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Brazilian Portuguese nasal vowels and their acoustic moments: Reflections on the phonological status

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ABSTRACT

The present study aims to investigate the vocalic nasality of Brazilian Portuguese from the observation of the acoustic moments that constitute the BP nasal vowels. Five hundred ninety-eight instances were analyzed from five Florianopolitano speakers. Data collection included a test for eliciting trisyllable pseudowords in a carrier phrase in which the nasal and oral vowels were presented in unstressed and stressed syllables and followed by plosive and fricative consonants. Data analysis relied on the acoustic signal from oral and nasal microphones. Results showed that the acoustic moments that constitute the nasal vowels seem to support the monophonemic phonological status for the nasal vowels in Brazilian Portuguese.

1. Introduction

Vowel nasality in Brazilian Portuguese (BP) has been the focus of many studies.[1] At one point or another, they all mention how complex it is to analyze this type of segment, be it due to its acoustic constitution (oral and nasal formants, antiformants, acoustic moments, etc.) or due to the recognized discussion about its phonological status, that is, if it is biphonemic (an oral vowel followed by an adjacent nasal consonant, /vN/) or monophonemic (a full nasal vowel, /ṽ/).

The task of inferring grammars of physical systems is not simple (Pierrehumbert & Pierrehumbert, 1990). However, defining the phonological status of nasal vowels based on experimental studies can broaden the bases for a long-standing discussion about the phonological status of BP nasal vowels. According to Demolin (2012), the experimental method allows formulating hypotheses about the phonological category and its primitive, as well as about the way the speaker controls their articulators during production. For the author, phonology without the phonetic dimension is an illusion, and phonetics without phonology brings nothing to the understanding of the categories on which language is built.

Considering that phonological interpretations should not underestimate the concrete phonetic manifestations of a language (Tláskal, 1980), the objective of the present study is to experimentally validate the hypothesis of the existence of full nasal vowels in BP, making this study another argument for those who advocate for their monophonemic status. To provide empirical evidence of the monophonemic status, we will investigate vowel nasality

[1] Camara Jr., 1953, 1969; Mateus, 1975; Cagliari, 1977; Couto, 1978; Duarte and Teixeira, 1979; Tlaskal, 1980; Callou and Leite, 1990; Moraes and Weltzels, 1992; Mateus and Andrade, 2000; Seara, 2000; Bisol, 2002; Medeiros, 2012; Mendonça, 2017, among others.

through a detailed analysis of the acoustic moments that constitute BP nasal vowels [ɐ̃], [ẽ], [ĩ], [õ], and [ũ], considering the global and nasal acoustic signals. A total of 598 data will be analyzed. Moraes and Wetzels (1992), Medeiros and Demolin (2006), Meireles et al. (2015), among others, have carried out experimental studies that provide arguments for the status of nasal vowels. However, in these and other studies, no in-depth description of BP nasal vowels is presented regarding their acoustic moments through the techniques used in the present study, although there is the same type of study in the literature of other languages, such as French (Delvaux, 2003; Amelot, 2004).

This work is based on an experiment conducted with five participants. Pairs of trisyllabic, paroxytone pseudowords (such as *cacaca* – *cacanca*) were recorded with a nasal microphone and a piezoelectric pickup vibration transducer to obtain the nasal acoustic signal, and with an acoustic microphone to obtain the global acoustic signal. We analyzed the constitution of BP nasal vowel, considering their acoustic moments (oral, nasal and murmur), according to Sousa (1994) and Seara (2000), in order to establish comparisons with the acoustic behavior of nasalized vowels in BP, as presented in Mendonça (2017). These comparisons will allow us to verify whether nasal vowels behave like nasalized vowels, supporting the biphonemic status, that is, an oral vowel nasalized by an adjacent consonant; or whether nasal vowels exhibit their own acoustic behavior, providing support for the monophonemic status and for the existence of a nasal vowel in the phonological system. We intend to support the phonological interpretation that BP nasal vowels are full vowels and complex units that comprise two or three acoustic moments, which consist of gradual articulatory movements with acoustic results that are also presented gradually.

