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The aerodynamics of nasalization in French

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Abstract

Nasalization in French involves a complex interplay between several phonetic and phonological factors that have been, for the most part, investigated separately over the last 40 years. The present study provides a detailed account of the aerodynamics of French nasalization from eight Belgian French speakers reading word lists. Patterns of tautosyllabic nasal coarticulation are investigated in CṼ, NṼ, CṼC, CṼ.CV, CV, NV, (C)VN, and NVN items, comparing different vowel and consonant types. Dependent variables involve temporal measures of both the extent of nasalization and its starting point relative to the oral–nasal boundary, and average flow rates across the acoustically defined segments. Results confirm previous findings that carryover nasalization is more extensive than anticipatory nasalization in French for both vowels and consonants. We further show that the temporal extent of intra-syllabic nasal coarticulatory airflow varies across vowel height and consonant manner of articulation and voicing. Various factors are considered in accounting for this variation.

Keywords: Aerodynamics; Coarticulation; French; Nasalization; Nasal airflow; Vowel

1. Introduction

Nasals and nasalization remain topics of considerable interest in phonetics and laboratory phonology because they involve a complex interplay between various phonetic and phonological factors and, within phonetics, between all the phases of speech production and speech perception. A basic premise underlying the current aerodynamic study of French nasalization is that a detailed account of the phonetic patterns can only be achieved by considering a large number of phonetic and phonological factors in interaction.

The exact way in which nasalization is phonetically realized not only depends on phonological specifications for the [nasal] feature, but also on other features within the segment (e.g. vowel height, consonant voicing), and on the combination with other segments in the speech stream (i.e. coarticulation). The details of nasal implementation can also be influenced by the phonemic inventory of the language (Ladefoged, 1982; Martinet,

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1955) and by prosodic effects (Fougeron, 2001; Gordon, 1996; Hajek, 1997; Krakow, 1989; Vaissière, 1988). These explanatory factors have been separately investigated in a number of languages. For example, there is a large body of research dedicated to the covariation between tongue height and velar height in oral vowel phonemes (Al-Bamerni, 1983; Bell-Berti & Krakow, 1991; Bell-Berti, Baer, Harris, & Niimi, 1979; Clumeck, 1976; Fritzell, 1969; Henderson, 1984; Künzel, 1977; Moll, 1962; Ohala, 1971; Whalen & Beddor, 1989). Additionally, many studies have focused on the patterns of nasal coarticulation in a variety of languages (Beddor, 2007; Bell-Berti & Harris, 1981; Benguerel, Hirose, Sawashima, & Ushijima, 1977a, 1997b; Clumeck, 1976; Cohn, 1990; Moll & Daniloff, 1971; Solé, 1995; Solé & Ohala, 1991; Ushijima & Sawashima, 1972). Nonetheless, relatively little is known about the interaction between these main factors in a given language. Are high and low oral vowels similarly affected by nasal coarticulation? Are these coarticulatory effects influenced by whether the language has contrastive nasalization for vowels? And might the interaction be affected by the size of the vowel inventory? The present study addresses these issues by investigating the aerodynamic parameters of tautosyllabic nasalization in French.

Aerodynamic data are of considerable interest in nasal studies for several reasons. First, it is a non-invasive technique that permits collection of larger datasets than in many other production studies. Second, aerodynamic parameters provide fine-grained information on both spatial and temporal aspects of nasalization, which is necessary to study coarticulation. Third, the aerodynamic phase provides a valuable viewpoint on nasalization processes because it is intermediary between the articulation and the acoustics. Nasal airflow is only indirectly related to the degree of velopharyngeal opening: for a given soft palate height nasal airflow may vary due to differences in oral configuration (Krakow & Huffman, 1993; Warren, Dalston, Trier, & Holder, 1985; Warren, Dalston, & Mayo, 1993). But the velum gesture itself is not monotonically related to the degree of acoustic nasalization. The spectral contribution of nasal cavities to overall acoustic output depends not only on coupling size (i.e. on velopharyngeal aperture), but also on the ratio of the acoustic masses of the oral to the nasal path (Stevens, 1998). It remains unclear whether the objects of speech perception are the articulatory gestures (here, the velopharyngeal opening gesture) as retrieved from the acoustic signal, or the acoustic events themselves (i.e. the degree of acoustic nasalization). In that sense, aerodynamic parameters may be considered as 'perception-neutral', and therefore constitute a valuable insight into the production of nasal vs. oral speech sounds.

French was selected as the focus of the study because it is of great interest for nasal studies. First, in French nasalization is contrastive for vowels as well as for consonants. Phonologically oral and nasal consonants and vowels occur in a wide range of contexts, permitting study of various nasal coarticulatory phenomena. Second, the language has a rich vowel inventory that includes 14 phonemes: /i, e, ɛ, a, ɔ, o, u, y, ø, œ, ə, ɛ̃, ɑ̃, ɔ̃/ (Fougeron & Smith, 1999).[1] Specifically, the language has four contrastive degrees of tongue height that permit a detailed analysis of the interaction between vowel height and nasalization. Third, the consonant inventory includes voiced and voiceless stops, fricatives and liquids of different places of articulation, which are expected to contribute to different patterns of nasal coarticulation.

1.1. Nasal coarticulation in French

There have been nearly as many techniques of investigation as there are production studies on French nasal coarticulation, from the phonological questionnaires used by Martinet (1945) to the electromagnetographic data collected by Rossato, Badin, and Bouaouni (2003); from acoustic transcriptions (Malécot & Metz, 1972), to nasographic traces (Clumeck, 1975, 1976), self-monitored phonological data (Dell, 1986), fiberoscopy (Benguerel et al., 1977a), electromyography (Benguerel et al., 1977b), (cine) radiography (Brichler-Labaeye, 1970; Botherel, Simon, Wioland, & Zerling, 1986; Rochette, 1973), and aerodynamics (Basset, Amelot, Vaissière, & Roubeau, 2001; Benguerel, 1974; Cohn, 1990).

[1] Since the status of /œ̃/ became increasingly marginal in the second half of the 20th century (Walter, 1994), standard (Parisian) French is now described as having three nasal vowels /ɛ̃, ɑ̃, ɔ̃/ (Fougeron & Smith, 1999). Although Belgian French is somewhat more conservative than standard French in terms of the disappearance of the contrast between /ɛ̃/ and /œ̃/ (Nève, 1984), nasal /œ̃/ (and oral vowels of corresponding height /œ, ø/) were not included in the corpus to be pronounced by the Belgian participants. Indeed, the low frequency of occurrence of /œ̃/ prevents it from appearing in most of the contexts selected for the present study: except for very rare words or proper nouns, there are no French words with the syllables /ʃœ̃/, /sœ̃/, /mœ̃/, /ʀœ̃/, etc.

One general finding across this body of work is the preeminence of carryover nasalization over anticipatory nasalization onto phonemically oral vowels and consonants. But this asymmetry remains unsatisfactorily documented despite the variety of studies on French nasalization. Even when specifically focusing on nasal coarticulation, articulatory and imaging studies collected data from a small number of speakers with limited data set due to the invasiveness of the techniques. In some cases, aspects of the methodology important to assessing the findings were only partially reported, such as corpus properties (Clumeck, 1975, 1976) or criteria for segmentation (Benguerel et al., 1977a, 1977b). Most of all, the aim of these studies was not to provide a precise quantification of the extent of coarticulation, so that illustrative traces across time were visually assessed with no further measurement (Benguerel et al., 1977a, 1977b; Cohn, 1990), or measurements were made in the middle of the segment only (Rossato et al., 2003). Although Basset et al. (2001) measured the temporal extent of anticipatory and carryover nasalization based on nasal airflow, they did not report information on the spatial extent of coarticulation, such as the maximal peak or average levels of oral and nasal airflow and volume; rather, coarticulatory nasalization was reported as soon as nasal airflow was greater than zero, even when airflow remained near zero for the major part of the segment. Moreover, the innovative comparison in that study between read and spontaneous speech—which proved non-significant—unfortunately resulted in a corpus that was limited and unbalanced regarding phonetic and prosodic context. Thus previous work provides important insights into French nasal coarticulation, yet leaves important questions unanswered, thereby serving as crucial underpinning for the current study. Of special interest is that in earlier work qualitative differences in nasal coarticulation were observed in relation to segment quality (i.e. vowel height, consonant manner of articulation), without systematic measures of nasal coarticulation across a wide range of segment types. Specific questions of interest are detailed below.

1.2. Vowels: nasalization and tongue height

One of the best documented phonetic factors influencing nasalization concerns the covariation between tongue height and velum height in phonologically oral vowels (Al-Bamerni, 1983; Bell-Berti et al., 1979; Brücke, 1856; Clumeck, 1976; Czermak, 1879; Fritzell, 1969; Henderson, 1984; Künzel, 1977; Moll, 1962; Ohala, 1971; Passavant, 1863). In oral contexts, high vowels are produced with higher velum and greater velopharyngeal closure force than low vowels (Bell-Berti, 1976; Bell-Berti & Krakow, 1991; Goto, 1977; Kuehn & Moon, 1998; Moon, Smith, Folkins, Lemke, & Gartlan, 1994). In nasal contexts, high vowels are generally realized with less velopharyngeal opening than low vowels (Al-Bamerni, 1983; Clumeck, 1976; Fritzell, 1969; Künzel, 1977; Moll, 1962; Ohala, 1971). Higher velum position and greater velopharyngeal closure force are achieved by the activation and the control of several muscles in addition to the *levator palatini* (Bell-Berti, 1973, 1980; Fritzell, 1969; Kuehn & Moon, 1998; Lubker, 1968). Ohala (1975) has proposed that the main reason for the covariation between velar height and tongue height is acoustic-perceptual. Acoustic studies show that a similar amount of coupling causes stronger acoustic effects on high than on non-high vowels (Fant, 1960; House and Stevens, 1956; Stevens, 1998). Perceptual studies confirmed that low vowels need a lower velum/greater amount of nasalization to be perceived as nasal (Beddor, 1993; Benguerel & Lafargue, 1981; Kingston & Macmillan, 1995; Macmillan, Kingston, Thorburn, Dickey, & Bartels, 1999; Maeda, 1993; Stevens, Fant, & Hawkins, 1987).

However, the articulatory covariation between tongue height and soft palate height has a number of exceptions, particularly in nasal contexts (Hajek, 1997; Shosted, 2006). A minority of the speakers and languages (e.g. Gujarati, Hindi) that were investigated in the production studies cited above did not exhibit differences in velopharyngeal opening between high vowels and non-high vowels (Al-Bamerni, 1983; Clumeck, 1976; Moll, 1962). In French in particular, the evidence is incomplete and somewhat conflicting. Nasographic studies showed differences between high, mid and low vowels, although they did not always reach significance, with high inter-speaker variation (Al-Bamerni, 1983; Clumeck, 1976). Articulatory studies showed that in nasal contexts the velum was lowered in phonologically oral high as well as low vowels in Ontario French (Bream, 1968) and North African French (Condax, Acson, Miki, & Sakoda, 1976). In standard French, Basset et al. (2001) found that the temporal extent of anticipatory nasal airflow was greater in phonologically oral high vowels, and that high and low vowels were both heavily affected by carryover nasalization. However, they regretted that "there was not enough data in the (…) study to establish a significant difference between the two vowel types" (2001, p. 91).

Thus, cross-language evidence indicates that the covariation between tongue height and velum height is not a universal pattern in coarticulation, suggesting that other phonetic factors intervene in the realization of oral vowels, particularly in nasal contexts. Languages that have distinctive vowel nasalization such as French may limit the amount of nasal coarticulation in both high and low vowels, in order to maintain the contrast between nasal and oral vowel phonemes (but see Gujarati and Hindi for languages with oral/nasal vowel contrasts where velopharyngeal opening is extensive for high back vowels; Al-Bamerni, 1983). Alternately, French may allow a high degree of nasal coarticulation in high oral vowels only since all French nasal vowels are low or mid-low: /ɛ̃, (œ̃), ɑ̃, ɔ̃/. In fact, the temporal extent of nasal coarticulation in French oral vowels needs to be reinvestigated in a systematic way. Phonologically oral vowels contrasting for tongue height should be systematically compared, in order to determine (i) whether the amount of nasalization in oral vowels is generally large or moderate and (ii) whether high vowels show as much nasalization as low vowels.

