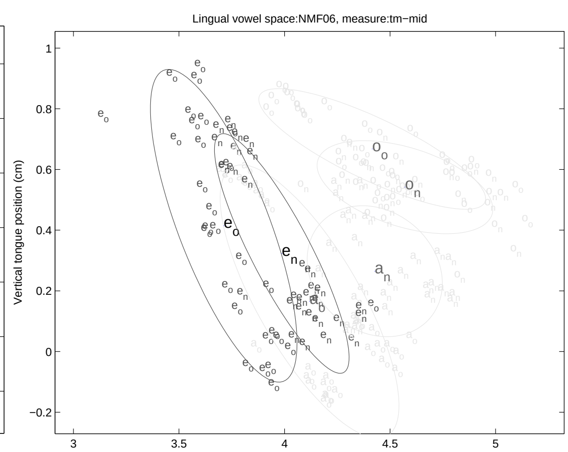
(c) Speaker NMF03 TM_{mid} lingual space, [ɛ]-[ɛ̃]



(d) Speaker NMF04 TM_{mid} lingual space, [ɛ]-[ɛ̃]

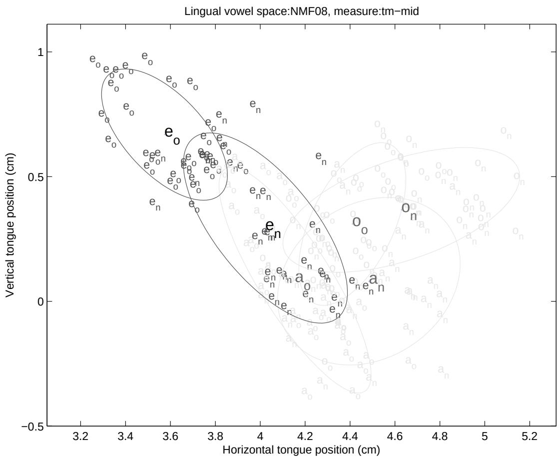


(e) Speaker NMF05 TM_{mid} lingual space, [ɛ]-[ɛ̃]

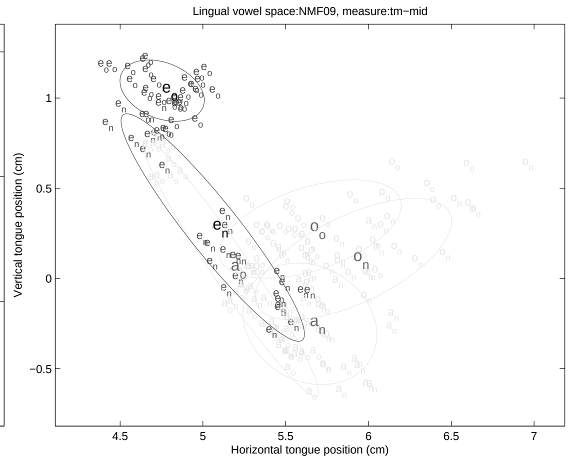


(f) Speaker NMF06 TM_{mid} lingual space, [ɛ]-[ɛ̃]

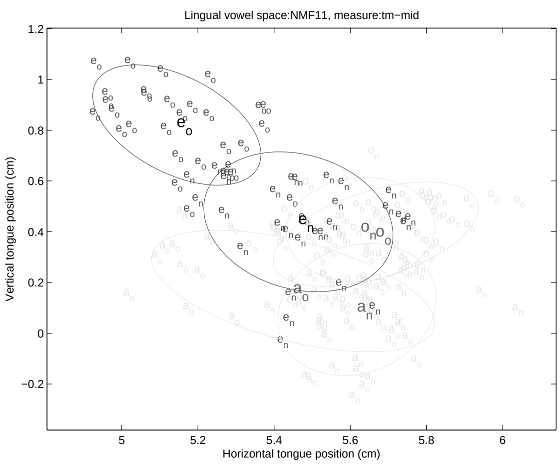
Figure 6.13: TM_{mid} lingual space for speakers NMF01-NMF06, with data sets for [ɛ]-[ɛ̃] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



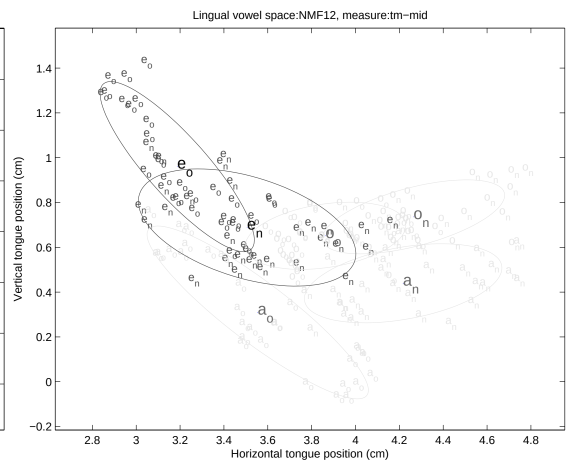
(a) Speaker NMF08 TM_{mid} lingual space, [ɛ]-[ɛ̃]



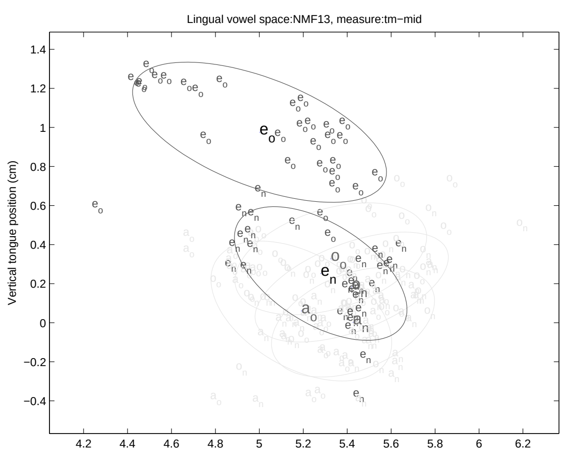
(b) Speaker NMF09 TM_{mid} lingual space, [ɛ]-[ɛ̃]



(c) Speaker NMF11 TM_{mid} lingual space, [ɛ]-[ɛ̃]

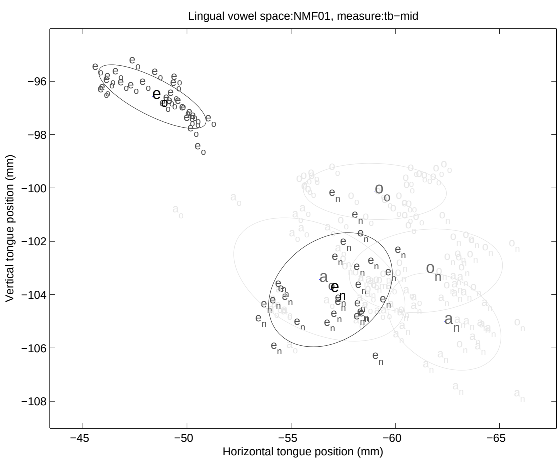


(d) Speaker NMF12 TM_{mid} lingual space, [ɛ]-[ɛ̃]

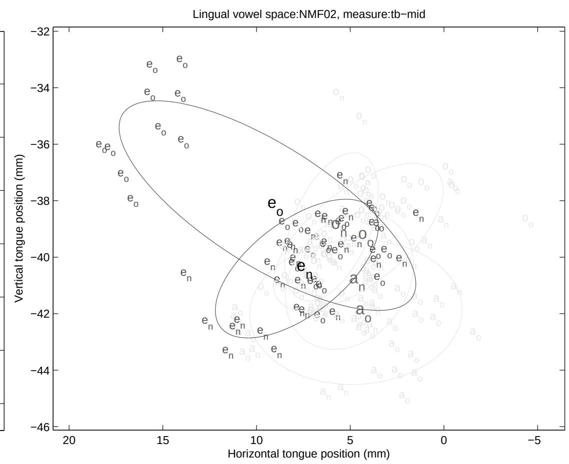


(e) Speaker NMF13 TM_{mid} lingual space, [ɛ]-[ɛ̃]

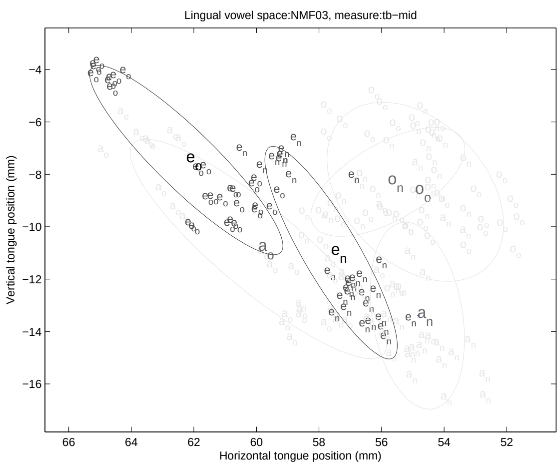
Figure 6.14: TM_{mid} lingual space for speakers NMF08-NMF13, with data sets for [ɛ]-[ɛ̃] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



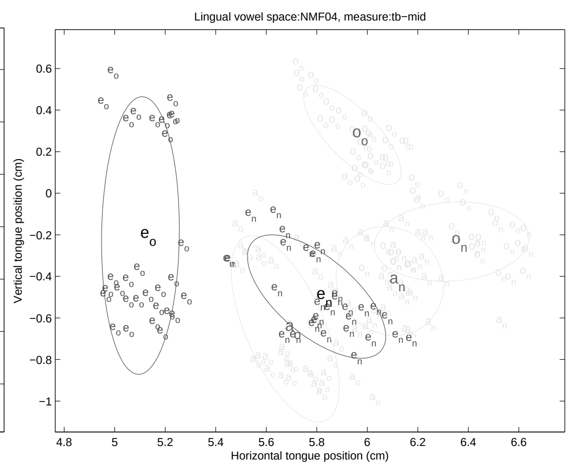
(a) Speaker NMF01 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]



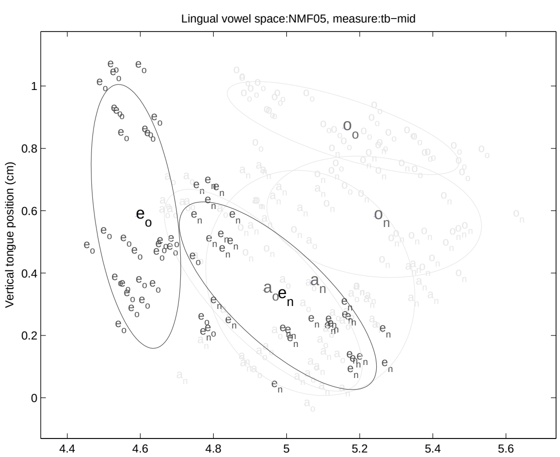
(b) Speaker NMF02 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]



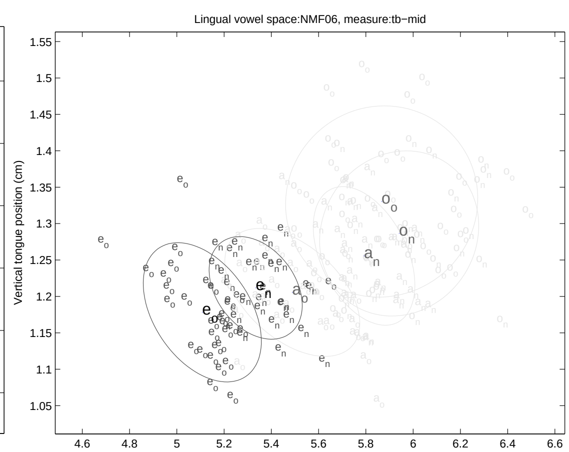
(c) Speaker NMF03 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]



(d) Speaker NMF04 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]

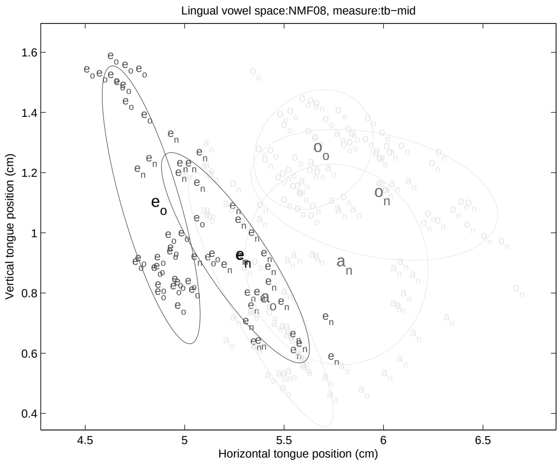


(e) Speaker NMF05 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]

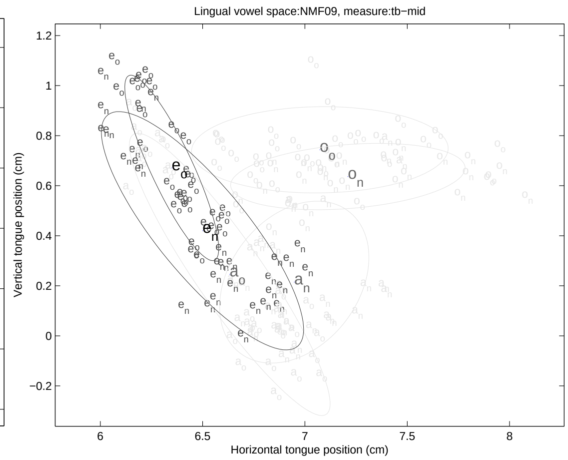


(f) Speaker NMF06 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]

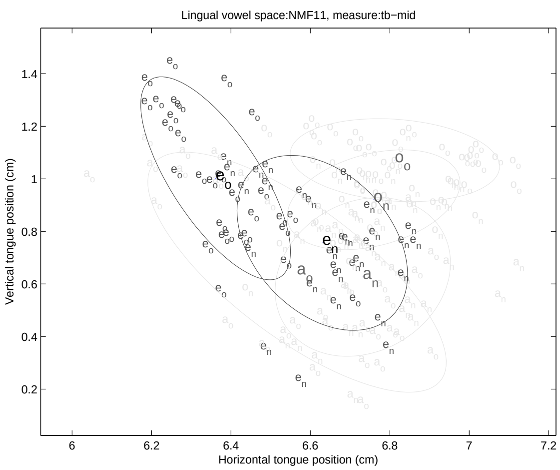
Figure 6.15: TB$_{mid}$ lingual space for speakers NMF01-NMF06, with data sets for [ɛ]-[ɛ̃] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



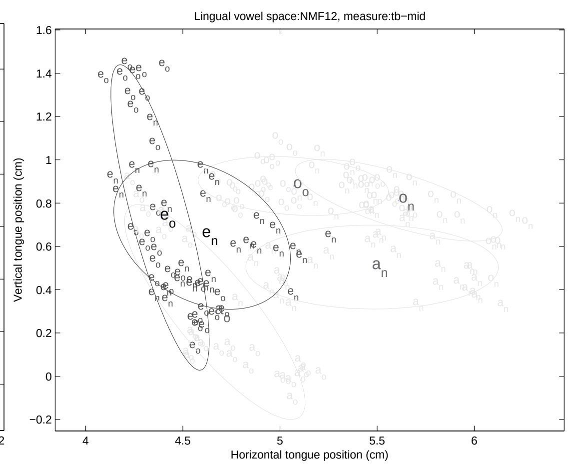
(a) Speaker NMF08 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]



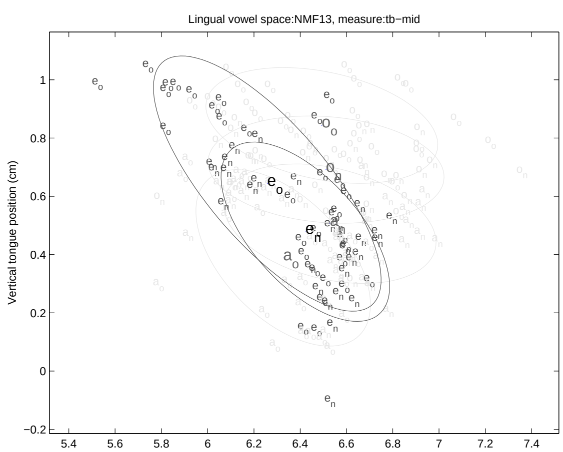
(b) Speaker NMF09 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]



(c) Speaker NMF11 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]



(d) Speaker NMF12 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]



(e) Speaker NMF13 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]

Figure 6.16: TB$_{mid}$ lingual space for speakers NMF08-NMF13, with data sets for [ɛ]-[ɛ̃] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

In summary, the following discrepancies are observed for the lingual articulation and acoustic realization of [ɛ̃] compared to [ɛ]:

- Speaker NMF06 produces [ɛ̃] with a higher tongue back than [ɛ], yet [ɛ̃] is realized with a higher F1 than [ɛ].

6.2.4 Northern Metropolitan French: Lingual articulation of [o]-[ɔ̃]

Figures highlighting the articulatory data for the vowel pair [o]-[ɔ̃] are shown below. Plots of the TT sensor data are given in Figures 6.17 and 6.18, plots of the TM sensor data are given in Figures 6.19 and 6.20, and plots of the TB sensor data are given in Figures 6.21 and 6.22. All data provided in these figures are measurements taken at the vowel midpoint. The most inter-speaker variation with regard to the acoustic output was observed for the vowel pair [o]-[ɔ̃] (see 6.1.3); similarly, the most inter-speaker variation with regard to lingual configuration is also observed for the vowel pair [o]-[ɔ̃]. However, this articulatory variation cannot account for the acoustic variation in all cases.

I return now to the predictions for individual speakers for lingual articulatory differences of [o]-[ɔ̃], outlined in 6.1.3, which are based on the acoustic realizations of their productions of [o]-[ɔ̃]. With regard to the results for tongue height, the following predictions are substantiated:

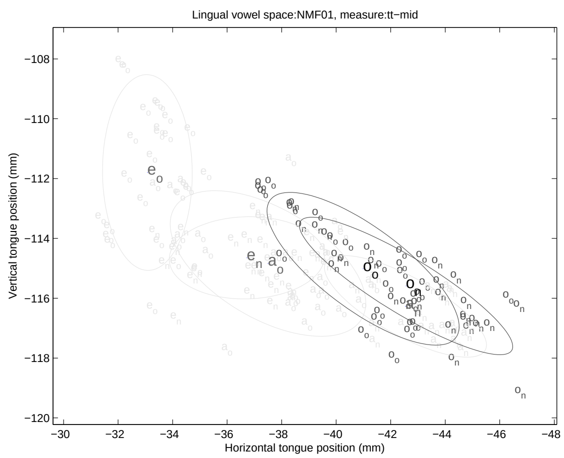
- Speakers NMF03 and NMF12 produce [ɔ̃] with a higher tongue position than [o].
- Speakers NMF06 and NMF08 produce [ɔ̃] with a lower tongue position than [o].

However, for seven of the 11 speakers, the predictions for lingual height are not substantiated by the data. Lingual height alone cannot explain the difference in F1 between oral [o] and its nasal counterpart [ɔ̃] in these cases. These articulatory/acoustic discrepancies are as follows:

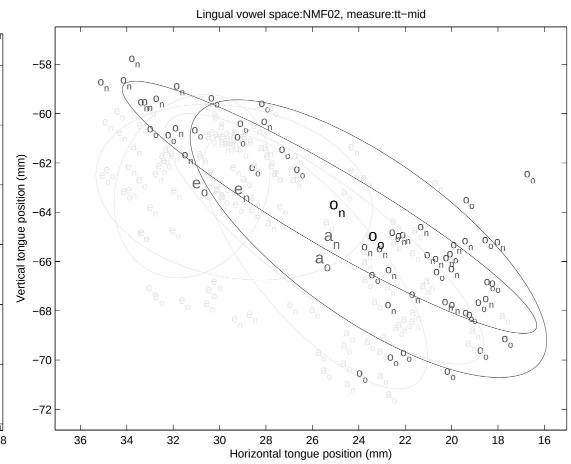
- Speakers NMF01 and NMF09 produce [ɔ̃] with a lower tongue position than [o], yet there is no difference in F1 between [ɔ̃] and [o].
- Speakers NMF04, NMF05, and NMF11 produce [ɔ̃] with a lower tongue position than [o], yet [ɔ̃] is realized with a lower F1 than [o].
- Speaker NMF02 produces [ɔ̃] with no difference in tongue height compared to [o], yet [ɔ̃] is realized with a lower F1 than [o].
- Speaker NMF13 produces [ɔ̃] with a lower tongue position than [o], yet [ɔ̃] is realized with a lower F1 than [o].

With regard to the results for horizontal tongue position, the following predictions are substantiated:

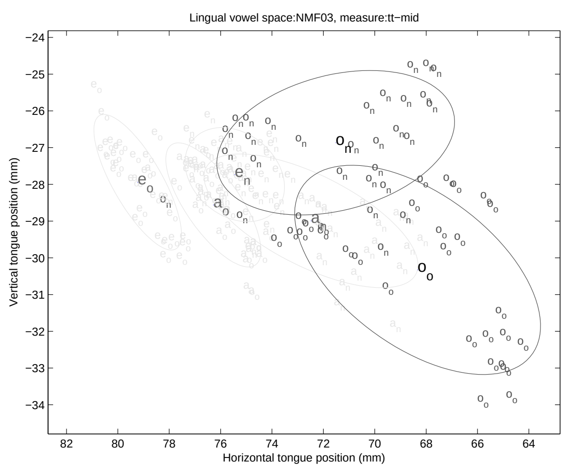
- Speakers NMF01, NMF04, NMF08, NMF09, and NMF12 produce [ɔ̃] with a more retracted tongue position than [o].



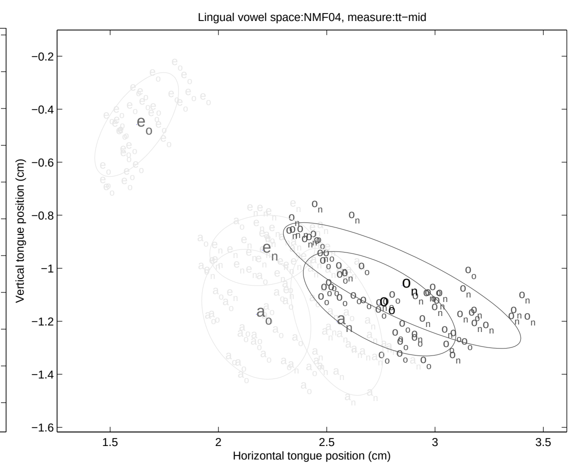
(a) Speaker NMF01 TT$_{mid}$ lingual space, [o]-[õ]



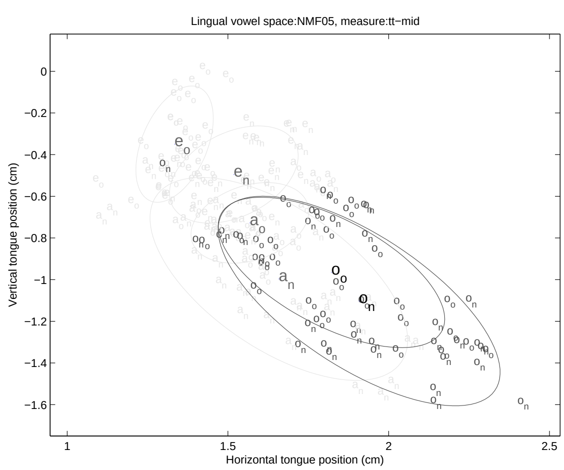
(b) Speaker NMF02 TT$_{mid}$ lingual space, [o]-[õ]



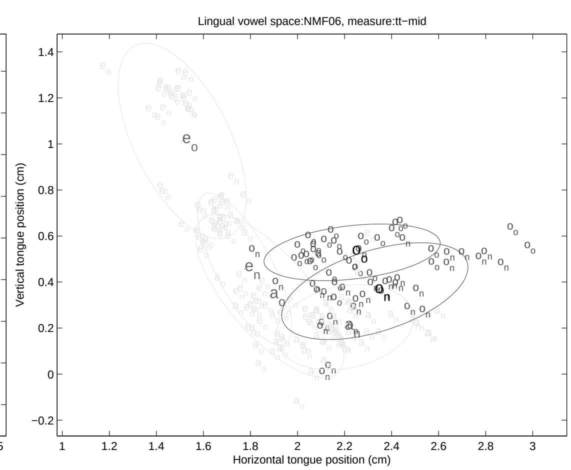
(c) Speaker NMF03 TT$_{mid}$ lingual space, [o]-[õ]



(d) Speaker NMF04 TT$_{mid}$ lingual space, [o]-[õ]

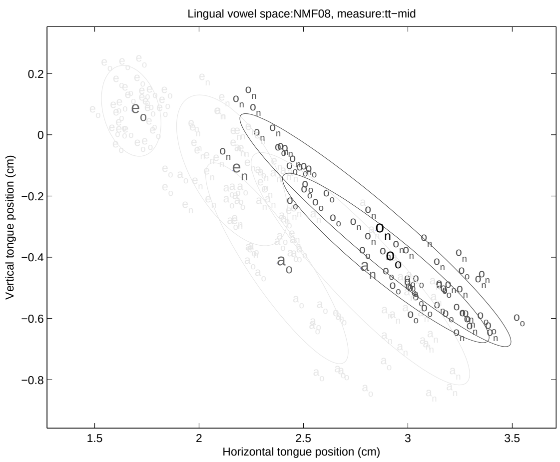


(e) Speaker NMF05 TT$_{mid}$ lingual space, [o]-[õ]

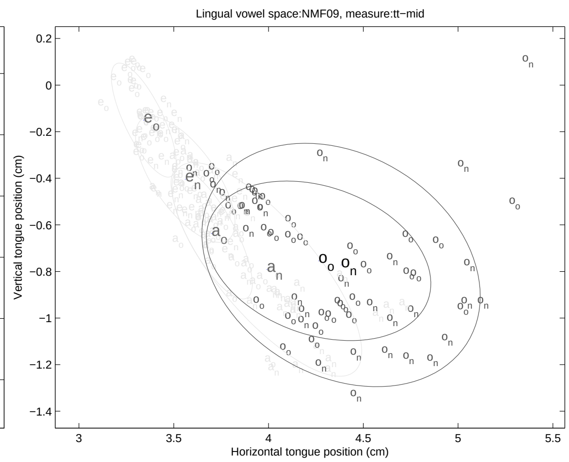


(f) Speaker NMF06 TT$_{mid}$ lingual space, [o]-[õ]

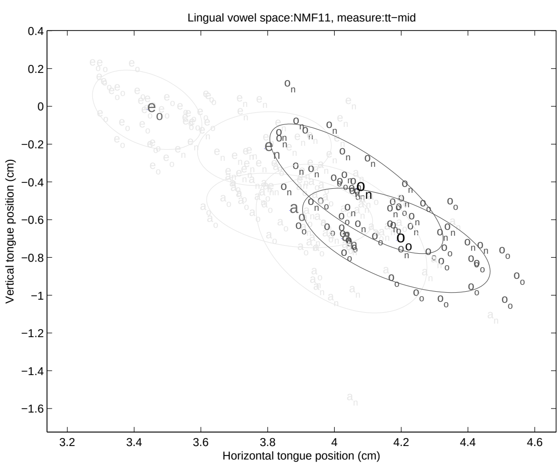
Figure 6.17: TT$_{mid}$ lingual space for speakers NMF01-NMF06, with data sets for [o]-[õ] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



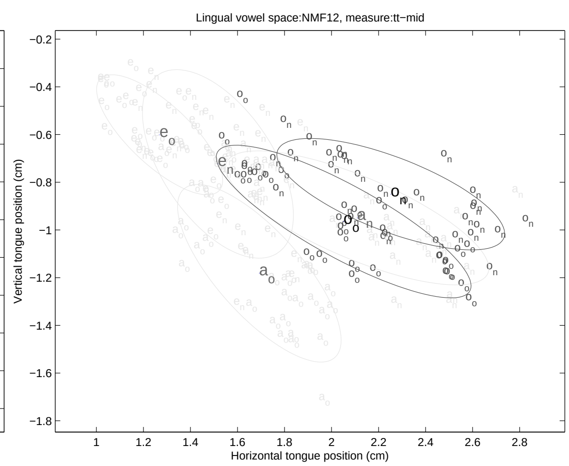
(a) Speaker NMF08 TT_{mid} lingual space, [o]-[õ]



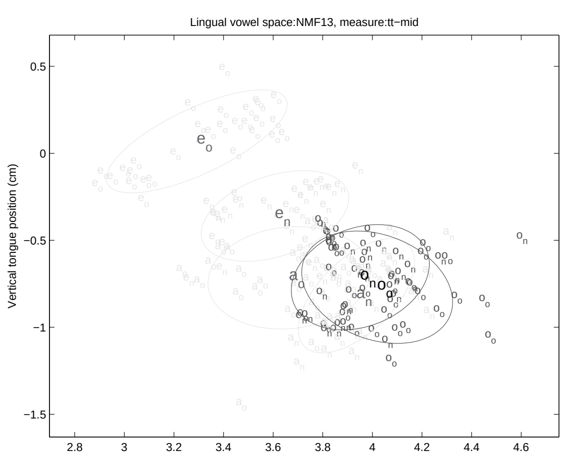
(b) Speaker NMF09 TT_{mid} lingual space, [o]-[õ]



(c) Speaker NMF11 TT_{mid} lingual space, [o]-[õ]

