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Compensatory articulation in American English nasalized vowels

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ABSTRACT

In acoustic studies of vowel nasalization, it is sometimes assumed that the primary articulatory difference between an oral vowel and a nasal vowel is the coupling of the nasal cavity to the rest of the vocal tract. Acoustic modulations observed in nasal vowels are customarily attributed to the presence of additional poles affiliated with the naso-pharyngeal tract and zeros affiliated with the nasal cavity. We test the hypothesis that oral configuration may also change during nasalized vowels, either enhancing or compensating for the acoustic modulations associated with nasality. We analyze tongue position, nasal airflow, and acoustic data to determine whether American English /i/ and /a/ manifest different oral configurations when they are nasalized, i.e. when they are followed by nasal consonants. We find that tongue position is higher during nasalized [ĩ] than it is during oral [i] but do not find any effect for nasalized [ã]. We argue that speakers of American English raise the tongue body during nasalized [ĩ] in order to counteract the perceived F1-raising (centralization) associated with high vowel nasalization.

1. Introduction

1.1. Compensation and enhancement in speech production

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 & Eefting, 1992). This covariation, compensation, or inter-articulatory coordination is also known as 'motor equivalence' (Abbs, 1986; Hughes & Abbs, 1976; MacNeilage, 1970; Perkell, Matthies, Svirsky, & Jordan, 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 & Gracco, 1984; Löfqvist, 1990; *inter alia*).

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 strengthen a particular acoustic property (Diehl & Kluender, 1989; Diehl, Kluender, Walsh, & Parker, 1991; Diehl, Molis, & Castleman, 2001; Kingston & Diehl, 1994; Kluender, 1994; Parker, Diehl, & Kluender, 1986). In addition to basic articulatory and acoustic information, speakers may store in memory information about how to enhance the contrasts between sounds (Keyser & Stevens, 2006); it is reasonable that speakers even store information about how to compensate for "contextual perturbation", arising from the phonetic environment (Ohala, 1993, p. 245). In this study, we test the hypothesis that English speakers adjust tongue height, either to compensate for or enhance one acoustic change caused by contextual nasalization.

1.2. Acoustics of vowel nasalization

The acoustic changes associated with nasalization have drawn considerable attention (Chen, 1973, 1975; Delattre, 1954; Fant, 1960; Feng & Castelli, 1996; Fujimura, 1961; Fujimura & Lindqvist, 1971; Hawkins & Stevens, 1985; House & Stevens, 1956; Kataoka, Warren, Zajaz, Mayo, & Lutz, 2001; Lonchamp, 1979; Maeda, 1993, 1982; Pruthi, Epsy-Wilson, & Story, 2007; Stevens, Fant, & Hawkins, 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). Nevertheless, 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

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passages is another source of extra pole-zero pairs (Stevens, 1998, p. 190).

According to a model based on sweep-tone measurements of vocal tract output, "all formants of a nasalized vowel shift monotonically upwards" with increased velopharyngeal opening (Fujimura & 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, Kluender, & Walsh, 1990). 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 may manifest a lowered F1. In American English, vowels in vowel+nasal sequences (VN) are often heavily nasalized (Bell-Berti, 1980; Bell-Berti & Krakow, 1991; Cohn, 1990; Krakow, 1993). Under these circumstances we expect F1-lowering for low vowels and F1-raising for high vowels.

1.3. *Perception of vowel nasalization*

The perceptual impact of nasalization has been studied in great depth, as well (Beddor & Hawkins, 1990; Beddor, Krakow, & Goldstein, 1986; Hawkins & Stevens, 1985; Huffman, 1990; Kataoka et al., 2001; Maeda, 1993). Ito, Tsuchida, and Yano (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. 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 lowest pole associated with the nasal transfer function, sometimes referred to as the nasal formant, has been shown to "merge" with the lowest pole of the oro-pharyngeal transfer function in the perceptual response of listeners (Maeda, 1993). Since the frequency of the perceived F1 may or may not be the same as the actual F1 of the oral transfer function, we refer to the perceived F1 of a vowel (oral or nasalized) as F1′. In cases where F1 is high (for low vowels like /a/) the effect of nasalization is to lower F1′ (if nasalization is more than merely moderate); in cases where F1 is low (for high vowels like /i/) the effect is to raise F1′. 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, 1983, pp. 91–104).

Krakow, Beddor, and Goldstein (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). Because there are two articulatory mechanisms which can independently modulate F1′, it may be possible for listeners to confuse these mechanisms when attending to nasal vowel quality.

Wright (1975, 1986) found that listeners may indeed 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] (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. Krakow et al. (1988) and Beddor et al. (1986) demonstrate that the acoustic modifications associated with increased velopharyngeal aperture can indeed be attributed to changes in oral tract configuration, though only for non-contextually nasalized vowels. They argue that misinterpretation of nasalization in terms of oral 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) and Macmillan, Kingston, Thorburn, Walsh Dickey, and Bartels (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.

1.4. *Lingual articulation of nasal vowels*

Aside from the so-called velic opening hypothesis (VOH; see Section 4.3), in much of the literature on vowel nasalization, oral and nasalized vowel congeners (e.g. [i] and [ĩ]) are often compared as if the only substantive physical difference between the two is coupling between the naso-pharyngeal and oral tracts (Morais-Barbosa, 1962; Narang & Becker, 1971; Paradis & Prunet, 2000). In other words, it is often assumed that nasal vowels are produced with the same lingual configuration 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 & Castelli, 1996; Pruthi et al., 2007; *inter alia*), the inputs to the model typically differ only in the degree of nasal-oral coupling.

In the description of nasal or nasalized vowels, 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 (Engwall, Delvaux, & Metens, 2006; Rong & Kuehn, 2010).

The reason for the absence of oral dynamics in the nasality literature 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] Without knowing the precise velopharyngeal aperture and the complex nasal geometry of the speaker, sorting out the naso-pharyngeal and nasal transfer functions from the oro-pharyngeal transfer function may be an intractable problem. One solution is to physically map the oral configuration and determine whether oral differences emerge under oral and nasal conditions, an option we investigate here.

There is a limited amount of research describing the coarticulatory link between velopharyngeal coupling and oral articulation. French nasal vowel articulation has come under primary focus (Bothorel, Simon, Wioland, & Zerling, 1986; Delvaux, Demolin, Harmegnies, & Soquet, 2008; Engwall et al., 2006; Maeda, 1993; Zerling, 1984). Using X-ray tracings of the vocal tract profiles of

[1] The Nasometer II (previously the Nasometer), marketed by KayPENTAX (Lincoln Park, NJ), presents one potential solution: record audio simultaneously using two microphones, one positioned at the lips and one at the nostrils, with the microphones separated by a plate resting on the upper lip and perpendicular to the face (Bae, Kuehn, & Ha, 2007; Dalston, Warren, & Dalston, 1991).

two male speakers, Zerling (1984) observed that the tongue body was slightly more retracted during the productions of the French nasal vowels [ɑ̃] and [ɔ̃] than during the production of their oral congeners. Tongue retraction for [ɔ̃] was more consistent across the two speakers. In a more recent study of Belgian French, Engwall et al. (2006) used MRI to observe lingual shape and position differences for nasal versus oral vowels. These articulatory differences were found across and within speakers. Speakers who produced the oral–nasal pair differently tended to retract and raise the tongue body for the nasal vowels. This articulatory configuration resulted in an enlargement of the oral cavity in front of the tongue constriction. The authors posit that these articulatory adjustments may be employed by speakers as a means of shifting the formants associated with the transfer function of the oral cavity, preventing them from being canceled out by nasal zeroes and thereby preserving vowel quality when the vowels are nasalized (Engwall et al., 2006, p. 7). Conversely, Maeda (1993, p. 163) argues that Zerling's (1984) evidence of gestural enhancement suggests a configuration intended to lower F1 in order to match the antiformant frequency of the nasal tract transfer function.

What emerges from this body of work is the need for a combination of both acoustic and physiological measures in order to observe as many aspects of vowel nasalization as possible. Specifically, simultaneous measurement of sound pressure, nasopharyngeal coupling, and lingual articulation is, to our knowledge, a novel method in speech research, one which is well suited to the study of vowel nasalization.

1.5. Interactions of acoustics and articulation in nasal vowels

Although vowel nasalization is characterized by various acoustic cues, in this paper we will focus on F1 because of its well-known correlation with tongue height. F1 frequency is largely determined by the vertical position of the tongue in the oral cavity (Perkell & Nelson, 1985; Stevens, 1998). Stevens (1998, pp. 261–262, 268–270) observes that there is an inverse correlation between F1 frequency and height of the tongue body for vowels. Because F1 has a demonstrable effect on the percept of nasalization and can be attributed to either nasalization or tongue height, the articulatory trigger for a change in F1 in phonetically nasalized vowels can be ambiguous.