Four additional sections comprise this manuscript. In the Theoretical Framework section, we present a summary of the phonological issues involving BP nasal vowels, as well as their characterization considering acoustic, articulatory, and aerodynamic aspects. Then, we detail the method used in this study, including more information about the participants, the *corpus*, the instruments used for data collection, and the acoustic treatment of the data. Finally, we present the analysis of the results and some final remarks.

2. Theoretical framework

The theoretical framework is divided into two subsections: The first briefly presents the different standpoints regarding the phonological status of BP nasal vowels, while the second discusses studies that used different physical approaches (acoustic, articulatory, and aerodynamic) to the data.

2.1. Phonological discussion

Widely discussed, the phonological status of BP nasal vowels still follows contentious paths regardless of the theoretical framework under which it is being observed. It is known from the beginning that nasal vowels in Portuguese have a distinctive function, as in *cinto* vs. *cito* (‘belt’ vs. ‘I cite’) and *junta* vs. *juta* (‘joint’ vs. ‘jute’) (Câmara Jr., 1969). What is not yet established is the nature of this distinctiveness; that is, the phonological representation assumed by these segments in the Portuguese language. There are two main perspectives shared by scholars in the field regarding the phonological status of BP nasal vowels: (i) The phonological representation of an oral vowel followed by a nasal consonant (/vN/) and (ii) the existence of the nasal vowel as a phonological unit (/ṽ/).

The biphonemic hypothesis (/vN/) of nasality in BP is supported by Câmara Jr. (1953), Cagliari (1977), Duarte and Teixeira (1979), Moraes and Wetzels (1992), Bisol (2002), Mateus (1975), Mateus and Andrade (2000), among other authors. For them, full vowel nasality does not exist in BP as it does in French, in which there is a distinction between a nasal vowel and a vowel followed by a nasal consonant (*bon* [bɔ̃], the masculine adjective for ‘good’ vs. *bonne* [bɔn], the feminine adjective for ‘good’). Thus, they argue that the nasal resonance found in the BP vowel is due to the presence of a subsequent nasal consonant in the same syllable.

Câmara Jr. (1953) argues and presents structural examples to support the biphonemic status. One of them concerns the syllable in which the nasal segment occurs. This syllable seems to function as a closed syllable, just like those with /l, s, r/. Thus, there would be no elision process in *jovem amigo* [ʒɔvẽamigu] (‘young friend’), but there would be, as in European Portuguese, in *grande amor* [gɾɐ̃damoɾ] (‘great love’), an example that presents, in fact, two vowels, one at the end of the first word and one at the beginning of the second word. Tláskal (1980) recalls, however, that in French — a language about which there is no doubt regarding the phonological status of nasal vowels and whose origin is shared with Portuguese — a nasal vowel before an oral vowel loses its nasality completely or partially, creating a full nasal consonant interspersed between two vowels, as in *mon ami* [mɔnami], so that elision does not occur. It should be noted, however, that the example used by Tláskal (1980) is a case of sandhi process. This is the same process used by Câmara Jr. (1953) as an argument for the biphonemic status of Portuguese nasality when compared to French nasality through the words *bon* and *bonne*, although one is considered internal sandhi and the other external sandhi.

The example mentioned by Tláskal (*op. cit*) would, in fact, be much stronger to argue for the presence of biphonemic vowels[2] in French than the one presented by Câmara Jr. (1953) for Portuguese. The case of external sandhi in Portuguese does not seem suitable for the discussion of the phonological nature of nasality, since nasal vowels at the end of words are — in most cases and in the *jovem amigo* example — produced as nasal diphthongs, not constituting, therefore, a phonetic-phonological environment for the occurrence of sandhi.