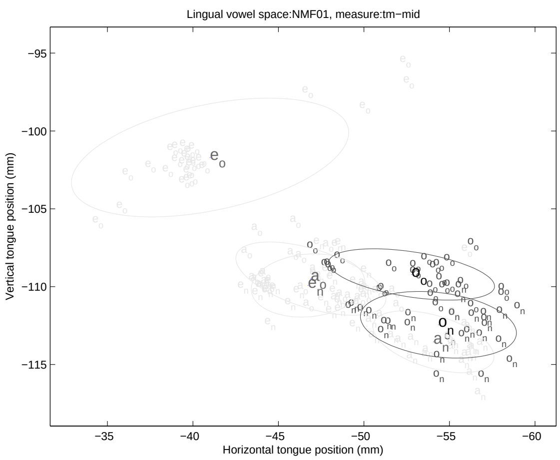


(d) Speaker NMF12 TT_{mid} lingual space, [o]-[õ]

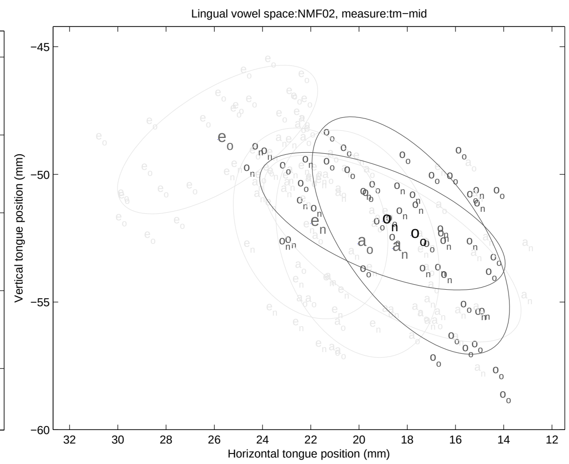


(e) Speaker NMF13 TT_{mid} lingual space, [o]-[õ]

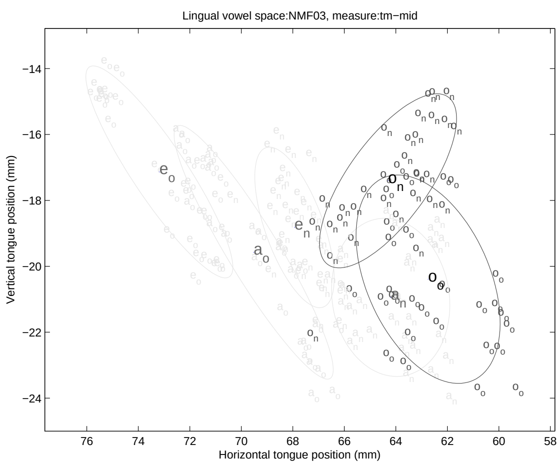
Figure 6.18: TT_{mid} lingual space for speakers NMF08-NMF13, with data sets for [o]-[õ] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



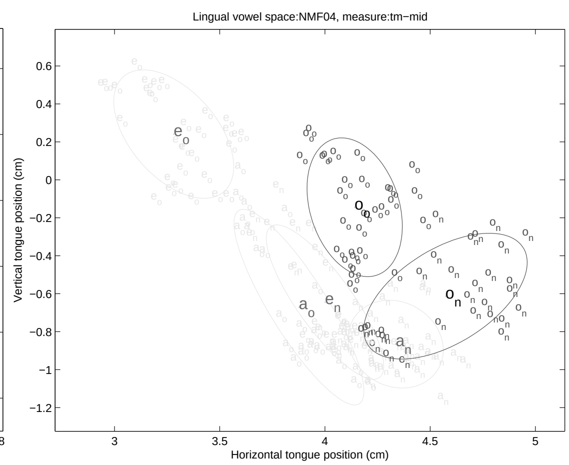
(a) Speaker NMF01 TM_{mid} lingual space, [o]-[ɔ̃]



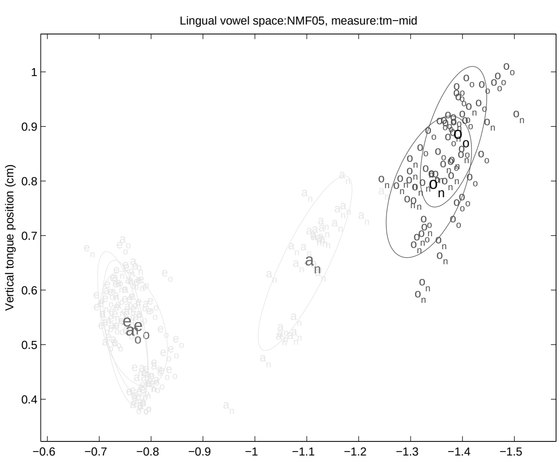
(b) Speaker NMF02 TM_{mid} lingual space, [o]-[ɔ̃]



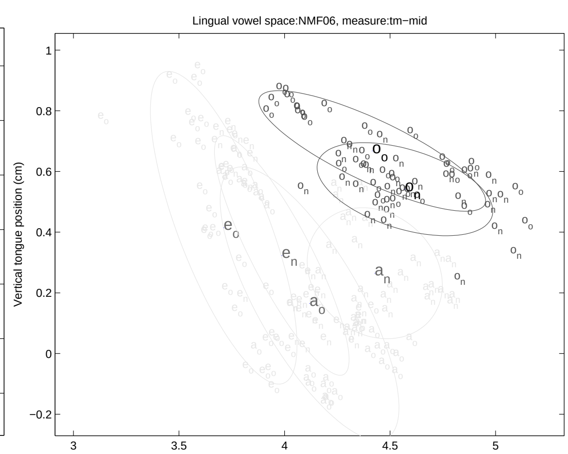
(c) Speaker NMF03 TM_{mid} lingual space, [o]-[ɔ̃]



(d) Speaker NMF04 TM_{mid} lingual space, [o]-[ɔ̃]

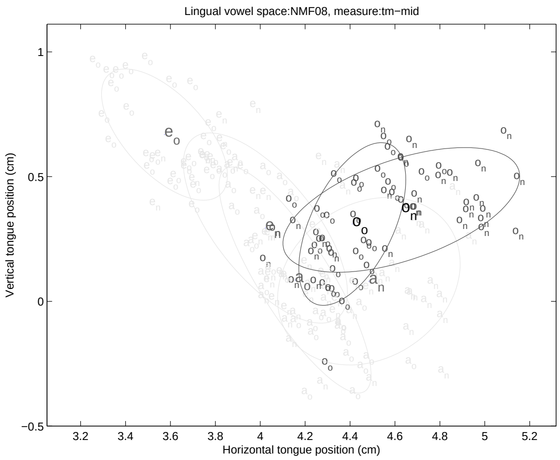


(e) Speaker NMF05 TM_{mid} lingual space, [o]-[ɔ̃]

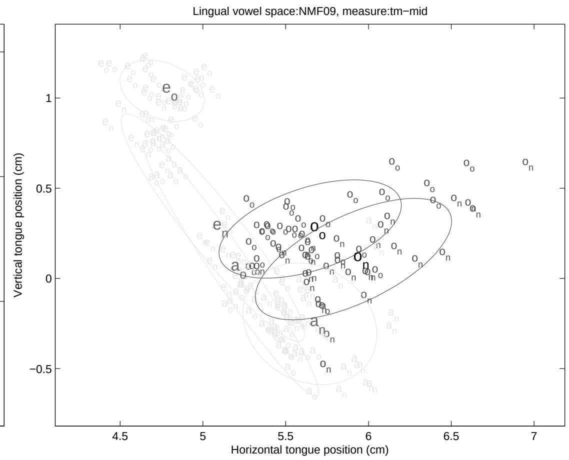


(f) Speaker NMF06 TM_{mid} lingual space, [o]-[ɔ̃]

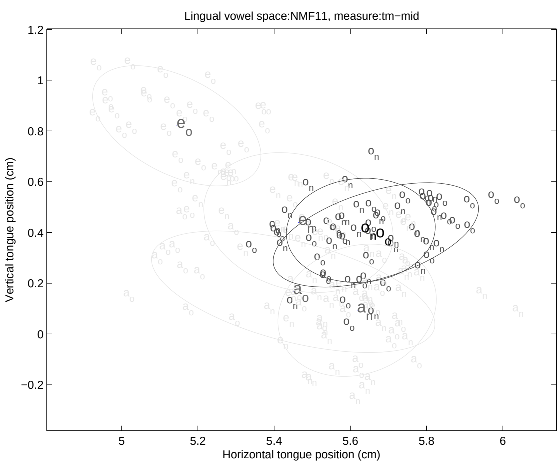
Figure 6.19: TM_{mid} lingual space for speakers NMF01-NMF06, with data sets for [o]-[ɔ̃] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



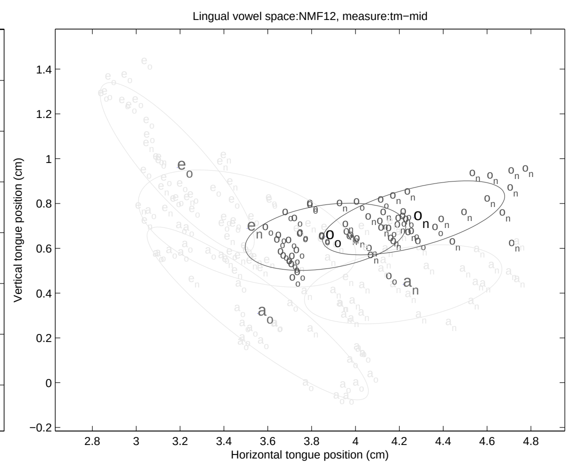
(a) Speaker NMF08 TM_{mid} lingual space, [o]-[õ]



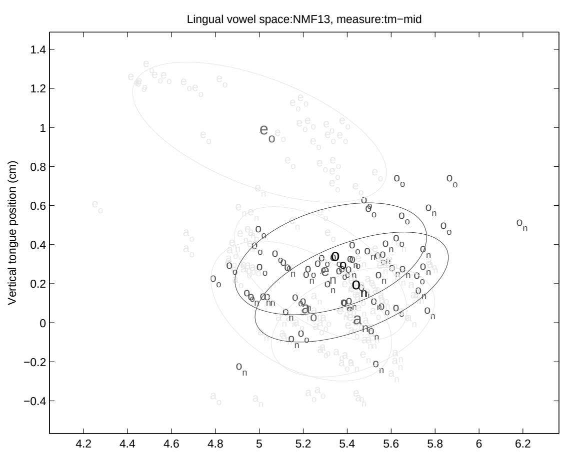
(b) Speaker NMF09 TM_{mid} lingual space, [o]-[õ]



(c) Speaker NMF11 TM_{mid} lingual space, [o]-[õ]

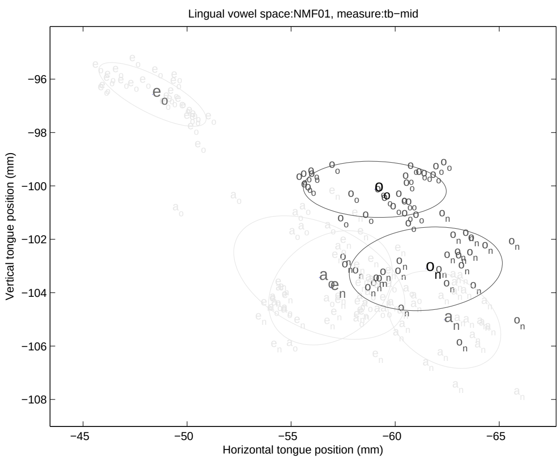


(d) Speaker NMF12 TM_{mid} lingual space, [o]-[õ]

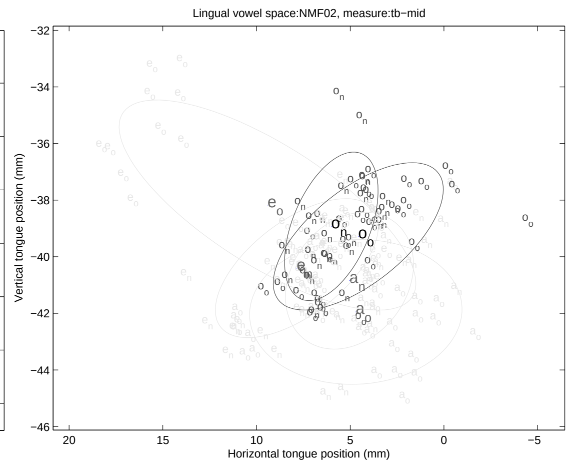


(e) Speaker NMF13 TM_{mid} lingual space, [o]-[õ]

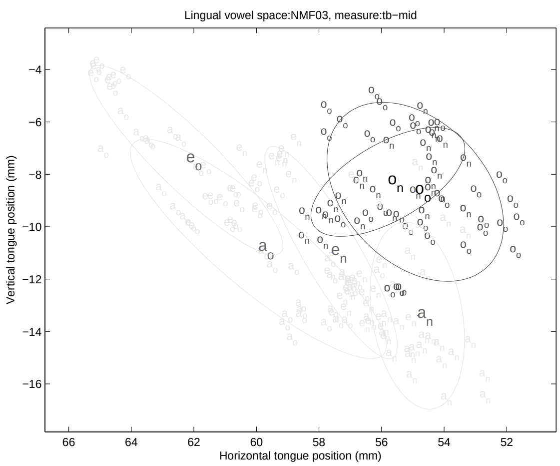
Figure 6.20: TM_{mid} lingual space for speakers NMF08-NMF13, with data sets for [o]-[õ] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



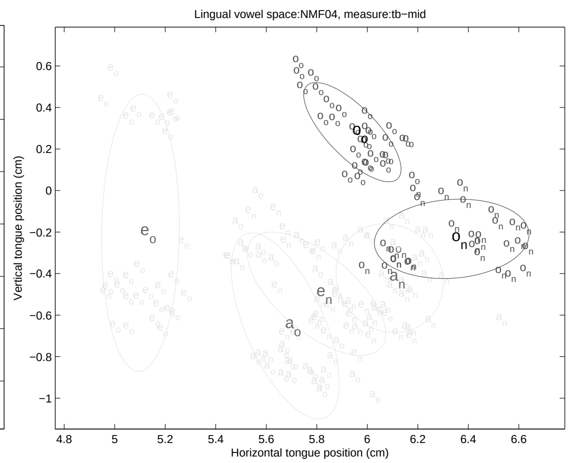
(a) Speaker NMF01 TB$_{mid}$ lingual space, [o]-[õ]



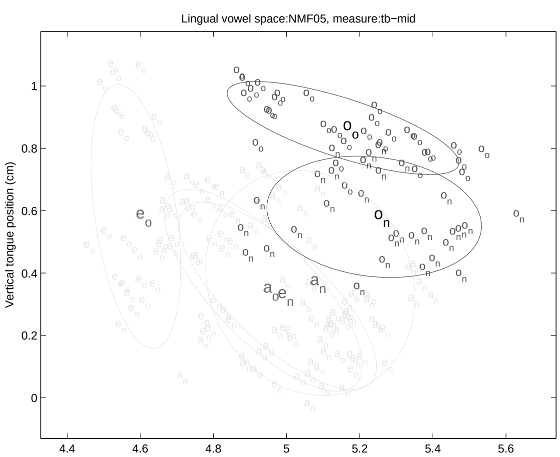
(b) Speaker NMF02 TB$_{mid}$ lingual space, [o]-[õ]



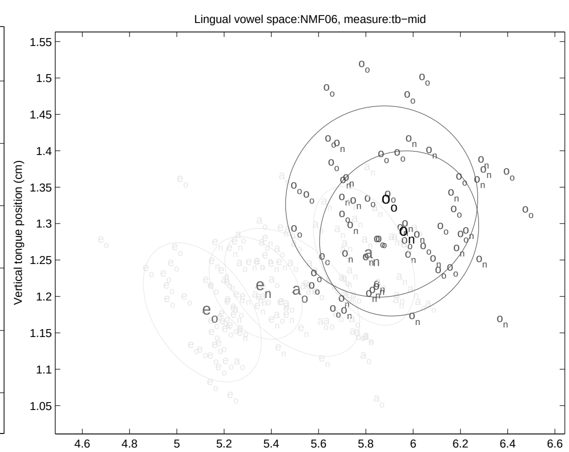
(c) Speaker NMF03 TB$_{mid}$ lingual space, [o]-[õ]



(d) Speaker NMF04 TB$_{mid}$ lingual space, [o]-[õ]

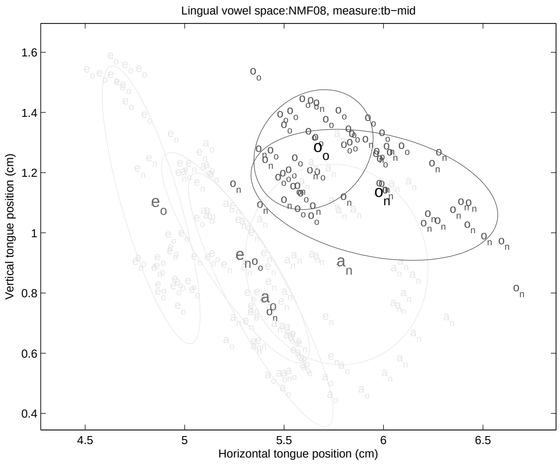


(e) Speaker NMF05 TB$_{mid}$ lingual space, [o]-[õ]

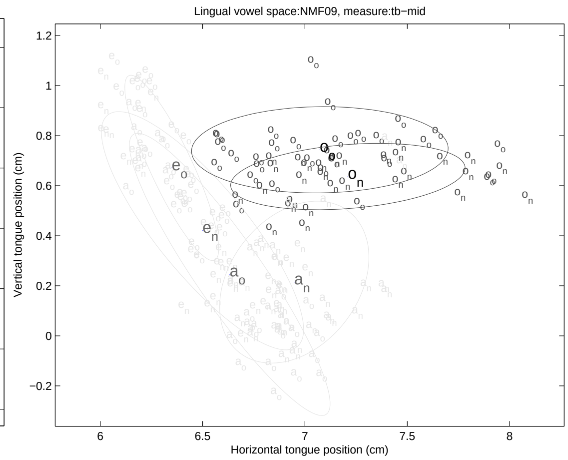


(f) Speaker NMF06 TB$_{mid}$ lingual space, [o]-[õ]

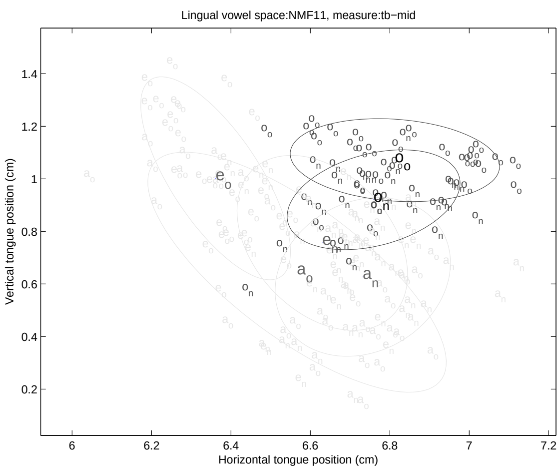
Figure 6.21: TB$_{mid}$ lingual space for speakers NMF01-NMF06, with data sets for [o]-[õ] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



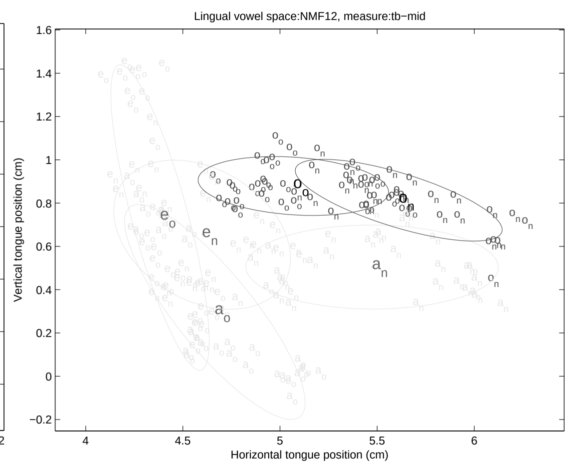
(a) Speaker NMF08 TB$_{mid}$ lingual space, [o]-[õ]



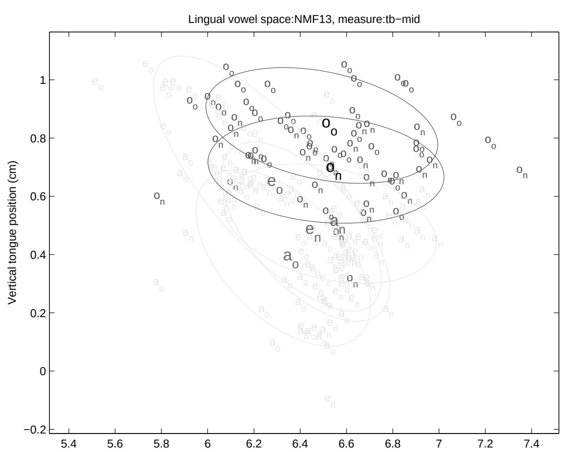
(b) Speaker NMF09 TB$_{mid}$ lingual space, [o]-[õ]



(c) Speaker NMF11 TB$_{mid}$ lingual space, [o]-[õ]



(d) Speaker NMF12 TB$_{mid}$ lingual space, [o]-[õ]



(e) Speaker NMF13 TB$_{mid}$ lingual space, [o]-[õ]

Figure 6.22: TB$_{mid}$ lingual space for speakers NMF08-NMF13, with data sets for [o]-[õ] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

- Speakers NMF06 and NMF13 produce [ɔ̃] with no difference in horizontal tongue position compared to [o].

However, for four of the 11 speakers, the predictions for horizontal lingual position are not substantiated by the data. The horizontal position of the tongue alone cannot explain the difference in F2 between oral [o] and its nasal counterpart [ɔ̃] in these cases. These articulatory/acoustic discrepancies are as follows:

- Speakers NMF03 and NMF05 produce [ɔ̃] with a more fronted tongue position than [o], yet [ɔ̃] is realized with a lower F2 than [o].
- Speakers NMF02 and NMF11 produce [ɔ̃] with either no difference in horizontal tongue position compared to [o], or possibly a slightly more fronted tongue position than [o], yet [ɔ̃] is realized with a lower F2 than [o].

The discrepancies between lingual configuration and the acoustic output of the vowel pair [o]-[ɔ̃] can be summarized as follows:

1. F1 is lower for [ɔ̃] than can be explained by tongue height alone.
   (a) F1 is lower, yet tongue is lower (predicted to raise F1).
   (b) F1 is lower, yet there is no difference in tongue height.
   (c) There is no difference in F1, yet tongue is lower (predicted to raise F1).
2. F2 is lower for [ɔ̃] than can be explained by horizontal tongue position alone.
   (a) F2 is lower, yet tongue is more fronted (predicted to raise F2).
   (b) F2 is lower, yet there is no difference in horizontal tongue position.

Given the results observed here for discrepancies between the lingual articulations and acoustic realizations of the three vowel pairs [a]-[ɑ̃], [ɛ]-[ɛ̃], and [o]-[ɔ̃] in the NMF dialect, the next step is to analyze the results for labial articulation in order to determine if the configuration of the lips can account for any of these discrepancies between lingual articulation and the acoustic output. These results for labial articulation are analyzed in the following section.

6.3 Northern Metropolitan French: Labial articulation

The results for the one-way ANOVAs with the labial protrusion and aperture measures outlined in 5.2.2 as the independent variable are provided in Tables 6.6 and 6.7. Table cells with measures which yield no significant difference are colored white. Cells with measures which yield a significant difference ($p < 0.05$) are highlighted in one of two shades of gray: cells which are highlighted in light gray correspond to a significant difference where the sensor value for the nasal vowel is significantly *lower* than the value for its oral congener (i.e., smaller labial aperture for distance and area measures, and more retracted labial articulation for *x*-dimension of UL and LL sensors), and cells which are highlighted in dark gray correspond to a significant difference where the sensor value for the nasal vowel is significantly *higher* than the value for its oral congener (i.e., larger labial aperture for distance and area measures, and more protruded labial articulation for *x*-dimension of UL and LL sensors).

The data for one speaker (NMF03) manifested ubiquitous tracking errors for the UL sensor. Therefore, the following measures—all of which necessitate data from the UL sensor for their calculation—are not included in the analysis for this speaker: UL *x*-dimension ("upper_x"), UL/LL euclidean distance ("distance"), and labial aperture area ("area"). These measures are marked "N/A" in the corresponding cell in the table. Thus, the labial analysis for this speaker only includes a single measure of lip protrusion via the LL *x*-dimension ("lower_x").

6.3.1 Northern Metropolitan French: Labial articulation of [a]-[ɑ̃]

There is some inter-speaker variation with regard to the differences in labial articulation for the vowel pair [a]-[ɑ̃]. Nevertheless, in general, nasal [ɑ̃] is characterized by greater lip protrusion—and, in some cases, more lip rounding—compared to [a], an articulatory configuration which is predicted to lower both F1 and F2. The labial configurations for individual speakers are:

- Speakers NMF08, NMF09, NMF11, and NMF12 produce [ɑ̃] with smaller labial aperture and greater labial protrusion compared to [a]. This articulatory configuration is indicative of great lip rounding and protrusion for [ɑ̃] v. [a].
- Speakers NMF01 and NMF02 produce [ɑ̃] with smaller labial aperture compared to [a]. This articulatory configuration is indicative of greater lip rounding for [ɑ̃] v. [a].
- Speakers NMF03, NMF04, and NMF13 produce [ɑ̃] with greater labial protrusion compared to [a].
- Speakers NMF05 and NMF06 produces [ɑ̃] with greater labial aperture and greater labial protrusion compared to [a]. This articulatory configuration is indicative of greater lip protrusion, but with a wider labial opening, for [ɑ̃] v. [a].

Table 6.6: Results of one-way ANOVA tests for speakers NMF01-NMF06, with nasality (oral/nasal) as a dependent variable, and labial measures described in 5.2.2 as independent variables. Labial measures of nasal vowels are specified with respect to their oral congeners. Significance level: $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$.

Speaker		[a]-[ã]		[ɛ]-[ɛ̃]		[o]-[ɔ̃]	
		Midpoint	Average	Midpoint	Average	Midpoint	Average
NMF01	upper$_x$						
	lower$_x$						
	distance	closed $F(1, 58) = 95***$	closed $F(1, 58) = 94***$	open $F(1, 58) = 20***$	open $F(1, 58) = 8**$		
	aperture	smaller $F(1, 42) = 183***$	smaller $F(1, 42) = 180***$				
NMF02	upper$_x$						
	lower$_x$			protruded $F(1, 57) = 10**$	protruded $F(1, 57) = 8**$		
	distance	closed $F(1, 58) = 139***$	closed $F(1, 58) = 125***$	closed $F(1, 57) = 15***$	closed $F(1, 57) = 13***$		
	aperture	larger $F(1, 45) = 6*$					
NMF03	upper$_x$	N/A	N/A	N/A	N/A	N/A	N/A
	lower$_x$	protruded $F(1, 58) = 6*$				protruded $F(1, 58) = 28***$	protruded $F(1, 58) = 25***$
	distance	N/A	N/A	N/A	N/A	N/A	N/A
	area	N/A	N/A	N/A	N/A	N/A	N/A
NMF04	upper$_x$	protruded $F(1, 58) = 820***$	protruded $F(1, 58) = 675***$			protruded $F(1, 58) = 9**$	protruded $F(1, 58) = 9**$
	lower$_x$	protruded $F(1, 58) = 73***$	protruded $F(1, 58) = 70***$				
	distance			open $F(1, 58) = 17***$		closed $F(1, 58) = 9**$	closed $F(1, 58) = 5*$
NMF05	upper$_x$	retracted $F(1, 56) = 13***$	retracted $F(1, 56) = 11**$	retracted $F(1, 58) = 49***$	retracted $F(1, 58) = 29***$	retracted $F(1, 58) = 5*$	
	lower$_x$	protruded $F(1, 56) = 595***$	protruded $F(1, 56) = 645***$			retracted $F(1, 58) = 13***$	retracted $F(1, 58) = 10**$
	distance	open $F(1, 56) = 133***$	open $F(1, 56) = 134***$				
NMF06	upper$_x$	protruded $F(1, 58) = 78***$	protruded $F(1, 58) = 77***$			retracted $F(1, 58) = 5*$	retracted $F(1, 58) = 5*$
	lower$_x$	protruded $F(1, 58) = 49***$	protruded $F(1, 58) = 41***$	retracted $F(1, 58) = 8**$		retracted $F(1, 58) = 7*$	retracted $F(1, 58) = 7*$
	distance	open $F(1, 57) = 96***$	open $F(1, 58) = 76***$	closed $F(1, 47) = 44***$	closed $F(1, 58) = 37***$	open $F(1, 57) = 23***$	open $F(1, 58) = 25***$

Table 6.7: Results of one-way ANOVA tests for speakers NMF08-NMF13, with nasality (oral/nasal) as a dependent variable, and average *y*-dimension EMA values (mm) for TT, TM and TB as independent variables. Tongue articulations of nasal vowels are specified with respect to their oral congeners. Significance level: $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$.