Using EMMA, Arai (2004, 2005) studied the acoustic and articulatory effects of anticipatory nasalization on the vowels [i, ɪ, ɛ, ʌ, æ, ɑ] in English nonce words. He found that F1 was raised under the influence of nasalization for all of the vowels. For the low vowel [ɑ] the nasal formant was observed at frequencies lower than F1, and became dominant as the velopharyngeal port opening increased, thus effectively lowering the energy of F1. With regard to articulatory effects, he found that /ɑ/ was the only vowel that exhibited any articulatory change when nasalized. This vowel was produced with a lower tongue dorsum in the nasal context. Arai posits that this may be a compensatory articulation for lower energy surrounding F1 due to nasalization: "this speaker might have tried to make a more extreme /ɑ/ to compensate for the F1 shift due to nasalization" (2004, p. 45). Arai's results are limited to a total of 60 observed utterances from one speaker. Additionally, nasalization is assumed to be constant throughout the vowel.

1.6. Research hypothesis

We test the hypothesis that English speakers adjust tongue height, either to compensate for or enhance the change in F1 due to nasalization of the vowels /a/ and /i/ in English VN sequences. Evidence of compensation might include: (a) higher tongue position during nasalized [ĩ] (lowering F1); or (b) lower tongue position during nasalized [ã] (raising F1). Evidence of enhancement might include: (a′) lower tongue position during nasalized [ĩ] (raising F1); or (b′) higher tongue position during nasalized [ã] (lowering F1). Based on Arai's (2004, 2005) findings for one speaker, we predict that the speakers in our study will adjust tongue height in order to compensate for the acoustic effect of nasalization on F1′: raising the tongue for nasalized /i/ and lowering the tongue for nasalized /a/.

We have chosen to investigate English for two reasons. First, vowels in VN sequences are often heavily nasalized in English, allowing for lingual articulation to be observed in a relatively large proportion of the vowel. Second, in the current study we are interested in the phonetics of allophonic vowel nasalization. In English, we can observe the purely synchronic aspects of lingual interaction with contextual vowel nasalization. By "purely synchronic", we mean that the lingual articulation of phonemic nasal vowels such as those in French, for example, has been influenced by diachronic evolution. Any possible lingual articulations which may have, at one time, been phonetic responses to contextual nasalization (i.e., purely synchronic) have since been phonologized (in the sense of Hyman, 2008). However, it should be noted that somewhat orthogonal research questions pertain to the study of oral co-articulation in phonemic nasal vowels, where diachronic processes may have already solidified particular oral tract configurations that may serve to enhance nasalization and/or better distinguish oral–nasal vowel pairs (for Hindi, Shosted, Carignan, & Rong, submitted for publication; for French, Carignan, in preparation).

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, 1983; Hajek, 1997; Sampson, 1999). To the extent that the change in F1′ is indeed enhanced by speakers of American English through lingual articulation, we might speculate that vowel nasalization is on a clearer path to phonologization. Conversely, to the extent that the nasal change in F1′ is compensated for through lingual articulation, we might speculate that there is some resistance to the phonologization of nasality in VN sequences.

2. Methodology

2.1. Materials and speakers

2.1.1. Materials

108 CVC nonce words were used as stimuli. These tokens had two types of nuclei (/a/ and /i/), six types of onset consonant (/p/, /b/, /t/, /d/, /k/, and /g/), and nine types of coda consonant (/p/, /b/, /m/, /t/, /d/, /n/, /k/, /g/, and /ŋ/). Inevitably, this variation resulted in some words which are homophones of real words (e.g., "beem" = *beam*), some words which were homographs of real words but pronounced differently (e.g., "been"), and some words which were both homophones and homographs of real words (e.g., "teen"). In order to minimize any lexical effects from these words, the participants were instructed during the initial training that they should behave as if they were teaching nonsensical words to a child and that they were to pronounce them according to phonetic, not lexical, criteria. Regarding the phonetic realization of the vocalic nuclei in a variety of contexts, it is true that lax vowels generally occur before /ŋ/ in American English. However, Ladefoged (1993, p. 88) points out that many young speakers produce /i/ before /ŋ/. The training was monitored by two native-English speaking experimenters (the first and second author), who agreed that the speakers successfully followed the instructions by producing /i/ and not /ɪ/ preceding /ŋ/.

Onset consonants varied in terms of place and manner of articulation, as well as in voicing. This variation was included in order to avoid any particular consonant exerting perseverative acoustic and articulatory effects on the target. Vowels occurring before labial, alveolar, and velar nasal coda stops can be compared to oral stops at the same places of articulation (POA).[2]

Blocks of the 108 individual stimuli were repeated three times. Each block was internally randomized for each speaker. This amounted to 324 tokens produced by each speaker. Each token (X) was embedded in the carrier phrase, ‘‘Say X again’’. The tokens were presented to the participants on a computer screen as a series of slides in Microsoft PowerPoint 2003. In the presentation materials, the vowel /i/ was represented orthographically by ‘ee’ and the vowel /a/ was represented orthographically by ‘ah’. The velar nasal /ŋ/ was represented by ‘ng’. The participants learned these conventions during a practice session. Participants were instructed to read sentences aloud at a comfortable speed and in a normal volume. During the practice session they read six example sentences of the type ‘‘Say X again’’. These practice sentences were monitored by the experimenters to ensure that participants produced the words according to phonetic, not lexical criteria.

2.1.2. Speakers

Five male speakers of American English between the ages of 22 and 65 participated in the study (median age 25). Speakers reported no hearing or speech deficits. Given the variation observed in the articulation of vowel nasalization between male and female speakers (Engwall et al., 2006), we decided to minimize this variation insofar as possible by recording only male speakers.

One speaker (Speaker 4, age 27) was excluded because he produced a large number of non-nasal vowels followed by a nasal consonant. 22/108 (20.4%) nasal tokens for this speaker manifested either no anticipatory nasalization or anticipatory nasalization less than the duration of a single glottal pulse. In the absence of contextual vowel nasalization, comparison between oral and nasalized vowels for this speaker would not be equivalent to the comparisons made for other speakers, i.e. a relatively large number of tokens would have to be excluded.

2.2. Equipment

2.2.1. Acoustics

The acoustic signal was pre-amplified and digitized at 16 kHz using a Countryman Isomax E6 directional microphone (Countryman Associates, Inc., Menlow Park, CA) positioned 4–5 cm from the corner of the mouth and an M-Audio Fast Track Pro preamplifier.

2.2.2. Carstens AG500 electromagnetic articulograph

The Carstens AG500 electromagnetic articulograph (EMA) system (Hoole & Zierdt, 2006; Hoole, Zierdt, & Geng, 2007; Yunusova, Green, & Mefferd, 2009) creates and sustains a controlled electromagnetic field inside a clear Plexiglas cube. The AG500 can record the location of up to 12 sensors in a three-dimensional space (plus yaw and tilt), with a median error of less than 0.5 mm (Yunusova et al., 2009). The electromagnetic amplitude/position data is recorded and automatically downsampled to 200 Hz.

Three sensors were fixed along the midline of the participant’s tongue, beginning 1 cm from the tongue tip. The other two sensors were placed at even intervals of 1–2 cm, depending on the length of the participant’s tongue. A surgical pen was used to mark the placement of the sensors before gluing them.[3] These three sensors were used for measuring the respective positions of the ‘‘tongue tip’’ (TT), ‘‘tongue midpoint’’ (TM), and ‘‘tongue back’’ (TB). Measures of the *z*-dimension (inferior/superior) displacement were used to infer the height of these three portions of the tongue. Additionally, 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 movement relative to the position of the head. Details about the calibration of the AG500 system are provided in Appendix A.

2.2.3. Aerodynamic system

Measurement of nasal pressure/flow allows for an inferential and indirect measure of velopharyngeal aperture during speech production. The onset of nasal flow can serve as an objective measurement of the onset of vowel nasalization across tokens for a given speaker, something that cannot be easily derived from the acoustic signal alone (Leeper, Tissington, & Munhall, 1998; Shosted, 2009; Warren & Dubois, 1964; Warren & Devereux, 1966; Yates, McWilliams, & Vallino, 1990). In order to measure nasal flow, participants wore a vented Scicon NM-2 nasal mask (Scicon R&D, Inc., Beverly Hills, CA; cf. Rothenberg, 1977). The mask was secured laterally using a Velcro strap running behind the ears and fastened at the back of the head; the mask was secured medially by a strap running from the top of the mask over the forehead and fastened at the back of the head. A tube (3 m long, 4 mm ID)[4] was connected to the open outlet of the nasal mask on one end and a Biopac TSD160A (operational pressure ± 2.5 cm H_2O; Biopac Systems, Inc., Goleta, CA) pressure transducer on the other. The resulting signal was digitized at 1 kHz and recorded using custom-written scripts (Sprouse, 2006) running in Matlab (version 7.11, The MathWorks, 2010) that accessed functions native to Matlab’s Signal Processing Toolbox (V6.8). Details about the calibration of the aerodynamic system are provided in Appendix A.