1.3. Consonants: nasalization and manner of articulation and voicing

The amount of contextual nasalization in French phonologically oral consonants is an under-investigated topic when compared to vowel nasalization. Investigating sequences of consonants, Rochette (1973) found that the transitional velic movement between a nasal consonant and a neighbouring oral consonant systematically occurred during the oral consonant, so that the nasal consonant was always fully nasalized. Other studies showed that most French oral consonants are nasalized in nasal vowel contexts, carryover nasalization being greater than anticipatory nasalization (Basset et al., 2001; Benguerel et al., 1977a; Cohn, 1990). However, results are divergent as to finer distinctions among oral consonants under nasal coarticulation, particularly in CṼ sequences. Cohn (1990, p. 98) reported that there was substantial anticipation only for liquids in her data, whereas nasal airflow was either simultaneous or delayed with respect to oral closure in both voiced and voiceless stops. The number of recorded fricatives was not sufficient for them to be included in the discussion. Basset et al. (2001) reported that voicing was the main factor explaining within-category variation in oral consonants nasalized by coarticulation, with voiced consonants being more nasalized (78% anticipation) than voiceless (34% anticipation) in CṼ sequences. Manner of articulation was not considered by the authors as a determinant although 38% of the stops vs. 77% of the fricatives were nasalized by anticipation.

The interaction between nasal coarticulation and consonant voicing and manner of articulation in French deserves to be fully assessed using an extensive aerodynamic data set, to be compared with the findings of Cohn (1990) and Basset et al. (2001). First, coarticulatory nasalization in fricatives should be disfavoured due to the phonetic requirements on the generation and sustaining of frication noise (Ohala, 1975; Ohala & Ohala, 1991; Solé, 2007a). However, Shosted (2006, 2007) showed that fricatives have significantly more integrated nasal airflow in nasal than oral contexts in French, English, and to a lesser extent in Brazilian Portuguese. The time course of nasal airflow requires a specific investigation, in order to confirm that the higher integrated nasal airflow reported by Shosted (2007) in these languages results from fricatives being nasalized at their onset/offset due to coarticulation. Second, the results from Basset et al. (2001) merit confirmation with a larger corpus, in particular the finding that, when nasalized, voiced stops are typically nasalized for 100% of their duration, both when following and preceding a nasal vowel. Although a small amount of nasalization may favour voicing in obstruents for aerodynamic as well as for acoustic-perceptual reasons (Solé, 2007b), oral stops are expected to have more anticipatory than carryover nasalization (and not to be entirely nasalized), since only prenasalization can occur without preventing the build up in pressure necessary for burst release (Ohala & Ohala, 1991).

1.4. The present study

The present study is an attempt to provide a detailed description of the aerodynamic parameters of French nasalization. This study is more complete than the previous ones on the topic in at least four respects: (i) eight speakers were recorded on a large corpus, which provides an extensive data set; (ii) oral airflow measurements are reported, since they can profitably complement nasal airflow data when comparing sounds differing in oral configuration; (iii) both the temporal and the spatial extent of nasalization were investigated; (iv) all segment types in French were considered: nasal vowels; low, low-mid, high-mid, high oral vowels from the front and back series; voiced and voiceless stops and fricatives from several places of articulation; liquids; and nasal consonants.

Two major restrictions ensured important control of the variables involved in the study, but narrowed its scope. First, read speech alone was examined here, given the methodological challenge implied by the study of spontaneous speech, and the fact that Basset et al. (2001) did not find significant differences between those conditions. Second, in order to avoid contamination from higher level morpho-syntactic processes, we focused on word-internal intra-syllabic nasalization in a single prosodic context. Within these confines, the aim of the present study is to provide a full-range comparison between contrastive and contextual nasalization, and, within contextual nasalization, between anticipatory and carryover effects as well as between vowels contrasting for tongue height and consonants contrasting for manner of articulation and voicing.

The aerodynamic parameters investigated here are oral airflow, nasal airflow, and proportional nasal airflow. Proportional nasal airflow is the mean proportion of nasal to total (oral plus nasal) airflow, and is by definition insensitive to variations in overall airflow. Variations in overall airflow may occur between speakers due to differences in lung capacity (Baken & Orlikoff, 2000), as well as within speakers as a correlate of speech style in general and emphasis in particular (Krakow & Huffman, 1993). Two kinds of measures were carried out. First, the average airflow rates across the acoustically defined segments were computed. These measures are primarily used to differentiate between major classes of sounds (e.g. oral consonants vs. nasal consonants, oral vowels (in oral context) vs. nasal vowels). Second, in order to study coarticulation, the time course of nasalization was investigated based on nasal airflow data. The onset of nasalization was located relative to the oral-nasal boundary and its temporal extent was measured as a proportion of segment duration.

2. Material and method

2.1. Participants

Four female speakers (S1–S4) and four male speakers (S5–S8) took part in the experiment. They were native French speakers from Belgium, aged 22–45 years. Phonetically and phonologically, middle-class Belgian French is close to standard Parisian French. Differences of interest are mentioned below.

2.2. Corpus

The task required speakers to read ten-item lists made up of the randomly ordered words of the corpus; each item was produced as an isolated utterance. Although there were no filler items, none of the speakers figured out that the focus of the investigation was nasalization. The corpus included 150 words, in which French oral and nasal vowels appeared in various oral and nasal phonological environments, i.e. CV, (C)VN, NV, NVN, CṼ, CṼC, CṼCV and NṼ items. The segments under investigation were: oral consonants /p, b, t, d, k, g, f, v, s, z, ʃ, ʒ, ʀ, l/, nasal consonants /m, n/, oral vowels /i, e, ɛ, a, ɔ, o, u, y/ and nasal vowels /ɛ̃, ɑ̃, ɔ̃/. In total, 2432 segments were analysed in this study, 304 segments for each speaker.[2]

Tables A1–A3 in the appendix give the words of the corpus in French together with their English translation. A phonological transcription is provided when the item differs from the exact combination of the column and line heads. Indeed, the target item did not always exist as a legal word in French. In such cases it was replaced by a bisyllabic word, where the desired phonological string also appeared as a word-final stressed syllable. These are underlined in the tables: /fy.zɛ/, /fy.zɛ̃/, /ba.nan/, etc. Where possible, bisyllabic words were formed by repeating the same syllable: /zo.zo/, /ko.ko/, etc. are real words in French. Proper nouns (e.g. 'Beaune', 'Nîmes') were avoided as far as possible. In Tables A1–A3, column and line heads are phonemes and should not be expected to provide a fine-grained phonetic transcription of the actual pronunciation of the items. In particular, nasal vowels /ɛ̃, ɑ̃, ɔ̃/ are usually realized as [æ̃, ɑ̃, õ] in Modern French (Brichler-Labaeye, 1970, Delvaux, Metens, & Soquet, 2002). Also note that none of the eight speakers had a

[2]Due to technical malfunctions during the recording sessions, some items are missing for two speakers. Finally, 2341 segments out of 2432 were available for analysis.

phonological distinction between /a/ and /ɑ/, and that most of their phonetic realizations were closer to a front [a], which is very common among speakers of Modern French.

Further information on the corpus is necessary, given the specific patterning of mid vowels in modern French. Generally speaking, /ɛ, e/ and /ɔ, o/ are in complementary distribution: low-mid vowels occur in closed syllables and high-mid vowels occur in open syllables. However, these sounds are not considered to be allophones in French since they do contrast in several cases, mostly in monosyllables (Fougeron and Smith, 1999). We used such cases to maximize the number of contrasts in NV and VN items in the corpus. Some of these cases are exceptions to the general rule, presumably due to spelling, e.g. ‘heaume’ /om/ (vs. ‘homme’/ɔm/), ‘naît’ /nɛ/ (vs. ‘nez’ /ne/). Others are dialect-specific exceptions, e.g. ‘mot’ /mɔ/ (vs. ‘maux’ /mo/). There were no exceptions in the case of tautosyllabic (C)eN, which are not legal sequences in French. Thus, heterosyllabic eN items were included in the corpus (‘ému’ /e.my/ and ‘énorme’ /e.nɔʀm/) even if in these words the oral vowel is unstressed and the nasal consonant is in coda position. Data analysis showed that these words did not differ in the general patterning of nasal airflow outlines from the other VN items (see Table 5 and related text below). Finally, the pattern of complementary distribution requires that word-final /o, e/ be realized as [o, e] in CV items. However, Belgian speakers usually pronounce word-final [o] but [ɛ], as did the Belgian speakers recorded in this study.

2.3. Hardware and software

Data were collected at the Phonology Laboratory of the Free University of Brussels, Belgium, using the *Physiologia* workstation. *Physiologia* is a multisensor data acquisition system allowing simultaneous recording of the speech signal and the oral and nasal airflow. The external part of the device consists of a mask covering the mouth alone plus two flexible rubber tubes (10 cm long) that are inserted in the nostrils by means of nasal olives. At the output of the oral mask and nasal tubes, there are pneumotachographs allowing measurements of oral and nasal airflow. An AKG C 419 microphone is positioned just behind the oral transducer. All these elements are hung on a thermostatic ‘handpiece’, which is connected to the *EVA* and *Physiologia* hardware (Ghio & Teston, 2004; Teston, Ghio, & Galindo, 1999).

Calibration of the pneumotachographs was accomplished using a flow rate of 250 cm^3/s delivered by a compressed air supply and rotameter. The pressure transducers of *Physiologia* compensate for the effects of temperature and gravity, so that the output of the system does not vary over time. Tests in the laboratory revealed that the pneumotachographs showed linearity in measurements of airflow from 0 to 250 cm^3/s with less than 3 cm^3/s deviation. Basset et al. (2001) tested the adequacy of the response time of *Physiologia* and concluded that there were no major differences with respect to *PcQuirer*.

The speech signal was sampled at 16 kHz (12 bits). Both the oral and the nasal airflow were sampled at 2 kHz (12 bits). The maximum level was fixed at 500 cm^3/s, except for the nasal airflow of female speakers, which was adjusted to 200 cm^3/s. The zero level was adjusted by the experimenter at the beginning of every recording session and checked regularly during the session. The estimated error of this procedure is about 2 cm^3/s.

The collected data were processed with SignalExplorer, a software package designed to display, segment and process the speech signal and other speech-related time-evolving signals such as airflow and pressure outlines (http://www.umh.ac.be/~compa). Statistical analyses were carried out using SPSS (http://www.spss.com).

2.4. Segmentation

Data segmentation was primarily based on the information provided by the acoustic waveform and the spectrogram. In VN items, voicing onset was taken as the indicator of the beginning of the vowel. In other items, consonant release was considered to mark vowel onset, since other acoustic features may be difficult to detect due to vowel nasalization. Consonant release was considered to be acoustically signalled as the burst offset in oral stops (French stops are typically realized with no positive VOT), the end of frication noise in fricatives, and the burst offset and/or the abrupt increase in energy above 1000 Hz in the case of nasal stops and liquids. The airflow outlines were used only to define the onset of word-initial voiceless stops. The segmentation was performed with minimal reference to airflow outlines so that it may serve as an independent reference for further airflow measurements.

2.5. Measures

As mentioned above, two kinds of measures were carried out. First, the average flow across each of the acoustically defined segments was computed: the oral airflow mean per segment (OAmean, in cm^3/s), the nasal airflow mean per segment (NAmean, in cm^3/s), and, for vowels only, the proportional nasal airflow mean per segment (PNAmean, in %).[3] If NAmean resulted in a negative value for a given vowel, PNAmean was automatically calculated as zero.