Speaker		[a]-[ã]		[ɛ]-[ɛ̃]		[o]-[ɔ̃]	
		Midpoint	Average	Midpoint	Average	Midpoint	Average
NMF08	$upper_x$	protruded $F(1,58) = 58***$	protruded $F(1,58) = 47***$			retracted $F(1,58) = 4*$	
	$lower_x$	protruded $F(1,58) = 125***$	protruded $F(1,58) = 94***$	protruded $F(1,58) = 6*$	protruded $F(1,58) = 7*$	retracted $F(1,58) = 11**$	retracted $F(1,58) = 10**$
	distance	closed $F(1,58) = 126***$	closed $F(1,58) = 59***$			closed $F(1,58) = 19***$	closed $F(1,58) = 14***$
NMF09	$upper_x$	protruded $F(1,58) = 39***$	protruded $F(1,58) = 33***$	retracted $F(1,58) = 17***$	retracted $F(1,58) = 17***$		
	$lower_x$	protruded $F(1,58) = 23***$	protruded $F(1,58) = 18***$				
	distance	closed $F(1,58) = 126***$	closed $F(1,58) = 94***$	open $F(1,58) = 11**$	open $F(1,58) = 9**$	closed $F(1,58) = 86***$	closed $F(1,58) = 88***$
NMF11	$upper_x$	protruded $F(1,58) = 73***$	protruded $F(1,58) = 69***$	protruded $F(1,57) = 6*$	protruded $F(1,58) = 6*$		
	$lower_x$	protruded $F(1,58) = 84***$	protruded $F(1,58) = 69***$			retracted $F(1,58) = 5*$	retracted $F(1,58) = 4*$
	distance	closed $F(1,58) = 23***$	closed $F(1,58) = 10**$	closed $F(1,57) = 13***$	closed $F(1,58) = 15***$	closed $F(1,58) = 35***$	closed $F(1,58) = 32***$
NMF12	$upper_x$	protruded $F(1,58) = 39***$	protruded $F(1,58) = 36***$				
	$lower_x$	protruded $F(1,58) = 123***$	protruded $F(1,58) = 82***$	retracted $F(1,58) = 6*$	retracted $F(1,58) = 5*$		
	distance	closed $F(1,58) = 299***$	closed $F(1,58) = 165***$			closed $F(1,58) = 122***$	closed $F(1,58) = 112***$
NMF13	$upper_x$	protruded $F(1,58) = 259***$	protruded $F(1,58) = 235***$	protruded $F(1,58) = 5*$	protruded $F(1,58) = 9**$	retracted $F(1,58) = 6*$	retracted $F(1,58) = 6*$
	$lower_x$	protruded $F(1,58) = 318***$	protruded $F(1,58) = 310***$				
	distance			open $F(1,58) = 6*$		closed $F(1,58) = 19***$	closed $F(1,58) = 16***$

As shown in 6.2.2, the following discrepancies were observed for the lingual articulation and acoustic realization of [ɑ̃] compared to [a]:

- Speakers NMF01, NMF03, and NMF09 produce [ɑ̃] with a lower tongue position than [a], yet [ɑ̃] is realized with a lower F1 than [a].
- Speakers NMF08 and NMF11 produce [ɑ̃] with the same tongue height as [a], yet [ɑ̃] is realized with a lower F1 than [a].
- Speaker NMF02 produces [ɑ̃] with the same horizontal tongue position as [a], yet [ɑ̃] is realized with a lower F2 than [a].

Taking into account the results from the labial measures for the productions of [a] and [ɑ̃], we can reason that labial configuration may explain the lingual/acoustic discrepancies in the following ways:

- Speakers NMF01, NMF03, NMF08, NMF09, and NMF11 produce [ɑ̃] with greater lip rounding and/or lip protrusion compared to [a], both of which are articulations which are predicted to lower F1. Therefore, for these 5 speakers, labial configuration may account for the lower F1 observed for [ɑ̃] v. [a] which cannot be explained by lingual configuration.

- Speaker NMF02 produces [ɑ̃] with greater greater lip rounding compared to [a], an articulation which is predicted to lower F2. Therefore, for this speaker, labial configuration may account for the lower F2 observed for [ɑ̃] v. [a] which cannot be explained by lingual configuration.

6.3.2 Northern Metropolitan French: Labial articulation of [ɛ]-[ɛ̃]

Compared to the productions of [a]-[ɑ̃], there is a relatively large amount of inter-speaker variation with regard to the differences in labial articulation for the vowel pair [ɛ]-[ɛ̃]. No generalizations can clearly be made about the labial articulation of [ɛ̃] v. [ɛ] due to this variation. The labial configurations for individual speakers are:

- Speakers NMF01 and NMF04 produce [ɛ̃] with wider labial opening compared to [ɛ]. However, since these speakers also produce [ɛ̃] with a lower tongue position than [ɛ], this larger labial opening may simply be a consequence of a lower jaw position.

- Speaker NMF02 produces [ɛ̃] with smaller labial aperture and greater lip protrusion compared to [ɛ]. This articulatory configuration is indicative of lip rounding and protrusion for [ɛ̃] v. [ɛ].

- Speaker NMF03 does not manifest any differences in labial articulation between [ɛ] and [ɛ̃] (nb: labial aperture measurements could not be calculated for this speaker).

- Speaker NMF05 produces [ɛ̃] with a more retracted upper lip compared to [ɛ], but it is not clear that this labial articulation would have any acoustic consequence, since the range of motion of the upper lip is relatively limited, and since this speaker does not manifest any other labial articulatory differences between [ɛ] and [ɛ̃].
- Speaker NMF06 produces [ɛ̃] with smaller labial aperture and a more retracted lower lip compared to [ɛ]. This articulatory configuration is indicative of greater lip rounding, and possibly lip spreading, for [ɛ̃] v. [ɛ].
- Speaker NMF08 produces [ɛ̃] with greater lip protrusion compared to [ɛ].
- Speaker NMF09 produces [ɛ̃] with greater labial aperture and a more retracted upper lip compared to [ɛ]. This articulatory configuration is indicative of a wider labial opening for [ɛ̃] v. [ɛ].
- Speaker NMF11 produces [ɛ̃] with smaller labial aperture and a more protruded upper lip compared to [ɛ]. This articulatory configuration is indicative of greater lip rounding for [ɛ̃] v. [ɛ].
- Speaker NMF12 produces [ɛ̃] with a more retracted lower lip compared to [ɛ]. This articulatory configuration is indicative of lip spreading, but the difference between [ɛ] and [ɛ̃] is marginally significant, and this speaker does not manifest any other labial articulatory differences between the two vowels.
- Speaker NMF13 produces [ɛ̃] with larger labial aperture and a more protruded upper lip compared to [ɛ]. This articulatory configuration is indicative of wider labial opening for [ɛ̃] v. [ɛ].

As shown in 6.2.3, the following discrepancies were observed for the lingual articulation and acoustic realization of [ɛ̃] compared to [ɛ]:

- Speaker NMF06 produces [ɛ̃] with a higher tongue back than [ɛ], yet [ɛ̃] is realized with a higher F1 than [ɛ].

Although the retracted lower lip for NMF06's production of [ɛ̃] compared to [ɛ] is predicted to raise F1 for [ɛ̃] due to the shortening of the length of the oral tract, the smaller labial aperture is predicted to lower F1 due to the constriction at the velocity antinode at the lips. Therefore, the higher F1 for NMF06's production of [ɛ̃] v. [ɛ] cannot be explained clearly by either lingual or labial configuration.

6.3.3 Northern Metropolitan French: Labial articulation of [o]-[ɔ̃]

Like for the vowel pair [ɛ]-[ɛ̃], there is much inter-speaker variation with regard to the differences in labial articulation for the vowel pair [o]-[ɔ̃]. Nevertheless, the following generalization can be made: *if* a speaker manifests a difference in labial articulation for this vowel pair (this is not the case for all speakers), it is an articulatory configuration indicative of a relatively tight labial opening via lip retraction and/or constriction. The labial configurations for individual speakers are:

- Speakers NMF08, NMF11, and NMF13 produce [ɔ̃] with more retracted lips and smaller labial aperture compared to [o]. This articulatory configuration is indicative of a general tightening and constriction of the lips, combined with lip rounding, for [ɔ̃] v. [o].
- Speakers NMF09 and NMF12 produce [ɔ̃] with smaller labial aperture compared to [o]. This articulatory configuration is indicative of greater lip rounding for [ɔ̃] v. [o].
- Speaker NMF04 produces [ɔ̃] with smaller labial aperture and a more protruded upper lip compared to [o]. This articulatory configuration is indicative of greater lip rounding for [ɔ̃] v. [o].
- Speaker NMF06 produces [ɔ̃] with more retracted lips and greater labial aperture compared to [o]. This articulatory configuration is indicative of a general tightening and constriction of the lips, combined with wider labial opening, for [ɔ̃] v. [o].
- Speaker NMF05 produces [ɔ̃] with more retracted lips, but with no change in labial opening, compared to [o]. This articulatory configuration is indicative of a general tightening and constriction of the lips for [ɔ̃] v. [o].
- Speaker NMF03 produces [ɔ̃] with greater labial protrusion compared to [o].
- Speakers NMF01 and NMF02 do not manifest any differences in labial articulation between [o] and [ɔ̃].

As shown in 6.2.4, the predictions for lingual configuration cannot explain the acoustic difference between oral [o] and nasal [ɔ̃] in the following cases:

- Speakers NMF01 and NMF09 produce [ɔ̃] with a lower tongue position than [o], yet there is no difference in F1 between [ɔ̃] and [o].
- Speakers NMF04, NMF05, and NMF11 produce [ɔ̃] with a lower tongue position than [o], yet [ɔ̃] is realized with a lower F1 than [o].
- Speaker NMF02 produces [ɔ̃] with no difference in tongue height compared to [o], yet [ɔ̃] is realized with a lower F1 than [o].
- Speaker NMF13 produces [ɔ̃] with a lower tongue position than [o], yet [ɔ̃] is realized with a lower F1 than [o].
- Speakers NMF03 and NMF05 produce [ɔ̃] with a more fronted tongue position than [o], yet [ɔ̃] is realized with a lower F2 than [o].
- Speakers NMF02 and NMF11 produce [ɔ̃] with either no difference in horizontal tongue position compared to [o], or possibly a slightly more fronted tongue position than [o], yet [ɔ̃] is realized with a lower F2 than [o].

Taking into account the results from the labial measures for the productions of [o] and [ɔ̃], we can reason that labial configuration may explain the lingual/acoustic discrepancies in the following ways:

- Speakers NMO3, NM04, and NMF09 produce [ɔ̃] with greater lip rounding and/or lip protrusion compared to [o], both of which are articulations which are predicted to lower F1 and F2. Therefore, labial configuration may account for the lower F1 observed for [ɔ̃] v. [o] for NMF04 and NMF09, and the lower F2 observed for NMF03, which cannot be explained by lingual configuration.

- Speakers NMF11 and NMF13 produce [ɔ̃] with greater lip rounding compared to [o], an articulation which is predicted to lower F1 due to the constriction at the velocity antinode at the lips. However, these two speakers also produce [ɔ̃] with a more retracted lip articulation than for [o], which is predicted to raise F1 due to the shortening of the length of the oral tract. Nevertheless, since the lip retraction is marginally significant for both speakers, whereas the lip rounding is highly significant, I contend that the net acoustic effect is a lowering of F1. Therefore, labial configuration may account for the lower F1 observed for [ɔ̃] v. [o] for these two speakers which cannot be explained by lingual configuration.

After considering the labial articulations for the vowel pair [o]-[ɔ̃], the following acoustic discrepancies still remain, which cannot be accounted for by either lingual or labial configuration:

- Speaker NMF01 produces [ɔ̃] with a lower tongue position than [o] (an articulation which is predicted to raise F1), yet there is no difference in F1 between [ɔ̃] and [o]. However, NMF01 does not manifest any difference in labial articulation between [o] and [ɔ̃]. Had evidence been observed of lip rounding and/or lip protrusion (articulatory configurations which are predicted to lower F1), the lingual/acoustic discrepancy might have been explained by the counteracting effects of lingual and labial configuration on F1. As it stands, however, neither lingual nor labial articulatory configurations can explain the acoustic output of NMF01's production of the vowel pair [o]-[ɔ̃].
- Speaker NMF02 produces [ɔ̃] with no difference in tongue height compared to [o], yet [ɔ̃] is realized with a lower F1 than [o]. Moreover, NMF02 produces [ɔ̃] with a slightly more fronted tongue position than [o] (an articulation which is predicted to raise F2), yet [ɔ̃] is realized with a lower F2 than [o]. However, NMF02 does not manifest any difference in labial articulation between [o] and [ɔ̃]. Therefore, neither lingual nor labial articulatory configurations can explain the lower F1 and lower F2 observed for NMF02's production of nasal [ɔ̃] compared to its oral congener [o].
- Speaker NMF05 produces [ɔ̃] with a lower tongue position than [o], yet [ɔ̃] is realized with a lower F1 than [o]. Moreover, NMF05 produces [ɔ̃] with a more fronted tongue position than [o], yet [ɔ̃] is realized with a lower F2 than [o]. Additionally, NMF05 produces [ɔ̃] with more retracted lips than [o], an articulation which is predicted to raise both F1 and F2 due to a shortening of the oral tract. Therefore, neither lingual nor labial articulatory configurations can explain the lower F1 and lower F2 observed for NMF05's production of nasal [ɔ̃] compared to its oral congener [o].

6.4 Northern Metropolitan French: Nasal vowel chain shift

With regard to the acoustic manifestations of the NMF nasal vowels, there is clear evidence for a counter-clockwise chain shift. [ɛ̃] is realized with a relatively high F1 and low F2 compared to [ɛ], a realization which brings [ɛ̃] into the acoustic space occupied by oral [a] (in fact, [ɛ̃] has an even *lower* F2 than [a] for all speakers). Whereas, historically, we would expect [ɑ̃] to occupy an acoustic space near its oral counterpart [a], it is realized instead with a relatively low F1 and F2 compared to [a], a realization which brings [ɑ̃] near the acoustic space occupied by oral [o] and nasal [ɔ̃]. For the majority of the NMF speakers, [ɔ̃]—in its turn—is realized with a relatively low F1 and F2 compared to [o], a realization which brings [ɔ̃] near the acoustic space occupied by the high oral [u], presumably ([u] was not included in the current study). In summary, in terms of realization in the F1-F2 vowel space, [ɛ̃] is lowered and retracted, while [ɑ̃]—in its turn—is raised and retracted, and [ɔ̃]—in its turn—is raised and slightly retracted (in fact, [ɔ̃] has an even *lower* F1 than [o] for most speakers). These acoustic realizations are consistent with a counter-clockwise chain shift. Moreover, in general, the acoustic realizations of the nasal vowels of NMF is characterized by a general lowering of F2 compared to the corresponding oral vowel system.

With regard to the oral articulations of the NMF nasal vowels, in general, most of the counter-clockwise chain shift apparent in the acoustic space can be explained by lingual position. [ɛ̃] is produced with a relatively low and retracted tongue position compared to [ɛ], which results in [ɛ̃] being manifested with a similar tongue position to [a]. Whereas, historically, we would expect [ɑ̃] to have a similar tongue position to its oral counterpart [a], it is realized instead with a relatively retracted tongue position compared to [a], which results in [ɑ̃] being manifested with a tongue position closer to that of oral [o] and/or nasal [ɔ̃]. As shown in 6.2.4, there is a large amount of inter-speaker variability with regard to the lingual production of [ɔ̃]. Nevertheless, we can observe that the majority of the NMF speakers do not produce a higher tongue position for [ɔ̃] compared to [o], an articulation which would be consistent with the counter-clockwise chain shift observed in the acoustic signal. However, in these cases, labial configuration is used instead of lingual configuration in order to raise and close [ɔ̃] in the peripheral track of the acoustic space. In summary, in terms of realization in the "lingual space", [ɛ̃] is lowered and retracted, while [ɑ̃]—in its turn—is retracted. These lingual realizations are consistent with a counter-clockwise chain shift. According to the acoustic realizations, the transcriptions [ɛ̃], [ɑ̃] and [ɔ̃] do not represent the synchronic forms in NMF observed in this study, as previously suggested by Montagu (2007). Instead of these traditional IPA conventions, I propose the following transcriptions for the phonetic realizations of the phonemic nasal vowels of NMF, conforming to the current state of this counter-clockwise chain shift:

/ɛ̃/ → [ɐ̃]

/ɑ̃/ → [ɔ̞̃]

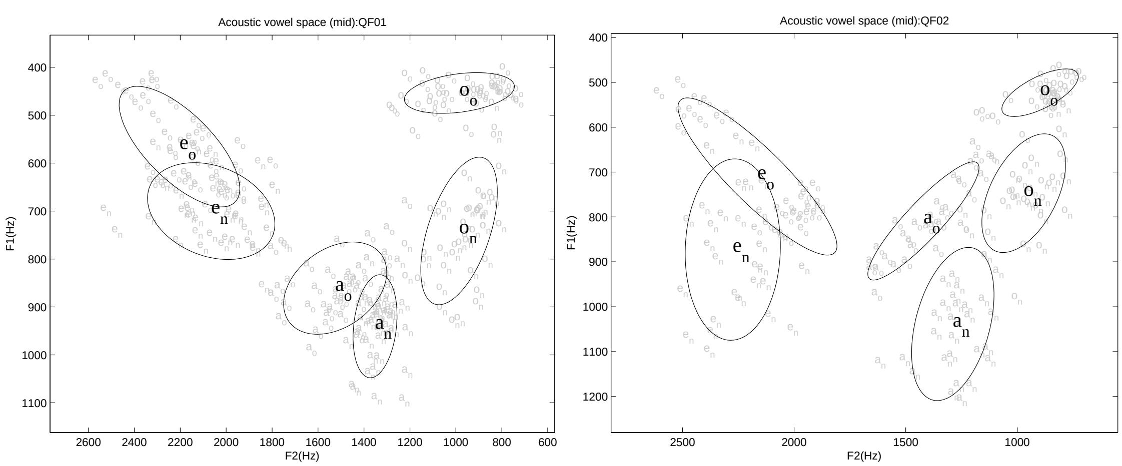
/ɔ̃/ → [õ̝]

Chapter 7

Quebecois French

7.1 Quebecois French: Acoustic results

Plots of F1 and F2—as measured at the vowel midpoint—are given in Figure 7.1 for both QF speakers. These figures do not confirm the existence of a clockwise shift in the acoustic manifestations of the nasal vowels of QF explained in 2.2.3 (at least, for these two speakers). Specifically, [ɔ̃] manifests a relatively high F1, which brings [ɔ̃] close the acoustic space for [ɑ̃], which is consistent with a clockwise chain shift. However, [ɑ̃] is not fronted in the acoustic space (i.e., higher F2), and [ɛ̃] is not fronted (high F2) or raised (low F1), acoustic manifestations which would be consistent with a clockwise chain shift. These results will be discussed further in 7.4. In general, all of the QF nasal vowels studied here are characterized, acoustically, by lower manifestations than their oral vowel counterparts (i.e., all three nasal vowels are realized with a higher F1 than their oral counterparts).



(a) Speaker QF01 acoustic space.

(b) Speaker QF02 acoustic space.

Figure 7.1: Acoustic space for QF speakers. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

The results for the one-way ANOVAs with F1 and F2 as independent variables are provided in Table 7.1. The formant values for a given vowel pair are displayed in their relevant cell, with the formant value for the oral vowel on the left and the formant value for its nasal congener on the right. Table cells with measures which yield no significant difference are filled white. Cells with measures which yield a significant difference ($p < 0.05$) are filled in one of two shades of gray: cells which are highlighted in light gray correspond to a significant difference where the formant value for the nasal vowel is significantly *lower* than the value for its oral congener (e.g., F2 of [ã] < F2 of [a]), and cells which are highlighted in dark gray correspond to a significant difference where the formant value for the nasal vowel is significantly *higher* than the value for its oral congener (e.g., F1 of [ɛ̃] > F1 of [ɛ]).

Table 7.1: Results of one-way ANOVA tests for QF speakers, with nasality (oral/nasal) as a dependent variable, and F1 (Hz) and F2(Hz) as independent variables. Significance level: $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$.

Speaker		[a]-[ã]		[ɛ]-[ɛ̃]		[o]-[ɔ̃]	
		Midpoint	Average	Midpoint	Average	Midpoint	Average
QF01	F1	861–940 $F(1,80) = 29***$	836–915 $F(1,80) = 32***$	566–700 $F(1,82) = 67***$	559–663 $F(1,82) = 46***$	454–742 $F(1,82) = 313***$	449–686 $F(1,82) = 471***$
	F2	1526–1352 $F(1,80) = 47***$	1526–1349 $F(1,80) = 48***$	2203–2065 $F(1,82) = 13***$	2176–2026 $F(1,82) = 17***$	985–986	980–988
QF02	F1	809–1039 $F(1,57) = 77***$	806–1028 $F(1,57) = 90***$	710–873 $F(1,58) = 26***$	705–838 $F(1,58) = 20***$	523–747 $F(1,58) = 170***$	522–729 $F(1,58) = 217***$
	F2	1421–1289 $F(1,57) = 12***$	1419–1295 $F(1,57) = 12**$	2164–2275 $F(1,58) = 5*$	2159–2264 $F(1,58) = 4*$	898–971 $F(1,58) = 6*$	906–996 $F(1,58) = 6*$

7.1.1 Quebecois French: Formant analysis of [a]-[ã]

The results for [a] v. [ã] are consistent for both QF speakers: nasal [ã] has a higher F1 and lower F2 compared to oral [a]. The acoustic difference for [ã] compared with [a] can be summarized as:

Both speakers manifest a **higher F1**, and a **lower F2**: F1 ↑ F2 ↓

Averaged across speakers, the differences are as follows: F1 of [ã] is, on average, 155 Hz (1.43 Bark) higher than F1 of [a] for vowel-midpoint measurements, and 151 Hz (1.38 Bark) higher for vowel-average measurements. F2 is, on average, 153 Hz (1.41 Bark) lower for vowel-midpoint measurements, and 151 Hz (1.38 Bark) lower for vowel-average measurements.

Given these acoustic differences, the lingual position for nasal [ã] is predicted to be lower (i.e., resulting in a higher F1) and more retracted (i.e., resulting in a lower F2) compared to oral [a]. However, modeling work by Feng and Castelli (1996); Serrurier and Badin (2008) predicts a lowering for F2 under the effect of nasalization for all of the vowels in the current study. Therefore, more retracted lingual position for [ã] compared with [a]—which is also predicted to lower F2—may not be observed in the articulatory data, after all: the lowered F2 observed in the acoustic signal may be due, rather, to the F2-related acoustic effect of velo-pharyngeal coupling, which also predicts a lower F2 for [ã] v. [a].

Given the inter-speaker uniformity with regard to the acoustic difference between [a] and [ɑ̃], I do not predict to observe any inter-speaker differences with regard to the lingual and labial articulations of these two vowels: the inter-speaker oral articulatory configurations for [a] v. [ɑ̃] are predicted to be uniform, as are the inter-speaker acoustic manifestations observed here. In other words, there is no inter-speaker variation observed in the acoustics of [a] v. [ɑ̃]; thus, I predict to find no inter-speaker variation in the oral articulatory configuration of [a] v. [ɑ̃].

7.1.2 Quebecois French: Formant analysis of [ɛ]-[ɛ̃]

Unlike the acoustic results for [a]-[ɑ̃], the acoustic results for [ɛ] v. [ɛ̃] are not completely consistent for the two QF speakers. The acoustic distinction between [ɛ] and [ɛ̃] which is consistent for both speakers is a higher F1 for nasal [ɛ̃] compared to its oral counterpart [ɛ]: F1 of [ɛ̃] is, on average, 149 Hz (1.36 Bark) higher than F1 of [ɛ] for vowel-midpoint measurements, and 119 Hz (1.0 Bark) higher for vowel-average measurements. However, the difference in F2 frequency between [ɛ] and [ɛ̃] is not the same for the two speakers: F2 of [ɛ̃] is lower than F2 of [ɛ] for QF01, while F2 of [ɛ̃] is higher than F2 of [ɛ] for QF02 (however, the difference for QF02 is only marginally significant). These acoustic differences with regard to the realization of [ɛ̃] compared to [ɛ] can be summarized as:

Speaker QF01 manifests a **higher F1**, and a **lower F2**:	F1 ↑	F2 ↓
Speaker QF02 manifests a **higher F1**, and a **higher F2**:	F1 ↑	F2 ↑

Given these acoustic differences, the lingual position for nasal [ɛ̃] is predicted to be lower (i.e., resulting in a higher F1) compared to oral [ɛ] for both speakers. The predictions for horizontal tongue position are different for the two speakers, given their respective acoustic manifestations of this vowel pair along the F2 dimension. Speaker QF01 is predicted to have a more retracted tongue position (i.e., resulting in a lower F2) for [ɛ̃] compared with [ɛ], while QF02 is predicted to have a more fronted tongue position (i.e., resulting in a higher F2) for [ɛ̃] compared with [ɛ]. The lingual predictions for the vowel pair [ɛ]-[ɛ̃] can be summarized as:

- Speaker QF01 will produce [ɛ̃] with a lower, more retracted tongue position than [ɛ].
- Speaker QF02 will produce [ɛ̃] with a lower, more fronted tongue position than [ɛ].

However, since the acoustic effect of nasalization for F2 is predicted to lower its frequency, a more retracted lingual position for [ɛ̃] compared with [ɛ] for QF01—which is also predicted to lower F2—may not be observed in the articulatory data, after all: the lowered F2 observed in the acoustic signal for speaker QF01 may be due, rather, to the F2-related acoustic effect of velo-pharyngeal coupling, which also predicts a lower F2 for [ɛ̃] v. [ɛ]. The effect of acoustic centralization under the influence of nasalization does not provide an immediately clear prediction for the realization of F1 for [ɛ̃] compared to the F1 of [ɛ], since [ɛ] is a mid-vowel (i.e., already relatively centralized). However, [ɛ] is relatively high in the QF acoustic space (indeed, [ɛ] is the second highest vowel in this vowel set for the QF dialect, manifested with an F1 frequency nearly as low as for [o]); thus, F1 is predicted to be higher for [ɛ̃] compared to [ɛ] due to the F1-related acoustic effect of nasalization. Therefore, a lowered tongue position for [ɛ̃] compared with [ɛ]—which is also predicted to raise F1—may not be observed in the articulatory data, after all: the higher F1 for [ɛ̃] compared to [ɛ] observed in the acoustic signal may be due, rather, to the F1-related acoustic effect of velo-pharyngeal coupling, which also predicts a higher F1 for [ɛ̃] v. [ɛ].

7.1.3 Quebecois French: Formant analysis of [o]-[ɔ̃]

Like the acoustic results for [ɛ]-[ɛ̃], the acoustic results for [o] v. [ɔ̃] are not completely consistent for the two QF speakers. The acoustic distinction between [o] and [ɔ̃] which is consistent for both speakers is a higher F1 for nasal [ɔ̃] compared to its oral counterpart [o]: F1 of [ɔ̃] is, on average, 256 Hz (2.57 Bark) higher than F1 of [o] for vowel-midpoint measurements, and 222 Hz (2.2 Bark) higher for vowel-average measurements. However, the difference in F2 frequency between [o] and [ɔ̃] is not the same for the two speakers: there is no significant difference in F2 frequency between [o] and [ɔ̃] for speaker QF01, while F2 of [ɔ̃] is higher than F2 of [o] for QF02 (however, the difference for QF02 is only marginally significant). These acoustic differences with regard to the realization of [ɔ̃] compared to [o] can be summarized as:

Speaker QF01 manifests a **higher F1**, and no difference in F2:	F1 ↑	
Speaker QF02 manifests a **higher F1**, and a **higher F2**:	F1 ↑	F2 ↑

Given these acoustic differences, the lingual position for nasal [ɔ̃] is predicted to be lower (i.e., resulting in a higher F1) compared to oral [o] for both speakers. The predictions for horizontal tongue position are different for the two speakers, given their respective acoustic manifestations of this vowel pair along the F2 dimension. Speaker QF01 is predicted to manifest no difference in horizontal tongue position between [o] and [ɔ̃], while QF02 is predicted to have a more fronted tongue position (i.e., resulting in a higher F2) for [ɔ̃] compared with [o]. The lingual predictions for the vowel pair [o]-[ɔ̃] can be summarized as:

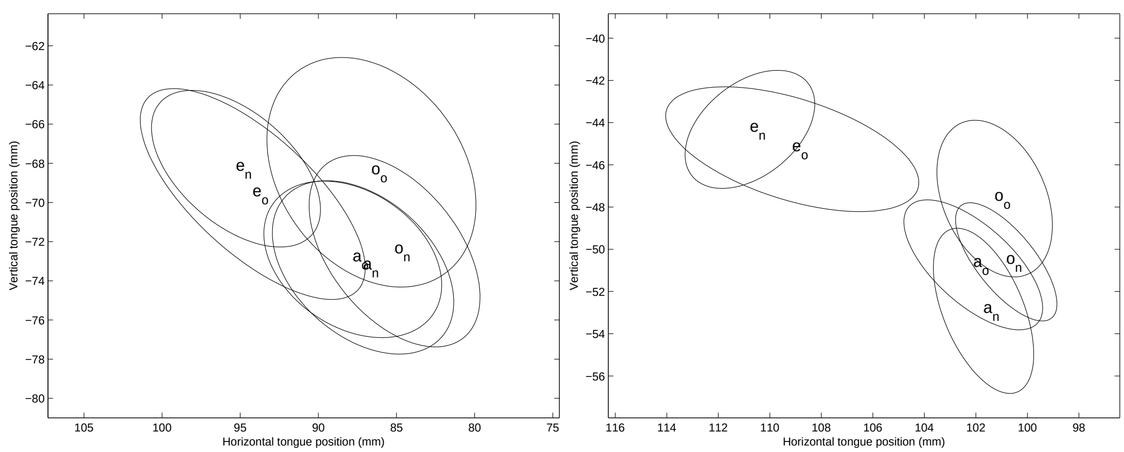
- Speaker QF01 will produce [ɔ̃] with a lower tongue position than [o], with no difference in horizontal tongue position.
- Speaker QF02 will produce [ɔ̃] with a lower, more fronted tongue position than [o].