2.2.4. System synchronization

The EMA and aerodynamic data were synchronized using the signal generated by the Sybox-Opto4 unit included with the AG500 articulograph. Synchronization was performed automatically with the native Carstens recording software, using voltage pulses at the beginning and at the end of each sweep. The signal carrying these pulses was split using a BNC Y-cable splitter and the duplicate signal was sent to the BNC-2110 (aerodynamic) data acquisition board. The sync signal was captured simultaneously with the aerodynamic data (sampling rate: 1 kHz). A custom Matlab script automatically identified the time points of the pulses and parsed the aerodynamic data between them. These parsed aerodynamic signals were later combined with the EMA and acoustic signals in Matlab data structures for routine analysis using custom scripts written by the second author.

[2] In what follows, we will refer to the place of articulation of the coda consonant only as ‘‘POA’’.

[3] Sensors occasionally became detached during the course of an experiment. On these occasions (typically once per session) the sensors were replaced according to the marks made with the surgical marker.

[4] Pressure variations are transmitted at near the speed of sound (approximately 35,000 cm/s) in the tube. Therefore, the length of the tube was not considered problematic, e.g. in terms of delayed response with respect to the audio and EMA signals (p.c. Aleksandar Dimov, Applications Specialist, Biopac Systems, Inc.). Indeed, a shorter tube was not feasible since metal objects and computer hardware must be removed from the vicinity of the emitter array to prevent disruption of the electromagnetic field. The length of the tube altered the tube’s transfer function, of course, but the high frequencies of the sound pressure wave were not directly relevant to the experiment.

2.3. Annotation

Each token was marked by hand with three points: (1) the vowel onset; (2) the onset of anticipatory nasalization; and (3) the vowel offset. Vowel onset was chosen based on the onset of regular modal vibration found in the sound pressure signal after consonant release. The vowel offset (i.e. end of the vowel) was chosen based on the sound pressure characteristics associated with the final stop, which was voiced, voiceless, or nasal. In the case of voiceless coda, the cessation of voicing was used as a boundary. In the case of voiced and nasal consonants the decrease in amplitude or dramatic change in wave shape was used as a boundary.

The onset of anticipatory nasalization in nasal tokens was chosen manually. A 5th order Butterworth, 75 Hz lowpass digital filter was applied to the nasal flow signal. The first differential (velocity or instantaneous rate of change; Estep, 2002) of the filtered signal was then calculated. A threshold was set at 20% above the average filtered nasal flow velocity for the sweep. The onset of nasalization was specified as the first positive velocity peak above this threshold which occurred after voice onset of the vowel. Locating a peak after vocalic voice onset was crucial to avoid choosing a velocity peak associated with velopharyngeal leakage during onset release. Fig. 1 provides a graphic example of the annotation and the temporal comparison of the acoustic, articulatory, and aerodynamic signals for one of Speaker 5's tokens of /bim/.

Working separately under the protocol described above, two annotators (the first and fourth authors) selected these boundaries: one annotated three speakers and the other annotated two. Both annotators also cross-annotated 10% of the data tokens (randomly selected) from each speaker in order to calculate inter-annotator reliability. The two annotators were judged to perform in a consistent and reliable manner in selecting the three boundaries. For the first boundary (vowel onset) the median difference between the points chosen by the two annotators was 6.29 ms. For the second boundary (nasalization onset) the median difference was 6.25 ms. For the third boundary (vowel offset) the median difference was 4.45 ms. Given the low f0 of the male speakers in this study, the median difference between the points chosen by the two annotators accounted for less than the length of a typical glottal pulse.

Our primary interest lay in characterizing lingual differences between nasalized and oral vowels. By definition this meant comparing a portion of the vowel in nasal contexts to a vowel (or portion thereof) in oral contexts. Comparing a portion of the vowel in nasal contexts to the entire vowel in oral contexts seemed unsuitable. Data associated with the vowel in oral contexts would include acoustic and lingual characteristics influenced by the token's onset consonant while the portion of the vowel in nasal contexts might not. Because some of our measures dealt with the trajectory of the tongue or some normalized aspect of lingual position during the vowel, we found it necessary to limit the coarticulatory effects of the onset consonant on our measures. The three repetitions of each speaker's token type (e.g. Speaker 1's /kam/) were used to calculate an average proportion of the vowel that was nasalized. This average proportion was then applied to the vowels of the corresponding oral tokens (e.g. Speaker 1's three repetitions of /kab/ and /kap/) and it was this portion of the oral vowel that was used for measurement. For example, if the nasalized proportion of the three repetitions of /kam/ for a given speaker was found to be on average 70% of the vowel, this portion of the nasalized vowel in each repetition of /kam/ was compared to 70% of the vowel in each repetition of /kab/ and each repetition of /kap/, calculated leftwards from the vowel offset. Since vowels preceding voiced obstruents are longer than those preceding voiceless obstruents in English, this method allowed for a normalized comparison between all words. The average measurements and standard

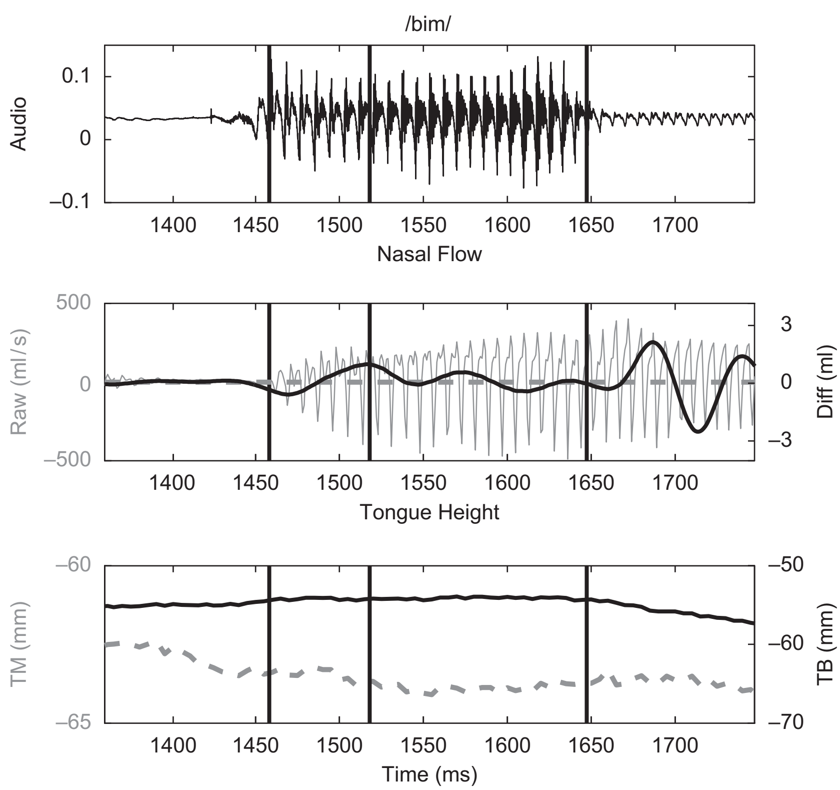

Fig. 1. Annotation of /bim/ (Speaker 5). The audio signal is shown in the top frame. The nasal airflow signal is shown in the middle frame, with the raw signal in gray and the filtered velocity in black. The EMA signal is shown in the bottom frame, with TM in gray (dashed) and TB in black (solid). For all channels, the leftmost black line is the beginning of the vowel, the rightmost black line is the end of the vowel, and the middle black line is the onset of nasalization.

Table 1
Table of means and standard deviations (in parentheses) of total vowel duration (ms) in nasalized context, duration of nasalized portion of the vowel, and nasalized proportion of the vowel.

Vowel	POA	Vowel (ms)	Nasalized portion (ms)	Proportion
a	Alveolar	198 (31)	143 (36)	0.72 (0.14)
	Bilabial	179 (32)	126 (34)	0.71 (0.14)
	Velar	185 (39)	127 (44)	0.68 (0.18)
i	Alveolar	181 (50)	124 (43)	0.68 (0.14)
	Bilabial	167 (40)	117 (35)	0.71 (0.14)
	Velar	174 (52)	123 (46)	0.71 (0.15)

deviations of the vowel durations (in ms) of vowels in the nasalized context, of the nasalized portion of the vowel (in ms), and of the nasalized proportion of the vowel are given in Table 1. The measurements shown in the table are collapsed across speakers (all except Speaker 4, who was excluded from the final analysis) and separated by vowel and by place of articulation of the nasal coda consonant.

2.4. Articulatory measures

The data were measured and normalized using both native and custom-written functions in Matlab. All measures dealt with the *z*-dimension (inferior–superior) of the lingual sensors: TT, TM, and TB.