Second, temporal properties of nasal coarticulation were measured by locating the onset/offset of nasalization relative to the oral–nasal boundary and by expressing the temporal extent of nasalization as a proportion of the duration of the appropriate segment (in %). The onset/offset of nasalization was considered as the time point at which nasal airflow crossed the zero level plus 5% of the maximum level of nasal airflow as calculated for each speaker in each segment type. The criterion level varied between 4 and 6 cm^3/s, i.e. at least twice the estimated error of the calibration procedure.

3. General results

Tables 1 and 2 present the results of the computations that were made across the entire segment, respectively for vowels ($N = 1155$) and for consonants ($N = 1186$). Four measures are reported: acoustic segment duration (in ms), OAmean (in cm^3/s), NAmean (in cm^3/s), and for vowels only: PNAmean (in %). In Tables 1 and 2, means (M), standard deviations (SD) and numbers of tokens (N) are given across segment type and phonological context. The results are given for all speakers pooled together. Although there was some cross-speaker variability, gender differences were not significant for PNAmean in vowels ($F(1,1154) = .719$; $p = .609$), nor for NAmean in consonants ($F(1,1185) = 2.232$; $p = .135$).

In Tables 1 and 2 as well as in the rest of the paper, vowel height (in phonologically oral vowels) is treated as a binary variable regarding nasal coarticulation. This does not result from an a priori perspective on the data, but from the data analysis itself. Table 3 gives PNAmean average values for all oral vowels in VN and NV items (in NVN items all the oral vowels are not represented), together with the results of post hoc (LSD) comparisons between all vowels. Post hoc tests revealed that PNAmean is not significantly different among /i, y, u/, nor among /e, a, o, ε, ɔ/, whereas high vowels have significantly more PNAmean than all other oral vowels.

4. Oral and nasal vowels

4.1. Means per segment

Table 4 gives the results of the MANOVA that was carried out on all the vowels of the corpus ($N = 1155$). The dependent variables are Duration, OAmean, NAmean and PNAmean, and the independent variables are Phonological context and Vowel type. Vowel type involves three groups: high oral vowels, non-high (low and mid) oral vowels, nasal vowels. Six phonological contexts are considered: C_, N_, (C)_N, N_N, C_C, C_.CV. As shown in Table 4, variation in both Vowel type and Phonological context, as well as the interaction between these main factors induce significant differences in the values of the four dependent variables: Duration, OAmean, NAmean and PNAmean. Phonological nasal vowels are significantly longer than phonological oral vowels, confirming the findings of Sampson (1999). The interaction between Vowel type and Phonological context mainly resides in the nasal vowels being shorter in CṼ.CV items, presumably due to unstressed position.

Fig. 1 demonstrates the interaction between Vowel type and Phonological context in the case of PNAmean using boxplots. The high variability of the PNAmean measure is attributable both to cross-speaker and

[3] PNAmean is not reported for consonants since the intra-category variability in oral configuration is considerable.

Table 1
General results for oral and nasal vowels ($N = 1155$)

	Non-high oral vowels			High oral vowels			Nasal vowels		
	M	SD	*N*	*M*	SD	*N*	*M*	SD	*N*
Duration									
C_	179	48	326				230	56	324
N_	188	57	79	151	35	45	233	62	45
(C)_N	137	79	76	148	52	45			
N_N	192	69	93	144	55	30			
C_C							280	50	69
C_.CV							151	32	23
Overall mean	177	60	574	148	47	120	234	61	461
OAmean									
C_	131	61	326				78	52	324
N_	77	44	79	52	46	45	53	39	45
(C)_N	108	58	76	91	57	45			
N_N	76	35	93	33	32	30			
C_C							88	53	69
C_.CV							109	60	23
Overall mean	112	60	574	62	53	120	79	53	461
NAmean									
C_	4	5	326				47	33	324
N_	36	17	79	67	27	45	62	38	45
(C)_N	8	16	76	24	30	45			
N_N	35	17	93	72	26	30			
C_C							50	30	69
C_.CV							41	25	23
Overall mean	14	18	574	52	35	120	48	33	461
PNAmean									
C_	5	24	326				41	25	324
N_	34	14	79	60	24	45	55	22	45
(C)_N	7	13	76	22	24	45			
N_N	32	12	93	74	20	30			
C_C							38	20	69
C_.CV							29	18	23
Overall mean	14	24	574	49	32	120	41	24	461

Statistical summary: mean (*M*), standard deviation (SD) and number of tokens (*N*) across Vowel type and Phonological context for four measures: acoustic duration (in ms) and the average flow rates per segment, i.e. OAmean (in cm^3/s), NAmean (in cm^3/s) and PNAmean (in %).

within-speaker (cross-vowel) variations, none of which are interrelated, neither do they interact with Phonological context (as shown for nasal vowels in Fig. A1 in the appendix).

Concerning Vowel type, Fig. 1 illustrates that PNAmean is greater for high than for non-high oral vowels in all contexts, with the difference being greatest in NVN items. Post hoc tests (LSD) showed that all three vowel types are significantly different from one another. In particular, PNAmean is significantly lower in phonologically nasal vowels than in phonologically oral high vowels. High oral vowels have particularly high values of PNAmean because they all occur in a nasal context in the present study. In order to reduce the size of the corpus, CV syllables with high vowels were not recorded systematically. It is the experience of the authors that in French, nasal airflow outlines remain flat throughout such sequences of oral phonemes, whatever the vowels included. An illustration is provided in Fig. A2 in the appendix for the word ‘fusait’ [fyzɛ].

As for Phonological context, PNAmean is larger for oral vowels following a nasal consonant (NV and NVN items) than for oral vowels simply preceding a nasal consonant (VN items). Separate post hoc (LSD) tests were carried out for oral and nasal vowels comparing PNAmean across Phonological contexts. For oral

Table 2
General results for oral and nasal consonants ($N = 1186$)

	Voiceless stops			Voiced stops			Voiceless fricatives			Voiced fricatives			Liquids			Nasals					
	Onset			Onset			Onset			Onset			Onset			Onset			Coda		
	M	SD	*N*	*M*	SD	*N*	*M*	SD	*N*	*M*	SD	*N*	*M*	SD	*N*	*M*	SD	*N*	*M*	SD	*N*
Duration																					
_V	144	25	71	167	52	70	208	42	71	161	49	68	164	51	46	159	47	124			
_Ṽ	138	26	69	179	54	68	200	43	69	167	52	71	166	44	47	149	49	45			
(C)V_																			163	68	121
_V_																125	37	121	205	61	125
Total	141	26	140	173	53	138	204	43	140	164	51	139	165	48	93	143	46	290	185	64	246
OAmean																					
_V	37	42	71	22	33	70	224	139	71	106	71	68	122	76	46	13	34	124			
_Ṽ	48	52	69	17	34	68	221	155	69	122	73	71	113	96	47	13	36	45			
(C)V_																			25	38	121
_V_																15	33	121	25	30	125
Total	42	47	140	19	34	138	222	146	140	114	72	139	118	86	93	14	34	290	25	33	246
NAmean																					
_V	7	5	71	13	14	70	11	8	71	17	15	68	9	7	46	69	34	124			
_Ṽ	5	8	69	10	12	68	19	24	69	21	23	71	18	22	47	66	31	45			
(C)V_																			71	33	121
_V_																67	35	121	69	30	125
Total	6	7	140	11	13	138	15	18	140	19	19	139	13	17	93	68	34	290	70	31	246

Statistical summary: mean (*M*), standard deviation (SD) and number of tokens (*N*) across Consonant type and Phonological context for three measures: acoustic duration (in ms) and the average flow rates per segment, i.e. OAmean (in cm^3/s) and NAmean (in cm^3/s).

Table 3
PNAmean average values and post hoc (LSD) multiple comparisons between oral vowels in nasal context (VN and NV items pooled together)

		u	i	y	e	a	o	ɛ	ɔ
PNAmean (%)		46.2	40.9	37.15	22.38	21.19	20.99	19.84	18.88
Post hoc tests	u								
	i	−5.31							
	y	−9.05	−3.75						
	e	−23.82**	−18.52**	−14.77*					
	a	−25.01**	−19.71**	−15.96**	−1.19				
	o	−25.21**	−19.91**	−16.16**	−1.39	−0.2			
	ɛ	−26.36**	−21.06**	−17.31**	−2.54	−1.35	−1.15		
	ɔ	−27.33**	−22.02**	−18.27**	−3.5	−2.31	−2.11	−0.96	

*$p < .05$. **$p < .001$.

vowels, PNAmean was significantly lower in CV items than in VN items, and significantly lower in VN items than in NVN and NV items. For nasal vowels, PNAmean was significantly higher in nasal contexts than in any other item type. The interaction between Vowel type and Phonological context is particularly noticeable from the PNAmean values of nasal vowels in oral context: in CṼ, CṼ.CV and CṼC items PNAmean is higher than in oral vowels followed by a nasal consonant (VN items) but is the same as or lower than in oral vowels preceded by a nasal consonant (NV and NVN items).

Table 4
Results of the MANOVA (F, p) for all vowels ($N = 1155$)

Dependent variable	Independent variable	F	p
Duration	Phonological context (PC)	$F(5,1144) = 23.1$	$p < .001$
	Vowel type (VT)	$F(2,1144) = 50.4$	$p < .001$
	PC*VT	$F(3,1144) = 5.8$	$p < .001$
OAmean	Phonological context (PC)	$F(5,1144) = 22.9$	$p < .001$
	Vowel type (VT)	$F(2,1144) = 33.9$	$p < .001$
	PC*VT	$F(3,1144) = 3.7$	$p < .001$
NAmean	Phonological context (PC)	$F(5,1144) = 52.9$	$p < .001$
	Vowel type (VT)	$F(2,1144) = 137.7$	$p < .001$
	PC*VT	$F(3,1144) = 8.7$	$p < .05$
PNAmean	Phonological context (PC)	$F(5,1144) = 56.3$	$p < .001$
	Vowel type (VT)	$F(2,1144) = 125.7$	$p < .001$
	PC*VT	$F(3,1144) = 10.1$	$p < .001$

Dependent variables are acoustic duration (in ms), OAmean (in cm^3/s), NAmean (in cm^3/s) and PNAmean (in %); independent variables are Vowel type (high oral vowels, non-high oral vowels, nasal vowels) and Phonological context (C_, N_, _N, N_N, C_C, C_.CV).

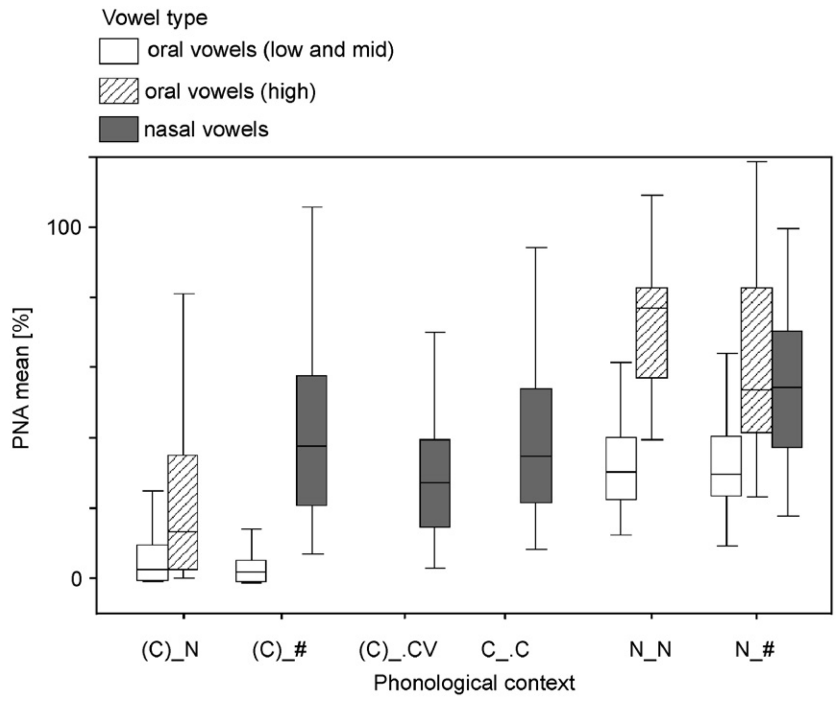

Fig. 1. Statistical summary using boxplots. PNAmean (in %) across Vowel type and Phonological context. All vowels included ($N = 1155$).