The effect of acoustic centralization under the influence of nasalization does not provide an immediately clear prediction for the realization of F1 for [ɔ̃] compared to the F1 of [o], since [o] is a mid-vowel (i.e., already relatively centralized). However, since [o] is a relatively high mid-vowel, F1 is predicted to raise slightly under the influence of nasalization. Therefore, a lowered tongue position for [ɔ̃] compared with [o]for both speakers—which is predicted to raise F1—may not be observed in the articulatory data, after all: the higher F1 for [ɔ̃] compared to [o] observed in the acoustic signal for both speakers may be due, rather, to the F1-related acoustic effect of velo-pharyngeal coupling, which also predicts a higher F1 for [ɔ̃] v. [o].

7.2 Quebecois French: Lingual articulation

7.2.1 Quebecois French: Lingual articulation summary

Plots of *x*-dimension and *y*-dimension (*z*-dimension for AG500 data) TM sensor values measured at the midpoint of the vowels are displayed in Figure 7.2. Observation of these plots reveals that, in general, the position of the midpoint of the tongue can account for some of the acoustic dispersion observed in 7.1, but not all. The results for the one-way ANOVAs with *y*-dimension values (vertical tongue position) of the TT, TM, and TB sensors as the independent variable are provided in Table 7.2. The results for the one-way ANOVAs with *x*-dimension values (horizontal tongue position) as the independent variable are provided in Table 7.3. Table cells with measures which yield no significant difference are colored white. Cells with measures which yield a significant difference ($p < 0.05$) are highlighted in one of two shades of gray: cells which are highlighted in light gray correspond to a significant difference where the sensor value for the nasal vowel is significantly *lower* than the value for its oral congener (i.e., lower tongue position for *y*-dimension values, and more retracted tongue position for *x*-dimension values), and cells which are highlighted in dark gray correspond to a significant difference where the sensor value for the nasal vowel is significantly *higher* than the value for its oral congener (i.e., higher tongue position for *y*-dimension values, and more advanced tongue position for *x*-dimension values).



(a) Speaker QF01 TM$_{mid}$ lingual space. (b) Speaker QF02 TM$_{mid}$ lingual space.

Figure 7.2: TM$_{mid}$ lingual space for QF speakers. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

Table 7.2: Results of one-way ANOVA tests for QF speakers, with nasality (oral/nasal) as a dependent variable, and average *y*-dimension EMA values (mm) for TT, TM and TB as independent variables. Tongue articulations of nasal vowels are specified with respect to their oral congeners. Significance level: $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$.

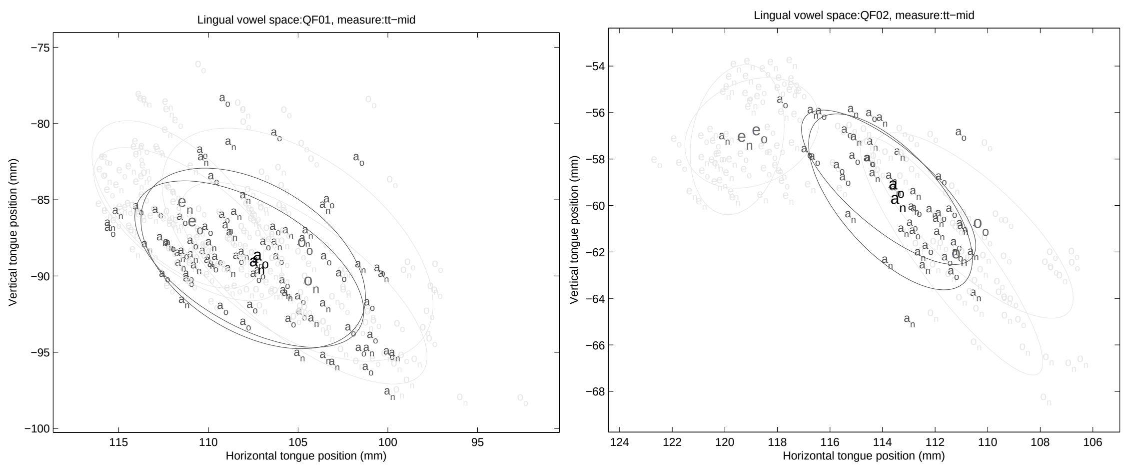
Speaker		[a]-[ã]		[ɛ]-[ɛ̃]		[o]-[ɔ̃]	
		Midpoint	Average	Midpoint	Average	Midpoint	Average
QF01	TT				higher $F(1,82) = 4*$	lower $F(1,80) = 5*$	lower $F(1,80) = 4*$
	TM					lower $F(1,82) = 27***$	lower $F(1,82) = 24***$
	TB			higher $F(1,80) = 8**$	higher $F(1,80) = 7**$	lower $F(1,82) = 8**$	lower $F(1,82) = 7**$
QF02	TT						
	TM	lower $F(1,57) = 13***$	lower $F(1,57) = 12**$			lower $F(1,57) = 28***$	lower $F(1,57) = 27***$
	TB	lower $F(1,53) = 8**$	lower $F(1,53) = 7*$	higher $F(1,53) = 15***$	higher $F(1,53) = 13***$	lower $F(1,57) = 31***$	lower $F(1,57) = 28***$

Table 7.3: Results of one-way ANOVA tests for QF speakers, with nasality (oral/nasal) as a dependent variable, and average *x*-dimension EMA values (mm) for TT, TM and TB as independent variables. Tongue articulations of nasal vowels are specified with respect to their oral congeners. Significance level: $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$.

Speaker		[a]-[ã]		[ɛ]-[ɛ̃]		[o]-[ɔ̃]	
		Midpoint	Average	Midpoint	Average	Midpoint	Average
QF01	TT						
	TM						
	TB						
QF02	TT						
	TM			fronted $F(1,57) = 6*$	fronted $F(1,57) = 5*$		
	TB			fronted $F(1,53) = 14***$	fronted $F(1,53) = 13***$		

7.2.2 Quebecois French: Lingual articulation of [a]-[ã]

Figures highlighting the articulatory data for the vowel pair [a]-[ã] are shown below. Plots of the TT sensor data are given in Figure 7.3, plots of the TM sensor data are given in Figure 7.4, and plots of the TB sensor data are given in Figure 7.5. All data provided in these figures are measurements taken at the vowel midpoint. For the vowel pair [a]-[ã], there is much discrepancy between the lingual configuration and the acoustic output: whereas both speakers manifest a higher F1 and a lower F2 for [ã] compared to [a], only QF02 produces [ã] with lower tongue position, and neither speaker produces [ã] with a more retracted tongue position compared to [a], lingual configurations which would account for the acoustic realizations of this vowel pair. Therefore, the acoustic difference between oral [a] and its nasal counterpart [ã] cannot be explained solely by lingual configuration.



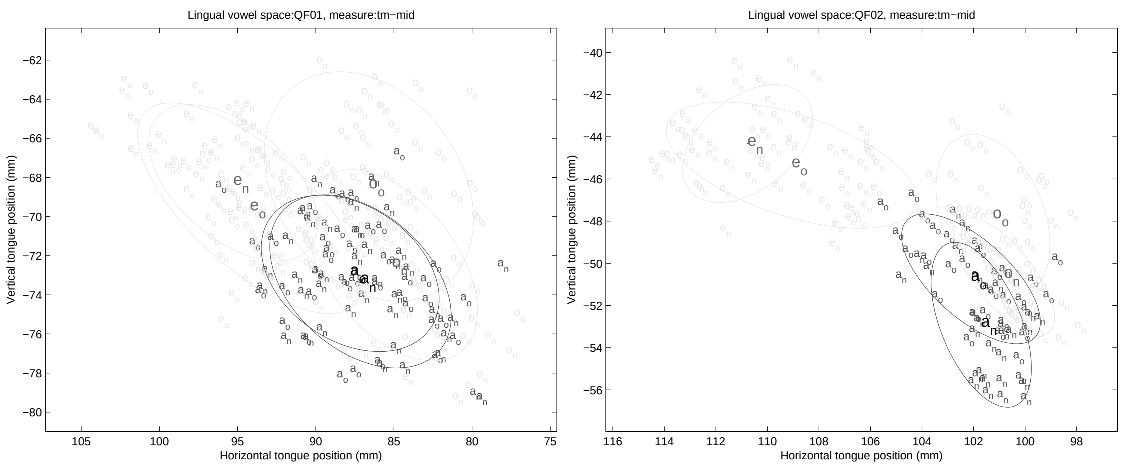
(a) Speaker QF01 TT$_{mid}$ lingual space, [a]-[ã]

(b) Speaker QF02 TT$_{mid}$ lingual space, [a]-[ã]

Figure 7.3: TT$_{mid}$ lingual space for QF speakers, with data sets for [a]-[ã] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

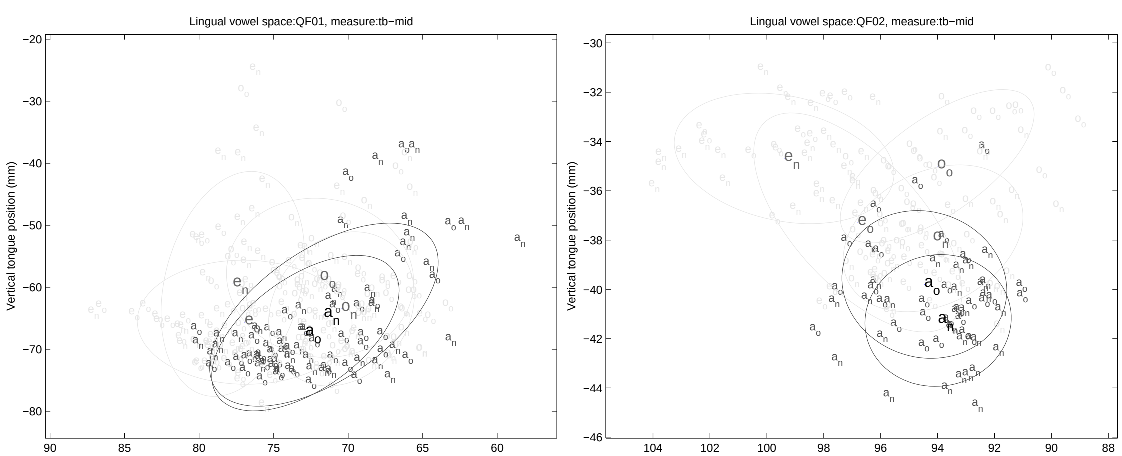
With regard to the results concerning tongue height and its relation to the results for F1, only speaker QF02 produces [ã] with a vertical tongue position which may possibly account for its relative acoustic realization compared to [a]: the tongue body is lower for [ã] than for [a]. For this speaker, the lower tongue position may account for the higher F1 observed for [ã] compared to [a]. The predictions with regard to tongue height are, therefore, substantiated by the results for this speaker. With regard to the results concerning horizontal tongue position and its relation to the results for F2, neither speaker produces a significant difference between [a] and [ã] with regard to horizontal tongue position. The following discrepancies are observed for the lingual articulation and acoustic realization of [ã] compared to [a]:

- Speaker QF01 produces [ã] with the same tongue height as [a], yet [ã] is realized with a higher F1 than [a].
- Speakers QF01 and QF02 produce [ã] with the same horizontal tongue position as [a], yet [ã] is realized with a



(a) Speaker QF01 TM$_{mid}$ lingual space, [a]-[ã] (b) Speaker QF02 TM$_{mid}$ lingual space, [a]-[ã]

Figure 7.4: TM$_{mid}$ lingual space for QF speakers, with data sets for [a]-[ã] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



(a) Speaker QF01 TB$_{mid}$ lingual space, [a]-[ã] (b) Speaker QF02 TB$_{mid}$ lingual space, [a]-[ã]

Figure 7.5: TB$_{mid}$ lingual space for QF speakers, with data sets for [a]-[ã] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

lower F2 than [a].

The discrepancies between lingual articulatory configuration and the acoustic output of the vowel pair [a]-[ɑ̃] can be summarized as follows:

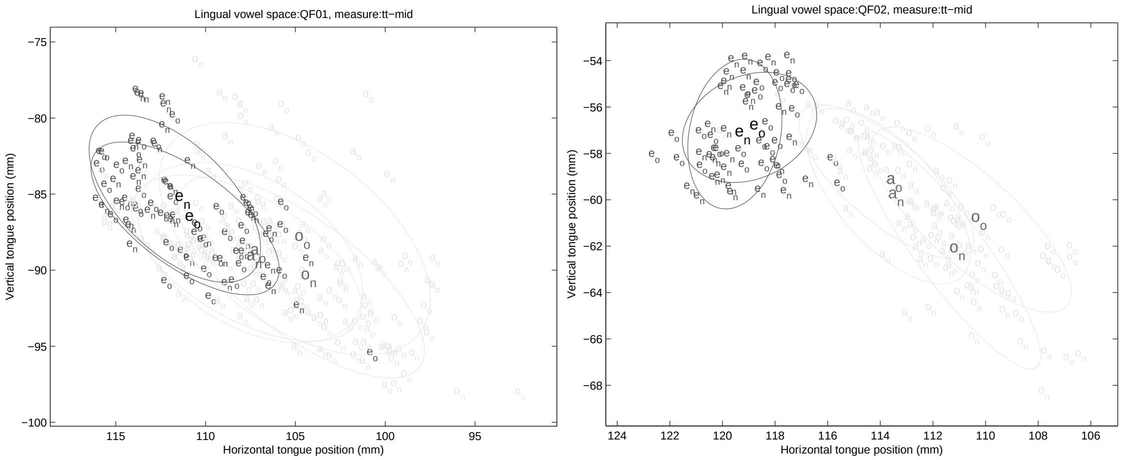
1. F1 is higher for [ɑ̃] than can be explained by tongue height alone.
    (a) F1 is higher, yet there is no difference in tongue height.
2. F2 is lower for [ɑ̃] than can be explained by horizontal tongue position alone.
    (a) F2 is lower, yet there is no difference in horizontal tongue position.

7.2.3 Quebecois French: Lingual articulation of [ɛ]-[ɛ̃]

Figures highlighting the articulatory data for the vowel pair [ɛ]-[ɛ̃] are shown below. Plots of the TT sensor data are given in Figure 7.6, plots of the TM sensor data are given in Figure 7.7, and plots of the TB sensor data are given in Figure 7.8. All data provided in these figures are measurements taken at the vowel midpoint. Like for the vowel pair [a]-[ɑ̃], there is much discrepancy between the lingual configuration and the acoustic output for the vowel pair [ɛ]-[ɛ̃]. Whereas both speakers manifest a higher F1 for [ɛ̃] compared to [ɛ], neither speaker produces [ɛ̃] with a lower tongue position compared to [ɛ], a lingual configuration which would account for the F1 realization of this vowel pair. Furthermore, whereas speaker QF01 manifests a lower F2 for [ɛ̃] compared to [ɛ], she does not produce [ɛ̃] with a more retracted tongue position than for [ɛ], a lingual configuration which would account for the F2 realization of this vowel pair. Therefore, the acoustic difference between oral [ɛ] and its nasal counterpart [ɛ̃] cannot be explained solely by lingual configuration.

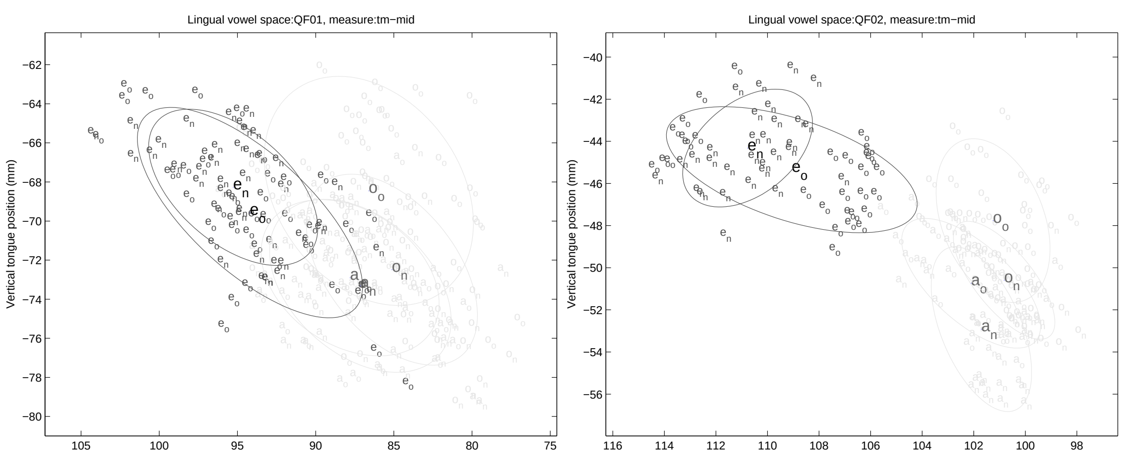
With regard to the results concerning tongue height and its relation to the results for F1, both QF01 and QF02 produce [ɛ] with the same tongue height as [ɛ̃], although [ɛ̃] is manifested with a higher F1 than [ɛ] for both speakers. The predictions with regard to tongue height, therefore, are not substantiated by the results for either speaker. With regard to the results concerning horizontal tongue position and its relation to the results for F2, speaker QF02 produces [ɛ̃] with a more fronted tongue position than for [ɛ], a lingual configuration which may account for the higher F2 observed for [ɛ̃] compared to [ɛ]. The predictions with regard to horizontal tongue position are, therefore, substantiated by the results for this speaker. The following discrepancies are observed for the lingual articulation and acoustic realization of [ɛ̃] compared to [ɛ]:

- Speakers QF01 and QF02 produce [ɛ̃] with a higher tongue position than for [ɛ] (which is predicted to lower F1), yet [ɛ̃] is realized with a higher F1 than [ɛ].



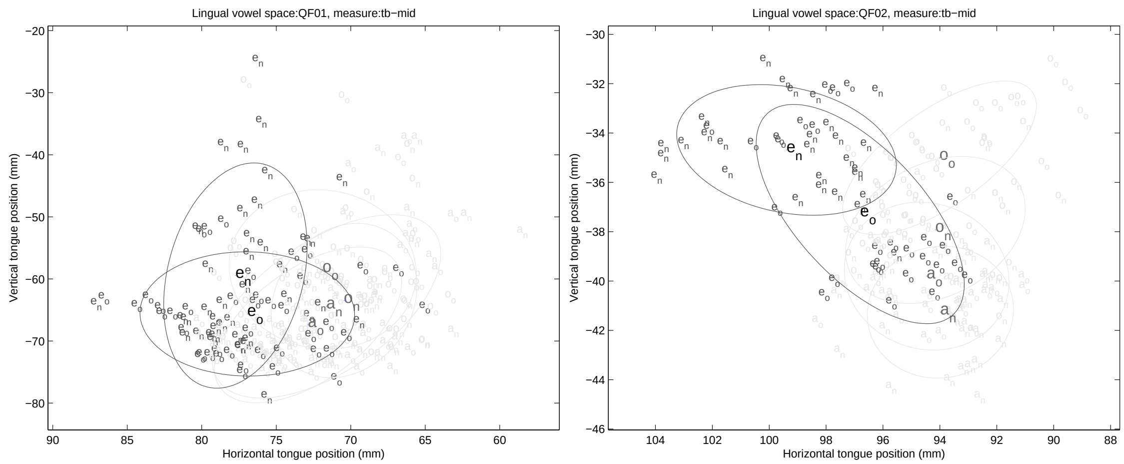
(a) Speaker QF01 TT$_{mid}$ lingual space, [ɛ]-[ɛ̃] (b) Speaker QF02 TT$_{mid}$ lingual space, [ɛ]-[ɛ̃]

Figure 7.6: TT$_{mid}$ lingual space for QF speakers, with data sets for [ɛ]-[ɛ̃] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



(a) Speaker QF01 TM$_{mid}$ lingual space, [ɛ]-[ɛ̃] (b) Speaker QF02 TM$_{mid}$ lingual space, [ɛ]-[ɛ̃]

Figure 7.7: TM$_{mid}$ lingual space for QF speakers, with data sets for [ɛ]-[ɛ̃] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



(a) Speaker QF01 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]　(b) Speaker QF02 TB$_{mid}$ lingual space, [ɛ]-[ɛ̃]

Figure 7.8: TB$_{mid}$ lingual space for QF speakers, with data sets for [ɛ]-[ɛ̃] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

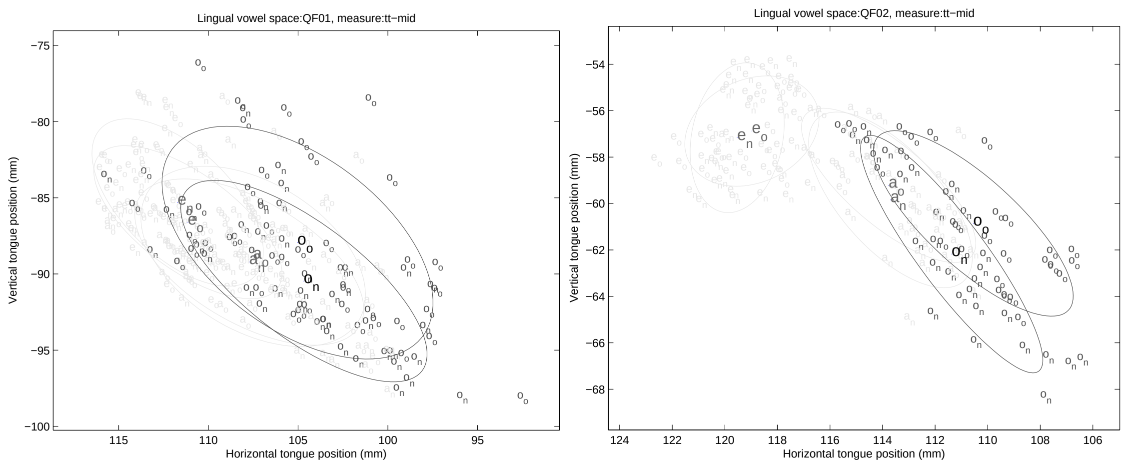
- Speaker QF01 produces [ɛ̃] with the same horizontal tongue position as [ɛ], yet [ɛ̃] is realized with a lower F2 than [ɛ].

The discrepancies between lingual articulatory configuration and the acoustic output of the vowel pair [ɛ]-[ɛ̃] can be summarized as follows:

1. F1 is higher for [ɛ̃] than can be explained by tongue height alone.
   (a) F1 is higher, yet tongue position is also higher.
2. F2 is lower for [ɛ̃] than can be explained by horizontal tongue position alone.
   (a) F2 is lower, yet there is no difference in horizontal tongue position.

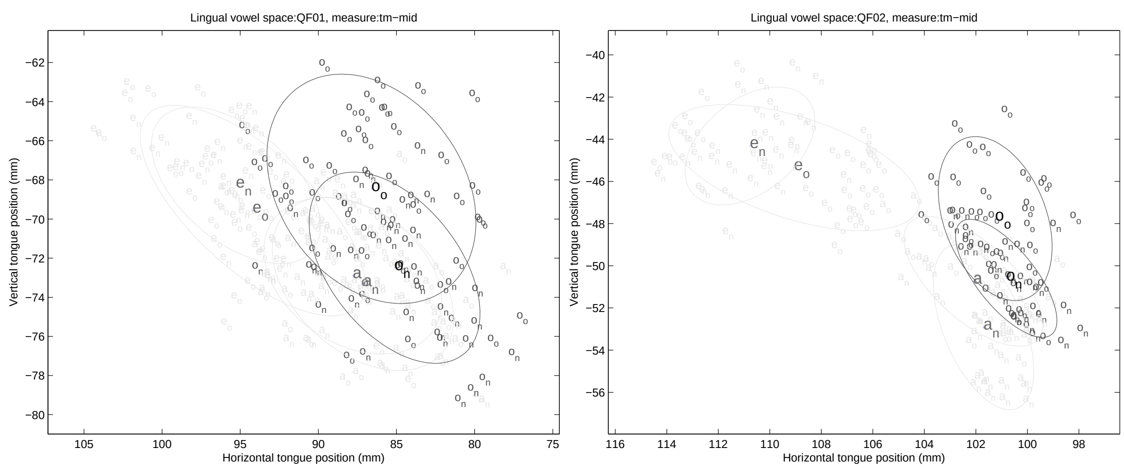
7.2.4 Quebecois French: Lingual articulation of [o]-[õ]

Figures highlighting the articulatory data for the vowel pair [o]-[õ] are shown below. Plots of the TT sensor data are given in Figure 7.9, plots of the TM sensor data are given in Figure 7.10, and plots of the TB sensor data are given in Figure 7.11. All data provided in these figures are measurements taken at the vowel midpoint. There is only discrepancy between the lingual configuration and the acoustic output for the vowel pair [o]-[õ] for one speaker, and only with regard to F2 and the horizontal position of the tongue. Whereas speaker QF02 manifests a higher F2 for [õ] compared to [o], she does not produce [õ] with a more fronted tongue position compared to [o], a lingual configuration which would account for the F2 realization of this vowel pair. Therefore, the acoustic difference between oral [o] and its nasal counterpart [õ] cannot be explained solely by lingual configuration for this speaker.



(a) Speaker QF01 TT$_{mid}$ lingual space, [o]-[õ] (b) Speaker QF02 TT$_{mid}$ lingual space, [o]-[õ]

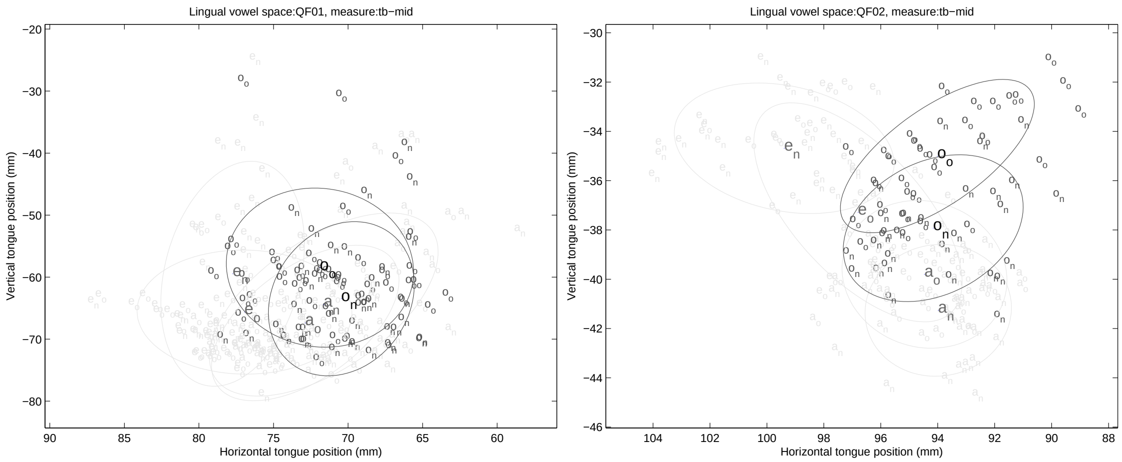
Figure 7.9: TT$_{mid}$ lingual space for QF speakers, with data sets for [o]-[õ] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.



(a) Speaker QF01 TM$_{mid}$ lingual space, [o]-[õ] (b) Speaker QF02 TM$_{mid}$ lingual space, [o]-[õ]

Figure 7.10: TM$_{mid}$ lingual space for QF speakers, with data sets for [o]-[õ] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

With regard to the results concerning tongue height and its relation to the results for F1, both QF01 and QF02 produce [õ] with a lower tongue position than [o]—a lingual configuration which is predicted to raise F1—and [õ] is manifested with a higher F1 than [o] for both speakers. The predictions with regard to tongue height, therefore, are substantiated by the results for both speakers. With regard to the results concerning horizontal tongue position and its relation to the results for F2, speaker QF01 produces [õ] with the same horizontal tongue position as [o], and



(a) Speaker QF01 TB_{mid} lingual space, [o]-[ɔ̃] (b) Speaker QF02 TB_{mid} lingual space, [o]-[ɔ̃]

Figure 7.11: TB_{mid} lingual space for QF speakers, with data sets for [o]-[ɔ̃] highlighted in dark gray. Large vowel labels for each vowel data set represent the mean values for the set. Ellipses encompass 1 SD of respective data sets.

there is no difference between [o] and [ɔ̃] with regard to F2. The predictions with regard to horizontal tongue position are, therefore, substantiated by the results for this speaker. The following discrepancies are observed for the lingual articulation and acoustic realization of [ɔ̃] compared to [o]:

- Speaker QF02 produces [ɔ̃] with the same horizontal tongue position as [o], yet [ɔ̃] is realized with a higher F2 than [o].