Next, data were to be fitted with polynomials in order to measure characteristics of the curves associated with each sensor's trajectory. The time-varying position data for each sensor were automatically divided into ten contiguous frames (each one-tenth the length of the original token). Samples were averaged inside each frame to generate exactly ten samples for each token. The average position during the fifth frame (which we will refer to as "Mid"; e.g., "TM Mid" means the position of the tongue midpoint sensor value in this frame) was logged. Next, the value of the first frame was subtracted from the value of all ten frames so that for each normalized series the first sample was reduced to zero. The first frame was chosen in order to normalize as far away from the nasal trigger as possible. Our research question involves observing possible lingual responses to anticipatory nasalization in word-final VN sequences. Normalizing closer to the nasal consonant (e.g. the fifth or the tenth frame) would mask any possible differences in lingual position in these regions. After normalization, a second-degree polynomial was fitted to each normalized series and the second coefficient of each function was logged. A visual representation of this normalization and polynomial-fitting procedure is given in Fig. 2. The second, or *b*-coefficient, is the slope of the line tangent to the quadratic function at its *y*-intercept (Estep, 2002; for a phonetic application see Andruski & Costello, 2004). If the *b*-coefficient is positive then it indicates an upward trajectory. The higher the absolute value of the *b*-coefficient, the steeper the curve. The *b*-coefficient is thus broadly descriptive of a sensor's trajectory, incorporating whether the sensor is moving up or down with its speed. Finally, the resulting functions were integrated using Simpson's adaptive quadrature. The integral can be taken as the total articulatory movement during the annotated (nasalized/corresponding oral) portion of the vowel.

Sensor errors were detected by visually inspecting sensor trajectories of each vowel in each onset condition for outliers. Inaccurate position estimates occur when sensor wires twist or approach an emitter too closely, or when the position estimation software fails to find a good solution. Error rates for each lingual sensor were found to be less than 10%. Tokens that manifested these errors were removed from the data set prior to further analysis. Because EMA sensors may manifest errors independently of one another, it was only necessary to exclude tokens

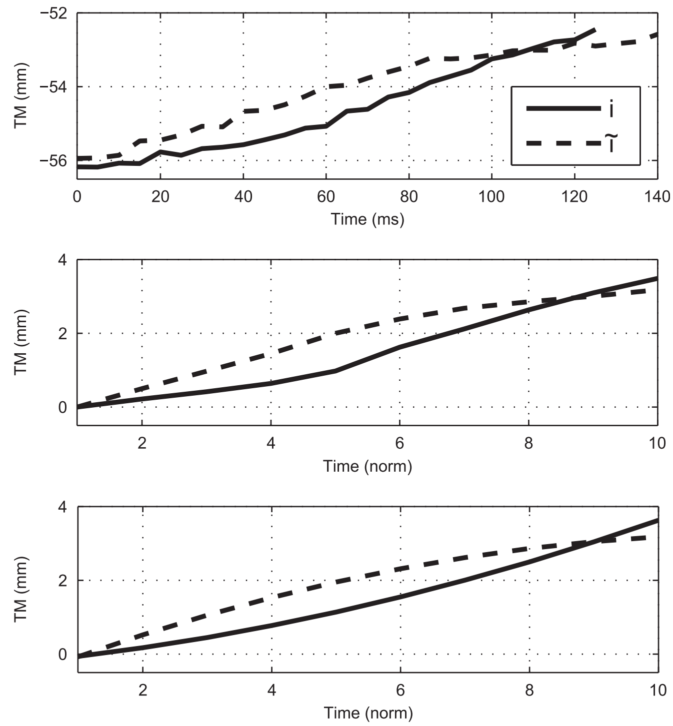

Fig. 2. Step-by-step normalization of TM sensor position during tokens /piŋ/ (dotted line) and /piɡ/ (solid line). Top frame is raw data. Middle frame is data normalized to 10 average data points on the *x*-axis; on the *y*-axis data is normalized by subtracting the value of the first (non-normalized) data point from all (non-normalized) data points (so all normalized signals start at the origin). Bottom frame shows second-degree polynomials fitted to the normalized data (note that the polynomials may not have the same *y*-intercept). Data shown is for Speaker 3.

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 TT but not TM.

2.5. Acoustic measures

Due to the addition of poles and zeros in the transfer function of nasalized vowels, traditional LPC analysis may be problematic for detection of F1. Previous studies (Beddor & Hawkins, 1990; Ito et al., 2001; Kataoka et al., 2001; Maeda, 1993) suggested that the overall spectral shape might play a more important role in characterizing vowel nasalization than individual formants do, especially in terms of perception. A reliable measurement of overall spectral shape is the center of gravity (COG) of a spectrum, which is a measurement of the average frequency weighted by amplitude. The inclusion of an additional pole in the region surrounding F1 can change the COG of this region without necessarily changing the frequency of F1 itself. Since nasalization introduces additional poles and zeros to the oral transfer function, and since F1 does not necessarily change when these poles and zeros are added, measuring the COG in the region of F1 is a way of measuring the change of the frequency of the energy around F1 in terms of both production and perception. COG was calculated using a window whose temporal midpoint coincided with the temporal midpoint of the observed portion of each vowel. The window length was 50% the length of the observed portion of the vowel such that 25% of the observed portion of the vowel on both the left and right edges was excluded from the calculation. COG was calculated in the band 0–1000 Hz for /a/ and 0–500 Hz for /i/ to include F1, along with its left and right skirts, for both vowels.

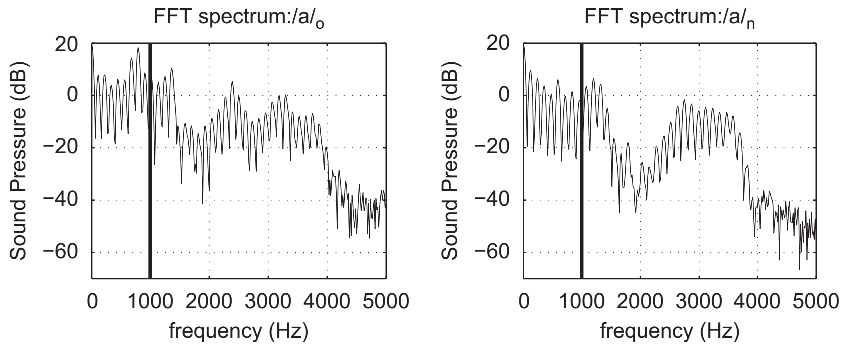

Fig. 3. Spectra of oral /a/ in the token /ɡad/ (left) and nasal /a/ in the token /tan/ (right) (Speaker 5). The vertical line represents the frequency cutoff for calculation of COG.

Therefore, COG was computed according to the following formulae, for /a/ and /i/, respectively:

$$COG_a = \frac{\int_0^{1000} f|S(f)|^2\,df}{\int_0^{1000} |S(f)|^2\,df}$$

$$COG_i = \frac{\int_0^{500} f|S(f)|^2\,df}{\int_0^{500} |S(f)|^2\,df}$$

where $|S(f)|^2$ is the power spectrum. The calculation was performed in Matlab using a script written by the fourth author. Graphical examples of the frequency range included below the cutoff frequency for the vowel /a/ are given in Fig. 3 for two spectra of /a/ (oral on the left, nasal on the right) with the same coda POA, as produced by Speaker 5.

2.6. Statistical analysis

Once tokens with relevant errors have been excluded from the data set, linear mixed-effects (LME) models were designed for each vowel and for each measure individually using the LME function in the nlme package of R 2.8.1 (R Development Core Team, 2008). In each analysis, the articulatory measure (e.g., minimum TM position) was the dependent variable with consonantal nasality (oral/nasal) and consonantal place of articulation (bilabial/alveolar/velar) as fixed effects. The interaction between nasality and place of articulation was also included as a fixed effect. Speaker and repetition were included in the model as random effects, thus obviating the need to average across repeated measures (Baayen, Davidson, & Bates, 2008). For analysis of COG, linear mixed-effects models were designed with COG as fixed effect and other effects as described above.

In a number of studies, it has been found that labial, mandibular, and lingual configuration differ for voiced, voiceless and nasal stops. Hamann and Fuchs (2010) found that, for speakers of German, /d/ is often produced with a more apical articulation than /t/ and has a more retracted place of articulation. Mooshammer, Philip, and Anja (2007) showed that /t/ is produced with a more fronted and sometimes higher tongue tip than /d/ and /n/. Jaw position was also found to be higher for /t/ than for /d/ and /n/ in numerous studies (Dart, 1991; Keating, Lindblom, Lubker, & Kreiman, 1994; Lee, 1996; Mooshammer, Hoole, & Geumann, 2006). Because of these differences, we tested for effects associated with the voicing of the coda. Separate linear mixed-effects models were designed for oral-coda tokens; articulatory measure (e.g. TM mid) was the dependent variable and consonantal voicing (voiced/voiceless) was the fixed effect. Speaker and repetition were included as random effects.

3. Results

3.1. Articulatory results

Fig. 4 displays shapes of the tongue for Speaker 2, constructed using data from the three tongue sensors. The data in the figure have been normalized in height and are taken at the normalized temporal midpoint (Mid). The data points for TT, TM, and TB have been averaged across repetitions for visualization. The oral tongue shapes are displayed in black and the nasal tongue shapes are displayed in gray. These normalized shapes suggest that in general the body of the tongue is concave for /a/ and convex for /i/ (Stone and Lundberg, 1996).