Later studies also mention Câmara Jr's (1953) arguments. Some use these arguments to support their discussion, such as Cagliari (1977). Others add different arguments to defend the biphonemic status (/vN/), such as Bisol (2002). Bisol adds as an argument the absence of a nasal vowel in the pre-final syllable of proparoxytones in the Portuguese lexicon — as in *capenga* ('crippled'), for example. For her, syllables with nasal vowels are heavy syllables, considering the presence of a nasal consonant following the vowel (vN). As proparoxytone words do not accept heavy syllables in the penultimate position, the word *capenga* is paroxytone ([kaˈpẽgɐ], and not *[ˈkapẽgɐ]). As such, another argument in favor of the biphonemic status is established (/vN/) according to the author. Regardless of their theoretical approach, these authors argue that there is no full nasal vowel underlying it, since Portuguese vowel nasality is conditioned by a subsequent nasal consonant in the same syllable.

The other hypothesis is the monophonemic, which defends the existence of full nasal vowels in the language. This hypothesis is also supported by a handful authors (Lüdtke, 1953; Pontes, 1972; Couto, 1978; Tláskal, 1980; Callou & Leite, 1990; Costa & Freitas, 2001, among others). There are several arguments for defending this view as well. Lüdtke (1953) mentions (i) the existence of a contrast between vowels even when there are nasal vowels (ii) the impossibility of the vowels /a/ or /ɐ/ and /ɐ̃/ to work (in unstressed position) as allophones of the same preceding and following contexts in European Portuguese. Thus, we can infer the existence of minimal pairs such as *tampar* ('to cap') /tɐ̃ˈpar/ vs. *tapar* ('to close') /tɐˈpar/, in the unstressed position, and *tanto* ('very') /ˈtɐ̃to/ vs. *tato* ('tact') /ˈtato/, in stressed position, indicating that /a/, /ɐ/ and /ɐ̃/ work as phonemes once they lead to differences in meaning.

Tláskal (1980) presents a dynamic view of these segments in Portuguese and refutes Câmara Jr.'s (1953) arguments looking for evidence in French, a language in which vowel nasality is reported as full. Câmara Jr. (*op. cit.*) uses the example of the phonetic realization of /s/ in *pensar* ('to think') to explain that the non-voicing of the intervocalic consonant indicates that the previous syllable is closed, that is, it contains a nasal consonant, which refers to the biphonemic status, contrary to what happens, for example, with *pesar* ('regret'). Tláskal (1980) points out, however, that the same occurs in French, *penser*, but that Câmara Jr. (op. cit.) does not doubt the existence of nasal vowels in that language. Mateus (1975) makes use of prefixal derivations (*importante* 'important', *inacabado* 'unfinished') and kinship semantic (*fim* 'finish' and *finalizar* 'finalize') to support his hypothesis of the biphonemic status of nasal vowels. Nonetheless, Tláskal (1980) mentions that the same occurs in French: *Impressioné*, *inadaptable* and *fin-finir, don-donner, son-sonner*.

The arguments in favor of the biphonemic status considered by Câmara Jr. (1953), the precursor of the discussion and one of the most cited scholars when this topic is debated, are not enough to refute, as just shown, the monophonemic status. However, it is evident that, regardless of the concept adopted and the arguments brought forward, the idea of vowel nasality in BP as a complex phenomenon is shared by all researchers.

[2] Which does not apply as French nasal vowels are monophonemic.

2.2. The acoustic moments: Acoustic, aerodynamic, and articulatory approach

According to Silva et al. (2019), nasal vowels can be analyzed through the following acoustic aspects: (i) Frequency of nasal formants, (ii) amplitude, (iii) frequency of oral formants, (iv) antiformants, and (v) duration. Observations of the dynamics exhibited by these physical parameters allow us to assert that nasal vowels consist of three acoustic moments — also called phonetic phases. Therefore, BP nasal vowels can be formed by moments that are typical for them: The oral, the nasal, and the murmur, referred to by other authors as nasal appendage or the closing consonant (Sousa, 1994; Seara, 2000; Barbosa & Madureira, 2015). These three acoustical moments can be organized in different ways within the constitution of nasal vowels, which will be addressed in more detail below. In this section, we discuss studies that deal specifically with the acoustic moments that constitute nasal vowels, not only from an acoustic point of view, but also from aerodynamic and articulatory points of view, which are fundamental for the present research.