Taken together, these results indicate that both phonological context and vowel type have an effect on the mean amount of (proportional) nasal airflow per vowel. The interaction between these main factors is complex, possibly because the dependent variables conflate spatial and temporal information into airflow means per segment. In the following section, we focus on the time course of nasal airflow in order to determine the specific contribution of differences in timing vs. differences in general level of airflow to the PNAmean variations reported above.

4.2. Time course measurements

Figs. 2–4 illustrate the time course of contextual nasalization in the oral vowels of our corpus. Fig. 2 plots the time-normalized nasal airflow outlines recorded in VN items for speaker S4. Time is normalized separately for segment 1 (V) and for segment 2 (N) and both segments are displayed with the same relative duration. On the same template as Fig. 2, Fig. 3 plots the time-normalized nasal airflow outlines recorded in NV and NṼ items for S5, as does Fig. 4 for the NVN items of S1. These plots were selected as being typical of the data from the rest of the speakers.

4.2.1. Anticipatory vs. carryover nasalization

As illustrated by comparing the flow outlines in Figs 2 and 3, the significant differences in PNAmean that were recorded between the oral vowels preceding a nasal consonant and those following one are linked to differences in the temporal extent of nasal coarticulation. In VN items, nasal airflow is negligible (i.e. remains around zero) for the main part of the vowel, then the nasal outline rises quite sharply at the transition between oral vowel and nasal consonant to reach a high level and remain there until the end of the consonant. NV

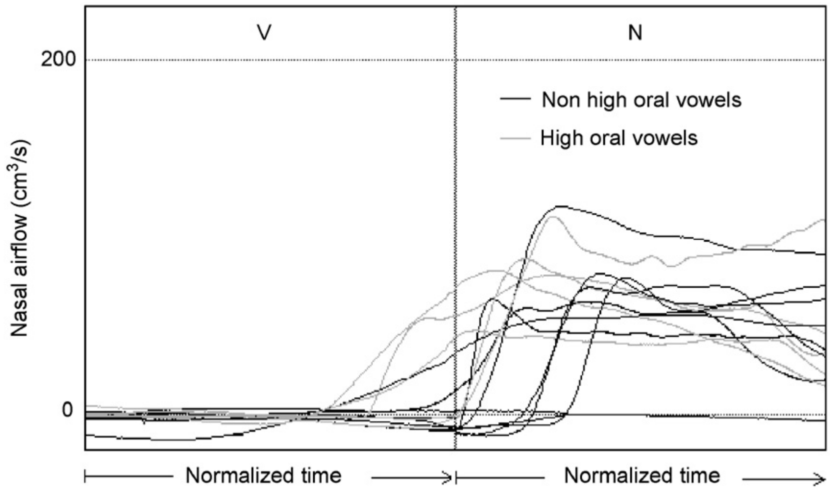

Fig. 2. Nasal airflow outlines recorded in VN items for female speaker S4. Time is normalized separately for vowels and consonants.

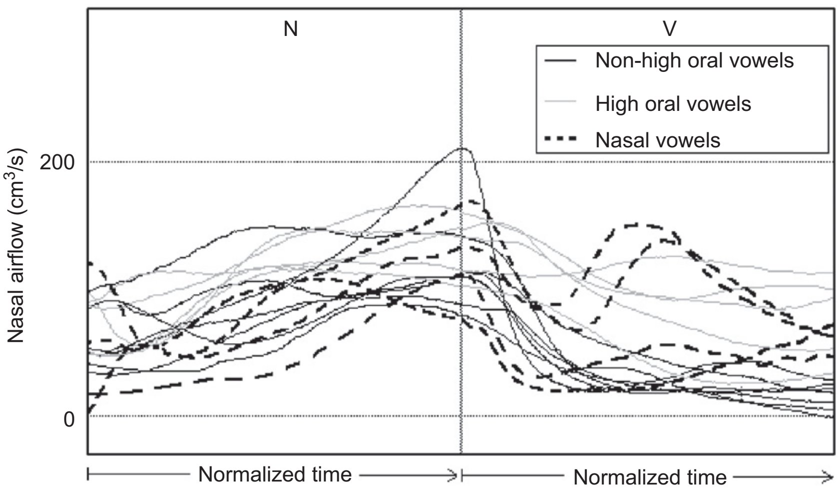

Fig. 3. Nasal airflow outlines recorded in NV and NṼitems for male speaker S5. Time is normalized separately for consonants and vowels.

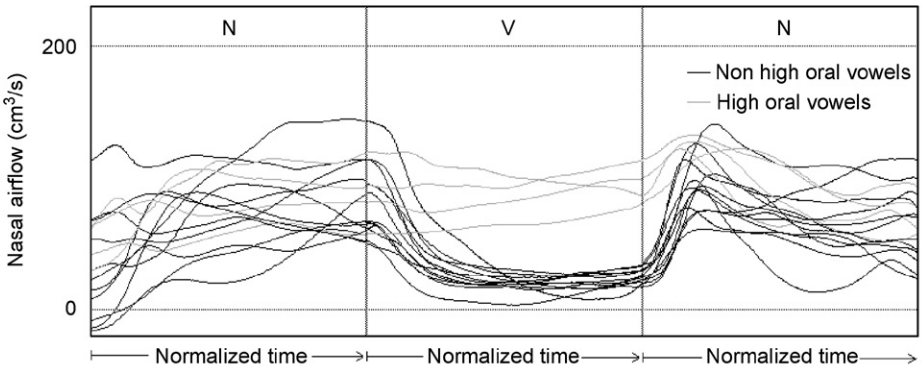

Fig. 4. Nasal airflow outlines recorded in NVN items for female speaker S1. Time is normalized separately for onset consonants, vowels and coda consonants.

Table 5
Measures of the time course of nasal airflow comparing high and non-high oral vowels in VN and NV items ($N = 245$)

	VN items				NV items			
	Non-high oral vowels		High oral vowels		Non-high oral vowels		High oral vowels	
	N	*TE*	*N*	*TE*	*N*	*TE*	*N*	*TE*
Contextual nasalization								
Anticipatory	12/76	−19%	21/45	−31%				
Synchronous	55/76	0%	24/45	(−2%)	0/79	N/A	0/45	N/A
Delayed	9/76	24%	0/45	N/A				
Carryover					18/79	82%	1/45	96%
Maximal carryover					61/79	(>100%)	44/45	(>100%)

Number of cases (*N*) and time extent (*TE*; expressed in percent of the appropriate segment duration) of the different types of contextual nasalization: anticipatory, synchronous, delayed, carryover and maximal carryover nasalization. See text for details.

items are not the mirror image of VN items since nasal airflow is well above zero level in the nasal consonant as well as during the major part of the contextually nasalized oral vowel.[4] These contextually nasalized oral vowels (NV items) differ somewhat from phonological nasal vowels (NṼ items) in the time evolution of the nasal airflow outline. In the former, nasal airflow consistently decreases, whereas in the latter the initial decrease is usually followed by an increase, which may then be followed by another decrease (see Fig. 3 for an illustration). As a result, PNAmean is generally very high in nasal vowels in NṼ items.

4.2.2. Vowel height and nasal coarticulation

Table 5 gives the results of the measurements that were computed specifically to compare the temporal extent of contextual nasalization in VN vs. NV items in high and non-high oral vowels (eight participants). VN items were divided into three groups depending on when nasalization starts relative to time reference. The time reference is a window centred on the boundary between segment 1 (here, the oral vowel) and segment 2 (here, the nasal consonant) and extending from −5% of segment 1 duration to +5% of segment 2 duration. Cases in which nasalization starts before the time reference window are labelled as anticipatory nasalization, cases in which nasalization starts at the time reference are labelled as synchronous nasalization, and cases in which nasalization starts after the time reference are labelled as delayed nasalization. The criterion for

[4]It is possible that the velum remain lowered in NV# items because V is in pre-pausal condition. However, unpublished data collected on the same speakers showed a similar nasal airflow pattern in (CV.)NVC items: 'maniaque' [maɲak] *maniac*, 'pignouf' [piɲuf] *cad*, 'eux nagent' [ønaʒ] *they swim*, as illustrated in Fig. A3 in the appendix.

nasalization is that nasal airflow exceeds the zero level (in cm^3/s) plus 5% of its maximum level in vowels as calculated for each speaker. The temporal extent of contextual nasalization is measured in percent of segment duration.

The results reported in Table 5 show that, in the majority of the VN items, nasalization is synchronous with the oral–nasal boundary. Moreover, there are more cases of anticipatory nasalization and fewer cases of delayed nasalization for high oral vowels. Also, average anticipatory nasalization extends over 31% of vowel duration in high vowels vs. 19% in non-high vowels, and this difference in temporal extent is significant ($t(31) = -3.936$; $p < .001$). These measurements complement PNAmean values for high vs. non-high oral vowels in VN items (see Table 1) by suggesting that the difference lies mainly in the different timing of velic lowering relative to oral closure.

Table 5 also reports the results for contextual nasalization in NV items. Here, the time reference window encloses consonant release minus 5% of consonant duration plus 5% of vowel duration. Cases are divided into three groups: synchronous nasalization, if nasal airflow crosses zero level (+5% of maximum nasal airflow level) at consonant release; carryover nasalization, if it happens after consonant release during the vowel; and maximal carryover nasalization, if it does not happen during the vowel at all, i.e. if the entire vowel is contextually nasalized.

From Table 5 it is clear that all oral vowels in NV items show extensive carryover nasalization. There is even more carryover nasalization in high vowels, as all but one are entirely nasalized in this context (vs. 61/79 non-high vowels). However, differences between high and non-high oral vowels are not limited to differences in timing. Fig. 3 (NV items) and Fig. 4 (NVN items) both illustrate that the *overall level* of nasal airflow is higher for high than for non-high oral vowels following a nasal consonant. In order to more closely examine the differences in general levels of airflow, Fig. 5 plots OAmean, NAmean and PNAmean averages for each vowel in all NV, NṼ and NVN items ($N = 292$). Fig. 5 is vertically divided into two groups according to the results of post hoc LSD comparisons on PNAmean: PNAmean is not significantly different among /a, ɔ, o, ɛ, e, ɛ̃/ and is significantly lower in these vowels than in all the others: /i, u, y, ɑ̃, ɔ̃/. Within the latter group, the

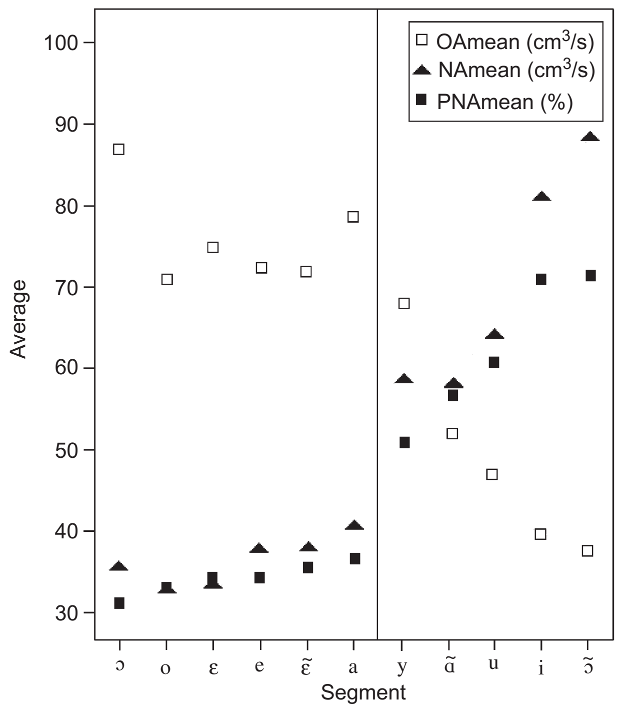

Fig. 5. Average OAmean (in cm^3/s), NAmean (in cm^3/s) and PNAmean (in %) across vowels in NV, NṼand NVN items ($N = 292$). The six vowels on the left of the vertical bar significantly differ in PNAmean from the five vowels on the right according to post hoc LSD comparisons.