Fig. 5 shows raw trajectories of TM during the annotated vowel portions for Speaker 3. The trajectories of the tongue articulation for the vowel /a/ are plotted on the top row and those for the vowel /i/ are plotted on the bottom row. Oral trajectories are displayed in black, and nasal trajectories are displayed in gray.

Normalized trajectories (as described in Section 2.4) are given in Fig. 6 for the same data shown in Fig. 5. The trajectories of the tongue articulation for the vowel /a/ are plotted on the top row and those for the vowel /i/ are plotted on the bottom row. Oral trajectories are displayed in black, and nasal trajectories are displayed in gray.

The four right-hand columns in Table 2 correspond to the variables that were significantly associated with nasality in the linear mixed-effects model for the vowel /i/. None of these variables generated significant results for the vowel /a/, so related measures for /a/ are not included. Rows in Table 2 include averaged observations and their standard deviations.

The linear mixed-effects model of the relationship between the normalized position of the tongue-mid sensor at the normalized midpoint of the observed portion of the vowel (TM Mid) and nasality, place of articulation (POA), suggested significant effects of both nasality [$F(1,626)=22.4$, $p<0.001$] and POA [$F(2,626)=144.4$, $p<0.001$] on the position of the tongue-mid sensor. The interaction term (nasality × POA) was not found to be significant. The standard deviation for the by-speaker random intercepts was estimated at 0.272 and the standard deviation for the by-repetition random intercepts was around 0.039. While the standard deviation for the fixed effects was 0.529, the intraclass correlation coefficient was estimated at 0.21, suggesting a moderate inter-speaker correlation. Therefore, introducing the by-speaker random effect explains a substantial amount of variance that cannot be explained by a multiple regression model. The coefficient for the intercept of the fixed effects is 1.129 (sd=0.150). The coefficient for nasality is −0.298 (sd=0.076), suggesting the mid sensor is higher in nasal vowels compared to oral vowels. The coefficient for POA is −0.874 (sd=0.088) for bilabials and −0.802 (sd=0.088) for velars, indicating that the mid sensor during bilabials is lower than it is during

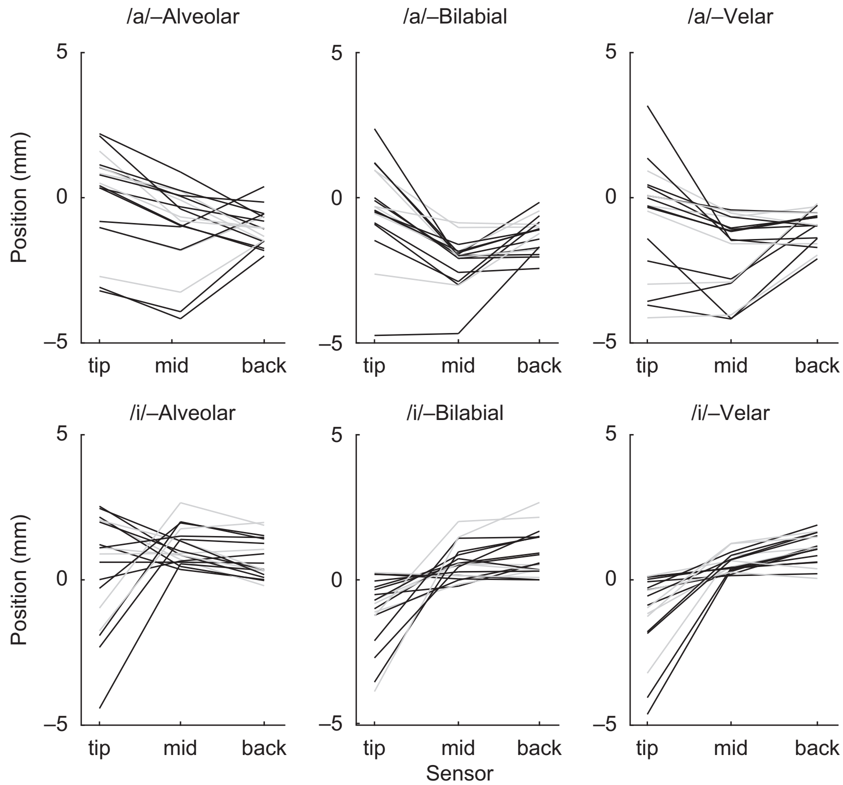

Fig. 4. Normalized vertical position of tongue sensors at the normalized temporal midpoint, averaged across repetitions (Speaker 2). Oral tongue shapes are in black, and nasal tongue shapes are in gray.

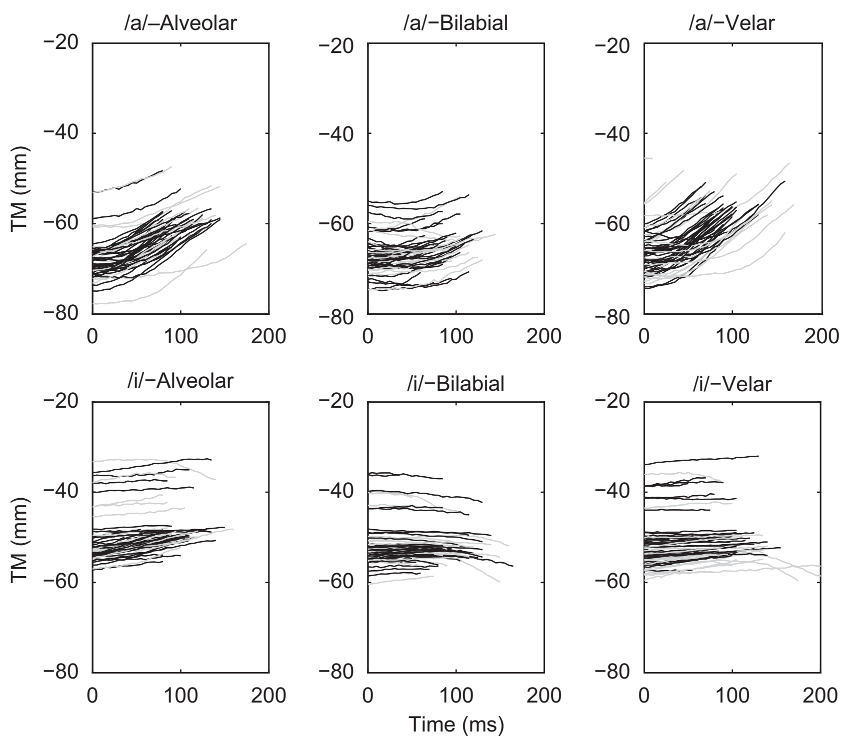

Fig. 5. TM sensor trajectories (raw, Speaker 3). Oral trajectories are in black, and nasal in gray.

alveolars and that the mid sensor is also lower during velars than it is during alveolars.

With regard to the relationship between integrated displacement (Integral) and nasality, POA, and the interaction between these two variables, significant effects of both nasality [$F(1,623)=13$, $p<0.001$] and POA [$F(2,623)=225$, $p<0.001$] were uncovered. The interaction term (nasality $\times$ POA) was not found to be significant. The standard deviations for the by-speaker and by-repetition random intercepts were estimated to be 1.811 and 0.709, respectively, while the standard deviation for the fixed effects was 5.159. The intraclass

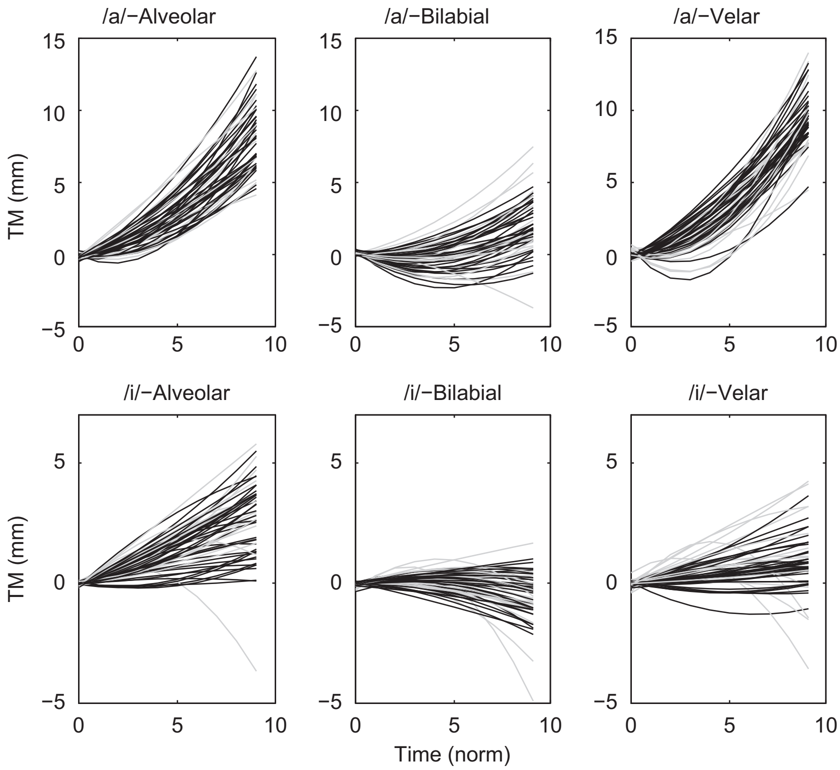

Fig. 6. TM sensor trajectories (normalized, Speaker 3). Oral trajectories are in black, and nasal in gray.