The discrepancies between lingual articulatory configuration and the acoustic output of the vowel pair [o]-[ɔ̃] can be summarized as follows:

1. F2 is higher for [ɔ̃] than can be explained by horizontal tongue position alone.

    (a) F2 is higher, yet there is no difference in horizontal tongue position.

Given the results observed here for discrepancies between the lingual articulations and acoustic realizations of the three vowel pairs [a]-[ɑ̃], [ɛ]-[ɛ̃], and [o]-[ɔ̃] in the QF dialect, the next step is to analyze the results for labial articulation in order to determine if the configuration of the lips can account for any of these discrepancies between lingual articulation and the acoustic output. These results for labial articulation are analyzed in the following section.

7.3 Quebecois French: Labial articulation

The results for the one-way ANOVAs with the labial protrusion and aperture measures outlined in 5.2.2 as the independent variable are provided in Table 7.4. Table cells with measures which yield no significant difference are colored white. Cells with measures which yield a significant difference ($p < 0.05$) are highlighted in one of two shades of gray: cells which are highlighted in light gray correspond to a significant difference where the sensor value for the nasal vowel is significantly *lower* than the value for its oral congener (i.e., smaller labial aperture for distance and area measures, and more retracted labial articulation for *x*-dimension of UL and LL sensors), and cells which are highlighted in dark gray correspond to a significant difference where the sensor value for the nasal vowel is significantly *higher* than the value for its oral congener (i.e., larger labial aperture for distance and area measures, and more protruded labial articulation for *x*-dimension of UL and LL sensors).

The data for one speaker (QF01) manifested ubiquitous tracking errors for the UL sensor. Therefore, the following measures—all of which necessitate data from the UL sensor for their calculation—are not included in the analysis for this speaker: UL *x*-dimension (“upper_x”), UL/LL euclidean distance (“distance”), and labial aperture area (“area”). These measures are marked “N/A” in the corresponding cell in the table. Thus, the labial analysis for this speaker only includes a single measure of lip protrusion via the LL *x*-dimension (“lower_x”).

Table 7.4: Results of one-way ANOVA tests for QF speakers, with nasality (oral/nasal) as a dependent variable, and labial measures described in 5.2.2 as independent variables. Labial measures of nasal vowels are specified with respect to their oral congeners. Significance level: $* = p < 0.05$, $** = p < 0.01$, $*** = p < 0.001$.

Speaker		[a]-[ã]		[ɛ]-[ɛ̃]		[o]-[õ]	
		Midpoint	Average	Midpoint	Average	Midpoint	Average
QF01	upper_x	N/A	N/A	N/A	N/A	N/A	N/A
	lower_x						
	distance	N/A	N/A	N/A	N/A	N/A	N/A
	aperture	N/A	N/A	N/A	N/A	N/A	N/A
QF02	upper_x	retracted $F(1,53) = 7*$	retracted $F(1,53) = 6*$				
	lower_x						
	distance					open $F(1,56) = 28***$	open $F(1,56) = 28***$
	aperture	larger $F(1,51) = 4*$	larger $F(1,52) = 5*$			larger $F(1,55) = 9**$	larger $F(1,55) = 8**$

7.3.1 Quebecois French: Labial articulation of [a]-[ɑ̃]

There is some inter-speaker variation with regard to the differences in labial articulation for the vowel pair [a]-[ɑ̃], although this may be due to the reduced number of labial measures available for speaker QF01. Labial configuration is used to distinguish these two vowels for speaker QF02, however. The labial configurations for individual speakers are:

- Speaker QF01 produces no difference in labial articulation between [a] and [ɑ̃].
- Speaker QF02 produces [ɑ̃] with a more retracted upper lip and greater labial aperture compared to [a], which is predicted to raise F1 and F2. This suggests greater lip rounding for [a] than for [ɑ̃].

After considering the labial articulations for the vowel pair [a]-[ɑ̃], the following acoustic discrepancies still remain, which cannot be accounted for by either lingual or labial configuration:

- Speaker QF01 produces [ɑ̃] with the same tongue height as [a], yet [ɑ̃] is realized with a higher F1 than [a]. However, QF01 does not manifest any difference in labial articulation between [a] and [ɑ̃]. Therefore, neither lingual nor labial articulatory configuration can explain the higher F1 observed for QF01's production of nasal [ɑ̃] compared to its oral congener [a].
- Speakers QF01 and QF02 produce [ɑ̃] with the same horizontal tongue position as [a], yet [ɑ̃] is realized with a lower F2 than [a]. Speaker QF01 does not manifest any difference in labial articulation between [a] and [ɑ̃], and QF02 manifests a slight upper lip retraction and larger labial aperture for [ɑ̃] which is predicted to slightly raise F2. Therefore, neither lingual nor labial articulatory configuration can explain the lower F2 observed for QF01's and QF02's production of nasal [ɑ̃] compared to its oral congener [a].

7.3.2 Quebecois French: Labial articulation of [ɛ]-[ɛ̃]

Labial configuration is not used by either QF speaker to distinguish [ɛ] from its nasal counterparts [ɛ̃]: none of the labial protrusion or aperture measures yield significant differences for either speaker. Therefore, after considering the labial articulations for the vowel pair [ɛ]-[ɛ̃], the following acoustic discrepancies still remain, which cannot be accounted for by either lingual or labial configuration:

- Speakers QF01 and QF02 produce [ɛ̃] with a higher tongue position than for [ɛ] (which is predicted to lower F1), yet [ɛ̃] is realized with a higher F1 than [ɛ]. However, neither QF01 nor QF02 manifests any difference in labial articulation between [ɛ] and [ɛ̃]. Therefore, neither lingual nor labial articulatory configuration can explain the higher F1 observed for QF01's and QF02's production of nasal [ɛ̃] compared to its oral congener [ɛ].
- Speaker QF01 produces [ɛ̃] with the same horizontal tongue position as [ɛ], yet [ɛ̃] is realized with a lower F2 than [ɛ]. However, QF01 does not manifest any difference in labial articulation between [ɛ] and [ɛ̃]. Therefore,

neither lingual nor labial articulatory configuration can explain the lower F2 observed for QF01's production of nasal [ɛ̃] compared to its oral congener [ɛ].

7.3.3 Quebecois French: Labial articulation of [o]-[ɔ̃]

There is some inter-speaker variation with regard to the differences in labial articulation for the vowel pair [o]-[ɔ̃], although labial articulation is clearly used to distinguish these two vowels for one of the speakers. The labial configurations for individual speakers are:

- Speaker QF01 produces no difference in labial articulation between [o] and [ɔ̃].
- Speaker QF02 produces [ɔ̃] with both greater labial distance and labial aperture compared to [o], which is predicted to raise F1 and F2 for [ɔ̃] v. [o]. This suggests greater lip rounding for [o] than for [ɔ̃].

As shown in 7.2.2, the following discrepancies were observed for the lingual articulation and acoustic realization of [ɔ̃] compared to [o]:

- Speaker QF02 produces [ɔ̃] with the same horizontal tongue position as [o], yet [ɔ̃] is realized with a higher F2 than [o].

Taking into account the results from the labial measures for the productions of [o] and [ɔ̃], we can reason that labial configuration may explain the lingual/acoustic discrepancies in the following ways:

- Speaker QF02 produces greater lip rounding for [o] than for [ɔ̃], which is predicted to result in a lower F2 for [o] v. [ɔ̃] (and, thus, a higher F2 for [ɔ̃] v. [o]). Therefore, labial articulatory configuration can explain the higher F2 observed for QF02's production of nasal [ɔ̃] compared to its oral congener [o], which lingual articulatory configuration cannot explain.

7.4 Quebecois French: Nasal vowel chain shift

With regard to both the acoustic and lingual manifestations of the QF nasal vowels, there is not much evidence observed for these two speakers which would be strongly indicative of a clockwise chain shift in the realization of the nasal vowels. Acoustically, [ɔ̃] is manifested with a relatively high F1 compared to [o], a realization which—together with a higher F2 created by differences in labial articulation—brings [ɔ̃] near to the acoustic space occupied by both oral [a] and nasal [ɑ̃]. With regard to lingual position, [ɔ̃] is produced with a lowered tongue position compared to [o], a lingual position which brings [ɔ̃] near to the lingual position of both oral [a] and nasal [ɑ̃]. These acoustic and lingual realizations are, indeed, consistent with a clockwise chain shift. However, [ɑ̃] does not—in its turn—manifest a relatively high F2, or a relatively fronted lingual position, compared to [a], a realization which would be consistent with a clockwise chain shift for this vowel; in fact, [ɑ̃] is realized with a *lower* F2 than [a] for both speakers, with no difference in horizontal lingual position between [ɑ̃] and [a] for either speaker. Moreover, [ɛ̃] does not manifest a relatively low F1 and/or high F2, or a relatively raised and/or fronted lingual position, compared to [ɛ], a realization which would be consistent with a clockwise chain shift for this vowel; in fact, [ɛ̃] is realized with *higher* F1 for both speakers, with no difference in tongue height, and a *lower* F2 for one speaker, with no difference in horizontal tongue position. These acoustic and lingual realizations do not seem to be consistent with a counter-clockwise chain shift. In general, with reference to the data for these two QF female speakers, the acoustic realizations of the nasal vowels of QF is not characterized by a counter-clockwise chain shift, but by a higher F1 compared to the corresponding oral vowel system. In other words, the nasal vowel space of QF is acoustically lower than the oral vowel space for these two speakers.

According to the acoustic realizations, I believe that the conventional IPA transcriptions [ɛ̃], [ɑ̃] and [ɔ̃] do fairly represent the synchronic forms in QF, with the following caveats:

1. The use of the lowering diacritic would be most appropriate for [ɛ̃], thus [ɛ̞̃].

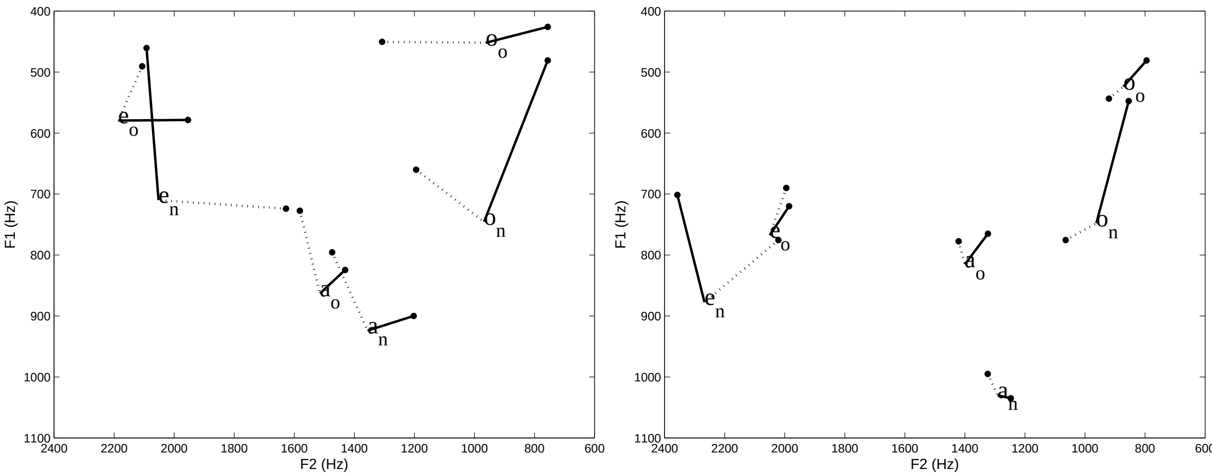
2. These transcriptions are appropriate if we are only considering formant values at the vowel midpoint and averaged over the entire vowel. Dynamic movement is clearly observed in the realization of these vowels, however, which will be discussed in the following section.

7.5 Quebecois French: Diphthong production

As summarized in 2.2.2, it has been previously claimed that the nasal vowels of the QF dialect can have diphthongized realizations only in closed syllables or in pretonic position (Walker, 1984), while articulatory evidence suggests that diphthong variants can also occur in open syllables (Charbonneau, 1971; Delvaux, 2006). On the one hand, since the target vowels for this study only appear in stressed, open syllables, we should expect to see no evidence of diphthongization of nasal vowels by the speakers of QF based on descriptions from Walker (1984); on the other hand, we should see evidence of diphthongization based on articulatory evidence from Charbonneau (1971); Delvaux (2006). Both the acoustic and articulatory results from the current study provide support to the latter case.

7.5.1 QF diphthong production: Acoustic results

The results for the dynamic acoustic measure for trisection-midpoints explained in 5.2.1 are given in Figure 7.12. For a given vowel, the two black dots represent the average formant values for the midpoint of the first and third vowel trisections. The vowel symbol represents the average formant values for the midpoint of the second vowel trisection, and are, thus, the same midpoint acoustic values provided in the 7.1 (i.e., the midpoint of the vowel). The following symbols represent the corresponding vowels: ‘a_o’ for [a], ‘a_n’ for [ɑ̃], ‘e_o’ for [ɛ], ‘e_n’ for [ɛ̃], ‘o_o’ for [o], and ‘o_n’ for [ɔ̃]. The dotted line connects the average midpoint value of the first trisection to the average midpoint value of the second trisection, while the solid line connects the average midpoint value of the second trisection to the average midpoint value of the third trisection. Thus, for a given vowel, the trace from the black dot at the beginning of the dotted line, through the vowel symbol, to the black dot at the end of the solid line provides a dynamic acoustic model for the entire vowel production.



(a) Speaker QF01 dynamic acoustic space.

(b) Speaker QF02 dynamic acoustic space.

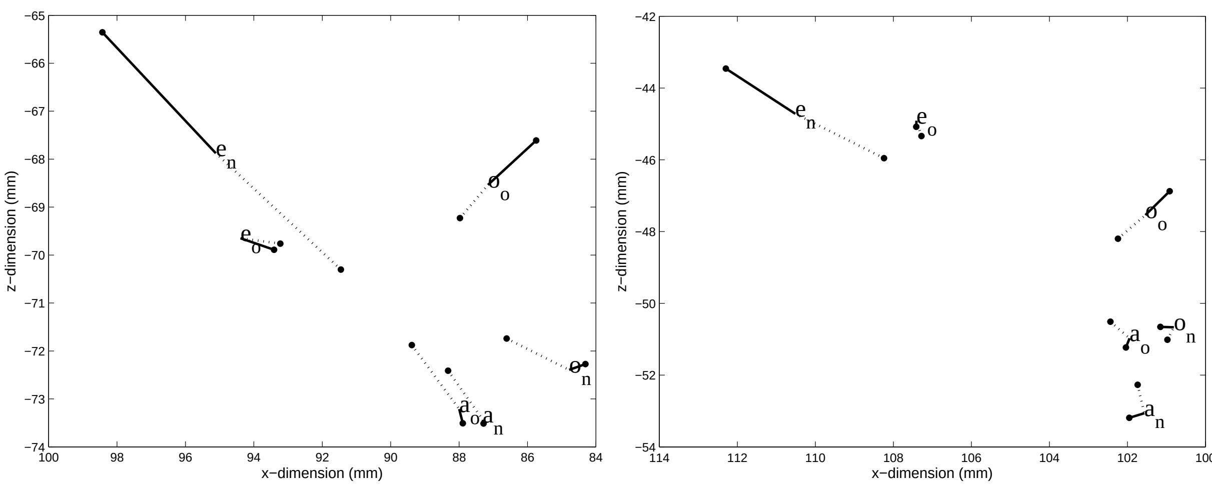
Figure 7.12: Averages for F1 and F2 values measured at the midpoints of each QF vowel trisection. For each vowel, the dotted line traces the dynamic change from the midpoint of the first trisection to that of the second, and the solid line traces the dynamic change from the midpoint of the second trisection to that of the third.

These figures reveal that nasal [ɛ̃] and [ɔ̃] are manifested acoustically as diphthongs for both speakers, and that oral [o] is manifested acoustically as a diphthong for speaker QF01. Nasal [ɑ̃] does not seem to manifested acoustically as a diphthong for either speaker. These results are consistent with the findings from Delvaux (2006). With regard to [ɛ̃], it is fronted and raised in the acoustic space for both speakers, with a decreasing F1 and an increasing F2 throughout the duration of the production. The increasing F1 is more apparent for QF01 than for QF02, since the acoustic manifestation of QF02’s production of [ɛ̃] is characterized by an increase in F1 into the middle of the vowel, and then a decrease in F1 out of the middle of the vowel. This F1 “dip”, however, is very likely due to co-articulation of the labial closure for the [p] both before and after the vowel, which is predicted to lower F1 in the transition from the preceding [p] and in the transition into the following [p]. With regard to [ɔ̃], it is retracted and raised in the acoustic space for both speakers, with a decreasing F1 and decreasing F2 throughout the duration of the production. With regard to [o], it is retracted in the acoustic space for speaker QF01, with a decreasing F2 throughout the duration of the production.

7.5.2 QF diphthong production: Articulatory results

Dynamic lingual articulation

The results for the dynamic articulatory measure for trisection-midpoints explained in 5.2.2 are given in Figure 7.13 for the TM sensor, and Figure 7.14 for the TB sensor; the results from these two sensors, together, gives a holistic representation of dynamic articulation of the tongue body. The dynamic lingual articulatory data presented in these figures are presented in the same way as for the dynamic acoustic data. Thus, for a given vowel, the trace from the black dot at the beginning of the dotted line, through the vowel symbol, to the black dot at the end of the solid line provides a dynamic lingual articulatory model for the entire vowel production.



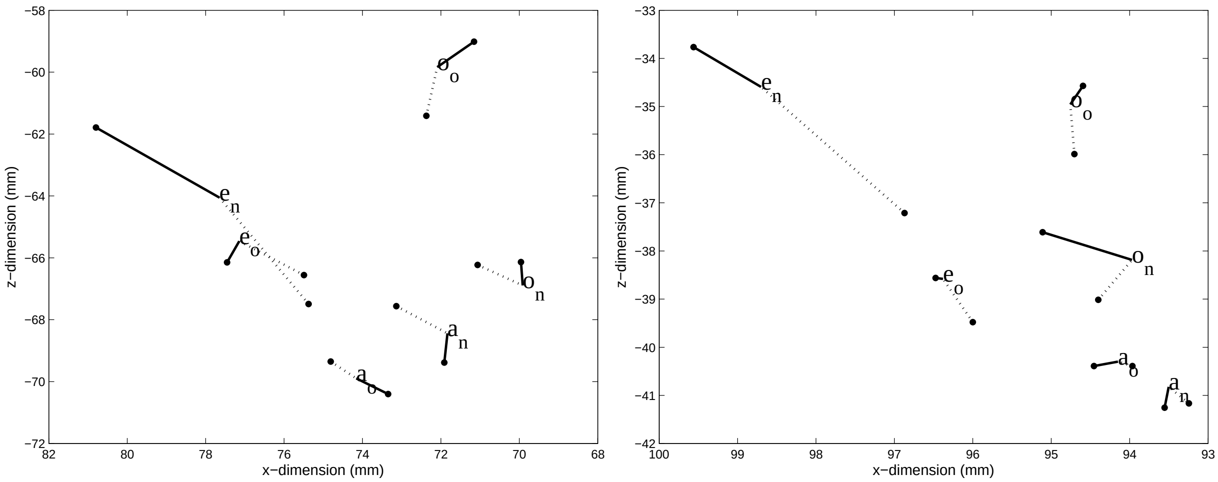
(a) Speaker QF01 dynamic lingual space, TM sensor.

(b) Speaker QF02 dynamic lingual space, TM sensor.

Figure 7.13: Averages for *x*-dimension and *y*-dimension TM values measured at the midpoints of each QF vowel trisection. For each vowel, the dotted line traces the dynamic change from the midpoint of the first trisection to that of the second, and the solid line traces the dynamic change from the midpoint of the second trisection to that of the third.

These figures reveal that dynamic acoustic change can only clearly be accounted for by lingual articulatory change for the vowel [ɛ̃]. For this vowel, the decreasing F1 and F2 observed for both speakers can be explained by the rising and fronting of body of the tongue, observed in the data from both the TM and TB sensors. Therefore, the diphthongization of [ɛ̃] is clearly due to lingual articulatory change. With regard to the diphthongization of [ɔ̃] observed in the acoustic signal for both speakers, the role of lingual articulation is less clear. Although there is a slight amount of retraction for the TM sensor for both speakers, the dynamic change is minimal compared to the TM change for [ɛ̃]. Moreover, with regard to the TB sensor, even less retraction is observed for speaker QF01, especially compared to [ɛ̃], while speaker QF02 manifests a *fronting* of the tongue back in the third trisection of the vowel[1]. Therefore, while the

[1]It is reasonable to consider this fronting as a consequence of the opening of the velo-pharyngeal port, which lowers and moves the soft palate forward. Since [ɔ̃] is a back vowel, the tongue may need to be moved forward slightly to “make way” for the lowered velum. However, since there is no corresponding lowering observed for the TB sensor, the lowering of the velum towards the back of the tongue is predicted to lower F2, which may also contribute to the dynamic acoustic change for [ɔ̃]. These results will be discussed further in 8.2.



(a) Speaker QF01 dynamic lingual space, TB sensor.

(b) Speaker QF02 dynamic lingual space, TB sensor.

Figure 7.14: Averages for *x*-dimension and *y*-dimension TB values measured at the midpoints of each QF vowel trisection. For each vowel, the dotted line traces the dynamic change from the midpoint of the first trisection to that of the second, and the solid line traces the dynamic change from the midpoint of the second trisection to that of the third.

body of the tongue may play a very minor role in the diphthongization of [ɔ̃] observed in the acoustic signal for both speakers, I predict labial configuration to be the primary articulatory cause of the acoustic change for this vowel. With regard to speaker QF01's dynamic lingual articulation of [o], it is reasonable to deduce that much of the decreasing F2 observed in the acoustic signal is due to lingual configuration, since both TM and TB manifest some retraction for throughout the vowel production (most evident for TM). However, I do anticipate observing dynamic change in the labial configuration for this vowel, as well, since the relatively slight lingual articulatory change is most likely not enough to explain the relatively large change in F2.

Dynamic labial articulation: [ɛ]-[ɛ̃]

The results for the dynamic labial articulation for trisection-midpoints explained in 5.2.2 are given in the boxplots in Figures 7.15 through 7.18 for the vowel pair [ɛ]-[ɛ̃][2]. In each figure, there are two subfigures: the left-most subfigure displays the dynamic labial articulation for the oral vowel [ɛ], and the right-most subfigure displays the dynamic labial articulation for its nasal counterpart [ɛ̃]. In each subfigure, the boxplots for the three trisection measures are displayed in linear order, from left to right: the first trisection is on the left, the second trisection is in the middle, and the third trisection is on the right. The boxplots in the two subfigures for each vowel pair are plotted in the same range; thus,

[2]As previously mentioned, the data for speaker QF01 manifested ubiquitous tracking errors for the UL sensor. Therefore, the labial distance and labial aperture area dynamic measures are not included in the analysis for this speaker. Thus, the dynamic labial analysis for this speaker only includes LL protrusion.

absolute comparisons can be made between the measures for the oral vowel and those for its nasal counterpart.

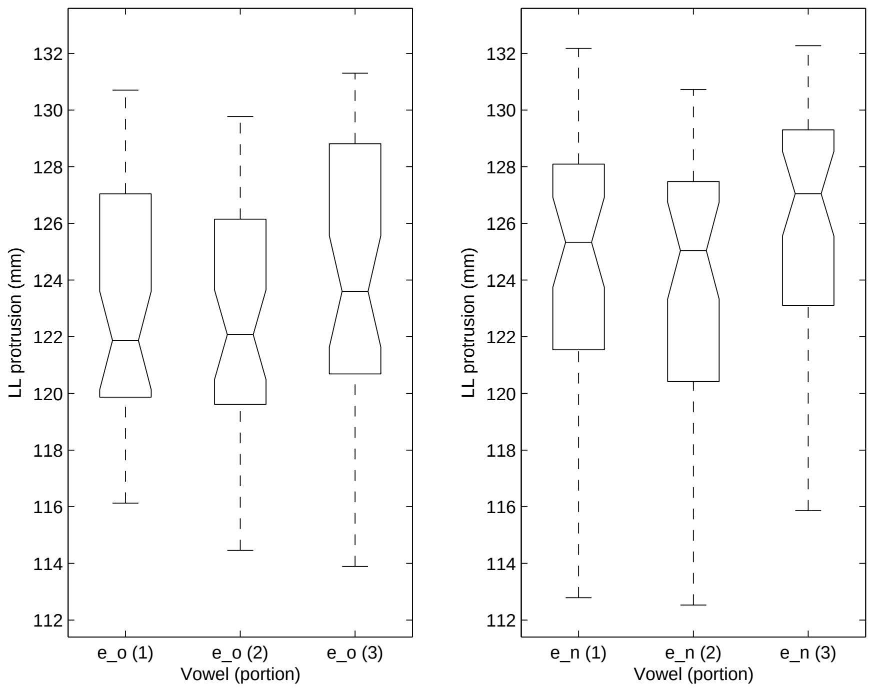


Figure 7.15: Speaker QF01 dynamic LL protrusion change for [ɛ]-[ɛ̃].

Although dynamic labial articulation was not predicted for nasal [ɛ̃], since the dynamic lingual articulation observed for both speakers can explain the dynamic acoustic change observed, the dynamic labial results suggest that [ɛ̃] is manifested with some degree of dynamic labial articulatory change for both speakers. Speaker QF01 gradually protrudes her lower lip throughout her productions of both oral [ɛ] and nasal [ɛ̃]. The same articulatory change can be observed for speaker QF02, along with a corresponding decline in both labial distance and labial aperture throughout the production both vowels. There are no observable absolute differences to speak of between [ɛ] and [ɛ̃]: the degree of lip protrusion and lip rounding is similar between the two vowels. These results suggests that lip rounding and protrusion is a dynamic characteristic of both [ɛ] and [ɛ̃] in the QF dialect. However, this labial change could be due to co-articulation with the following [p]; nevertheless, the asymmetry in this labial articulation suggests that the co-articulation is less for the preceding [p]. These results should be interpreted conservatively, and more research should be carried out before any strong generalizations can be made.

Dynamic labial articulation: [o]-[ɔ̃]

The results for the dynamic labial articulation for trisection-midpoints explained in 5.2.2 are given in the boxplots in Figures 7.19 through 7.22 for the vowel pair [o]-[ɔ̃].

Due to the limited number of dynamic labial measures available for speaker QF01, we will first discuss the dynamic

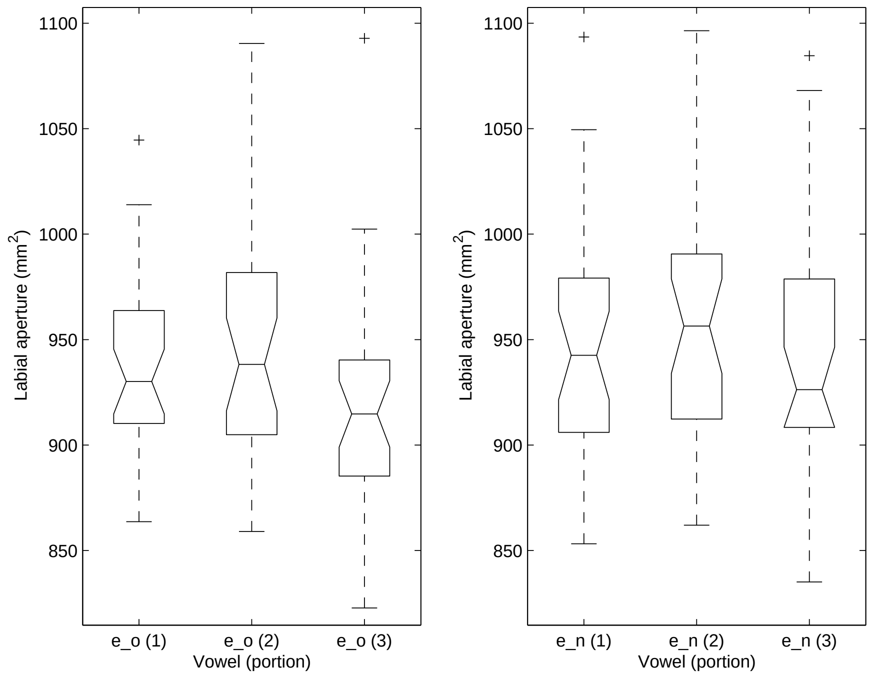


Figure 7.16: Speaker QF02 dynamic labial aperture change for [ɛ]-[ɛ̃].