PNAmean of /u/ does not significantly differ from the PNAmean of the other four vowels; /y, ɑ̃/ are not significantly different from each other, nor are they from /u/; similarly, /i, ɔ̃/ are not different from each other, nor are they from /u/.

It is noteworthy from Fig. 5 that not all French nasal vowels are in the high (P)NAmean group. Specifically, /ɛ̃/ is not significantly different in PNAmean from its oral counterpart /ɛ/. Since PNAmean is an average computed across the entire vowel, it may neutralize potential differences between oral and nasal vowels in the time evolution of the nasal airflow outline, some of which are illustrated in Fig. 3 (see above). Also, the contrast between nasal /ɛ̃/ and nasalized oral /ɛ/ may be supported by differences in vowel quality: /ɛ̃/ is typically described as a more open and less fronted vowel than /ɛ/ (Brichler-Labaeye, 1970; Delvaux et al., 2002; Zerling, 1984), and the acoustic effects of these articulatory adjustments have been shown to enhance the nasal percept for French listeners especially in nasal context (Delvaux, Demolin, Soquet, & Kingston, 2004; Delvaux, in press).

4.3. Correlation between OAmean and (P)NAmean

Results reported above show that NAmean and PNAmean values are significantly different between high vowels /i, u, y/ and other oral vowels /a, ɔ, o, ɛ, e/, all of them being heavily nasalized in NV and NVN items. Apart from a moderate difference in the temporal extent of nasal coarticulation, there is also a difference in the spatial extent of nasal coarticulation, i.e. in the general level of nasal airflow. This spatial difference may be due to three factors potentially acting separately or in combination: (i) a difference in overall airflow due to (artifactual) variations in emphasis, (ii) a difference in oral configuration, (iii) a difference in velopharyngeal port size. Since high oral vowels differ significantly from low oral vowels in PNAmean as well as in NAmean in NV and NVN items (recall the results of post hoc tests reported above), the effect of the first factor will be considered as marginal. Concerning the other factors, high vowels do differ by definition from non-high vowels as regards oral configuration, whereas we cannot say much of the amplitude of velic lowering because it is only indirectly evidenced by aerodynamic data. However, if NAmean variations across vowel type were due to differences in oral configuration only—velic lowering being equal—OAmean values would be expected to correlate closely with NAmean values in all these vowels. This should be particularly true in NV, NṼ and NVN items since almost all vowels are produced entirely with a lowered velum in this context. Fig. 5 indicates that vowels with high averages of OAmean /a, ɔ, o, ɛ, e, ɛ̃/ have low averages of (P)NAmean; conversely vowels with higher averages of (P)NAmean /i, u, y, ɑ̃, ɔ̃/ have lower averages of OAmean. The correlation hypothesis was tested by performing a Spearman non-parametric correlation test on all vowels in NV, NṼ and NVN items ($N = 292$). This test revealed that OAmean and PNAmean are negatively correlated (Spearman's rho $= -.723$; $p < .001$) and that NAmean and PNAmean are positively correlated (Spearman's rho $= +.695$; $p < .001$), which could be expected from the definition of PNAmean. But OAmean and NAmean are not correlated: Spearman's rho ($-.091$) is not significant ($p = .121$).

Taken together, the results of these analyses suggest that in French, there is more carryover nasal coarticulation in high oral vowels than in non-high oral vowels both in temporal extent and spatial extent.

5. Oral consonants

5.1. Means per segment

Table 6 gives the results of the MANOVA that was carried out on oral consonants in CV and CṼ items ($N = 557$). The dependent variables are Duration, OAmean, and NAmean, and the independent variables are Phonological context (_V vs. _Ṽ), Manner (of articulation: stops vs. fricatives), and Voicing (voiceless vs. voiced). Concerning OAmean, both Voicing and Manner and their interaction are significant. Voiceless consonants have significantly larger OAmean than do voiced consonants, presumably due to different impedance at the larynx. OAmean is also significantly larger for fricatives than for stops and the difference due to voicing is all the larger for fricatives, which could be expected since fricatives are continuants whereas stops have oral airflow only at consonant release (Shadle & Scully, 1995). Neither Phonological context alone nor its interaction with Voicing and/or Manner has a significant effect on OAmean.

Table 6
Results of the MANOVA (F, p) for oral consonants ($N = 557$)

Dependent variable	Independent variable	F	p
Duration	Phonological context (PC)	$F(1,549) = .04$	$p = .839$
	Voicing (V)	$F(1,549) = 1$	$p = .319$
	Manner (M)	$F(1,549) = 50.7$	$p < .001$
	PC*V	$F(1,549) = 4.4$	$p < .05$
	PC*M	$F(1,549) = .3$	$p = .606$
	V*M	$F(1,549) = 92.7$	$p < .001$
	PC*V*M	$F(1,549) = .1$	$p = .725$
OAmean	Phonological context (PC)	$F(1,549) = .4$	$p = .535$
	Voicing (V)	$F(1,549) = 79.4$	$p < .001$
	Manner (M)	$F(1,549) = 346.4$	$p < .001$
	PC*V	$F(1,549) = .1$	$p = .947$
	PC*M	$F(1,549) = .1$	$p = .855$
	V*M	$F(1,549) = 33.3$	$p < .001$
	PC*V*M	$F(1,549) = 1.5$	$p = .227$
NAmean	Phonological context (PC)	$F(1,549) = 2.6$	$p = .109$
	Voicing (V)	$F(1,549) = 11.7$	$p < .05$
	Manner (M)	$F(1,549) = 43.2$	$p < .001$
	PC*V	$F(1,549) = 1$	$p = .297$
	PC*M	$F(1,549) = 11.3$	$p < .05$
	V*M	$F(1,549) = .4$	$p = .533$
	PC*V*M	$F(1,549) = .3$	$p = .598$

Dependent variables are acoustic duration (in ms), OAmean (in cm^3/s) and NAmean (in cm^3/s); independent variables are Phonological context (PC: _V vs. _Ṽ), Voicing (V: voiced vs. voiceless consonants) and Manner of articulation (M: stops vs. fricatives).

As reported in Table 6, Voicing has a significant effect on NAmean ($p < .05$): NAmean is larger for voiced than for voiceless consonants. Manner and the interaction between Manner and Phonological context also have significant effects. Fricatives have significantly more NAmean on average than do stops, the difference being significantly larger in CṼ items. However, some of these variations in NAmean may be partly due to the presence or absence of respiratory airflow in word-initial oral consonants, and not to any difference in coarticulation. It is necessary to complement the analysis with time course measurements that separate the effects of respiratory airflow from those of contextual nasalization.

5.2. Time course measurements

In oral consonants in isolated CV and CṼ words, nasal airflow may be above zero level at the very beginning of the consonant as a result of respiration and/or at the end of the consonant due to anticipatory nasalization. By 'respiratory nasal airflow', we refer below to any expiratory nasal airflow recorded at the edges of an isolated word that is unlikely related to speech per se, i.e. (i) positive or negative airflow resulting from breathing just before/after the production of a speech sound; (ii) word-initial positive nasal airflow caused by the raising of the soft palate in preparation for speech (an illustration of the phenomenon can be seen in Fig. A2 in the appendix); (iii) word-final positive nasal airflow due to the relaxing of the soft palate from its 'speech' position (see Fig. A3 in the appendix for an example). In any case 'respiratory nasal airflow' represents neither intended nasalization nor coarticulatory nasalization and is thus dealt with separately in the following analysis.

Table 7 reports the measurements of both contextual nasalization and initial respiratory airflow for oral consonants in CṼ items ($N = 324$). Contextual nasalization was measured using the same method as described above for vowels, with consonant release as the centre of the time reference window. If nasal airflow is at or below zero level (+5% of the speaker's maximum level of nasal airflow in oral consonants) at the onset of the oral consonant, any nasal airflow above zero level in the consonant is considered to be contextual nasalization.

Table 7
Measures of the time course of nasal airflow in CṼ items across consonant type ($N = 324$): voiceless stops, voiced stops, voiceless fricatives, voiced fricatives, liquids

	Voiceless stops		Voiced stops		Voiceless fricatives		Voiced fricatives		Liquids	
	N	*TE*	*N*	*TE*	*N*	*TE*	*N*	*TE*	*N*	*TE*
Contextual nasalization										
Anticipatory	7/69	−9%	4/68	−6%	20/69	−14%	24/71	−20%	20/47	−19%
Synchronous	9/69	(+1%)	5/68	(−2%)	30/69	(−2%)	33/71	(−1%)	23/47	(0%)
Delayed	53/69	+23%	59/68	+21%	19/69	+19%	14/71	+14%	4/47	+20%
Respiratory airflow										
Initial	0/69	N/A	12/68	18%	21/69	16%	15/71	19%	6/47	7%

Number of cases (*N*) and time extent (*TE*; expressed in percent of the appropriate segment duration) of the different types of contextual nasalization (anticipatory, synchronous and delayed nasalization) and of initial respiratory airflow. See text for details.

Indeed in such cases it never happens that nasal airflow falls back to or below zero level (+5%) before consonant release. If nasal airflow is above zero level (+5%) at the starting point of the oral consonant, it is automatically considered to be respiratory airflow as long as it drops to baseline (zero level +5%) before consonant release. If it is not the case, i.e. if there is a certain amount of nasal airflow along the entire oral consonant, the experimenter uses the (visually defined) inflexion points of the nasal outline to differentiate between respiratory and coarticulatory nasal airflow. Inflexion points were necessary in 18 cases out of a total of 324 oral consonants. Fig. 6 illustrates the results reported in Table 7 by plotting time-normalized nasal airflow outlines in CṼ and CV items for two speakers: S3 (on the left) and S7 (on the right). From top to bottom, the five panels (a–e), respectively represent items in which C are voiceless stops (a), voiced stops (b), voiceless fricatives (c), voiced fricatives (d) and liquids (e).

In CV and CṼ items, voiced stops differ from voiceless stops in that the former may have some nasal airflow at the onset (12/68 cases in CṼ items) whereas the latter never do. A conservative position was adopted here in considering this nasal airflow as 'respiratory'. It could be analysed as intended nasalization, e.g. to favour voicing. But it is unlikely anticipatory nasalization since the consonant release is not nasalized, nor is the onset of the following nasal vowel. Indeed, both voiced and voiceless stops tend to delay nasalization: in the vast majority of the cases nasal airflow crosses the zero level (+5%) after consonant release and well into the following nasal vowel, so that the first 20% of the vowel on average is not nasalized (by the criterion established here). Fricatives contrast with stops in that anticipatory, synchronous and delayed nasalization are more evenly distributed. In fricatives and liquids, nasal airflow increase is synchronous with consonant release in almost half of the cases. Within the remaining half there are more cases of anticipatory nasalization than of delayed nasalization, anticipatory nasalization being slightly more extensive on average for liquids and voiced fricatives than for voiceless fricatives. Fricatives differ from liquids in that both voiced and voiceless fricatives show a moderate amount of respiratory airflow, whereas most nasal airflow in liquids comes from anticipatory nasalization. These results show that the significant effect of Manner on NAmean reported above relates to a difference in the extent of nasal coarticulation between stops and fricatives, and not to an artefact due to respiration.

Table 8 summarizes the measurements of coarticulatory and final respiratory airflow that were made on C_2 in CṼC and CṼ.CV items. By definition, there is no respiratory airflow when C_2 is in word-medial position, i.e. in CṼ.CV items. In CṼC items, 16/21 voiceless fricatives vs. 2/46 voiceless stops have word-final respiratory airflow.