Table 2
Means and standard deviations of measures for significant variables found in linear mixed-effects model for the vowel /i/ (S=speaker).

Nasality	POA	S	TM mid (mm)	TM *b*-coeff	TM Integral	TB *b*-coeff
Nasal	Alveolar	1	0.58 (0.37)	0.13 (0.19)	6.63 (3.24)	0.16 (0.08)
Oral	Alveolar	1	0.55 (0.25)	0 (0.13)	6.76 (2.58)	0.18 (0.42)
Nasal	Bilabial	1	0.32 (0.12)	0.21 (0.04)	2.22 (1.54)	0.01 (0.45)
Oral	Bilabial	1	0.24 (0.2)	0.15 (0.11)	1.77 (1.66)	0.05 (0.37)
Nasal	Velar	1	0.01 (0.13)	0.05 (0.04)	−0.74 (1)	0.08 (0.04)
Oral	Velar	1	−0.09 (0.24)	0 (0.08)	−1.24 (2.03)	0.01 (0.08)
Nasal	Alveolar	2	1.2 (0.47)	0.32 (0.17)	12.36 (5.65)	0.3 (0.07)
Oral	Alveolar	2	0.94 (0.53)	0.21 (0.19)	10.3 (5.22)	0.2 (0.13)
Nasal	Bilabial	2	0.14 (0.34)	0.24 (0.17)	−0.65 (2.51)	0.31 (0.22)
Oral	Bilabial	2	0.04 (0.29)	0.11 (0.08)	−0.4 (3.23)	0.2 (0.14)
Nasal	Velar	2	0.88 (0.64)	0.37 (0.21)	6.86 (4.36)	0.42 (0.13)
Oral	Velar	2	0.26 (0.46)	0.02 (0.15)	3.16 (4.22)	0 (0.16)
Nasal	Alveolar	3	1.37 (0.74)	0.48 (0.27)	12.26 (6.86)	0.49 (0.29)
Oral	Alveolar	3	1.05 (0.57)	0.36 (0.22)	9.59 (5.03)	0.39 (0.24)
Nasal	Bilabial	3	0.76 (0.82)	0.45 (0.26)	4.85 (7.52)	0.49 (0.39)
Oral	Bilabial	3	0.48 (0.47)	0.3 (0.19)	2.81 (4.46)	0.36 (0.23)
Nasal	Velar	3	0.78 (0.41)	0.19 (0.12)	8.13 (3.24)	0.19 (0.19)
Oral	Velar	3	0.48 (0.26)	0.08 (0.08)	5.22 (2.55)	0.2 (0.2)
Nasal	Alveolar	5	1.37 (0.43)	0.01 (0.18)	17.72 (3.83)	0.27 (0.08)
Oral	Alveolar	5	0.78 (0.42)	−0.08 (0.21)	11.33 (4.54)	0.17 (0.07)
Nasal	Bilabial	5	−0.2 (0.25)	−0.13 (0.09)	−0.8 (2.1)	0.03 (0.05)
Oral	Bilabial	5	−0.21 (0.25)	−0.09 (0.09)	-0.93 (1.9)	0.03 (0.06)
Nasal	Velar	5	−0.38 (0.38)	−0.07 (0.14)	−4.34 (3.12)	0.03 (0.1)
Oral	Velar	5	−0.24 (0.24)	−0.03 (0.1)	−2.83 (1.97)	0.04 (0.04)

correlation coefficient was estimated to be around 0.124. By introducing the by-speaker random effects, the inter-speaker correlation was accounted for by the model. The coefficient for the intercept of the fixed effects is 12.243 (sd=1.110). The coefficient for nasality is −2.747 (sd=0.745), suggesting integrated displacement is greater in nasal vowels compared to oral vowels. The coefficient for POA is −10.839 (sd=0.860) for bilabials and −9.755 (sd=0.866) for velars, indicating that integrated displacement for bilabials is lower than it is for alveolars and that integrated displacement for velars is lower than it is for alveolars.

The linear mixed-effects model of the relationship between the *b*-coefficient (trajectory) of the tongue-mid sensor and nasality, POA, and the interaction term indicated significant effects of both nasality [$F(1,623)=30.9$, $p<0.001$] and POA [$F(2,623)=13.25$, $p<0.001$] on the trajectory. The interaction term (nasality × POA) was not found to be significant. The standard deviations for the by-speaker random and by-repetition intercepts were estimated to be 0.151 and 1.379e−5, respectively, while the standard deviation for the fixed effects was about 0.214. The intraclass correlation coefficient was estimated at 0.332, suggesting a moderate inter-speaker correlation. The coefficient for the intercept of the fixed effects is 0.233 (sd=0.080). The coefficient for nasality is −0.111 (sd=0.031), suggesting the trajectory of the tongue-mid sensor is steeper in nasal vowels compared to oral vowels. The coefficient for POA is −0.042 (sd=0.036) for bilabials and −0.097 (sd=0.036) for velars, indicating that the trajectory of the tongue-mid sensor for bilabials is flatter than it is for alveolars and that the trajectory for velars is flatter than it is for alveolars.

In terms of the relationship between *b*-coefficient (sensor trajectory) of the tongue-back sensor and nasality, POA, and the interaction between these two variables, significant effects of both nasality [$F(1,603)=6.5$, $p<0.05$] and POA [$F(2,603)=10.6$, $p<0.001$] were uncovered. The interaction term (nasality × POA) was not found to be significant. The standard deviations for the by-speaker and by-repetition random intercepts were estimated to be 0.116 and 1.615e−5, respectively, while the standard deviation for the fixed effects was about 0.341. The intraclass correlation coefficient was estimated to be around 0.104. The coefficient for the intercept of the fixed effects is 0.302 (sd=0.071). The coefficient for nasality is −0.062 (sd=0.05), suggesting the trajectory of the tongue back sensor is steeper in nasal vowels compared to oral vowels. The coefficient for POA is −0.105 (sd=0.058) for bilabials and −0.116 (sd=0.058) for velars, indicating that the trajectory for bilabials is flatter than it is for alveolars and that the trajectory for velars is flatter than it is for alveolars.

Generally speaking, the tongue-mid sensor was higher for the vowel /i/ when nasalized (Fig. 7). Additionally, the greater integrated displacement during nasalized /i/ suggests more upward movement for nasalized /i/ than for oral /i/ (Fig. 8).

The results indicate that the tongue body is raised during the nasalized portion of the vowel, a gesture associated with lower F1. This may suggest compensation for a perturbation associated with nasalization, i.e. raising of F1 during /i/.

3.2. Acoustics results

Linear mixed-effects models with COG as fixed effect and other effects as described above showed that nasality was significantly associated with COG for the vowel /a/ [$F(1,622)=107$, $p<0.001$] but not for /i/ ($p>0.05$). Neither POA nor the interaction between POA and COG were significant for either vowel. For /a/, the standard deviation for the by-speaker random intercepts was estimated as 90.298 and the standard deviation for the by-repetition random intercepts was around 0.006. The coefficients for the intercept of the fixed effects is 329.95 (sd=46.76). The coefficient for nasality is 108.82 (sd=14.9), suggesting that COG is lower in nasal versus oral /a/. Table 3 gives the means and standard deviations of COG by nasality, place of articulation, and speaker.

Table 3
Means and standard deviations of COG for the vowels /i/ and /a/ by nasality, place of articulation (POA), and speaker.