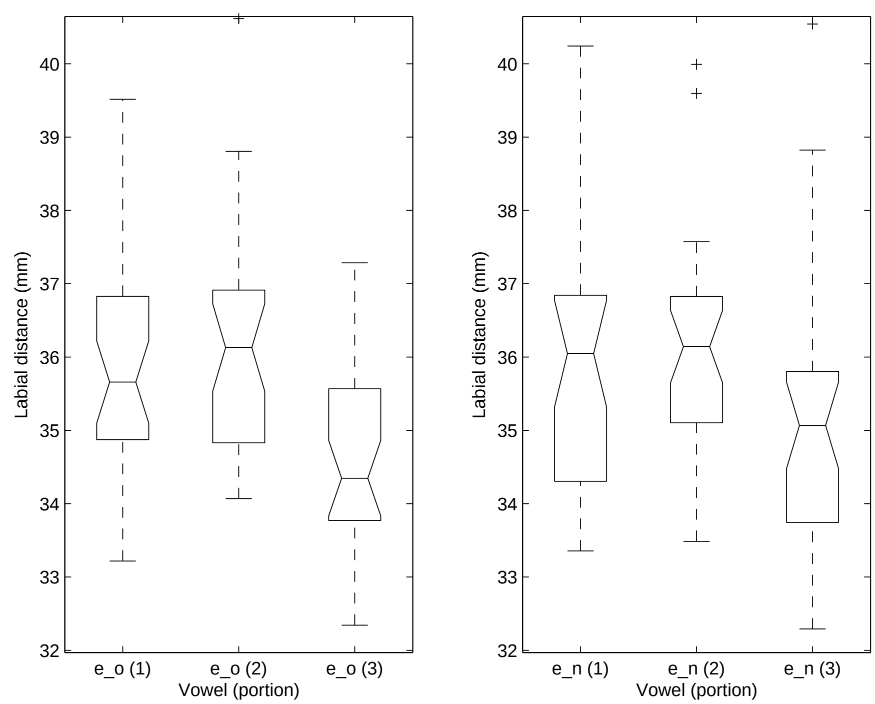


Figure 7.17: Speaker QF02 dynamic labial distance change for [ɛ]-[ɛ̃].

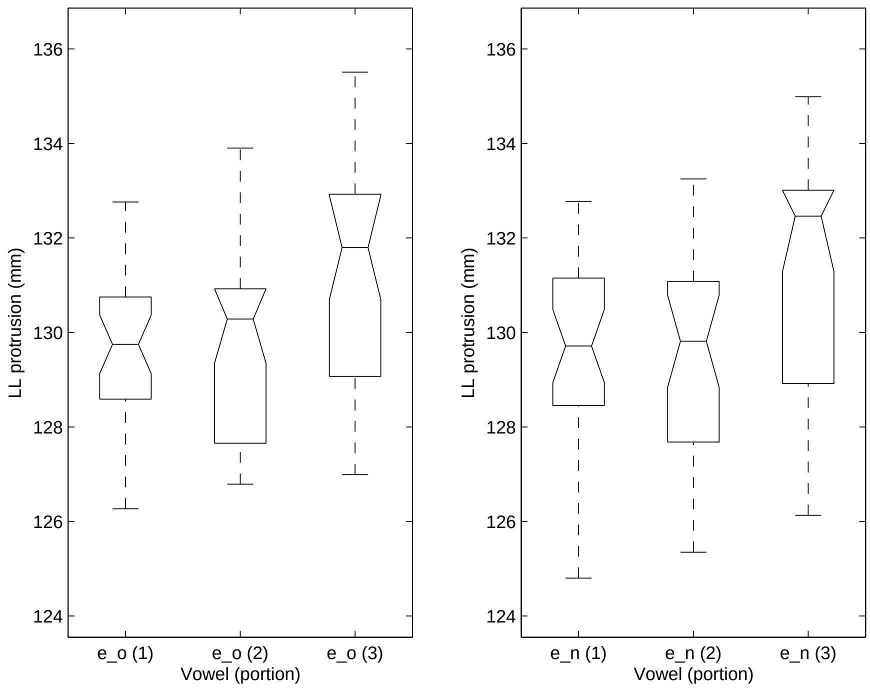


Figure 7.18: Speaker QF02 dynamic LL protrusion change for [ɛ]-[ɛ̃].

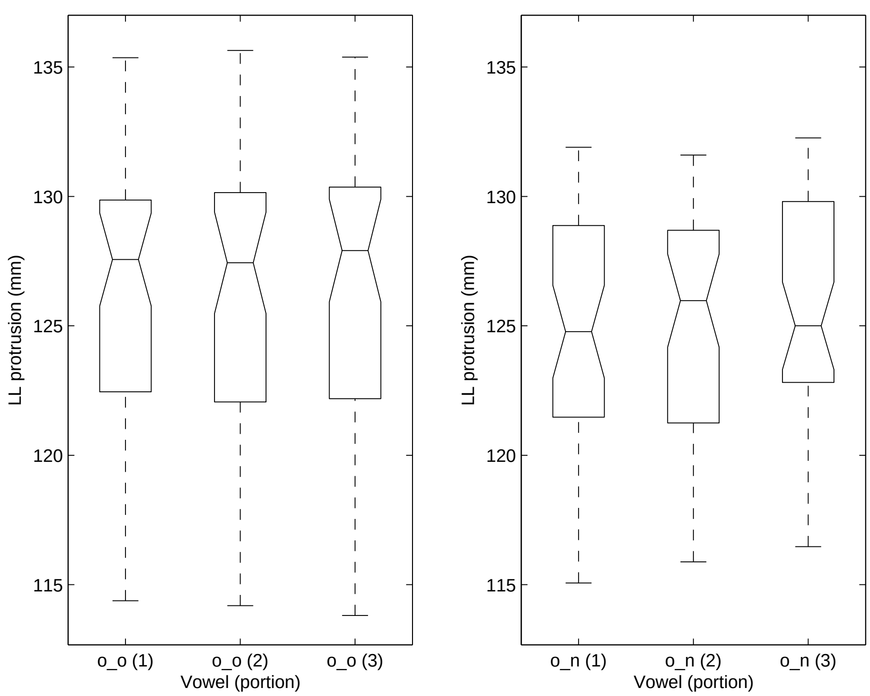


Figure 7.19: Speaker QF01 dynamic LL protrusion change for [o]-[õ].

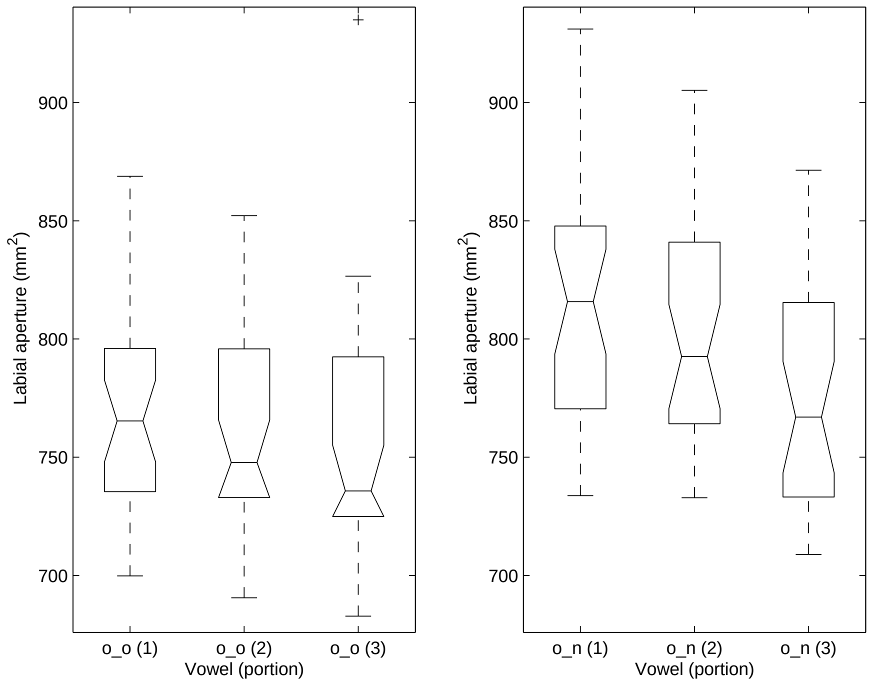


Figure 7.20: Speaker QF02 dynamic labial aperture change for [o]-[õ].

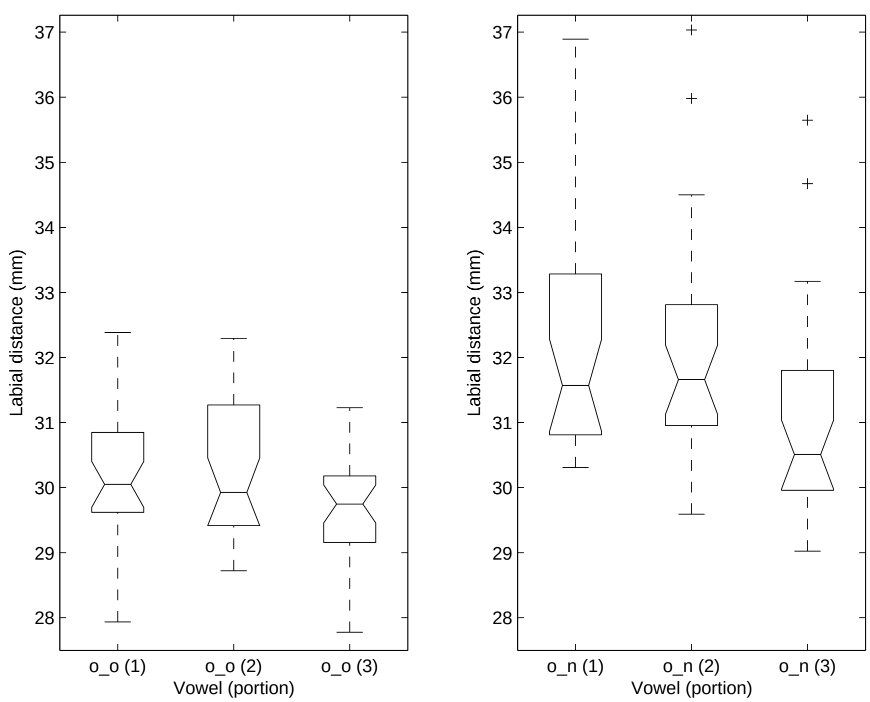


Figure 7.21: Speaker QF02 dynamic labial distance change for [o]-[õ].

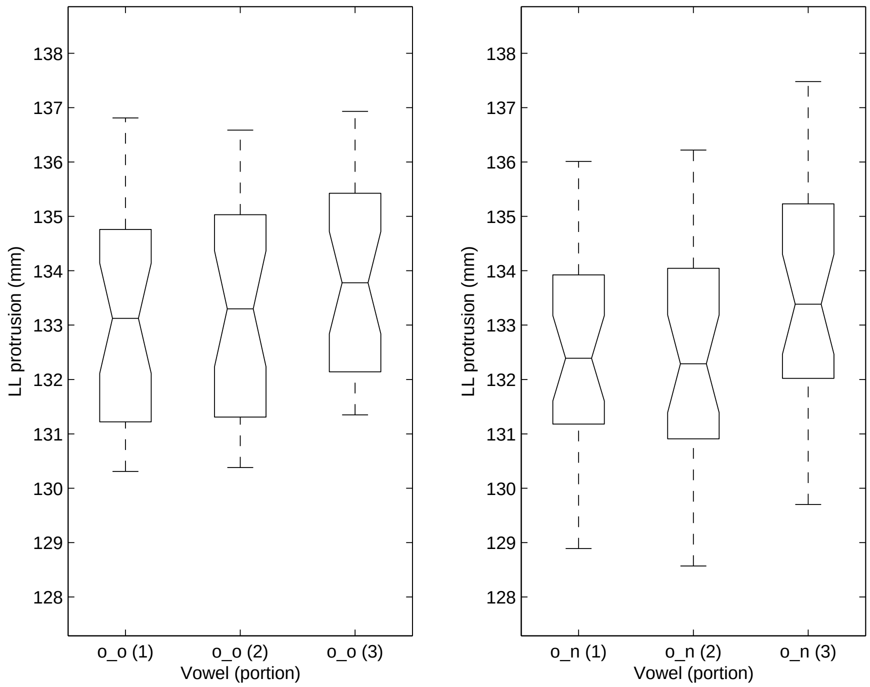


Figure 7.22: Speaker QF02 dynamic LL protrusion change for [o]-[ɔ̃].

labial articulation of [o]-[ɔ̃] for speaker QF02. The results for QF02 suggest that both lip rounding and lip protrusion are dynamic articulatory characteristics for both oral [o] and nasal [ɔ̃]: throughout the duration of the vowel, labial aperture and distance decrease, and lower lip protrusion increases. Moreover, lip rounding is generally greater for [o] than for [ɔ̃] throughout the dynamic change, as already seen for static vowel measurements in 7.3.3. With regard to speaker QF01, there is not any evidence that lower lip protrusion is used as a dynamic articulatory characteristic of either [o] or [ɔ̃]. Given the very clear evidence for dynamic change in labial aperture for speaker QF02, one wonders if similar data from QF01 would show the same pattern. Unfortunately, due to the fact that measures which incorporate data from the UL sensor could not be used for QF01, it is impossible to know if dynamic lip rounding without lip protrusion is manifested in QF01's production of this vowel pair. In general, however, the results for dynamic labial articulation of [ɔ̃] support previous descriptions and findings (Charbonneau, 1971; Delvaux, 2006; Martin, 2002; Walker, 1984).

7.6 Quebecois French: Post-vocalic nasal consonant

During annotation of the tokens, it quickly became evident through visual analysis of the signals that both QF speakers displayed evidence of an epenthetic nasal consonant at the end of the nasal vowels (most notably, [ɛ̃]). The evidence for this epenthesis was three-fold: (1) acoustically, the amplitude of the sound pressure signal dropped to a level similar to that of a nasal consonant, but not to a level of complete silence. This level was the threshold used for annotation of the end of the vowel (20% of the maximum amplitude of the vowel), and was established using electropalatography (EPG) data to be an appropriate level for nasal consonant production in Portuguese[3]; (2) aerodynamically, the peak of the nasal flow generally did not occur during the nasal vowel itself, but rather during the consonant closure that followed the vowel; and (3) the measurements of tongue height suggest that the tongue continues to rise after the lips have closed for the following bilabial consonant. Crucially, it is the tongue, not the lips, which is the articulatory cause of this nasal consonant, suggesting that the phenomenon is not due to anticipatory assimilation to the following consonant [p]. Rather, since there is no specific lingual gesture for the following consonant, the differences that we find in lingual height can be assumed to be an intentional gesture which is characteristic of the vowel itself. The combination of the three observed evidences suggests that a variable epenthetic nasal consonant exists in nasal vowel production of QF. As mentioned, the most consistent pattern of nasal consonant epenthesis can be observed following the production of [ɛ̃]. Where evidence of this epenthetic nasal consonant does occur, the TM and TB sensors—most notably, TB—are higher during the temporal portion following [ɛ̃] than following [ɛ], suggesting that the place of articulation of the lingual closure is either post-palatal or velar (i.e., [ŋ]).

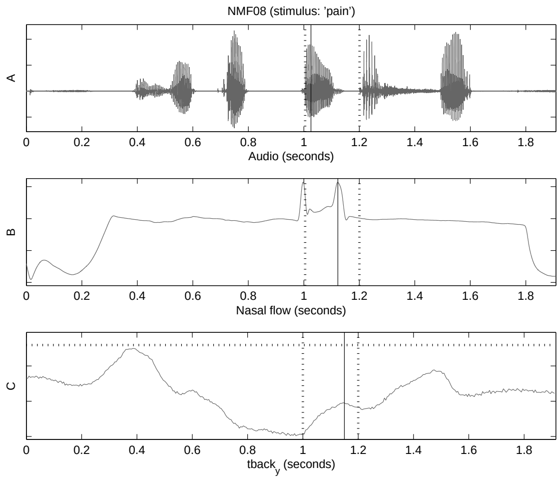
In order to use EMA technology to investigate whether palatal contact has occurred, one must either use a palatal model created from tracing the palate with a sensor, or create a *probabilistic palate* using maximal sensor height during speech. There are two main reasons to use a probabilistic reconstruction of the palate height instead of palate height reconstructed from a trace of the palate. The first reason—and, arguably, the most important one—is that EMA sensor trajectories provide information about the articulatory gestures of *flesh points*, not of the entire tongue surface itself. Therefore, in order to determine if contact has occurred with the palate, the researcher must know *a priori* which point of the tongue will contact the palate. Contact that occurs at a point of the tongue between the flesh points represented by two sensors cannot be confirmed to have occurred. Conversely, if palatal contact does not occur in a given sensor's trajectory, this is not indisputable evidence that contact has *not* occurred. Moreover, the current study was not designed to research palatal contact and, thus, the research questions and methodology were not created with this goal in mind. Even if the current study had been designed to research this question, I could not have had *a priori* knowledge of where to attach the sensors in order to observe such contact. The second reason to avoid using a palatal trace to investigate the possible occurrence of palatal contact is that, by definition, EMA can never be used to obtain incontrovertible evidence of palatal contact. One must remember that a sensor has physical dimensions, one of which is height. In the strictest interpretation of the data, the trajectories provided by the EMA system allow researchers to observe the gestures of the sensors themselves, not of the flesh to which they are attached. In other words, if a

[3] I am grateful to Professor Ryan Shosted for the suggestion of this annotation method, and for allowing me access to this EPG data.

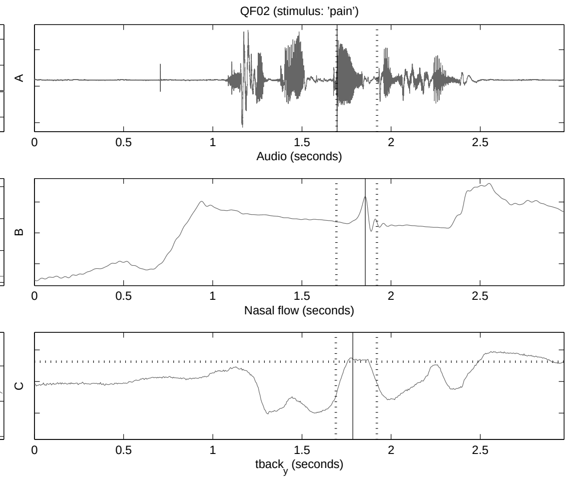
given sensor's signal provides evidence which suggests that palatal contact has occurred, what the evidence suggests in actuality is that the *sensor itself* has contacted the palate, not necessarily the tongue surface.

In order to calculate a probabilistic reconstructed palate in the velar region, a custom-written Matlab function was used to calculate the median maximal heights of TB trajectory movement during velar onset consonant productions. Segmentation of the beginning of the onset consonants was not deemed necessary during the creation of the methodology for this study, since the research questions only involved articulation of the vowel. Therefore, in lieu of precise consonant segmentation, and because only the maximum sensor values were needed, a temporal window which sufficiently covered the duration of consonant production was used. To do this, the beginning of vowel onset was used as the end of the onset consonant window, and the beginning of the window was calculated as 1000 ms prior to this time point. If there was not 1000 ms worth of data from the start of the file to the vowel onset, the first data point was used as the beginning of the window. For each target word which contained a velar onset consonant (e.g. "quand","coco","coquin", etc.), the maximum TB value in the *y*-dimension (i.e., vertical displacement; *z*-dimension for AG500 data) was calculated during the 1000 ms window. The median of the values of these maximum heights was calculated and used as the probabilistic palate heights for all of the sweeps. We assume *a priori* that the tongue back is touching the underside of the soft palate during the production of velar [k] and that the velum is raised in order to maintain the necessary aerodynamic constraints for the voiceless oral consonant production (i.e., positive pressure build-up). Therefore, we can reason that the TB sensor will reach its maximum height during the production of this consonant. Thus, calculating palate height in this way yields a robust probabilistic measure of palate height in the velar region which can be used for all of the target words, regardless of the place of articulation of the onset consonant.

Figures 7.23 and 7.24 display examples of this reconstructed palate height measurement. Subfigure 7.23a is a token of "pain" produced by NMF08, and subfigure 7.23b is a token of "pain" produced by QF02. These subfigures allow a direct comparison of the dynamic nature of NMF [ɛ̃] to that of QF [ɛ̃]. Subfigure 7.24a is a token of "paix" produced by QF02, and subfigure 7.24b is another token of "pain" produced by QF02. These subfigures allow a direct comparison of the dynamic nature of QF [ɛ] to that of QF [ɛ̃]. Each subfigure has three subplots: subplot A is the audio signal, subplot B is the (filtered) nasal flow signal, and subplot C is the TB sensor trajectory in the *y*-dimension. For each subplot, the left-most vertical dotted line represents the onset of the vowel, while the right-most vertical dotted line represents the onset of the burst of the following consonant. The vertical solid line in each subplot represents the time point of the maximum signal within these two dotted lines, and are shown simply for reference purposes. For each subfigure, the dotted horizontal line in subplot C represents the reconstructed palate height in the velar region for the respective speaker.

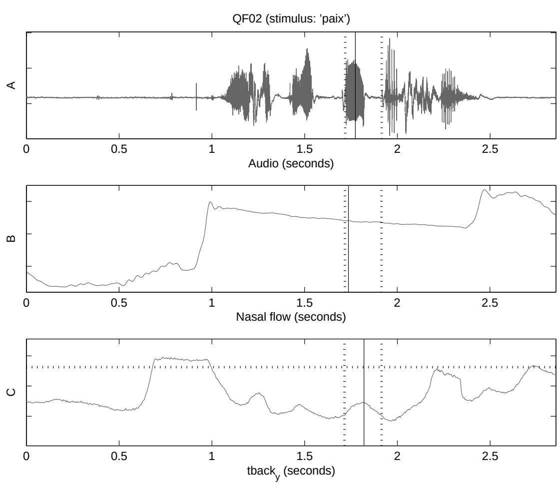


(a) Palate height, NMF08: “pain”.

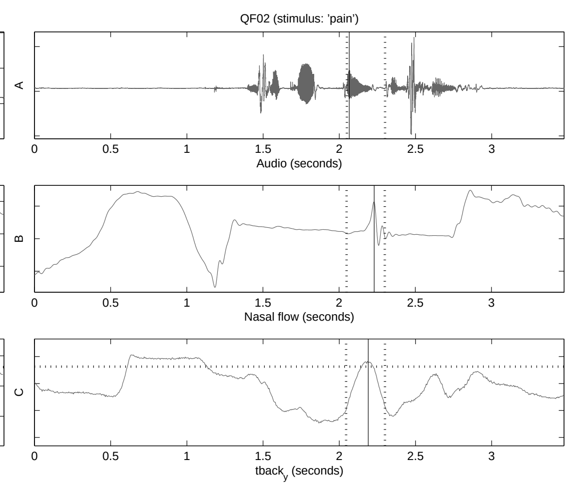


(b) Palate height, QF02: “pain”.

Figure 7.23: Examples of reconstructed velar palate heights. Subplot A: audio, Subplot B: nasal flow, Subplot C: TB sensor trajectory (*y*-dimension). Palate heights are shown by the horizontal dotted line in Subplots (a):C and (b):C.



(a) Palate height, QF02: “paix”.



(b) Palate height, QF02: “pain”.

Figure 7.24: Examples of reconstructed velar palate heights. Subplot A: audio, Subplot B: nasal flow, Subplot C: TB sensor trajectory (*y*-dimension). Palate heights are shown by the horizontal dotted line in Subplots (a):C and (b):C.

In these examples, we can observe that the TB sensor contacts the reconstructed palate for QF [ɛ̃], but not for QF [ɛ] nor for NMF [ɛ̃]. These results, though not conclusive for reasons aforementioned, suggest the production of [ɛ̃] in the QF dialect may include a variation which is characterized by an epenthetic post-vocalic nasal, most likely [ŋ]. However, further research will certainly need to be carried out to confirm the existence of this epenthetic nasal consonant, ideally using EPG, in order to provide conclusive evidence that palatal contact occurs, and to determine where along the palate the contact does occur. If, indeed, QF manifests some nasal vowels with a post-vocalic nasal consonant, this phonetic phenomenon may provide important insight into the phonological status of nasal vowels in this variety of French, from a comparative point of view. There is some evidence which suggests the existence of a process wherein the diachronic deletion of nasal coda consonants reverses, and the consonants reemerge (sometimes referred to as ‘restoration’) after a nasal vowel (see Sampson (1999, p. 146, 150f., 207, 260) for cross-linguistic examples). This ‘restored’ nasal consonant may also have a variable place of articulation, sometimes based on the quality of the preceding vowel. Hajek (1991, p. 262) claims that this process may be more likely for high vowels, where a raised tongue dorsum during the articulation of a nasalized glide “facilitates contact between the raised tongue body and the lowered velum, resulting in the closure of the oral cavity.” This phenomenon of nasal coda restoration has been posited for Southern French (Léon and Carton, 1983; Sampson, 1999), Brazilian Portuguese (Shosted, 2003, 2006, 2011) and, to a lesser extent, Hindi (Shosted, 2011). The evidence presented here for QF suggests that nasal coda restoration may exist in this variety of French, and that it is especially apparent in the realization of the high, front nasal /ɛ̃/.

Discussion and Conclusion

Chapter 8

Discussion

8.1 Articulatory enhancement and attenuation of nasalization, revisited

I outlined in 2.3 the combinatory possibilities of oral articulatory configurations which are predicted to enhance or attenuate the formant-frequency-related acoustic effects of nasalization, as well as the different possible phonological ramifications based on whether vowel nasalization is a phonemic or phonetic characteristic in a language. In a language where vowel nasalization is phonemic, an oral articulatory configuration which enhances, or reinforces, the formant-frequency-related acoustic effects of nasalization will help maintain the phonemic distinction; conversely, an oral articulatory configuration which attenuates, or counteracts, the formant-frequency-related acoustic effects of nasalization could eventually lead to a phonemic merger. On the other hand, in a language where vowel nasalization is a purely phonetic phenomenon, an oral articulatory configuration which enhances, or reinforces, the formant-frequency-related acoustic effects of nasalization could lead to a phonemic split (thus, making vowel nasalization phonemic); conversely, an oral articulatory configuration which attenuates, or counteracts, the formant-frequency-related acoustic effects of nasalization will help resist such a phonemic split. Historical evidence suggests that lingual enhancement of the formant-frequency-related acoustic effects of nasalization occurred during the evolution from Latin (where oral vowels were not heavily nasalized via assimilation to a following nasal consonant), through Old French (where vowel nasalization was phonetic, via assimilation to a following tautosyllabic nasal), to modern Northern Metropolitan French (where vowel nasalization is phonemic) (see 1.2.1, 8.3, and Sampson (1999)). Recent articulatory evidence suggests that compensatory lingual articulation occurs during the production of phonetically nasalized vowels in American English (AE) that are tautosyllabic with a following nasal consonant (Arai, 2004; Carignan et al., 2011). This articulatory compensation is predicted to attenuate the acoustic effect of the co-articulatory nasalization on the F1 dimension and, effectively, help resist a phonemic split. A schematic representation of these combinatory possibilities, as well as the synchronic example for AE and the diachronic example for Latin $\rightarrow$ OF $\rightarrow$ NMF, are summarized in Table 8.1.

What remains to be observed are examples of these combinatory possibilities in languages in which vowel nasalization is phonemic. In the current study, I believe to have found evidence of examples of both oral articulatory

Table 8.1: Schematic representation of possible articulatory enhancement or attenuation for vowel systems with, respectively, phonemic or phonetic vowel nasalization. Examples are included from: the transition from Latin to Old French (OF) to Northern Metropolitan French (NMF); and American English (AE).

	Enhancement	Attenuation
Phonemic	Maintain phonemic distinction	Phonemic merger
Phonetic	**Latin → OF → NMF** tongue position helps promote phonemic split	**AE** tongue position helps resist phonemic split

enhancement and attenuation of the formant-frequency-related acoustic effects of nasalization in NMF and QF, respectively. The most telling examples involve the realization of the vowel /ɛ̃/ in both dialects. In the NMF dialect, 10 of the 11 speakers produced [ɛ̃] with a lower tongue position than [ɛ] (predicted to raise F1), and all 11 speakers produced [ɛ̃] with a more retracted tongue position than [ɛ] (predicted to lower F2). /ɛ/ is realized as a relatively high mid vowel, generally produced with a higher tongue position than all of the other NMF vowels in this study (even higher than the high-mid [o]). As detailed in 2.1.1, the predicted effect of velo-pharyngeal coupling on F1 is to raise the frequency, while the predicted effect on F2 is to lower the frequency. Therefore, the lingual articulatory configuration of [ɛ̃] compared to [ɛ], with regard to both the vertical and horizontal dimensions, is predicted to make changes to the F1 and F2 frequencies which are also predicted by velo-pharyngeal coupling. This, then, is an example of a modification of the oral articulatory configuration of a phonemic nasal vowel that enhances the formant-frequency-related acoustic effects of nasalization.