As illustrated in Fig. 7 for S7, in CṼC items respiratory nasal airflow appears in the last quarter of the fricative whereas nasal airflow increases later for stops, precisely at stop release. There is no respiration during the final vowel of CṼ.CV items. For coarticulatory nasal airflow, the main result is that all 90 oral consonants without exception (i.e. across speakers, consonant type, and vowel type) show carryover nasalization after a phonologically nasal vowel. The temporal extent of carryover nasalization does not differ significantly between CṼC and CṼ.CV items: whether voiceless stops are codas of a monosyllabic word (+46%) or onsets

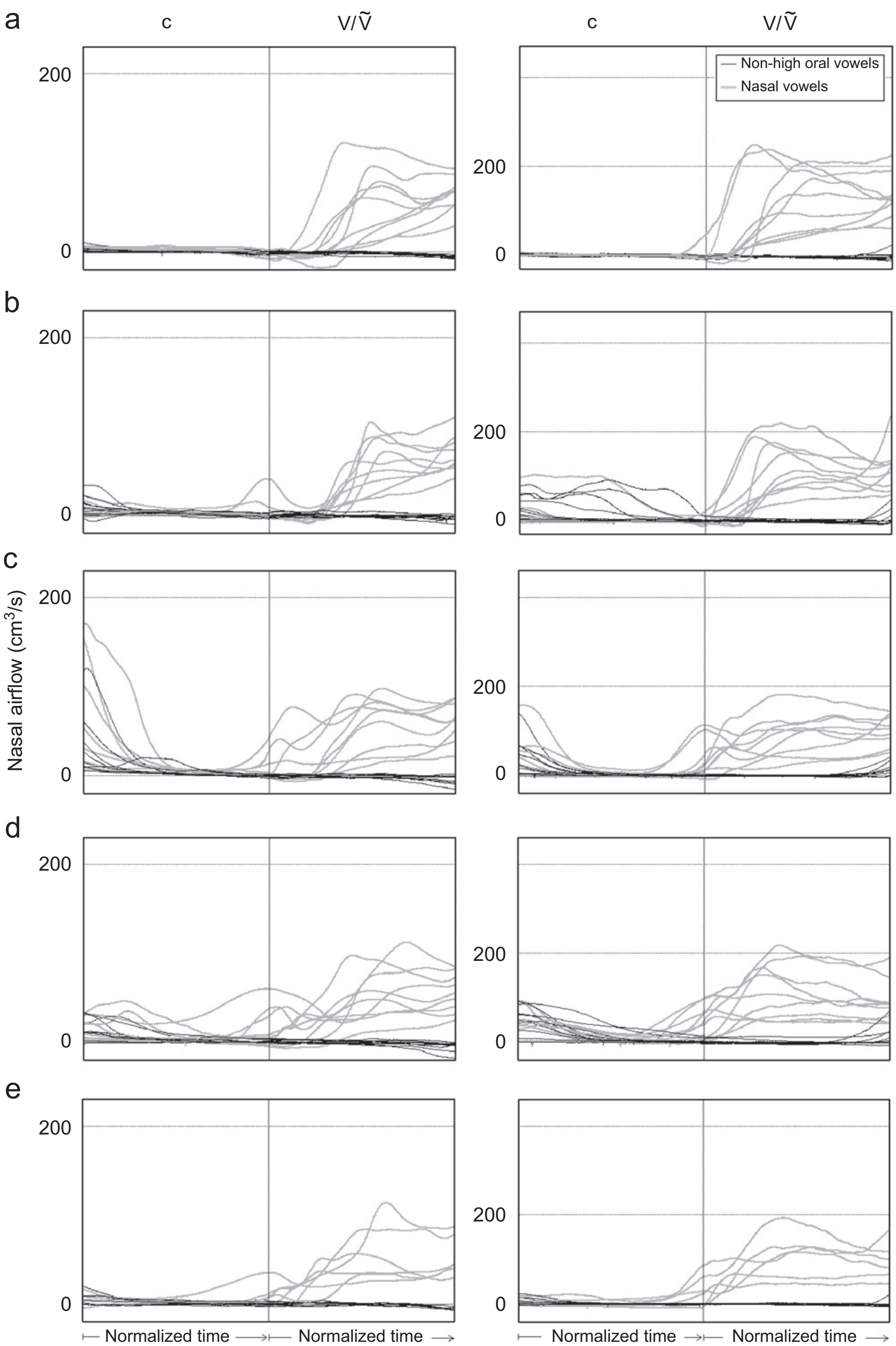

Fig. 6. Nasal airflow outlines for all the oral vowels recorded in CV and CṼitems for female speaker S3 on the left and male speaker S7 on the right: (a) voiceless stops, (b) voiced stops, (c) voiceless fricatives, (d) voiced fricatives, (e) liquids. Time is normalized separately for consonants and vowels.

Table 8
Measures of the time course of nasal airflow in C_2 in $C\tilde{V}C$ and $C\tilde{V}.CV$ items across consonant type ($N = 90$): voiceless stops, voiceless fricatives

	$C\tilde{V}C$ items				$C\tilde{V}.CV$ items	
	Voiceless stops		Voiceless fricatives		Voiceless stops	
	N	*TE*	*N*	*TE*	*N*	*TE*
Contextual nasalization						
Anticipatory	0/46	N/A	0/21	N/A	0/23	N/A
Synchronous	0/46	N/A	0/21	N/A	0/23	N/A
Carryover	46/46	+46%	21/21	+45%	23/23	+51%
Respiratory airflow						
Final	2/46	8%	16/21	22%	N/A	N/A

Number of cases (*N*) and time extent (*TE*; expressed in percent of the appropriate segment duration) of the different types of contextual nasalization (anticipatory, synchronous and carryover nasalization) and of final respiratory airflow. See text for details.

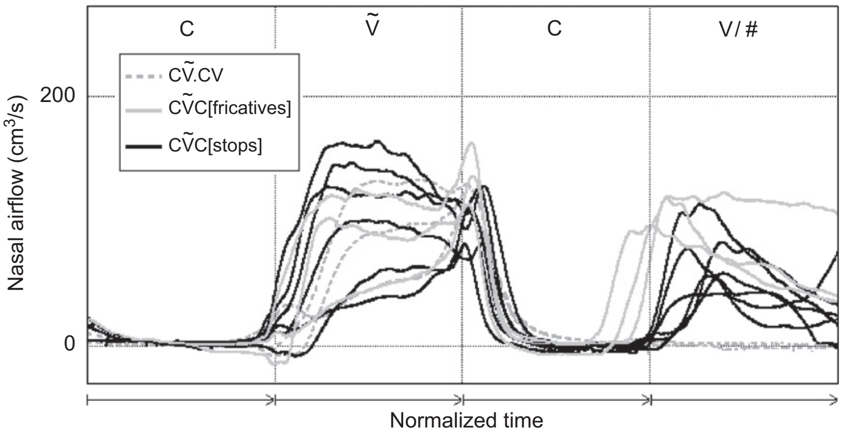

Fig. 7. Nasal airflow outlines recorded in $C\tilde{V}C$ and $C\tilde{V}.CV$ items for male speaker S7. Time is normalized separately for segment 1, segment 2, etc.

of the second syllable (+51%) in a bisyllabic word does not have a significant effect ($t(67) = -1.367$; $p = .184$). As illustrated in Fig. 7, at $\tilde{V}C_2$ boundary nasal airflow first increases then dramatically decreases at the beginning of the consonant. In our data, the first increase in nasal airflow is always perfectly timed with a decrease in oral airflow, so it may be hypothesized that both phenomena are due to the same cause, presumably oral constriction. The decrease in nasal airflow that directly follows would then be attributed to velopharyngeal rising alone. Our results thus show that in French, there is more carryover than anticipatory nasal coarticulation in consonants as well as in vowels.

Note that none of the oral consonants that exhibit coarticulatory nasal airflow in the present study sounded nasalized to the experimenters, nor did the experimenters notice any significant effect of nasalization on their acoustic properties. Indeed, in $C\tilde{V}$ items the temporal extent of anticipatory nasalization is limited to the last portion of the consonant, and in $C\tilde{V}C$ and $C\tilde{V}.CV$ items, the second consonant is always a voiceless obstruent, so that even heavy carryover nasalization is unlikely to be detected.

6. Nasal consonants

Nasal consonants typically exhibit small values for OAmean and high values for NAmean (see above, Table 2). This was expected since nasal consonants have oral airflow only at consonant release whereas they have nasal airflow throughout, due to the velopharyngeal port opening. *T*-tests revealed that onset position significantly differed from coda position in duration ($t(518) = -9.055$, $p < .001$) and in OAmean ($t(518) = -3.773$, $p < .001$), but not in NAmean ($t(518) = -.719$, $p = .473$).[5] Most (but not all) of the nasal consonants that are in onset position in our corpus are also in word-initial position, and even in utterance-initial position, due to the absence of frame sentences. Initial nasal consonants have been shown to be produced with a higher velum and greater linguo-palatal contact, particularly in higher prosodic constituents (Fougeron, 2001; Fujimura, 1977; Gordon, 1996; Krakow, 1989). As a consequence, in the present study, initial nasals were expected to show a lesser amount of nasal airflow due to reduced velopharyngeal opening, and a higher amount of oral airflow due to higher pressure just before consonant release. However, in our nasal consonants there is no difference in NAmean across syllable positions, and the significant difference in OAmean is contrary to expectations. The higher rate of oral airflow in word-final nasal consonants may be due to expiratory airflow.

7. Discussion

7.1. Anticipatory vs. carryover nasalization

The results of the present study confirm that in French, carryover nasalization is more extensive than anticipatory nasalization, both for oral vowels and for oral consonants. In VN items, nasal airflow onset is either synchronous with oral closure or anticipated through about 25% of the vowel duration whereas in NV items, nasal airflow remains above zero level through 80% or more of the vowel. As a consequence, NAmean and PNAmean are significantly higher in vowels following nasal consonants than in vowels preceding nasal consonants. In CṼ items, only a few stops and less than half of fricatives and liquids show anticipatory nasalization. The effect is moderate since nasal airflow starts in the last 25% or later of the consonant. Nasalization is even delayed in the majority of stops. Conversely, all oral consonants following a nasal vowel are nasalized without exception, in that nasal airflow extends through half of the second consonant in CṼC and CṼ.CV items.

The asymmetry between anticipatory and carryover nasalization in French vowels is not a new finding (e.g. Benguerel et al., 1977a; Botherel, Simon, Wioland, & Zerling, 1986; Clumeck, 1976; Cohn, 1990; Rossato et al., 2003), although the precise quantification offered here is a new contribution. Of the previous articulatory and aerodynamic studies on nasal coarticulation in French, only Basset et al. (2001) systematically reported the temporal extent of nasalization and its direction relative to the oral–nasal boundary for both vowels and consonants. Their results are generally consistent with those of the present study, especially the asymmetry between anticipatory and carryover nasalization in vowels, although they reported temporally more extensive nasalization (both anticipatory and carryover) than found here, possibly due to methodological differences in identifying the nasalization threshold.

The reasons why French favours carryover over anticipatory coarticulation still need to be clarified, and we offer here a couple of working hypotheses. The first one concerns a potential universal in the perception of contextual nasalization. The second one is related to language-specific prosodic organization.

First, note that French is not exceptional in its preference for carryover over anticipatory nasal coarticulation. Although Clumeck (1976) found that the temporal extent of anticipatory nasalization was high in Brazilian Portuguese, American English, and Swedish (short vowels), many studies that focused on the differences between carryover and anticipatory nasalization concluded on the preeminence of the first over the second, i.e. in Italian (Farnetani, 1986), in Japanese (Ushijima & Hirose, 1974) in Dutch (Schouten & Pols, 1979) in Akan (Huffman, 1989), in Ikalanga (Beddor & Onsuwan, 2003), in Greek (Diakoumakou, 2005), and in French as confirmed in the present study (Basset et al., 2001; Benguerel et al., 1977a; Botherel, Simon, Wioland, & Zerling, 1986; Cohn, 1990, Rochet & Rochet, 1991; Rossato et al., 2003). Inversely, in American English most evidence points to anticipatory nasalization being heavier than carryover nasalization (Moll, 1962; Moll & Daniloff, 1971; Ohala, 1971; Rochet & Rochet, 1991; Solé, 1992).

[5] Data from heterosyllabic VN items were excluded from the calculations.