Coda POA	Speaker	/i/		/a/	
		COG (Hz) oral	COG (Hz) nasal	COG (Hz) oral	COG (Hz) nasal
Alveolar	1	143 (9)	150 (6)	539 (26)	342 (23)
Alveolar	2	232 (7)	224 (7)	487 (24)	522 (25)
Alveolar	3	102 (11)	165 (11)	439 (33)	355 (18)
Alveolar	5	171 (5)	126 (7)	531 (13)	350 (13)
Bilabial	1	151 (13)	154 (4)	550 (23)	380 (17)
Bilabial	2	239 (7)	232 (3)	502 (22)	522 (23)
Bilabial	3	113 (11)	171 (1)	456 (37)	428 (49)
Bilabial	5	171 (6)	132 (6)	518 (29)	386 (11)
Velar	1	156 (15)	162 (10)	539 (30)	386 (43)
Velar	2	239 (7)	232 (4)	518 (27)	529 (32)
Velar	3	116 (31)	164 (9)	422 (31)	358 (13)
Velar	5	176 (9)	136 (5)	525 (26)	416 (24)

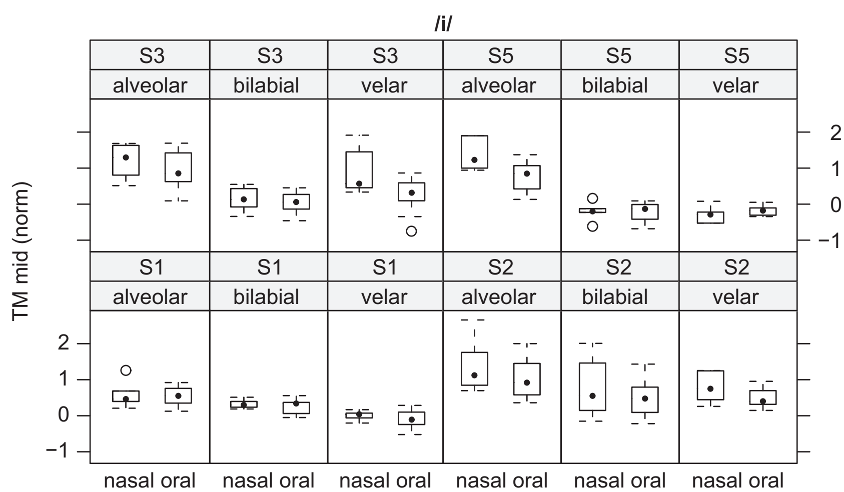

Fig. 7. TM position at the fifth normalized frame of the observed portion of /i/. Values have been normalized so that each trajectory begins at 0 mm but the magnitudes have not been warped.

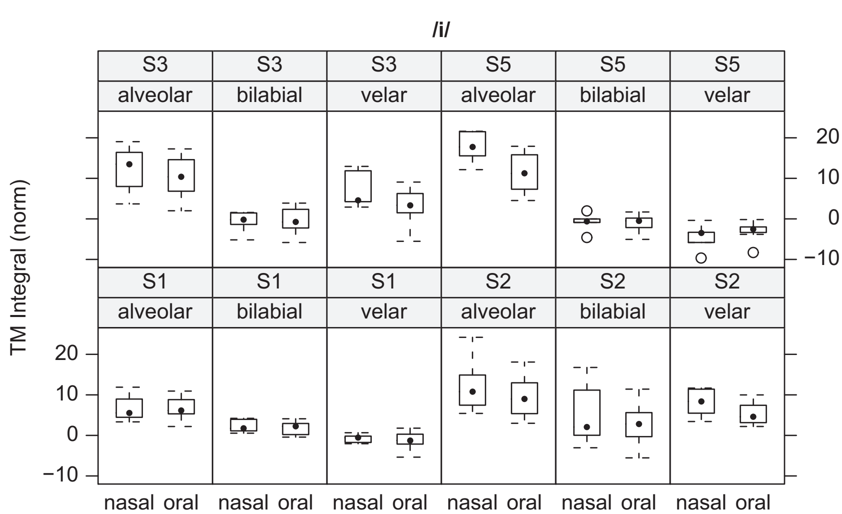

Fig. 8. Integrated displacement (Integral) for normalized (quadratic polynomial) TM trajectories during observed portion of /i/.

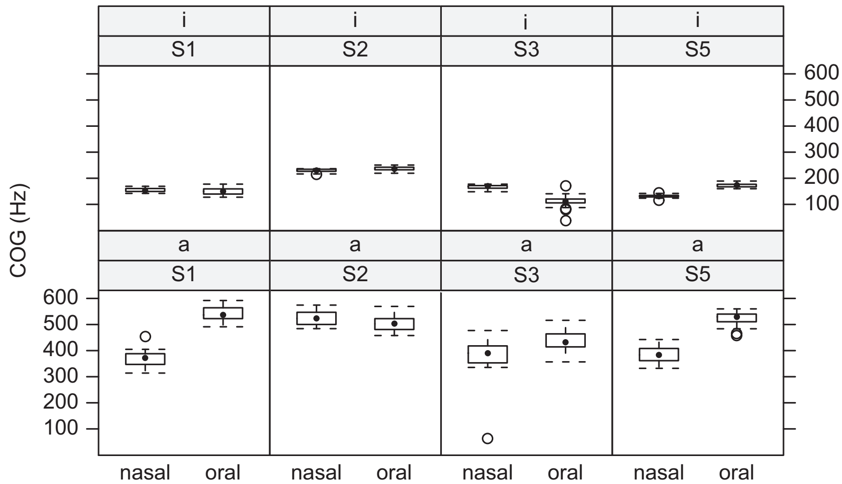

Fig. 9. Boxplots of F1 COG for the vowels /i/ and /a/.

Boxplots of the average F1 COG frequencies for each speaker are given in Fig. 9. The pattern of lower F1 COG for nasalized [ã] vs. oral [a] is evident for Speakers 1, 3 and 5. No pattern is evident for /i/.

3.3. *Post-hoc results for oral coda voicing*

Linear mixed-effects models with coda voicing as fixed effect and other effects as described above showed that none of the articulatory measures, which were found to be significant in Section 3.1 were significantly associated with coda-voicing for the vowel /a/ or /i/ ($p > 0.05$).

4. Discussion

4.1. *Summary of findings*

We compared lingual position during oral and nasalized /a/ and /i/ then compared their low-frequency spectral COG (in the vicinity of F1). Nasalized /a/ had a lower F1 COG than oral /a/. However, no change in tongue height was observed for nasalized /a/ compared to oral /a/. Since our articulatory experiment suggests that lingual position did not change in the oral-nasalized /a/ pair, we assume that the lower F1 COG found in nasalized /a/ is caused by nasal coupling, not oral configuration. The observed difference follows the well-supported generalization that the first pole of the nasal transfer function lies below F1 of /a/, effectively lowering COG in a low-frequency band (in this case 0–1 kHz) (Beddor, 1983; Krakow et al., 1988; *inter alia*).

F1 COG of nasalized /i/ did not differ significantly from that of oral /i/. Specifically, nasalized COG did not increase, as acoustic theories of nasalization predict: the first pole of the nasal transfer function should occur above F1 of /i/. Nevertheless, various articulatory measures suggest that the tongue body and dorsum were elevated during nasalized /i/. Given that raising the tongue is well known to result in a lower F1, we argue that the tongue-raising gesture during nasalized /i/ offsets the acoustic effects of nasalization to some degree. This can be considered an example of articulatory compensation (tongue elevation) for an acoustic phenomenon (F1′-raising) caused by another articulatory event (velopharyngeal opening).

4.2. *Limitations of the study*

We must note some important limitations of our study. As numerous investigations have shown, acoustic nasalization is realized through the modulation of many acoustic variables, only one of which is directly related to vowel height. We have investigated F1 COG (not intensity or formant bandwidth) precisely because of the relationship between F1 and tongue height. We acknowledge that other acoustic correlates of nasality, which cannot be associated so easily (or at all) with changes in tongue height, are important to the production and perception of nasality.

Another important limitation has to do with how we measured oral articulation, focusing on the position of the tongue. In fact, F1 can be modulated by a variety of changes in the oral tract that have relatively little to do with vertical tongue position. For example, F1 can be lowered by closing and/or protruding the lips or expanding the pharynx. During the production of nasal vowels, speakers of some languages with phonemic nasal vowels appear to contract the pharyngeal wall, which may raise F1 (Demolin, Delvaux, Metens, & Soquet, 2002; da Matta Machado, 1993). Several studies suggest that nasal vowels in French are produced with more lip protrusion and/or more lip rounding as compared to their oral congeners, effectively lowering F1 (Bothorel et al., 1986; Delvaux et al., 2008; Engwall et al., 2006; Zerling, 1984). We cannot rule out the possibility that articulators other than the tongue play a role in the production of nasality.

4.3. *Possible mechanisms for oral adjustment*

We now consider what mechanism might promote a lingual/oral response to nasalization. There are at least two possibilities: (1) The tongue changes position based on an intrinsic muscular connection between the soft palate and the tongue; or (2) Speakers monitor their speech production and adjust lingual position accordingly.