Whereas /ɛ̃/ is realized with a lower, more retracted tongue position in NMF (i.e., [ɐ̃]), it is realized with a rising, fronting dynamic tongue articulation—followed, possibly, by an epenthetic post-palatal or velar nasal—in QF (i.e., [æɛɛ̃ĩ(ŋ)] for speaker QF01 and [ɛɛ̃ĩ(ŋ)] for speaker QF02). Although the tongue position for [ɛ̃] at the beginning of the vowel is similar to [ɛ] for speaker QF02, and even lower and more retracted than [ɛ] for speaker QF01, the lingual position quickly increases in both height and anteriority throughout the duration of the vowel. By the middle of the vowel, the tongue is higher (predicted to lower F1) for [ɛ̃] v. [ɛ] for both speakers, and more fronted (predicted to raise F2) for speaker QF02. Therefore, the lingual articulatory configuration of [ɛ̃] compared to [ɛ], with regard to both vertical and horizontal dimensions, predicts changes to the F1 and F2 frequencies which are opposite those predicted by velo-pharyngeal coupling. Although it seems that at the vowel midpoint the tongue position is not sufficient to counteract the acoustic effect of velo-pharyngeal coupling on F1 (e.g., the tongue is higher for [ɛ̃] v. [ɛ] for both speakers, yet F1 is also higher for both speakers), as the dynamic articulation continues, the effect of the position of the tongue on F1 and F2 is predicted to further attenuate the acoustic effect of nasalization on F1 and F2. In other words, rising and fronting lingual articulation for [ɛ̃] results in a tongue position for the majority of the vowel duration which attenuates the formant-frequency-related acoustic effects of nasalization. Thus, this is a phonetic context which has the possibility for a phonemic merger of [ɛ̃] and [ɛ] due to the attenuation of the formant-frequency-related acoustic effects of nasalization caused by the articulatory configuration of the tongue. In summary, when comparing the realization of /ɛ̃/ in NMF to the realization of /ɛ̃/ in QF, we observe evidence of two lingual articulations which are predicted to have opposite interactions with the formant-frequency-related acoustic effects of nasalization. Nevertheless, there are two characteristics of this QF nasal vowel which may help preserve the phonemic contrast, and which contribute to the overall distinctive "nasality" of [ɛ̃] in the dialect: a nasal coda consonant and dynamic lingual movement. Whereas the nasal coda contributes to the percept of nasality of the vowel in a direct and obvious way (i.e., [ŋ] is nasal), the dynamic lingual movement provides a temporal distinction between the two vowels (i.e., the nasal vowel is produced as a diphthong by both speakers, whereas I do not find evidence of a diphthong realization for its oral counterpart). Although this temporal distinction is not directly related to nasalization *per se*, it very well may be the case that the dynamic movement is linked to the percept of nasality for this vowel. Research on this question would be of great interest, but it is beyond the scope of the current study.

In conclusion, both diachronic and synchronic evidence from various languages and dialects—including the results from the current study—support the viewpoint that oral articulatory configurations can either enhance or attenuate the formant-frequency-related acoustic effects of nasalization on a vowel, and that this interaction has the potential to maintain or resist a phonemic split or merger. These combinatory possibilities, as well as the language examples given here for both phonemic and phonetic vowel nasalization, are summarized in Table 8.2, with all of the possibilities represented[1].

8.2 Motor equivalence: The many-to-one problem, expanded

As previously mentioned in 2.4, 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. In this section, I will highlight how this many-to-one problem can be interpreted in terms of motor equivalence, with respect to lingual position and velo-pharyngeal coupling in the NMF dialect, specifically. 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 con-

[1] Secondary articulation, such as labial rounding (or the lack thereof), should also be considered in these enhancement/attenuation scenarios, and tested systematically for perceptual effects, ideally. In order to simplify discussion, however, I do not include these secondary articulations with the possibilities presented in this schematic representation.

Table 8.2: Schematic representation of possible articulatory enhancement or attenuation for vowel systems with, respectively, phonemic or phonetic vowel nasalization. Examples are included from: Northern Metropolitan French (NMF); Quebecois French (QF); the transition from Latin to Old French (OF) to NMF; and American English (AE).

	Enhancement	Attenuation
Phonemic	**NMF** tongue position helps maintain phonemic distinction	**QF** nasal coda & motion help maintain phonemic distinction
Phonetic	**Latin → OF → NMF** tongue position helps promote phonemic split	**AE** tongue position helps resist phonemic split

tribute to that output." The notion of motor equivalence seems well-suited to explain the production of vowel nasality: multiple articulatory variables (velo-pharyngeal coupling and oral articulatory configurations) can produce similar acoustic manifestations (nasality). Motor equivalence in speech production has been tested in numerous studies that typically debilitate one speech articulator in order to better understand the compensatory strategies that may manifest in another (de Jong, 1997; Guenther et al., 1999; Perkell et al., 1993, *inter alia)*. Unlike traditional motor equivalence studies, the present study does not involve the perturbation of an articulator. Instead, the articulatory evidence which will be discussed here suggests that lingual, labial, pharyngeal, and even velic articulatory configurations can be interpreted as an enhancement of nasalization, at least in terms of the acoustic effect of velo-pharyngeal coupling on F1 and F2.

The results for the F1 differences between nasal vowels and their oral counterparts in NMF, which are detailed in 6.1, are summarized in Table 8.3 (left). The parallel results for tongue height differences, which are detailed in 6.2, are summarized in Table 8.4 (right). The vast majority of the acoustic output is predicted by velo-pharyngeal coupling. However, much of the acoustic output is also predicted by lingual position, though the distinctions between these vowel pairs are not uniform across speakers with regard to how the vowels are articulated. The cells in Table 8.4 which are shaded gray are those for which the vertical position of the tongue cannot explain (i.e., does not predict) the corresponding change in F1 frequency. We can clearly observe that there is very little inter-speaker variation in the acoustic output (in fact, the *only* acoustic variation is for the vowel pair [o]-[ɔ̃]), while there is a relatively high degree of inter-speaker variation in the vertical position of the tongue. In other words, when taking into account only one input variable (tongue height), there is variation which is not realized in the output variable (F1 frequency). As detailed in 6.3, many—but not all—of these lingual/acoustic discrepancies can be explained by labial configuration. However, there is at least one other articulatory variable which may contribute to the F1 frequency of the nasal vowels: the constriction or expansion of the pharynx. Using real-time MR imaging technology to observe—simultaneously—the oral cavity, the upper pharynx, and the lower pharynx of an additional NMF speaker (see Appendix C for details about the methodology and results of this MRI study; see also Carignan et al. (accepted)), we find evidence which suggests that constriction and expansion of the lower pharynx, as well as lingual configuration, are also used as secondary articulations to help distinguish the vowel pairs [a]-[ɑ̃] and [ɛ]-[ɛ̃] by reinforcing the F1-related acoustic effect of nasalization. What all of this evidence suggests is that tongue height, labial articulation, and pharyngeal aperture enhance and reinforce the F1-related acoustic effect of velo-pharyngeal coupling in the production of NMF nasal vowels.

Table 8.3: F1 results for NMF.

	[ɑ̃] v. [a]	[ɛ̃] v. [ɛ]	[ɔ̃] v. [o]
NMF01	lower	higher	
NMF02	lower	higher	lower
NMF03	lower	higher	lower
NMF04	lower	higher	lower
NMF05	lower	higher	lower
NMF06	lower	higher	higher
NMF08	lower	higher	higher
NMF09	lower	higher	
NMF11	lower	higher	lower
NMF12	lower	higher	lower
NMF13	lower	higher	lower

Table 8.4: *y*-dimension results for NMF. Gray cells are cases for which the vertical position of the tongue does not predict the corresponding F1 frequency.

	[ɑ̃] v. [a]	[ɛ̃] v. [ɛ]	[ɔ̃] v. [o]
NMF01	lower	lower	lower
NMF02		lower	
NMF03	lower	lower	higher
NMF04	lower	lower	lower
NMF05	higher		lower
NMF06			lower
NMF08		lower	
NMF09	lower	lower	lower
NMF11		lower	
NMF12	higher	lower	higher
NMF13		lower	lower

The results for the F2 differences between nasal vowels and their oral counterparts are summarized in Table 8.5 (left). The parallel results for differences in horizontal tongue position are summarized in Table 8.6 (right). The cells in Table 8.6 which are shaded gray are those for which the horizontal position of the tongue cannot explain (i.e., does not predict) the corresponding change in F2 frequency. Compared to the results for F1 and tongue height, we can observe that there is even less inter-speaker variation in F2 realizations, as well as nearly no inter-vowel variation. Indeed, the results for F2 are ubiquitous and uniform: for nearly all speakers and all vowels, nasal vowels have a lower F2 than their oral counterparts. This result is consistent with modeling work performed by Feng and Castelli (1996); Serrurier and Badin (2008) and perceptual work performed by Delvaux (2009). Combining the F2 results for all NMF speakers and for all the three vowel pairs, 31 out of the 33 combinations yield a lower F2 frequency for a given speaker's production of a given nasal vowel compared to its oral counterpart (the two examples which do not yield this result are NMF06's and NMF13's productions of [ɔ̃] v. [o]). As with the results for F1 and tongue height, this universal lowering of F2 for the nasal vowels is predicted as an acoustic effect of velo-pharyngeal coupling. We can clearly observe that, while there is very little inter-speaker variation in the acoustic output, there is a higher degree of inter-speaker variation in the horizontal position of the tongue (albeit much less than for the vertical position of the tongue). In other words, when taking into account only one input variable (horizontal tongue position), there is variation which is not realized in the output variable (F2 frequency). As detailed in 6.3, many—but not all—of these lingual/acoustic discrepancies can be accounted for by labial configuration.

There is at least one other articulatory variable which may contribute to the frequency of F2 of the nasal vowels: the lowering of the velum. 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)). The acoustic–perceptual outcome of velo-pharyngeal coupling is most often considered in terms of the contributions of the nasal cavity and sinuses. However, the lowered velum itself creates a constriction in the oral cavity that also affects the acoustics. Specifically, the velic constriction created by the lowered velum against the back of the tongue is predicted to lower F2. Although this articulation may be "passive" (i.e., it is an indirect consequence of an articulatory gesture), the result is an important acoustic effect which should not be disregarded in the acoustic analysis of the nasalization of any vowel[2]. In other words, the lowering of the velum is usually assumed to be an articulation for which the intended result is the coupling of the nasal tract to the oro-pharyngeal tract. However, a (perhaps unintended) consequence of this articulatory gesture is the velic constriction in the oro-pharyngeal tract which is predicted to alter the acoustic transfer function associated with the tract. Further research is needed to determine how much this F2-lowering can be be generalized to vowel nasalization in other languages, but based on modeling work by Feng and Castelli (1996); Serrurier and Badin (2008) (see 2.1.1) and perception work by Delvaux (2009) (see 2.1.1), it is reasonable to consider F2-lowering due to velo-pharyngeal coupling a factor in the results for NMF: the ubiquitously lower F2 values observed for all of these NMF nasal vowels, and for all of the speakers, suggest that this velic constriction may be a contributing factor to the acoustic manifestation of these vowels. What all of this evidence suggests is that horizontal tongue position, labial articulation, and velic constriction enhance and reinforce the F2-related acoustic effect of velo-pharyngeal coupling in the production of NMF nasal vowels.

With regard to specific vowel pairs, I posit that speakers of the NMF dialect use idiosyncratic combinations of the following articulations in order to create F1/F2 frequency differences which help distinguish oral/nasal vowel pairs:

- [a]-[ɑ̃]
  - F1 distinction is due to velo-pharyngeal coupling, pharyngeal expansion, and lip rounding and/or protrusion.
  - F2 distinction is due to velo-pharyngeal coupling, lingual retraction, lip rounding and/or protrusion, and velic lowering.

[2]This F2-lowering due to velo-pharyngeal coupling is predicted to be especially relevant for back vowels, for which the retracted tongue dorsum would conceivably create an even greater constriction with the lowered velum. Shosted et al. (2012a, p. 462) posit that this may explain the lower F2 observed for non-front nasal vowels compared to their oral vowel counterparts in Hindi.

Table 8.5: F2 results for NMF.

	[ɑ̃] v. [a]	[ɛ̃] v. [ɛ]	[ɔ̃] v. [o]
NMF01	lower	lower	lower
NMF02	lower	lower	lower
NMF03	lower	lower	lower
NMF04	lower	lower	lower
NMF05	lower	lower	lower
NMF06	lower	lower	
NMF08	lower	lower	lower
NMF09	lower	lower	lower
NMF11	lower	lower	lower
NMF12	lower	lower	lower
NMF13	lower	lower	

Table 8.6: *x*-dimension results for NMF. Gray cells are cases for which the horizontal position of the tongue does not predict the corresponding F2 frequency.

	[ɑ̃] v. [a]	[ɛ̃] v. [ɛ]	[ɔ̃] v. [o]
NMF01	retracted	retracted	
NMF02		retracted	
NMF03	retracted	retracted	retracted
NMF04	retracted	retracted	retracted
NMF05	fronted	retracted	retracted
NMF06	retracted	retracted	
NMF08	retracted	retracted	retracted
NMF09	retracted	retracted	retracted
NMF11	retracted	retracted	
NMF12	retracted	retracted	retracted
NMF13	retracted	retracted	

- [ɛ]-[ɛ̃]
  - F1 distinction is due to velo-pharyngeal coupling, lower tongue position, and pharyngeal constriction.
  - F2 distinction is due to velo-pharyngeal coupling, lingual retraction, and velic lowering.
- [o]-[ɔ̃]
  - F1 distinction is due to velo-pharyngeal coupling, and lip rounding and/or protrusion. Further research is needed in order to determine if pharyngealization may also be a speaker-dependent variable.
  - F2 distinction is due to velo-pharyngeal coupling, lingual retraction, lip rounding and/or protrusion, and velic lowering.

In conclusion, the articulatory and acoustic evidence provided here suggests that speakers use a combination of multiple speech articulators in order to produce a similar acoustic output for the nasal vowels of NMF, which I regard as a representative example of motor equivalence in speech. As interesting as this finding may be, it is perhaps even more interesting to note that individual NMF speakers seem to employ idiosyncratic combinations of these articulatory variables in speaker-specific gestural strategies in order to reach a singular acoustic goal. In the light of motor equivalence, this suggests not only that multiple input variables are used to achieve an output goal, but that these separate input variables can be used in conjunction with one another *in varying degrees* to reach this goal. These findings support the hypothesis, arising from a growing body of work (Arai, 2004; Carignan et al., 2011, accepted; Engwall et al., 2006; Rong and Kuehn, 2010; Shosted et al., 2012a), that the acoustic characteristics of nasalization can be attained by an assortment of speech gestures that include, but are not limited to, the coupling of the nasal cavity to the oro-pharyngeal cavity via the opening of the velo-pharyngeal port. Additionally, the inter-speaker variation observed for the production of /ɔ̃/ may, in fact, explain some of the conflicting results from previous studies detailed in 2.1.2. However, even though the inter-speaker variation was observed mainly for the oral articulation of /ɔ̃/, with relatively less inter-speaker variation in the acoustic realization of /ɔ̃/, the fact that I have not observed inter-speaker uniformity in the acoustic output suggests that the possible variability in the realization of /ɔ̃/ discussed in 1.2.2 is indeed present in NMF. In other words, for some speakers, /ɔ̃/ is realized as a high mid-vowel; for others, it is realized as a low mid-vowel. Nevertheless, the majority of the NMF speakers in this study produce /ɔ̃/ as a very high mid-vowel.

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 (1986, 1990); Liberman and Mattingly (1985)), by showing that speakers use a variety of articulatory combinations in order to achieve a similar acoustic output. As explained in 1.1, 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 and Mattingly, 1985)) or via direct perception ("direct realist" theory of speech perception (Fowler, 1986, 1989, 1990, 1991)). However, there is other evidence that articulations co-vary because their acoustic effects enhance one another (Diehl and Kluender, 1989; Diehl and Walsh, 1989; Kluender et al., 1988) or are integrated components of a single perceptual object (Diehl et al., 1991b; Kingston et al., 1990; Kingston, 1991, 1992; Ohala, 1996). If speakers perceive information about the configuration of speech articulators themselves, then we should find minimal inter-speaker variability with regard to the articulatory strategies employed, since variable articulations would lead to variability in perception. On the other hand, if speakers perceive only acoustic information about speech sounds—and any articulatory variablity in the production of a speech sound is integrated into a single perceptual object—then we should not be surprised to observe inter-speaker variability with regard to the articulatory strategies used to produce speech sounds, and relatively less variability with regard to the corresponding acoustic output.

The observation in the current study that speakers use a variety of articulatory combinations in order to reach a singular acoustic target gives considerable weight to the theory that the goal of speech acts is acoustic. Although the current study does not involve investigating the perception of these articulatory and acoustic realizations, it is reasonable to assume that the large degree of inter-speaker variability observed with regard to the articulatory configurations used to produce the oral/nasal vowel distinction in NMF does not precipitate a similarly large degree of variability in the perception of this distinction, since all of the vowels studied here are phonemes in the language. In other words, if the same degree of inter-speaker variability observed in the oral articulatory strategies used to produce the nasal/oral vowel distinction were present in the perception of this distinction, we should anticipate that these phonemes would be changing, splitting, and merging rapidly in the language and that the language would be riddled with ubiquitious phoneme confusions, neither of which is the case in NMF. Investigation of the perceptual effects of both the articulatory variability and the acoustic variability of the oral/nasal vowel distinction in NMF is needed to determine if perception is, indeed, correlated with the acoustic output and not the articulatory source. This is beyond the scope of the current study, however, I am currently involved in creating a research program to investigate the perceptual effects of the articulatory and acoustic data presented in the current study.

8.3 Nasalization as a catalyst for sound change

The "Ohalian" view of sound change (Ohala, 1975, 1981, 1993a,b, 1996) considers change to be initiated by the listener via misperception of the acoustic effects of the articulatory source. In this view, sound change most commonly involves evolution in the perception of natural overlapping acoustic variation of sounds. A conceivable example would be the change in vowel quality from [ɪ] to [e] in a given language, since the acoustic variations of these two vowels are likely to overlap. In this case, the variation of one sound is misperceived a possible variant of a sound that is an acoustic neighbor (i.e., an acoustic neighbor in the vowel space, in this example), and subsequent modification of the articulation of the sound occurs. However, in this understanding of sound change as listener-based, change can also involve modification of the articulatory source if the acoustic variations of two articulators (even at distant points in the vocal tract) happen to overlap. A classic example is the articulatory change of velar stops in Proto-Indo-European to labio-velar stops in Classical Greek, as shown in 8.1 (Meillet, 1967). An example of a similar change in Proto-Bantu to West Teke is shown in 8.2 (Guthrie, 1967–1970)[3].

(8.1)	Proto-Indo-European	Classical Greek	
	**ekwos*	*hippos*	'horse'
	**gwiwos*	*bios*	'life'

(8.2)	Proto-Bantu	West Teke	
	**-kumu*	*pfumu*	'chief'

These examples of extreme articulatory sound change are difficult to account for in articulatory terms, but easy to account for in acoustic terms, since a lowering of F2 is common for both the velar constriction and the labial constriction. The results from the current study support this view of sound change: the formant-frequency-related acoustic effects of nasalization may be misperceived by listeners as changes in tongue/lip articulation and, in turn, produced as changes in tongue/lip articulation (presumably to match perception). If this is indeed the case, we should anticipate evidence of articulatory changes in the history of French nasal vowel production which are consistent with the formant-frequency-related acoustic effects of nasalization.

[3] Both examples are reproduced from Ohala (1989, p. 182), 4(a-b).

Sampson (1999, pp. 65–83) uses written accounts of prescriptive views on pronunciation, as well as clues from orthography, to provide evidence of patterns of change in nasal vowels in the history of the French language. According to these records, in the 11th century [ẽ] began lowering to [ɛ̃], which then merged with [æ̃]. [æ̃] further lowered and retracted to [ã] by the 13th century. The initial lowering of [ẽ] to [ɛ̃] is consistent with predictions regarding the acoustic centralization of the vowel space along the F1 dimension, as is the merger of [ɛ̃] with [æ̃] (depending on how high [ɛ̃] was actually realized at the time). The backing of [æ̃] to [ã] is consistent with predictions regarding the lowering of F2 under the effect of nasalization, especially considering that [æ̃] is a front vowel. An alternative view of the changes of these vowels is that the initial lowering of [ẽ] to [ɛ̃] began a sound change which simply continued on a predictable path to [ã] along the periphery of the vowel space, and that [ɛ̃] merged with [æ̃] in the process. With regard to high vowels, [ĩ, ỹ, ũ] lowered to [ẽ, ø̃, õ], respectively, in the 13th century. This lowering is also consistent with the acoustic centralization of the vowel space along the F1 dimension under the effect of nasalization. By the 16th century, [ẽ]/[ø̃] had already begun to lower to the [ɛ̃]/[œ̃] of modern French, a vowel pair which most would argue has since merged to [ɛ̃] in NMF. Similar to the lowering of [ẽ] in the 11th century, the lowering of [ẽ]/[ø̃] to [ɛ̃]/[œ̃] in the 16th century is consistent with the prediction for the acoustic effect of nasalization with regard to F1, given that [ẽ]/[ø̃] are relatively high mid-vowels. There is some evidence that [ĩ] had re-emerged by the end of the 17th century, but was confined to the prefix *in-*/*im-* found in learned words. As was the case for [ĩ] in the 13th century, this newly emergent nasal vowel suffered the same fate, lowering to merge with [ɛ̃] by the end of following century. Again, this gradual lowering in the nasal vowel space is consistent with the acoustic centralization of the vowel space along the F1 dimension due to nasalization. In summary, the diachronic changes in quality of the nasal vowels in French are consistent with the formant-frequency-related acoustic effects of nasalization on the vowel space. This suggests that these changes in vowel quality are not merely coincidental, but are due, very likely, to misperception by the listener: the acoustic modulation due to nasalization would have been misperceived as a change in the position of the tongue and/or lips, and subsequently produced as such.

Aside from changes in vowel quality, there are other systematic changes observable in the historical record of French nasal vowels which can be explained by predictions regarding the acoustic effect of nasalization. Firstly, we can observe that the nasal vowel space has been considerably reduced over time (see Figure 8.1). The nasal vowel space has been reduced in two ways:

1. It has been reduced with regard to the number of vowels in the system (from five nasal vowels in the 11th century to three nasal vowels in modern NMF). This is consistent with observations that there is a tendency for the number of contrastive nasal vowels in a language to be less than the number of contrastive oral vowels (Beddor, 1982; Hajek, 1997).

2. It has been reduced with regard to the overall frequency range of the system (F1 is raised and F2 is lowered,

generally), resulting in a more compact acoustic space. This is consistent with the acoustic predictions of nasalization detailed in 2.1.1.

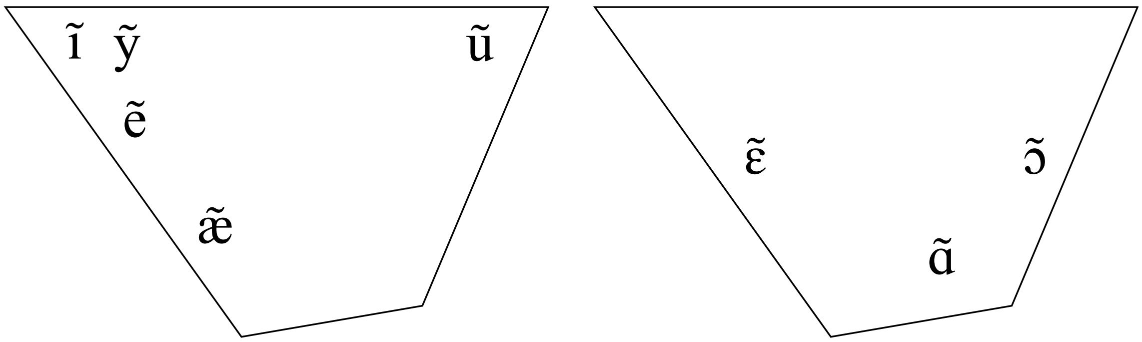


Figure 8.1: 11th century French nasal vowel space (left) and modern NMF nasal vowel space (right).

Secondly, the mergers of acoustic neighbors are also predicted by some of the acoustic effects of nasalization. Specifically, the merger of [ɛ̃] and [æ̃] (to [æ̃]) is consistent with the centralization of F1 due to nasalization, as well as the widening of the F1 bandwidth, which would lead to even further ambiguity of the F1 frequencies of these two acoustic neighbors. Additionally, the merger of [ɛ̃] and [œ̃] (to [ɛ̃]) can be explained not necessarily by the effect of nasalization on formant frequencies, but by its effect on formant bandwidths. In this case, the widening of the F2 bandwidth would lead to ambiguity in the distinct F2 frequencies of these two acoustic neighbors. In summary, the diachronic articulatory reduction of the nasal vowel space in French, with regard to both the total number of vowels and F1/F2 frequencies of the vowels, is consistent with predictions for a number of the acoustic effects of nasalization on the vowel space. Moreover, it is likely that the counter-clockwise chain shift in the realizations of the NMF nasal vowels was initiated by the lowering and merging of the front nasal vowels, resulting in a push chain-shift in the nasal vowel system. Once more, this evidence suggests that these diachronic articulatory changes are due to misperception by the listener—followed by subsequent articulatory modification—rather than by mere coincidence. In other words, the diachronic change of the nasal vowels of French can be explained—at least, in part—by the inherent characteristics of vowel nasality rather than by circumstances that are specific to the evolutionary development of French. Contrary to this view, Sampson (1999, p. 1) claims that the diachronic developments of the nasal vowel system of French "have arisen from exceptional circumstances rather than from some general guiding principle of change", and that the overall findings for nasal vowel systems in Romance do not provide clear support for the centralization of the vowel space observed in French being a universal tendency, citing the perseverance of high nasal vowels in Portuguese and Sardinian, for example (Sampson, 1999, p. 342). However, I would argue that the historical evolution of the nasal vowel space in French does represent a "guiding principle of change" or, rather, a tendency which is inherent to the nature of nasalization itself. Of course, this tendency is not a linguistic inevitability, an end-state to which all nasal vowel systems are destined to arrive; the existence of counter-examples is proof enough of the error in making that assumption (e.g., high nasal vowels in Portuguese and Sardinian). Rather, velo-pharyngeal coupling centralizes the acoustic space along the F1 dimension and lowers F2, and due to listener-based misperception of the articulatory source of these acoustic changes which is likely to occur, the natural consequence is the generation of a propensity for the oral articulation of nasal vowels to evolve in a way which enhances these acoustic effects. From the results observed here, French—and, more specifically, the NMF dialect—simply represents an example of this propensity coming to fruition.

8.3.1 Predictions for the NMF nasal vowel system

Taking into account the changes in vowel quality observed the historical record of the nasal vowel system in French, the results from this study suggest that a systematic sound change is still occurring with regard to the realization of the nasal vowels of NMF. Figure 8.2 displays the NMF nasal vowel system as it is traditionally represented using IPA symbols in the left-most subfigure, as well as the transcription of the NMF nasal vowel system that I propose, in light of the results from this study, in the right-most subfigure. A comparison of these two representations of the nasal vowel system reveals that the realizations of these three nasal vowels are continuing along a path which is consistent with a counter-clockwise chain shift: [ɛ̃] has continued to lower and retract to [ɐ̃], while [ɑ̃] has risen to [ɔ̝̃], and [ɔ̃] has risen to [õ̝] (for the majority of the speakers in this study). References to the manifestation of this chain shift in NMF (see 1.2.2 and 2.2.3) most commonly describe /ɛ̃/ as realized as [æ̃], /ɑ̃/ as realized as [ɑ̝̃], and /ɔ̃/ as realized as [õ]. Since the speakers in the current study are all young adults, the discrepancy between the common reference to the realizations of the nasal vowel chain shift and the findings observed in this study suggest that this counter-clockwise chain shift has continued to evolve, and that the realizations have progressed even farther in the speech of younger French speakers (at least in the speech of the young adult female speakers studied here).

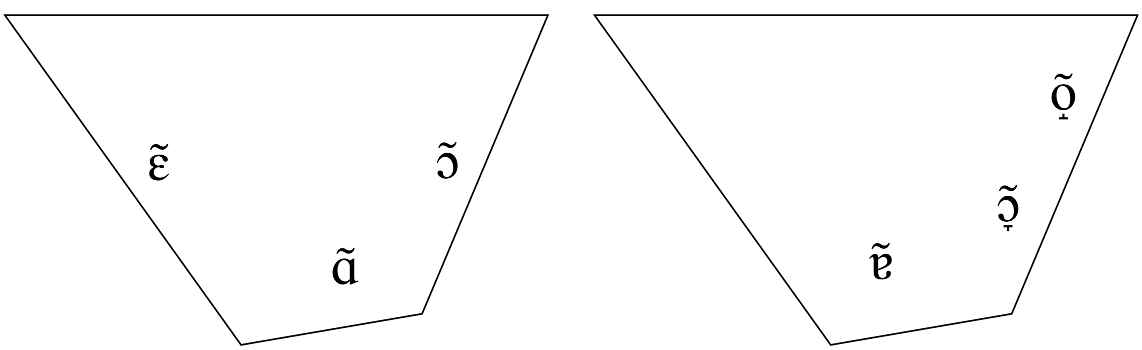


Figure 8.2: Traditional IPA transcription of NMF nasal vowel space (left) and NMF nasal vowel space realization observed in the current study (right).

If this chain shift continues along the same path that it has taken until now, there are certain predictions that we can make regarding the possible future realizations of the nasal vowels in NMF. If the nasal vowel system follows the same course of evolution, we can predict that [ɐ̃] (e.g., *pain* [pɐ̃]) will continue to retract to [ɑ̃], that [ɔ̝̃] (e.g., *paon* [pɔ̝̃]) will continue to raise to [õ]), and that [õ̞] (e.g., *pont* [põ̞]) will continue to raise to [ũ]. The stability of [ũ] is problematic, however, given the predictions concerning the F1-related acoustic effect of nasalization and its interaction with the perception of vowel height, as well as the aforementioned historical evidence. Since [ũ] is a high vowel (with a low F1), the effect of nasalization on F1 is to raise the frequency. Thus, the tendency would be for [ũ] to be eventually lowered back to [õ] (as previously happened to [ũ] in the 13th century). However, this lowering would be problematic if [ɔ̝̃] (e.g., *paon* [pɔ̝̃]) does, indeed, continue to raise to [õ]. The resulting consequence could either be for the two vowels to merge (in favor of [õ], due to the F1-related acoustic effect of nasalization creating a tendency for high vowels to lower) or for [ũ] to be fronted towards a realization closer to [ʉ̃]. The latter prediction is more likely, perhaps, given previous occurrence of /u/ fronting in the history of French. Alternatively, the chain shift could simply cease to progress, with the realizations [ɑ̃], [õ], and [ũ] remaining somewhat stable for an indeterminate period of time. In this latter case, the importance of maintaining phonemic distinctions would override the tendency for [ũ] to be lowered to [õ] due to the acoustic raising of F1 under the effect of nasalization[4].