Several studies on nasal vowels (Sousa, 1994; Seara, 2000; Seara et al., 2019, among others) have identified different acoustic moment constitutions in the production of these sounds. They are: (i) Oral moment + nasal moment + murmur; (ii) nasal moment + murmur; (iii) oral moment + murmur. The study by Seara (2000) reveals, from the observation of acoustic data, a higher rate of the constitutions of the types (i) oral + nasal + murmur and (ii) nasal + murmur regardless of the vowel and the stress of the syllable in which they are located. The nasal vowel, however, is usually permeated almost entirely by nasality. According to Barbosa and Madureira (2015), the nasal acoustic moment is the only one that is always present. Our data contradict this position. The authors mention that the lowering and lifting of the soft palate mean that the oral moment cannot always be discriminated in the acoustic spectrogram. They further state that the closing consonant (or murmur) varies between individuals and appears to be context-dependent. Our data contradict this last statement, since we found murmur in all investigated contexts. Sousa (1994) also mentions that, as the soft palate is a slow articulator, the oral acoustic moment (present in the oral moment + nasal moment + murmur of nasal vowels) could be a consequence of the slow velopharyngeal opening that takes a while to lower until the air passing through the nasal cavity and its respective formants can be detected. It should also be noted that the movement of the soft palate, in its most varied heights (Cagliari, 1977; Delvaux, 2003), is crucial for phonological distinctiveness in several languages. This means that speakers can control the timing of the alternation between the lowering and lifting configurations of the veil, that is, they control the coupling and uncoupling of the oral and nasal tracts in order to make phonemic distinctions (Bell-Berti, 1980). However, this does not seem to occur in the oral moment present in the oral moment + murmur of the nasal vowel constitution. In this case, since the oral acoustic moment occupies the vowel substantially, its longer duration makes it seem as if the oral moment is planned and not just a consequence of the anatomy of the articulator.

The acoustic moments that constitute the nasal vowel can be observed from its physical characteristics, visualized via spectrogram and waveform, as illustrated in Figure 1. Figure 1 shows the physical aspects present in the production of the BP nasal vowel [ẽ]. In this figure, we see that the oral acoustic moment (O) has a greater amplitude than the nasal acoustic moment (N) of the vowel, relative to the first marking below the waveform. The nasal moment (N) is marked by a decrease in amplitude in relation to the oral moment, shown in the waveform of this acoustic signal and by the appearance of additional resonances — the nasal formants observed in the spectrogram. The last acoustic moment — the murmur (M) —, referring to the third marking, is quite visible in the waveform considering the great drop in amplitude in relation to the two previous acoustic moments and the characteristic formant pattern, similar to that of a nasal consonant, displayed by the spectrogram.

The murmur, also present in nasal consonants, is characterized by the lowering of the soft palate and the exit of air through the nasal tract only since there is generally a constriction in the oral tract. Thus, murmurs can be easily identified in the context adjacent to the stop — such as in *campo* 'camp', where there is total obstruction of the oral air passage due to the closing of the lips necessary for the production of [p]. On the other hand, it is more difficult to occur and to be detected in a posterior fricative context, since, in this case, the air also escapes through the oral tract, as in *canso* 'I fatigue'. According to Sousa (1994), it is very difficult to separate the murmur from the nasal vowel itself since the transition between these two acoustic moments is extremely gradual. For the author, although the extremes of this continuum present clear differences, it is practically impossible to define with certainty the end of the nasal acoustic moment and the beginning of the murmur: 'without the murmur, nasals would barely be distinguishable from their oral counterparts' (Sousa, 1994, p. 98, our translation). However, for the present work, it is important to delimit these acoustic moments based on the characteristics that arise from the global acoustic signal, mainly from the nasal acoustic signal, which will reveal more explicit inferences from the lowering of the soft palate. This allows for a clearer observation of the murmur. Certainly, the treatment of the nasal acoustic signal (henceforth NAS)[3], observed separately from the oral acoustic signal, will aid in the delimitation of these acoustic moments.