As for (1), the velic opening hypothesis (VOH; Al-Bamerni, 1983; Bell-Berti, 1993; Clumeck, 1976; Chen & Wang, 1975; Hajek, 1997; Hombert, 1987; Ohala, 1975; Ruhlen, 1973; Shosted, 2003) posits an association between a lowered tongue body and a lowered velum. Lubker, Fritzell, and Lindquist's (1970) "gate-pull" model offers an explanation for this. A contraction of the *palatoglossus* (PG), which connects the anterior surface of the soft palate and the sides of the tongue dorsum (Zemlin, 1998, p. 256), should lower the velum and raise the tongue body. If the *levator veli palatini* (LVP), which lifts the soft palate, is not activated, the soft palate will remain in a state of intermediate tension. Hence, when LVP is not activated, a low tongue body may drag down the velum. Our results suggest lingual compensation for the vowel /i/, where PG is not stretched and no downward vector on the velum is anticipated as a result of tongue position. However, Kuehn and Azzam (1978, p. 358) observe that PG's attachment site to the soft palate occurs in "a region which is clearly not a rigid anchoring point toward which the tongue might be pulled." Kuehn and Azzam (1978, p. 358) conclude that "this suggests a limited mechanical ability for [PG] in elevating the tongue". Thus, we find it unlikely that the VOH is relevant to our results. However, Arai (2004, 2005) finds evidence of a lowered tongue position during [ɑ̃], which presents an interesting dilemma. According to Lubker et al. (1970) the further the tongue is lowered, the lower the velum descends (given weak or no activity in LVP). This would result in greater velopharyngeal port opening and hence greater nasalization, even though the acoustic effect of tongue-lowering would be to raise F1. Thus, taken with the gate-pull model, Arai's (2004, 2005) observation of a lower tongue position in [ɑ̃] suggests that the tongue-lowering gesture leads to both acoustic compensation (higher F1) and articulatory enhancement (wider velopharyngeal aperture) simultaneously. Our results do not corroborate Arai's somewhat problematic observations regarding the vowel and we are led to conclude that, at least for the high vowel, the gate-pull model does not account for the data. Moreover, given the relatively small (or non-existent) contribution of PG to tongue elevation (Kuehn & Azzam, 1978), we favor explanation (2), i.e. a monitoring process is responsible for the compensatory behavior we report.

We consider at least three types of monitoring, which speakers may use in relation to their speech: (a) monitoring auditory feedback; (b) monitoring somatosensory feedback relating to the position of the velum; or (c) monitoring gestural primitives.

We believe that (b) is unlikely to explain our data because there is abundant evidence that speakers are largely unable to sense their own velic position, probably due to the absence of ordinary muscle spindles in the muscles that interdigitate with the *palatine aponeurosis* (Bell-Berti, 1993; Stål & Lindman, 2000).

A thorough review of theories relating to gestural primitives and how they might be monitored by the speaker (c) is beyond the scope of this paper. For the time being, we cannot rule out the possibility that speakers of American English acquire lingual gestures associated with nasalization and then exploit these primitive gestures during production. However, we cannot at present conceive of an experiment to test this hypothesis.

The auditory feedback hypothesis (a), on the other hand, can be tested experimentally. The existence of an auditory self-monitoring system is well-attested for production of f0 and formant structure (Jones & Munhall, 2000, 2005; *inter alia*) but not for production of nasalization per se. Kingston and Macmillan (1995) and Macmillan et al. (1999) found that F1 and nasalization synergistically enhance the percept of nasality, regardless of whether nasalization is intrinsic or extrinsic (cf. Beddor et al., 1986; Krakow et al., 1988). Our results suggest that speakers are capable of compensating for the effect of F1′ shift through adjustment of lingual posture. Evidence of a nasal auditory-monitoring mechanism may be corroborated by degrading and/or modifying auditory feedback in future experiments. By observing the effects of a nasal-like auditory perturbation on tongue height it should be possible to test this explanation of our results.

4.4. Articulatory control and category maintenance

Implicit to our argumentation is the notion that speakers exercise articulatory control in response to auditory feedback. If the speakers in our study compensated for modification of F1′ by adjusting tongue position, why was this compensation observed for nasalized /i/ but not for nasalized /a/? The acoustic correlates (e.g. F1) of any vowel may vary across productions but of course this variation is not necessarily equal. For example, studies suggest that there is as much as two times the variation in F1 for American English /a/ vs. /i/ (Hillenbrand, Getty, Clark, & Wheeler, 1995; Perkell & Nelson, 1985). The limited F1 variation in /i/ is perhaps associated with the existence of the phonemic vowel /ɪ/, which has an F1 close to that of /i/. The vowel space of American English presents no such near neighbor for /a/, at least in terms of F1. The acoustic effects of nasalization, therefore, may be more consequential for the vowel /i/ than for /a/ since a relatively slight raising of F1 will situate nasalized /i/ in the territory of /ɪ/. Conversely, a relatively slight lowering of F1 in /a/ is not expected to result in confusion, e.g. with /ə/. To be sure, there are other acoustic differences between /i/ and /ɪ/, e.g. duration and F2. Nevertheless, given the relation between F1 and tongue height, we argue that lingual compensation is more likely for /i/: variation in F1, which may lead to variation in F1′, may have greater consequences on the perception of /i/ than /a/.

Arai's (2004, 2005) results indicate that the single speaker in his study compensated for nasalization of /ɑ/ by lowering the tongue, but did not compensate for the nasalization of /i/. Speakers in the current study appear to compensate for the effect of nasalization on the F1 of /i/ by elevating the tongue (there is no analogous effect for /ɑ/ as in Arai, 2004, 2005). Neither Arai's research nor our own provides evidence of a lingual gesture that might exaggerate or enhance nasalization in terms of F1. This suggests that English may be resisting phonologization of vowel nasalization. Hyman (2008) notes the traditional use of the term *phonologization* as it relates to "intrinsic phonetic variations which tend to become extrinsic and phonological" (p. 383). The phonologization of anticipatory nasalization (e.g. /an/ > /ã/) may be considered in the same light, viz. the grammaticalization of the intrinsic phonetic variation that accompanies a lowered velum. With this understanding of phonologization in mind, our findings suggest that the inherent acoustic properties of vowel nasalization can be perceived by speakers, and that the grammaticalization of these properties is resisted by modifying lingual articulation in such a way that it offsets the acoustic effects of nasalization. This is a different path than the one documented in a variety of Romance languages (Sampson, 1999), where Latin VN sequences were eventually phonologized as nasal vowels, often with enhancement-based changes in vowel quality, e.g. the raising of the vowel in Late Latin /an/ to [ɐ̃] in modern Portuguese, or the lowering of /in/ to [ɛ̃] in modern French (Sampson, 1999).

5. Conclusion

Our study adds to a growing body of literature indicating that phonetically nasalized and phonemically nasal vowels have different oral configurations than their oral counterparts. We further posit that these oral differences may bear some relation to the acoustic properties of nasalization. We present evidence that American English speakers raise their tongue during the production of nasalized /i/ and suggest that this compensates for the low-frequency shift in spectral energy which accompanies velopharyngeal opening. Because this lingual gesture may counteract the effects of nasalization, we hypothesize that speakers of American English may be resisting phonological vowel nasalization.

Oral differences may be applied to enhance nasalization, as well, though we do not find evidence of this here. In languages with phonemic nasal vowels, e.g. French, Hindi, and Brazilian Portuguese, we may find evidence that oral articulation bears some relation to the enhancement of acoustic nasality and/or the acoustic differentiation of oral and nasal vowel pairs. Our results challenge the traditional notion that nasality is a purely velopharyngeal phenomenon and suggest that, in the evolution of phonemically nasal vowels, oral articulation plays an important, if complex, role.

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Appendix A. Calibration

A.1. EMA calibration

The AG500 uses proprietary calibration software created by the manufacturer of the articulograph. 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. During the calibration, the twelve sensors 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 center of the cube, and the AG500 rotates the circal 360°. During this rotation, the 3D position, tilt, and yaw of each sensor with relation to the six electromagnetic emitters is recorded. The AG500 system later uses this information to calculate the position of the sensors by converting the voltage amplitude of each of the six frequency-distinct electromagnetic fields into a position relative to the emitters. The calibration session file can be used multiple times with the same set of sensors, until the sensor set requires recalibration. Two calibration sessions were conducted in the two-month course of data collection.

Each speaker was situated near the center of the cube, in order to obtain the most reliable position calculations of the sensors. Examination of results in the *x*-dimension (anterior–posterior) suggests that the speakers may have differed by as much as 80 mm in their anterior–posterior placement within the cube. However, using the coordinates of the three reference sensors, the articulatory data of the tongue sensors was calculated in relation to the movement of the head. The tongue movement data were corrected for head movement using the native Carstens software.

A.2. Aerodynamic calibration

The aerodynamic system was calibrated before each recording session, i.e. for each speaker. The Scicon NM-2 mask (connected to a Biopac TSD160A tranducer and to the BNC-2110 data acquisition interface) was held against a custom-designed plaster negative of the mask, creating an airtight seal. A tube runs from a hole drilled in the plaster negative to a quad-headed gas pump. The pump generates an outflow of 515 ml/s and an inflow of −515 ml/s with a pause (0 ml/s) between pulses. Positive and negative pulses were recorded separately. The electrical response of the transducer was measured individually for the positive pulses, negative pulses, and pauses (zeros). The electrical response of the transducer was plotted against the known value of the flow pulses and a linear function was fitted to the data points. The coefficients of this function defined the calibration function, which was used to transform the raw electrical output of the transducer. The measurement accuracy was estimated at approximately ± 10 ml/s.

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