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Research Article

Oropharyngeal articulation of phonemic and phonetic nasalization in Brazilian Portuguese

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ABSTRACT

The phonological feature [±NASAL] does not distinguish systematic oropharyngeal differences between oral, nasal, and phonetically nasalized vowels. A variety of studies now show that oropharyngeal shape may systematically enhance or compensate for the acoustic effects of nasal coupling. Additionally, the phonetic implementation of [−NASAL] vowels in oral and nasal contexts is a matter of some controversy. While the velopharyngeal opening of these vowels has been inferred from aerodynamics, we know of no attempt to directly study the oropharyngeal articulation of underlyingly oral vowels in nasal and oral contexts in a language that may also have phonemically [+NASAL] vowels. In this study, real-time magnetic resonance imaging (rt-MRI) is used to study vocal tract configuration in Brazilian Portuguese (BP), a language that arguably has [+NASAL] (phonemically nasal) vowels and two classes of [−NASAL] vowels (oral and phonetically nasalized). Results show oropharyngeal differences between nasal and oral vowel congeners /a∼ã/, /i∼ĩ/ and /u∼ũ/, which arguably enhance well-known acoustic effects of nasal coupling on vowel height. In addition, nasal coda consonants emerge following nasal vowels. Phonetically nasalized vowels, on the other hand, show no sign of nasal enhancement, including nasal coda emergence, implying they are underlyingly oral vowels, despite the environment in which they occur. We argue that nasal vowels in BP are underlyingly /Ṽ/, rather than /VN/ sequences, the latter distinction being reserved for nasalized vowels. Articulatory divergence of [+NASAL] and [−NASAL] vowels has implications in perception, sound change, and the phonetic implementation of nasality.

1. Introduction

The phonological status of nasal vowels[1] has been of interest for some time, and their underlying representation, particularly in Brazilian Portuguese (BP), is a matter of some debate. One theory posits that nasal vowels are composed of two underlying segments—an oral vowel followed by a nasal segment, which is either specified as a particular lexically-dependent phoneme, or a nasal archiphoneme with a phonetic implementation dependent on the following sound (Almeida, 1976; Cagliari, 1977; Câmara, 1970, 1977; Guimarães & Nevins, 2013; Lipski, 1973; Lipski, 1975; Paradis & Prunet, 2000). According to this theory, which stems from both historical and phonetic accounts, [Ṽ] is the surface form of the vowel, though the underlying form is /VN/ (Mateus & d'Andrade, 2000). Nasal airflow, which indirectly reflects velopharyngeal opening, is gradual in both French and BP nasal vowels (Cohn, 1990; Desmeules-Trudel, 2015). Desmeules-Trudel (2015) interprets this as indicative of an oral vowel followed by a nasal consonant. Cohn (1990, p. 89) also regards such behavior as indicative of phonetic nasalization, particularly in languages with no phonological opposition between oral and nasal (like English). An opposing theory, based on historical and instrumental evidence, claims that nasal vowels are inherently /Ṽ/ in their underlying form, as well as their surface representation (Sampson, 1999; Shosted, 2003). Understanding the underlying form of nasal vowels is important for explaining nasalization itself, and for

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[1] Barbosa and Albano (2004) use the term "nasalized" vowels to describe these vowels. However, we follow the conventions in Stevens (2000) and refer to these as *(phonemic) nasal* vowels, as they are arguably phonemically distinct from oral vowels. Following Cohn (1990), we use the term *(phonetically) nasalized* to refer to oral vowels that undergo nasalization due to proximity to a nasal segment.

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making predictions regarding the evolution of languages with nasal vowels in their inventories.

Recent instrumental advances allow direct comparison of the articulatory configurations of oral/nasal vowel congeners, presumed in previous works to differ only with respect to velopharyngeal opening (see Section 1.1.2). These methodologies provide phonetic evidence directly related to the debate over the phonological status of nasal vowels. If nasal vowels assume systematically different oropharyngeal[2] configurations with respect to their oral congeners, this suggests oral and nasal vowels in BP are produced using a distinct set of purposeful oropharyngeal motor targets and trajectories (a motor plan) that involves more than just oral/nasal coupling. Given that phonological contrast is routinely ascribed to those speech sounds that (a) result in lexical distinctions and (b) manifest systematic phonetic differences, we argue that at least some of the nasal vowels of BP should be regarded as phonemic. As in French—an arguably better-studied language with regard to vowel nasalization—we believe that oropharyngeal differences between oral and nasal vowels must be taken into account in studying BP dialectology and sound change.

The objective of this study is to substantiate the acoustic differences between these vowels that cannot be ascribed to nasal coupling, such as F1 raising for nasal high vowels compared to oral high vowels. We do this through an articulatory comparison of nasal and oral vowel congeners in BP. A further contribution is to explore whether phonetically nasalized vowels assume different articulatory targets with respect to their underlyingly oral and nasal congeners.