[4] As an aside, this problem of instability may be the reason why [ɔ̃]—or, rather, [õ̞], as the case seems to be—has displayed the most acoustic and articulatory variability in this study, since it is a relatively high vowel: the ambiguity of the source of F1 is predicted to be especially apparent with relatively high and low nasal vowels.

Chapter 9

Conclusion

This study includes acoustic and articulatory data from 11 Northern Metropolitan French (NMF) and two Quebecois French (QF) young adult female speakers. I performed articulatory and acoustic analyses on, and made comparisons between, the productions of oral and nasal vowel counterparts /a/-/ɑ̃/, /ɛ/-/ɛ̃/, and /o/-/ɔ̃/ in both dialects. Lingual and labial articulatory data were collected using the Carstens AG500 electromagnetic articulography (EMA) system at the University of Illinois (for three NMF speakers and both QF speakers), and using the Carstens AG200 electromagnetic midsagittal articulography (EMMA) system at Université Stendhal-Grenoble 3. Sensors were adhered to the tongue at three equal intervals along the midline, in order to capture position data related to the tongue tip, tongue midpoint, and tongue back. Labial articulatory measures differed for the two systems, with 2-D and 3-D measurements for data collected with the AG500, and 2-D measurements for data collected with the AG200. For speakers recorded with the AG500 system, four sensors were adhered around the mouth: the upper lip, lower lip, and both corners of the mouth. Using these sensors, I obtained measurements of the area of the polygon created by the positions of these four sensors, the euclidean distance between the upper and lower lip, and the horizontal protrusion of the upper and lower lip. For speakers recorded with the AG200 system, two sensors were adhered to the upper lip and the lower lip. Using these sensors, I obtained measurements of the euclidean distance between the upper and lower lip, as well as the horizontal protrusion of the upper and lower lip. The articulatory data were time-synchronized with acoustic data and nasal flow data obtained via a nasal mask and pressure transducer. These nasal flow data were recorded in order to confirm the presence or absence of nasal flow in the vowel productions. To my knowledge, this is a methodology which had never before been implemented in or out of the field of speech research before its implementation by our research group at the University of Illinois (Carignan et al., 2011; Shosted et al., 2012a).

Nasal vowels, by definition, are characterized by some degree of coupling between the nasal and oral cavities (i.e., velo-pharyngeal coupling, commonly referred to as "nasalization"). It is well known that nasalization significantly alters the acoustic spectrum of vowels. However, recent work suggests that lingual and labial configurations may differ for oral versus phonetically nasal and phonemically nasal vowels. Furthermore, some of the formant-frequency-related acoustic effects of nasalization (namely, changes to F1 and F2 frequencies) can also be achieved by changes to the configuration of the oral tract. By studying the position and movement of the tongue and lips during oral and nasal vowels, we are able to separate the effects of velo-pharyngeal coupling and oral articulatory configurations on the acoustic output of the vocal tract. Accordingly, we can predict four types of differences between oral/nasal vowel pairs in which the nasal vowel manifests (after Shosted et al. (2012a)):

- (Type-I): No acoustic or oral articulatory difference (with respect to the oral vowel).
- (Type-II): Oral articulatory difference with no acoustic difference.
- (Type-III): Acoustic difference with no articulatory difference.
- (Type-IV): Both articulatory and acoustic differences.

The results from this study suggest the occurrence of Type-II, Type-III, and Type-IV differences in NMF. Additionally, the results suggest the occurrence of Type-III and Type-IV differences in QF. The occurrence of Type-IV differences supports findings from previous research which suggest that the nasal vowels in these two French dialects differ not only with respect to the relative presence or absence of velo-pharyngeal coupling, but also with respect to their oral articulatory configurations. The occurrence of Type-II differences suggests that oral articulation can "attenuate", or counteract, the formant-frequency-related acoustic effects of nasalization (in effect, cancelling the formant-frequency-related acoustic effects, yielding no acoustic difference between a nasal vowel and its oral counterpart with regard to F1 and F2). The occurrence of Type-III differences suggests that the acoustic distinction of these vowels is one which is due to velo-pharyngeal coupling alone.

Results for NMF confirm some well-known observations about nasal vowels in this variety of French, and also bring to light new findings. My results confirm earlier reports of a counter-clockwise shift in the realizations of the nasal vowels /ɛ̃/, /ɑ̃/, and /ɔ̃/. However, the results from the current study suggest that the realizations of these vowels are [ɐ̃] (e.g., *pain* [pɐ̃]), [ɔ̝̃] (e.g., *paon* [pɔ̝̃]), and [õ̞] (e.g., *pont* [põ̞]), respectively, rather than the conventional transcriptions [ɛ̃], [ɑ̃], and [ɔ̃]. I interpret these findings as being indicative of evidence that this counter-clockwise chain shift is an on-going sound change in NMF. Additionally, the results from this study suggest that the oral articulations of the nasal vowels have evolved over time to "enhance", or reinforce, the acoustic effect of velo-pharyngeal coupling on F1 and F2 frequencies: centralization along the F1 dimension, and a lowering of F2. Nevertheless, I have observed inter-speaker variability with regard to the manner and degree of these oral articulatory modifications, with more or less variability depending upon the vowel pair: [ɛ]-[ɛ̃] has the least amount of inter-speaker variability, [a]-[ɑ̃] has a moderate amount, and [o]-[ɔ̃] has a large amount. These findings suggest that the articulatory realization of the oral/nasal vowel distinction in NMF is both vowel- and speaker-dependent, and that the realization of distinctive nasality in NMF nasal vowels is a combination of velo-pharyngeal coupling and oral articulatory configurations, rather than the traditional view that nasal vowels differ from their oral counterparts only with respect to the presence or absence of velo-pharyngeal coupling.

Results for QF confirm some well-known observations about nasal vowels in this variety of French, and also bring to light new findings. My results confirm earlier reports of diphthongized realizations of QF nasal vowels and the existence of nasal codas, referred to as "nasal appendices" (*appendices nasales*; see Léon and Carton (1983)). These findings partially lend support to Walker (1984, p. 81)'s description of the Canadian French nasal vowel system. However, I do not find compelling evidence which suggests a clockwise shift in the realizations of QF nasal vowels compared to the NMF system: although [ɔ̃] is indeed lowered toward the acoustic space occupied by [ɑ̃], [ɑ̃] does not—in its turn—manifest a realization indicative of a clockwise chain shift. Furthermore, [ɛ̃] is produced with a rising, fronting dynamic lingual gesture, a realization which is consistent with a clockwise shift only with regard to its dynamic articulatory character. The beginning of the vowel, however, is not fronted and raised compared to [ɛ]. I can therefore only partially confirm the existence of a clockwise chain shift in the QF dialect, as much of the evidence from this study suggests otherwise.

With regard to the possible existence of a nasal coda in QF, the evidence comes primarily from the production of [ɛ̃]. This evidence is three-fold: aerodynamically, the peak of the nasal flow often did not occur during the vowel itself, but rather following the vowel. This is consistent with aerodynamic evidence from Delvaux (2006), who finds that nasalization is temporally delayed in QF nasal vowels. Articulatorily, this portion following the vowel is often characterized by a raised tongue back; the results suggest that this articulatory gesture includes contact with the palate, but substantiating the presence of this contact is beyond the scope of the present study. Acoustically, the amplitude during this closure portion was at a level which has been established using EPG data in Portuguese to be consistent with a nasal consonant, not a nasal vowel. This evidence suggests an oral vowel followed by a nasal consonant, which is a new finding, since based on Walker (1984, p. 81)'s description and Poiré et al. (2006)'s corpus data, these vowels are presumed to be nasal. As opposed to Poiré et al. (2006, p. 283), who conclude that the nasal coda in French spoken in Ontario is "probably not a case of a [phonological] nasal consonant", my findings suggest that it is indeed a consonant. If, indeed, QF manifests some nasal vowels with a post-vocalic nasal consonant, this phonetic phenomenon may provide important insight into the phonological status of nasal vowels in this variety of French, from a comparative point of view. There is some evidence which suggests the existence of a process wherein the diachronic deletion of nasal coda consonants reverses, and the consonants reemerge (sometimes referred to as 'restoration') after a nasal vowel (see Sampson (1999, p. 146, 150f., 207, 260) for cross-linguistic examples). This 'restored' nasal consonant may also have a variable place of articulation, sometimes based on the quality of the preceding vowel. Hajek (1991, p. 262) claims that this process may be more likely for high vowels, where a raised tongue dorsum during the articulation of a nasalized glide "facilitates contact between the raised tongue body and the lowered velum, resulting in the closure of the oral cavity." This phenomenon of nasal coda restoration has been posited for Southern French (Léon and Carton, 1983; Sampson, 1999), Brazilian Portuguese (Shosted, 2003, 2006, 2011) and, to a lesser extent, Hindi (Shosted, 2011). The evidence presented here for QF suggests that nasal coda restoration may exist in this variety of French, and that it is especially apparent in the realization of the high, front nasal /ɛ̃/.

Diphthongization is present only for the realizations of /ɛ̃/ and /ɔ̃/ for the two QF speakers studied here. With regard to the diphthong realization of /ɛ̃/, it is characterized by a fronting and raising of the tongue body. With regard to the diphthong realization of /ɔ̃/, it is characterized by a very slight retraction of the tongue body, but primarily by dynamic lip rounding and protrusion. Crucially, these diphthong manifestations are not reserved to closed syllables (i.e., when the nasal vowel is followed by a tautosyllabic obstruent). This also confirms previous articulatory findings from Charbonneau (1971); Delvaux (2006), but is contrary to the description of QF nasal vowels by Walker (1984).

In light of these results, it is clear that a traditional analysis of vowel nasalization in both QF and NMF as a process of simply coupling the nasal cavity to an unaltered oral tract configuration needs further consideration. Without question, speakers of both dialects have distinct oral articulatory configurations for nasal and oral "counterparts". In other words, the articulatory strategy for the nasal phonemic distinction is one which involves not only a lowering of the velum, but also gestural interaction of the tongue and/or lips (and, possibly, the pharynx; see Appendix C). In the light of motor equivalence, which is "the capacity of a motor system to achieve the same end-product with considerable variation in the individual components that contribute to that output" (Hughes and Abbs, 1976, p. 199), these results suggest that multiple articulatory variables are used to achieve a singular acoustic output, and that these separate input variables can be used in conjunction with one another in varying degrees to reach this goal. These findings support the hypothesis, arising from a growing body of work (Arai, 2004; Carignan et al., 2011, accepted; Engwall et al., 2006; Rong and Kuehn, 2010; Shosted et al., 2012a), that the acoustic characteristics of nasalization can be attained by an assortment of speech gestures that include, but are not limited to, the coupling of the nasal cavity to the oro-pharyngeal cavity via the opening of the velo-pharyngeal port. Moreover, 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 (1986, 1990); Liberman and Mattingly (1985)).

Appendices

Appendix A

Word lists

Word list A (QF01)

Onset C	/a/	/ɑ̃/	/ɛ/	/ɛ̃/	/o/	/ɔ̃/
/p/	*pas* 'step'	*paon* 'peacock'	*paix* 'peace'	*pain* 'bread'	*pot* 'jar'	*pont* 'bridge'
/t/	*ta* 'your'	*temps* 'weather'	*tait* '(it) keeps quiet'	*teint* 'complexion'	*tôt* 'early'	*thon* 'tuna'
/k/	*cas* 'case'	*quand* 'when'	*quai* 'platform'	*co.quin* 'scoundrel, rascal'	*co.co* 'coconut'	*con* 'idiot, jerk'
/b/	*bas* 'low'	*banc* 'bench'	*baie* 'berry'	*bain* 'bath'	*bot* 'club (foot)'	*bon* 'good'
/d/	*da.da* 'hobby, pet subject'	*dans* 'in'	*des* 'some'	*daim* 'deer'	*dos* 'back'	*don* 'gift'
/g/	*gars* 'guy, lad'	*gant* 'glove'	*gai* 'happy'	*gain* 'earnings'	*car.go* 'freighter'	*gond* 'hinge'
/s/	*sa* 'his/her (f.)'	*sang* 'blood'	*c'est* 'it is'	*saint* 'saint'	*sot* 'idiot'	*son* 'sound'
/z/	*Za.za* 'Zaza'	*fai.san* 'pheasant'	*fu.sait* '(it) burst out'	*fu.sain* 'charcoal'	*zo.zo* 'nit(wit)'	*fai.sons* '(we) do'
/f/	*fa* 'F (musical note)'	*faon* 'fawn'	*fait* 'fait'	*fin* 'end'	*faux* 'false'	*font* '(they) do'
/v/	*va* 'go'	*vent* 'wind'	*vais* '(I) go'	*vin* 'wine'	*vos* 'your (plural)'	*vont* '(they) go'
/ʃ/	*chat* 'cat'	*chant* 'singing, song'	*lâ.chait* '(it) let go'	*ma.chin* 'thing'	*chaud* 'hot'	*man.chon* 'muff, sleeve'
/ʒ/	*dé.jà* 'already'	*gens* 'people'	*geai* 'jay(bird)'	*geint* '(it) wipes'	*Jo.jo* 'Jojo'	*jonc* 'rush'
/l/	*là* 'there'	*lent* 'slow'	*laid* 'ugly'	*lin* 'linen'	*vé.lo* 'bicycle'	*long* 'long'
/ʀ/	*rat* 'rat'	*rend* '(it) gives back'	*rai* 'ray'	*rein* 'kidney'	*rot* 'burp, belch'	*rond* 'round'

Word list B (QF02, NMF01)

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

Word list C (NMF02-03)

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

Word list D (NMF04-13)

Onset C	/a/	/ɑ̃/	/ɛ/	/ɛ̃/	/o/	/ɔ̃/
/p/	*pa.pa* ‘daddy’	*paon* ‘peacock’	*pep.si* ‘Pepsi’	*pain* ‘bread’	*pot* ‘jar’	*pont* ‘bridge’
/t/	*ta* ‘your’	*temps* ‘weather’	*taie* ‘cover’	*teint* ‘complexion’	*tôt* ‘early’	*thon* ‘tuna’
/k/	*ca.ca* ‘poop’	*quand* ‘when’	*cep.stral* ‘cepstral’	*co.quin* ‘scoundrel, rascal’	*co.co* ‘coconut’	*con* ‘idiot, jerk’

Appendix B

Speaker background

NMF01

Sex: female

Age: 32

Place of birth: Privas, France

Parents' origin: Italy

NMF02

Sex: female

Age: ?

Place of birth: ?

Parents' origin: ?

NMF03

Sex: female

Age: ?

Place of birth: ?

Parents' origin: ?

NMF04

Sex: female

Age: 26

Place of birth: Douai, France

Parents' origin: (north) France

NMF05

Sex: female

Age: 30

Place of birth: Chambéry, France

Parents' origin: Turkey

NMF06

Sex: female

Age: 25

Place of birth: Pontarlier, France

Parents' origin: le Doubs, France — Argentina (never spoke in Spanish to NMF06)

NMF07

Sex: female

Age: 26

Place of birth: Douai, France

Parents' origin: Douai, France

NMF08

Sex: female

Age: 25

Place of birth: Paris

Parents' origin: Paris, France — Wervicq-Sud

NMF09

Sex: female

Age: 25

Place of birth: Pontarlier, France

Parents' origin: France — Argentina

NMF10

Sex: female

Age: 20

Place of birth: Lyon, France

Parents’ origin: Normandy, France — Burgundy, France

NMF11

Sex: female

Age: 20

Place of birth: Livry-Gargan, France

Parents’ origin: Clichy Sous-Bois, France — Alsace, France

NMF12

Sex: female

Age: 20

Place of birth: Decines, France

Parents’ origin: (south-west) France

NMF13

Sex: female

Age: 40

Place of birth: Lima, Peru (L1: French, raised in Grenoble, France)

Parents’ origin: Grenoble, France

NMF14 (rtMRI)

Sex: female

Age: 27

Place of birth: Paris 13, Ile-de-France

Parents’ origin: Paris, France — Saint-Etienne, France (living in Paris for the past 35 years)

QF01

Sex: female

Age: 26

Place of birth: Abitibi-Témiscamingue, Québec, Canada

Parents' origin: Abitibi-Témiscamingue, Québec, Canada

QF02

Sex: female

Age: 31

Place of birth: Alma, Québec, Canada

Parents' origin: St-Ambroise, Québec, Canada — Riviére-du-Loup, Québec, Canada

Appendix C

Real-time MRI study

C.1 Preliminary results on pharyngeal aperture as an enhancing oral articulation in NMF nasal vowels

The following preliminary real-time MRI (rtMRI) study was conceived after reviewing the articulatory and acoustic results from this dissertation, in order to investigate the possibility of pharyngealization playing a role in the acoustic realizations of the oral/nasal vowel distinction in NMF. Thus, the study presented here was not part of the original methodology of this larger work, and the creation of this rtMRI experiment involves an *ad hoc* solution for attempting to explain some of the results presented in 6. As such, I believe that it would be incongruous to include the methodology and results from this preliminary study along with those of the primary study presented above. Therefore, I made the decision to present the methodology, results, and discussion of this rtMRI study here as an appendix. This study will also appear as a proceedings article from INTERSPEECH 2013 (Carignan et al., accepted).

In 6.2 it was shown that seven of the 11 NMF speakers manifest an F1 frequency for nasal [ɔ̃] compared to the oral counterpart [o] which is lower than predicted by the lingual configuration for this vowel. Crucially, this lower F1 frequency is not predicted by the acoustic centralization of F1, either, due to the fact that [ɔ̃] is not a low vowel (see 2.1.1). In Carignan et al. (accepted), I have therefore proceeded further and hypothesized that this articulatory/acoustic discrepancy may be explained by another articulatory configuration which is known to change F1 frequency: modification to the size of the pharynx (Stevens, 1998, *inter alia)*. Given the proximity to a node in the velocity wave of F1, a constriction in the lower pharynx is predicted to raise F1, while an expansion is predicted to lower F1. Therefore, I also investigated the size of pharyngeal aperture for the productions of [ɔ̃] and [o], using rtMRI with another NMF speaker (NMF14), since the pharynx is an area of the vocal tract which is prohibitively inaccessible using other speech research methodologies. Given the F1 lowering found for [ɔ̃] which was not accounted for by the other articulatory configurations measured using EMA, I hypothesize to find evidence of pharyngeal expansion (predicted to lower F1) for [ɔ̃] compared to [o].

The word list which was used contained the six target words from list D, described in 4.2. With the order randomized, phrases were presented to the speaker in the 3T Siemens Trio MRI scanner at the Beckman Institute for Advanced Science and Technology, at the University of Illinois. The speaker was instructed to repeat the phrase at a normal rate, until the noise of the scanner ceased (about 5 minutes). Due to variation in speaking rate and the start of speech after scanner initialization, an unequal number of tokens was collected for each lexical item: *papa* (101), *paon* (123), *paix* (104), *pain* (101), *pôt* (105), and *pont* (101). Structural rt-MR images were obtained using partially separable functions (Fu et al., 2012; Liang, 2007), allowing for a relatively high frame rate during multi-slice imaging. Specifically, we achieve around 25 fps for each of four simultaneous slices with this method. A slice was placed at each of the following four locations in the vocal tract; the position and orientation of each slice was selected during restful breathing:

1. Oral cavity (OC): A coronal slice placed at the horizontal midpoint of the tongue body, located ≈ 2.6 cm from the tongue tip.

2. Velopharynx (VP): An oblique slice, rotated $\approx 45°$ from the transverse plane, running through the VP port.

3. Mediopharynx (MP): A transverse slice placed in the medio-pharynx, located ≈ 5.2 cm above the glottis.

4. Lower pharynx (LP): A transverse slice placed in the lower pharynx, located at the epiglottis, ≈ 2.6 cm above the glottis.

The placement and orientation of these slices is illustrated in the left image in Figure C.1, with an example of a resulting LP slice in the right image. Image resolution of each slice is 128×128 voxels, and the resolution of each voxel is 2.2 mm×2.2 mm×8.0 mm (through-plane depth).

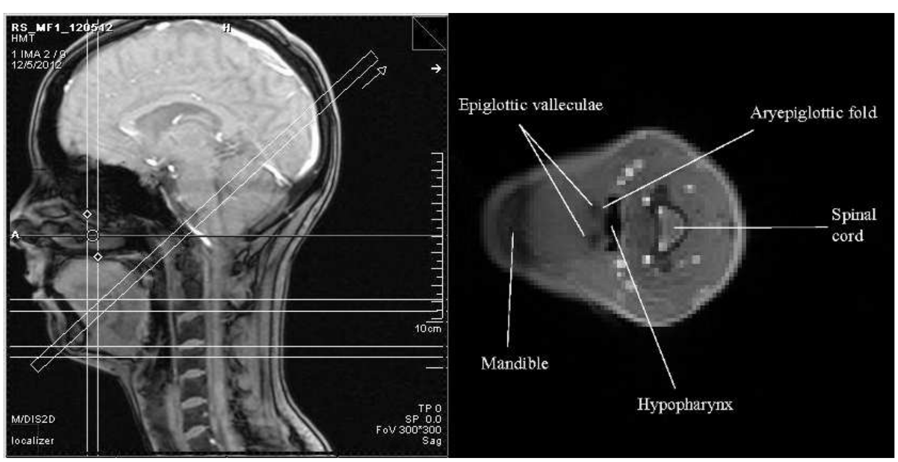


Figure C.1: Placement and orientation of MRI planes (left), and an example of the axial MRI slice used to measure hypo-pharyngeal aperture (right).

Vocal tract apertures were calculated by further developing methods used in Shosted et al. (2012b). Several

OC slices were examined in GIMP 2.8.2[1] as cavity references: the edges of the air/tissue boundary were manually selected and confirmed by the first and second authors. The average intensity of the voxels in the selected cavity was measured in 8 bpp (bits per pixel) space (values 0–255), and the upper-end of the range of these values was logged as a threshold, τ. τ was used to convert each MR image in Matlab 2012a to a two-value image space, with each voxel having the intensity i: for any voxel with $i \leq \tau$, the voxel was changed to black; for any voxel with $i > \tau$, the voxel was converted to white. An example of applying this technique is shown in Figure C.2. A region of interest (ROI) surrounding the cavity of interest (i.e., oral cavity, velo-pharyngeal port, medio-pharynx, lower pharynx) was selected after examination of various images. Due to slight variations between recordings with regard to the position of NMF14's head inside the MRI scanner, the placement of this box was shifted as needed by positioning the box in the same location in each recording with reference to static structures located in each of the six images (usually bone). For each MR image, the number of black pixels in the ROI was summed and multiplied by 4.84, the squared in-plane voxel resolution. The result is a time-varying function of the aperture area. An example of this time-varying function is given in Figure C.3 for the LP slice during three repetitions of an utterance. The test vowels were segmented manually using the spectrogram derived from a synchronized, noise-cancelled audio recording. Using the time points of this segmentation, the average aperture area (AAA) for each vowel was calculated by slice.

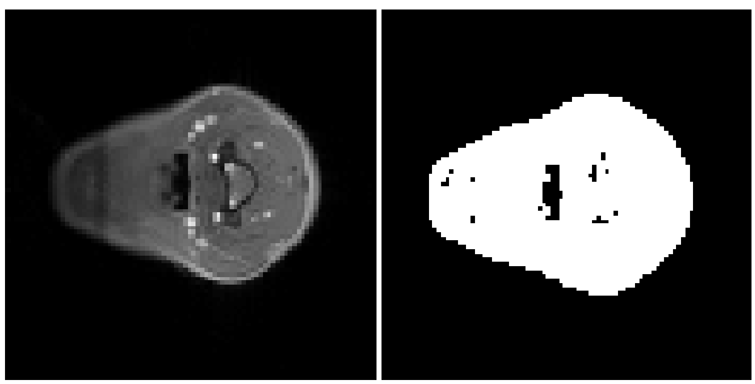


Figure C.2: Example of threshold conversion: MRI image of [ɔ̃] (left) and conversion using threshold (right).

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

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

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

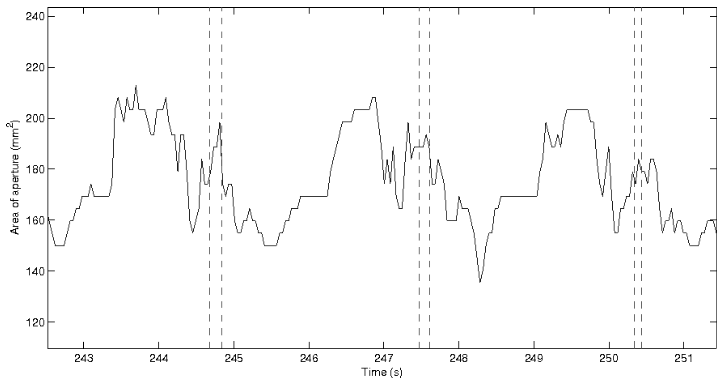


Figure C.3: AAA function of LP slice for three repetitions of *Il retape pont parfois*. Dashed lines delineate the target vowels.

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

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

With regard to the OC slice, the AAA of [ɑ̃] is smaller than that of [a], suggesting a smaller oral cavity due to a higher lingual position for [ɑ̃]. The OC AAA of [ɛ̃] is greater than that of [ɛ], suggesting a larger oral cavity due to a lower lingual position for [ɛ̃]. The OC AAA of [ɔ̃] is smaller than that of [o], suggesting a smaller oral cavity due to a higher lingual position for [ɔ̃]. These results are consistent with the counter-clockwise chain shift in the acoustic realization of nasal vowels previously described for NMF (Fónagy, 1989; Hansen, 2001b; Maddieson, 1984; Malderez, 1991) and summarized in 6.4.

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

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

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

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

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

The F1 frequency of [a]—a relatively low vowel with a relatively high F1 frequency—is predicted to lower under the effects of nasalization. Additionally, [ɑ̃] manifested smaller OC AAA (interpreted as higher tongue position) than

[a], which is also predicted to result in a lower F1 for [ɑ̃] compared to [a]. Furthermore, [ɑ̃] manifested greater LP AAA than [a], which is also predicted to result in a lower F1 for [ɑ̃] compared to [a]. Therefore, there are at least two oral articulatory configurations observed here which are predicted to enhance the VP-induced lowering of F1 for [ɑ̃], traditionally claimed to be due to VP coupling alone.

The F1 frequency of [ɛ]—a relatively high vowel[2] with a relatively low F1 frequency—is predicted to rise under the effects of nasalization due to centralization along the F1 dimension. Additionally, [ɛ̃] manifested larger OC AAA (interpreted as a lower tongue position) than [ɛ], which is also predicted to result in a higher F1 for [ɛ̃] compared to [ɛ]. Furthermore, [ɛ̃] manifested smaller LP AAA than [ɛ], which is also predicted to result in a higher F1 for [ɛ̃] compared to [ɛ]. Therefore, there are at least two oral articulatory configurations observed here which are predicted to enhance the VP-induced raising of F1 for [ɛ̃], traditionally claimed to be due to VP coupling alone.

There are (at least) three articulatory variables which are predicted to change the F2 frequency of nasal and nasalized vowels: VP coupling, tongue "backness" (i.e., posteriority), and labial aperture. VP coupling is predicted to lower F2 frequency for all vowels. Tongue backness lowers F2 frequency, as well. Finally, labial constriction also lowers formant frequencies, as mentioned earlier. We posit an additional articulatory mechanism which is predicted to change the F2 frequency of nasal vowels. The lowering of the soft palate creates a 'velic' constriction (with the velum lowering towards the tongue dorsum rather than the tongue dorsum rising towards the velum (Shosted, 2006, p. 52)). Shosted et al. (2012a, p. 462) argue that this articulation also lowers F2. We regard this as a secondary but significant formant-frequency-related acoustic effect of nasalization, one that has perhaps been overlooked in the literature until recently. The acoustic–perceptual outcome of VP opening is most often considered in terms of the contributions of the nasal cavity and sinuses. However, the lowered velum itself creates a constriction in the oro-pharyngeal tube that also affects the acoustics. Moreover, the ubiquitously lower MP AAA values for the nasal vowels compared to their oral congeners suggest that tongue retraction is also used to enhance the F2-related acoustic effect of nasalization for the nasal vowels of NMF.

Based on the modeling work by Feng and Castelli (1996); Serrurier and Badin (2008) and perception work by Delvaux (2009), it is hypothesized that F2 lowers for all of the nasal vowels studied here. Additionally, all nasal vowels were observed to manifest a smaller MP AAA (interpreted as a more retracted tongue position) than their oral congeners, an articulation which is also predicted to result in a lower F2 for the nasal vowels. Moreover, the lowering of the velum during VP coupling creates a velic constriction and is also predicted to result in a lower F2 for the nasal vowels. Therefore, there are at least two oral articulatory configurations which are predicted to enhance the VP-induced lowering of F2 that is increasingly observed in the literature (Delvaux, 2009; Feng and Castelli, 1996; Serrurier and Badin, 2008).

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

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