Second, distinctive nasalization mostly evolves from anticipatory vowel nasalization in tautosyllabic V + N sequences (Beddor, 1993; Greenberg, Ferguson, & Moravcsik, 1978; Kawasaki, 1986; Ruhlen, 1975, 1978; Schourup, 1972).[6] Thus, most of the languages that have been studied up to date allow larger *carryover* effects in contextual nasalization, whereas *anticipatory* effects are more likely to become one of the distinctive properties of the vowel. It is possible that carryover nasalization is not treated in the same way as is anticipatory nasalization by the auditory/perceptual system. A working hypothesis is that carryover nasalization mainly contributes to the percept of the preceding nasal consonant whereas anticipatory nasalization may as well be perceived as an attribute of the vowel, thereby potentially leading to sound change. In other words, listeners would be more efficient in parsing the speech signal when the coarticulatory source precedes the vowel than when it follows the vowel, and speakers would compensate for this, resulting in anticipatory nasalization to be limited in the world's languages. Obviously, a specific experimental study is necessary for comprehensive evaluation of this hypothesis.[7] An element in its disfavour is that anticipatory nasalization (Fowler & Brown, 2000; Malécot, 1960) as well as carryover nasalization (Beddor & Onsuwan, 2003; Maturi, 1991) have been shown to enhance the percept of neighbouring nasal consonants.

Another potential reason why carryover nasalization is favoured in French, as well as in other languages, concerns language-specific prosodic organization. Diakoumakou (2004, 2005) suggested that the direction and/or extent of contextual vowel nasalization in a language may be linked to that language's preference for open or closed syllable structures. In Modern Greek, stressed NV syllables can be described as having a large nasal gesture timed to syllable onset with high carryover vowel nasalization. Based on the Greek case as well as on a review of nasalization studies in several other languages, Diakoumakou found that languages that tend toward open syllable structure have temporally less extensive anticipatory vowel nasalization. Indeed, six out of the seven languages cited above in which carryover exceeds anticipatory nasalization do prefer open over closed syllables, i.e. Italian, Japanese, Akan, Ikalanga, Greek and French (but not Dutch). Conversely, American English has more closed than open syllables, as well as more anticipatory than carryover vowel nasalization. Further research is in order to confirm that preeminence of carryover nasalization and preference for open syllables do not simply co-occur because both tendencies are most frequent in the world's languages, but that there may be a causal link between them.

7.2. Nasal coarticulation and vowel height

According to Basset et al. (2001, p. 91), their results were conclusive regarding the difference between anticipatory and carryover nasalization in French vowels, but were only tentative regarding more extensive contextual nasalization of high than of non-high vowels due to lack of sufficient data. The present study established a significant difference in contextual nasal airflow between high and non-high vowels. In VN items, the difference lay mostly in timing: anticipatory nasalization was more frequent and its temporal extent was longer in high vowels. In NV items, all vowels showed extensive carryover nasalization, but the proportion of maximally nasalized high vowels exceeded that of non-high vowels. Moreover, the overall level of nasal airflow was higher in high vowels in NV and NVN items. Consequently, NAmean was significantly higher in these vowels. Since PNAmean was also significantly higher, the difference between high and low vowels could not result from variations in overall airflow, although it could be due to a difference in resistance to airflow in the oral cavity, such as a difference in oral configuration and particularly in tongue height. High vowels had significantly less OAmean than low vowels in our corpus. But in NV and NVN items, NAmean was found not

[6]Occasionally, phonemic nasal vowels evolve from earlier N + V sequences, e.g. in Portuguese (Sampson, 1999), in South Min Chinese (Chen, 1975) and possibly in Kwa (Hyman, 1972). There are also cases of so-called 'spontaneous nasalization' when oral vowels become distinctively nasalized due to the influence of neighbouring consonants that are produced with an open glottis (for a review, see Ohala & Busà, 1995). In Eastern Algonquian, a nasalized vowel even developed without a consonantal conditioning environment (Whalen & Beddor, 1989).

[7]For example, Beddor (2007) and Beddor, Brasher, and Narayan (2007) showed that in VN sequences vowel and consonant nasalization are heard as perceptually equivalent by listeners of American English and Ikalanga, which is consistent with the diachronic evidence on the emergence of distinctive vowel nasalization. A similar experimental design could be used to test the perceptual equivalence hypothesis in NV sequences.

to correlate with OAmean. Also, nasal airflow patterns were not found here to differ among /e, a, o, ɛ, ɔ/, although these non-high oral vowels are of three different values for tongue height. This suggests that the difference observed between high and non-high oral vowels in terms of carryover nasalization is not—or is not exclusively—an artifact of tongue height differences, but could be partly due to a difference in velopharyngeal aperture.

Even if the high level of nasal airflow in French high vowels were due to differences in oral resistance only, velum height being equal, it remains a finding of interest because the contribution of the nasal cavities to the overall acoustic output does not only depend on the size of the velopharyngeal port, but also on the ratio of the total acoustic mass of the nasal cavities to that of the oral resonator. Our aerodynamic findings correspond to the acoustic results of Rochet and Rochet (1991), who used nasometry to study coarticulatory nasalization in Canadian French and English. Their results, like ours, showed that coarticulatory nasality had a higher level and a longer duration in high vowels than in non-high vowels.[8] Of course, the aerodynamic and the acoustic parameters of speech sounds are mapped onto each other in a complex and indirect way, but both in the aerodynamic phase (Krakow & Huffman, 1993) and in the acoustic phase (Stevens, 1998) of the speech production mechanism, a similar velopharyngeal opening has a larger effect on high vowels than on low vowels: in the former the narrowest constriction is situated after the velopharyngeal port (i.e. in the alveolar region) whereas in the latter it is situated at the velum or before it, in the pharyngeal region. It would seem to be the case that speakers of many of the world's languages compensate for this (Ohala & Ohala, 1991), resulting in high vowels being realized with less velopharyngeal opening in nasal contexts (Al-Bamerni, 1983; Clumeck, 1976; Fritzell, 1969; Künzel, 1977; Moll, 1962; Ohala, 1971), and with greater velar height and velopharyngeal closure force in oral contexts (Bell-Berti, 1976l; Bell-Berti & Krakow, 1991; Goto, 1977; Kuehn & Moon, 1998; Moon et al., 1994). The results reported here suggest that French is exceptional, together with Gujarati, Hindi (Al-Bamerni, 1983) and Swedish (short vowels: Clumeck, 1976), and with certain speakers of American English (Moll, 1962; Van Reenen, 1982).

In explicating the patterning of nasal coarticulation in French high vowels, we return to the two 'output constraints' (Manuel, 1990) invoked in Section 1 that might play a role here. First, French might be expected to restrict contextual nasalization in all high and non-high oral vowels in order to maintain the contrast between oral and nasal phonemes. Our results do not confirm this hypothesis insofar as aerodynamic parameters are concerned, since carryover nasalization was found to be extensive in all vowels and maximal in high vowels. Also, note that output constraints would wrongly predict anticipatory nasalization to exceed carryover nasalization since French contrasts NV and NṼ but not (tautosyllabic) VN and ṼN. Second, we speculated that French high vowels might be allowed a high degree of nasal coarticulation because they do not contrast with high nasal vowel phonemes in the language. Indeed, /i, y, u/ were found to be heavily nasalized [ĩ, ỹ, ũ] after a nasal consonant, and they surely cannot be misperceived as /ɛ̃, ɑ̃, ɔ̃, œ̃/, unlike contextually nasalized /ɛ, ɔ, ɑ, œ, e, a, o, ø/. However, the issue remains of the potential confusion between [ĩ, ỹ, ũ] and /e, ø, o/, since in both nasal and oral contexts high vowels have been found to be perceptually lower when nasalized (Beddor, Krakow, & Goldstein, 1986; Kingston & Macmillan, 1995; Krakow, Beddor, Goldstein, & Fowler, 1988; Macmillan et al., 1999; all studies on American English).

7.3. Nasal coarticulation and consonant manner of articulation and voicing

The main results concerning contextual nasalization in French oral consonants are: (i) carryover nasalization is considerably greater than anticipatory nasalization for all oral consonants; (ii) the amount of anticipatory nasal coarticulation differs across oral consonants: when followed by a nasal vowel, voiced and voiceless stops tend to delay nasalization relative to consonant release whereas voiceless fricatives and, more often, voiced fricatives and liquids, can be moderately nasalized by anticipation. These results converge with the main tendencies exhibited by contextually nasalized oral vowels in the language, and are consistent with the phonetic constraints on the production of French oral consonants. First, assuming that the timing between

[8] In contrast, Rochet and Rochet's finding of a high degree of acoustic nasalization in English high vowels does not converge with other results on the same language (e.g. Bell-Berti, 1993).

the movements of the velum and those of the other articulators cannot be perfect, a number of cases of anticipatory, carryover and delayed nasalization were expected in CṼ, CṼC and CṼ.CV items. Second, the language tends to favour carryover over anticipatory nasalization. Third, the phonetic requirements on the different oral consonants involved may account for a large part of the variation observed: (i) the onset but not the offset of a stop may exhibit nasal airflow since what must be preserved is the integrity of the final burst (Ohala, 1975; Ohala & Ohala, 1991); (ii) both the onset and the offset of fricatives can be nasalized (or contaminated by breathing) as long as turbulent airflow is generated in the oral cavity and maintained for a sufficient part of the consonant (Shosted, 2006; Solé, 2007a); and (iii) within these limits, voiced obstruents may allow more nasal airflow than voiceless obstruents because nasal leakage can help to maintain the balance of pressure that is appropriate for voicing. Nasalization and voicing in obstruents may also have convergent acoustic properties (Solé, 2007b).

All of our measures are compatible with the general phonetic principles stated above, even if some of our specific results are not predicted by them. For example, it was expected that liquids would be more nasalized by coarticulation than voiced fricatives because the aerodynamic constraints on their production are less strict. In our data, the proportion of liquids showing anticipatory nasalization (20/47) is larger than in all the other consonant types, but the temporal extent of coarticulation is comparable with that of voiced fricatives (19% vs. 20% of consonant duration). Another unexpected result is the absence of onset nasal airflow in word-initial voiceless stops, in contrast to all other consonants. If initial expiratory nasal airflow were used as a strategy to maintain voicing, it would preferably occur in voiced stops and voiced fricatives, but not in voiceless fricatives as it does in our data. The absence of such airflow in voiceless stops may be due to the way the segmentation was carried out, since the oral airflow outline was used to define consonant onset in word-initial voiceless stops only.

Our findings for ṼC sequences are comparable to those of Basset et al. (2001): a vast majority of oral consonants, whether stops or fricatives, voiced or voiceless, were heavily nasalized when following a nasal vowel. However, our findings for CṼ sequences exhibited different patterns in two main respects. First, Basset et al. reported complete nasalization of voiced stops (both before and after a phonological nasal vowel).[9] In the specific prosodic context that was investigated here we observed no such fully nasalized allophones of voiced stops in CṼ sequences, nor did Cohn (1990), who recorded her corpus within a sentence frame. Cohn's findings on anticipatory nasalization in oral consonants match ours: there was anticipation for liquids in her data, whereas nasal airflow was either simultaneous or delayed with respect to oral closure in both voiced and voiceless stops.

Second, in CṼ sequences, the temporal extent of anticipatory nasalization (but not that of delayed nasalization) is always considerably longer in the measures of Basset et al. It is possible that the specific utterance-initial context investigated here disfavoured large anticipatory effects in oral consonants. Similar to our findings, Benguerel et al. (1977a) also reported a minimal amount of anticipatory velic lowering in word-initial voiceless obstruents that, like our recordings, were produced without a frame sentence. Several studies have shown evidence of a high velum in initial position. Both oral and nasal segments have been shown to have a higher velum in word- and syllable-initial position than in final position (Fujimura, 1977; Krakow, 1989; Vaissière, 1988). Moreover, the higher the initial prosodic domain, the higher the velum position, as suggested by Fougeron and Keating's (1996, 1997) and Fougeron's (2001) findings for nasal airflow for initial /n/ in French. However, in the present study, while utterance-initial oral consonants were least compatible with contextual nasalization—possibly for prosodic reasons—the results for initial nasal consonants did not show strong evidence of a relatively high velum position. Specifically, nasal consonants did not differ in NAmean between initial and final position. Although the measures are different in the two studies—we measured NAmean whereas Fougeron and colleagues measured the peak of maximal nasal airflow—both are expected to decrease with an increased velum height, overall airflow being equal. Further research is in order to demonstrate that French prosody requires a high velum in utterance-initial consonants.