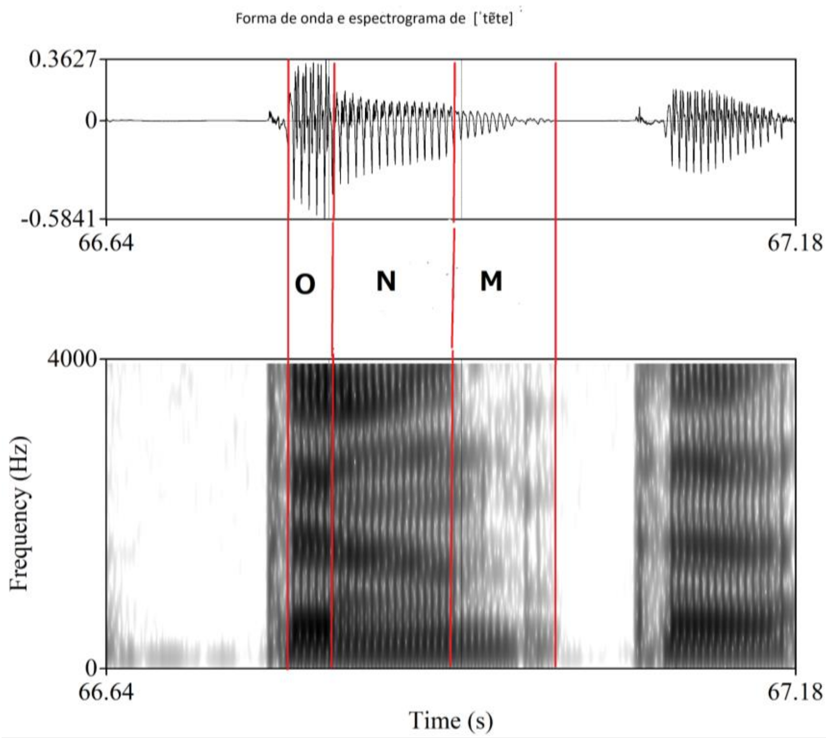

Figure 1. Waveform and spectrogram of [ˈtẽta], extracted from the *tatanta* pseudoword. "O" refers to the oral acoustic moment; "N", to the nasal acoustic moment; and "M", to the murmur.

As stated earlier, the three acoustic moments will not necessarily appear in the constitution of all nasal vowels, as many of them may present only the nasal acoustic moment and the murmur or the oral acoustic moment and the murmur. According to Seara (2000), the oral acoustic moment + murmur constitution could only be found for the vowels [ĩ], [ẽ], [ũ] in both stressed and unstressed positions. The vowels [ɐ̃] and [õ] do not seem to accept this type of composition regardless of the stress of the syllable in which they are found. Hence, in general, there are more occurrences of nasal vowels consisting of the three acoustic moments or just the nasal acoustic moment and murmur in the Portuguese nasal vowel system, as observed by Seara (2000).

Although many studies have employed acoustic analysis to investigate Portuguese nasal vowels and they mention the existence of acoustic moments (Cagliari, 1977; Sousa, 1994; Seara, 2000; Jesus, 2002; Medeiros, 2007, 2012; Souza, Pacheco, 2012; Moraes, 2013; Santos, 2013; Barbosa, Madureira, 2015; Teixeira-Correa et al., 2018; Mendonça, 2017), only in Seara (2000) the percentage of occurrence of nasal vowels considering its constituent acoustic moments is reported.