1.1. Vowel nasalization

1.1.1. Acoustic effects of nasalization

The description and quantification of nasal acoustics requires significant attention, as the coupling of additional cavities to the oropharyngeal tube adds complexity to the acoustic signal emanating from the vocal tract (Chen, 1975; Fant, 1960; Feng & Castelli, 1996; Fujimura & Lindqvist, 1971; Maeda, 1982a, 1982b; Pruthi & Espy-Wilson, 2007; Stevens, 2000). Nasalization is roughly defined by the lowering of the velum, which results in the opening of the velopharyngeal port, thereby coupling the oropharyngeal and nasal passages. The nasal cavity's larger surface area (due primarily to the tissue covering the scroll-like nasal turbinates), as well as the paranasal sinuses, absorb and reduce energy in some frequency bands. The general effect is to lower amplitudes and increase formant bandwidths in all cases. Additional spectral perturbations are due to the presence of formants and antiformants associated with particular vocal tract geometries. These effects are of particular consequence in the lower frequencies surrounding the first formant (Stevens, 2000). The phonological implications of this effect are well-studied (Beddor, 1983; Beddor & Hawkins, 1990).

The effect of nasalization on F1 can also be cast in terms of the increase in the number of pole-zero pairs in the transfer function (Maeda, 1993; Stevens, 2000), also known as nasal formants and antiformants. Because there are already poles and zeroes in the oropharyngeal transfer function, it is difficult to posit the frequency of the nasal antiformants *a priori*. A spectral comparison of oral and nasal vowel congeners is helpful but this procedure, too, is problematic. It assumes identical oropharyngeal configurations (aside from velopharyngeal opening) for the contrastive vowels. This assumption is now well-known to be misleading (see Section 1.1.2).

Many measures have been posited to quantify the acoustic effects of nasality (e.g., $A1, A1-P0, A1-P1$, Center of Gravity below $1000Hz$, where $A1$ is the amplitude of the first formant, $P0$ is the amplitude of the first nasal formant, and $P1$ is the amplitude of the second nasal formant (Berger, 2007; Chen, 1997; Glass & Zue, 1985; Pruthi & Espy-Wilson, 2007; Styler, 2017)). Styler (2017) shows that $A1-P0$, F1 bandwidth, and spectral tilt are the most robust measures for definitively distinguishing oral/nasal congeners in French.

The coupling of oral and nasal cavities systematically affects the frequency domain of the lower formants. Fujimura and Lindqvist (1971, p. 552) claim that all formants of nasalized vowels "shift monotonically upwards." When velopharyngeal opening is large enough to create a high-amplitude nasal formant, the formant values of low vowels decrease (Diehl, Kluender, Walsh, & Parker, 1991). The opening of the velopharyngeal port shifts the expected resonances of the oral cavity (relative to comparable vowels with a closed velopharyngeal port), due to the overall change in tract configuration. For non-low vowels, the nasal formant occurs in a frequency range above that of F1, thereby spreading the distribution of energy upwards. For the low vowels that already exhibit a high F1, the nasal formant occurs below F1, thereby spreading energy lower compared to its oral congener. Thus, nasal vowels are often considered to be centralized along the height axis (Beddor, 1993). Serrurier and Badin (2008) also claim that F2 of front vowels is lowered as an effect of nasalization. This has been confirmed elsewhere (Feng & Castelli, 1996; Carignan, 2013), and is possibly due to velic lowering itself (Shosted, Carignan, & Rong, 2012).

1.1.2. Articulatory enhancement and nasalization

Phonemic nasal vowels are considered distinct from oral vowels in the vowel inventory of a language because they differentiate minimal pairs. For example, the French words /pɛ/ *paix* 'peace' and /pɛ̃/ *pain* 'bread' nominally differ only in the nasal quality of the vowel. Some previous studies of nasalization compare phonemic oral and nasal vowel pairs assuming that the only physical difference between the two is the positioning of the velum; that is, a nasal vowel is produced by opening the velopharyngeal port and maintaining the oropharyngeal configuration associated with the oral vowel (Berger, 2007; Feng & Castelli, 1996; Jacques, 2014; Maeda, 1982b; Narang & Becker, 1971; Pruthi, 2007; Pruthi, Espy-Wilson, & Story, 2007). However, other studies, including articulatory analyses, suggest that the position of the tongue, lips, and pharynx, as well as the velum, may differ between oral and nasal vowel congeners, discussed below.

The oropharyngeal articulation of French phonemic nasal/oral vowel congeners has been thoroughly studied—these vowels display differences in tongue height, labial aperture, pharyngeal constriction (Bothorel, Simon, Wioland, & Zerling, 1986; Brichler-Labaeye, 1970; Carignan, 2013; Carignan,

[2] Throughout this paper, we use the term oropharyngeal to refer to non-velopharyngeal articulations.