[9] Such nasalized allophones of oral stops in nasal environment have been previously reported in French, but mostly in heterosyllabic groups of consonants (and in hypospeech): cadenas /kadəna/ [kanna], submerger /sybmɛʀʒe/ [symmɛʀʒe], etc. (Dell, 1986). See also Malécot and Metz (1972) for a report on progressive nasalization in oral stops prior to a word juncture, e.g. grande ville /gʀɑ̃d(ə)vilə/ [gʀɑ̃nvil].

8. Conclusion

French nasalization involves a complex interplay between several factors. The present study provided a detailed description of the aerodynamic parameters of French nasalization in isolated words, comparing patterns of contextual nasalization across vowels contrasting for tongue height, lip rounding, and place of articulation; and consonants differing in manner of articulation and voicing.

Although the approach taken in this study should be extended to a wider range of prosodic conditions, the results generally confirmed the main tendency of the previous studies on French nasal coarticulation, i.e. that the temporal extent of carryover nasalization is greater than that of anticipatory nasalization in both vowels and consonants. We further showed that vowel height and consonant manner of articulation and voicing yield significant differences in the temporal extent of intra-syllabic nasal coarticulatory airflow. Unlike previous studies, most of the variation reported here in the case of oral consonants can be accounted for by referring to the phonetic requirements on the production of voicing, turbulent airflow (for fricatives) and burst release (for stops). In the case of oral vowels, the general level of coarticulatory nasal airflow as well as its temporal extent were shown to be significantly higher in /i, u, y/ than in /ɛ, e, ɔ, o, a/. These groups differ in tongue height as well as in the presence vs. absence of a nasal counterpart in the phonemic inventory of the language, so that studies on other languages are necessary to further specify the role of these factors in nasal coarticulation. In addition, the exact relation between the aerodynamic parameters of French nasalization and the degree of both velopharyngeal aperture and acoustic nasalization still needs to be established. Complementary acoustic and perceptual studies are in order to fully apprehend the patterns of nasal coarticulation in French.

Acknowledgements

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Appendix

See Figs. A1–A3 and Tables A1–A3.

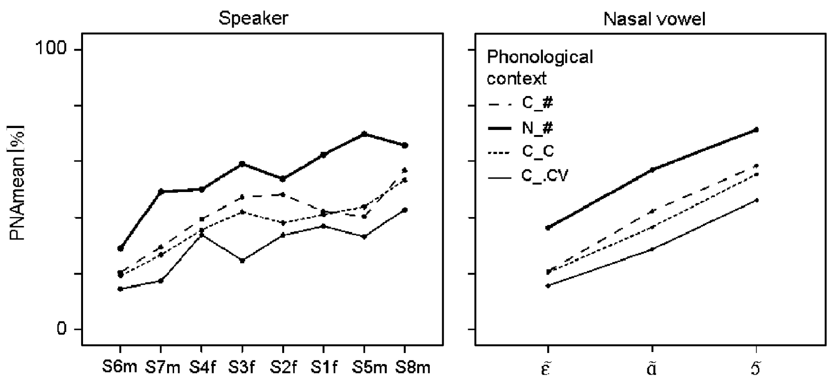

Fig. A1. Cross-speaker (on the left) and cross-vowel (on the right) variations in PNAmean average values (in %) as a function of Phonological context (nasal vowels only). Speakers are identified by their number (S_i) and their gender (m/f).

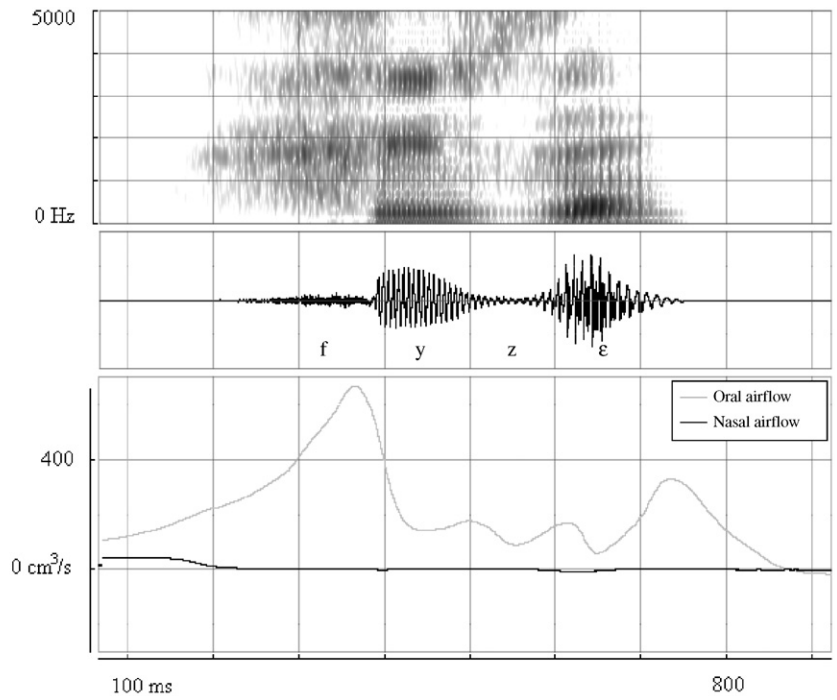

Fig. A2. Spectrogram, acoustic waveform and oral and nasal airflow outlines for /fyzε/ (male speaker S8).

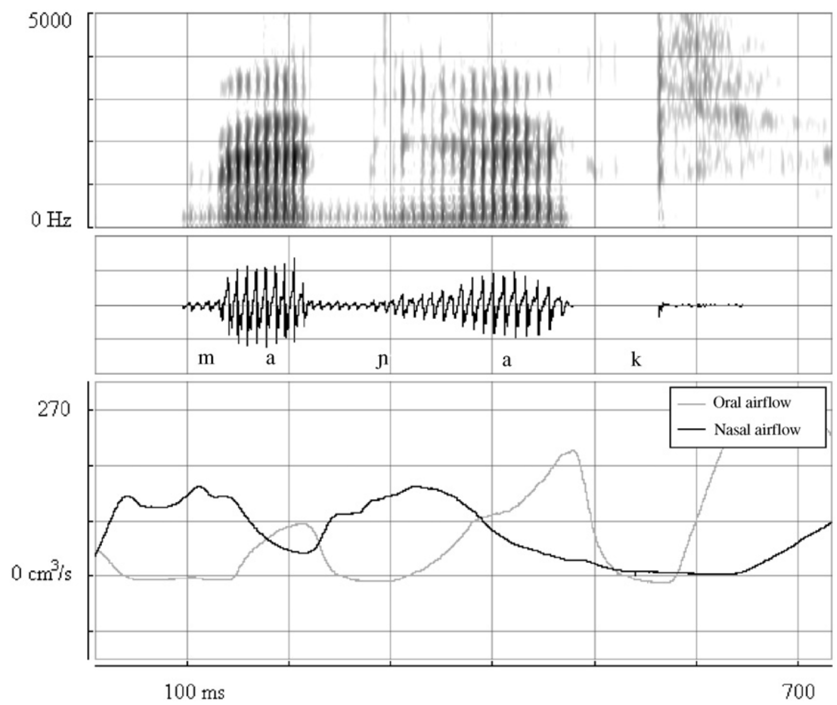

Fig. A3. Spectrogram, acoustic waveform and oral and nasal airflow outlines for /maɲak/ (male speaker S7).

Table A1
Corpus: items involving oral vowels in an oral context

		ε		a		o	
CV	p_	paix	*peace*	pas	*step*	pot	*pot*
	b_	baie	*berry*	bas	*low*	bot	*club (foot)*
	t_	tait	*(he) doesn't mention*	ta	*your*	tôt	*early*
	d_	des	*some*	dada /da.da/	*pet topic*	dos	*back*
	k_	quai	*platform*	cas	*case*	coco /ko.ko/	*bloke*
	g_	gai	*happy*	gars	*fellow*	cargo /kaʀ.go/	*cargo boat*
	f_	fait	*fact*	fa	*F*	faux	*false*
	v_	vais	*(I) go*	va	*go*	vos	*your*
	s_	c'est	*it is*	sa	*her*	sot	*idiot*
	z_	fusait /fy.zε/	*(it) bursted out*	Zaza /za.za/	*Zaza*	zozo /zo.zo/	*nitwit*
	ʃ_	lâchait /la.ʃε/	*(it) let go*	chat	*cat*	chaud	*hot*
	ʒ_	geai	*jay*	déjà /de.ʒa/	*already*	Jojo /ʒo.ʒo/	*Jojo*
	R_	rai	*ray*	rat	*rat*	rot	*burp*
	l_	laid	*ugly*	là	*there*	vélo /ve.lo/	*bike*

Table A2
Corpus: items involving oral vowels in a nasal context

		i	e	ε	a	ɔ	o	u	y
NV	m_	mis	mémé /me.me/	mais	ma	mot	maux	mou	mu
	n_	nid	nez	naît	na	nos	panneau /pa.no/	nous	nu
VN	_m	dîme /dim/	ému /e.my/	aime	âme	homme	Beaune /bon/	boum /bum/	hume
	_n	fine /fin/	énorme /e.nɔʀm/	haine	Anne	tonne	heaume	foufoune /fu.fun/	une
NVN	m_m	mime		même	hammam /a.mam/	môme			
	n_n	Lenine /le.nin/		naine	banane /ba.nan/	nonne			
	m_n	mine		mène	manne	Simone /si.mɔn/			
	n_m	Nîmes		phonème /fɔ.nεm/	Viêt Nam /vjεt.nam/	bonhomme /bɔ .nɔm/			

Table A3
Corpus: items involving nasal vowels in oral and nasal contexts

		ε̃		ɑ̃		ɔ̃	
CṼ	p_	pain	*bread*	paon	*peacock*	pont	*bridge*
	b_	bain	*bath*	banc	*bench*	bon	*good*
	t_	teint	*complexion*	temps	*weather*	thon	*tuna*
	d_	daim	*deer*	dans	*in*	don	*gift*
	k_	coquin /kɔ.kε̃/	*rascal*	quand	*when*	con	*stupid*
	g_	gain	*earnings*	gant	*glove*	gond	*hinge*
	f_	fin	*thin*	faon	*fawn*	font	*(they) do*
	v_	vin	*wine*	vent	*wind*	vont	*(they) go*
	s_	saint	*saint*	sang	*blood*	son	*sound*
	z_	fusain /fy.zε̃/	*charcoal*	faisan /fœ.zɑ̃/	*pheasant*	faisons /fœ.zɔ̃/	*(we) do*
	ʃ_	machin /ma.ʃε̃)/	*thing*	chant	*song*	manchon /mɑ̃.ʃɔ̃/	*muff*
	ʒ_	geint	*(he) wipes*	gens	*people*	jonc	*rush*
	R_	rein	*kidney*	rend	*(he) keeps*	rond	*round*
	l_	lin	*linen*	lent	*slow*	long	*long*

Table A3 (*continued*)

		ɛ̃		ɑ̃		ɔ̃	
CṼC	t_t	teinte	*shade*	tante	*aunt*	tonte	*mowing*
	p_t	peinte	*painted*	pente	*slope*	ponte	*laying*
	p_s	pince	*pliers*	panse	*belly*	ponce	*pumice*
CṼ.CV	t_.te	teinter	*to tinge*	tenter	*to attempt*	ton thé	*your tea*
NṼ	m_	main	*hand*	ment	*(he) lies*	mon	*my*
	n_	nain	*dwarf*	manant /ma.n̲ɑ̃/	*peasant*	non	*no*

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