Even scarcer are studies that use aerodynamic tools for nasal analysis (Mendonça, 2017; Vieira, 2017; Seara et al., 2019). Seara et al. (2019) sought to evaluate and visualize the acoustic moments of the NAS from BP nasal vowels as generated by a piezoelectric vibration transducer and by a nasal microphone,

[3] We use the term *Nasal Acoustic Signal* (NAS), translated from Montagu and Amelot (2005).

which allow them to infer the movements of the soft palate and the aerodynamics of the nasal air flow. The authors observed three curve patterns for BP nasal vowels, which correspond exactly to the three aforementioned acoustic moments: Two of these patterns (Pattern 1: oral moment + murmur; Pattern 2: oral moment + nasal moment + murmur) present greater nasal intensity in the offset of the nasal vowel and a delay of the nasal signal in the onset of the vowel; and a third pattern in which the nasal sign is in sync with the onset of the nasal vowel (Pattern 3: nasal moment + murmur).

Mendonça and Seara (2015) investigated the behavior of the nasal acoustic signal curve of nasalized vowels in relation to the subsequent nasal consonant. They reported that, when the following context is bilabial, the consonant nasalizes about 25% of the previous vowel (as in *papama – pamapa*), that is, the spreading of regressive nasality occurs over ¼ of the vowel preceding the bilabial nasal consonant, as verified in the NAS. However, when the following context is alveolar (as in *papana – panapa*), the spreading of the NAS curve over the preceding vowel is of about 50%. When the following context is palatal (as in *papanha – panhapa*), there is greater regressive coarticulation, spreading nasality over about 75% of the vowel preceding the palatal nasal consonant.

Regarding nasal vowels, an articulatory study with two French speakers by Amelot et al. (2008) showed a difference of 30 and 40 ms between the onset of the velopharyngeal port opening and the onset of the soft palate lowering. This suggests that there is always a part of the nasal vowel that is not nasalized and that this non-nasalized part is not conditioned by the adjacent context, unlike what happens with nasalized vowels in BP (Mendonça & Seara, 2015). However, Maeda (1993), in a study on the degree of opening of the velopharyngeal port for the perception of nasality, found that for the vowel [ĩ] a small opening of the velopharyngeal port would be sufficient for the perception of nasality, unlike what happens with the nasal vowel [ẽ], which requires a much larger aperture. This indicates that each nasal vowel has an intrinsic nasalization, considering the minimum amount of nasality necessary for it to be perceived as nasal. Therefore, for nasal vowels, vowel quality is relevant, and not necessarily the context, as observed for the nasalized vowels in BP (Mendonça & Seara, 2015).

Although the previously mentioned works carry relevant contributions about the characterization of the segments in question, only few use an experimental method to position themselves about the phonological status of nasal vowels in BP. As experimental studies on nasal vowels, we find Moraes and Wetzels (1992), Costa and Freitas (2001), Medeiros and Demolin (2006), Meireles et al. (2015), and Marques and Scarborough (2020). Moraes and Wetzels (1992), for example, argue that the longer duration of nasal vowels is a strong argument for the biphonemic status. For them, the nasal consonant, postulated at the base for contrastive nasality, is suppressed from the phonetic representation, spreading its feature [+nasal] to the preceding vowel and leaving, as a trace on the surface, only the longest duration, that is, the compensatory lengthening.

Costa and Freitas (2001) observed speech data from ten monolingual Portuguese children and presented arguments for the monophonemic status. The first one concerns children producing oral vowels instead of nasal vowels in the first age groups, which is in line with the fact that oral vowels are those that are unmarked and, therefore, acquired early. Furthermore, according to the authors, if the coda were really consonantal, target words with nasal vowels would be avoided in the initial stages, as they do with fricative codas (Freitas, 1997). That is, they observed that children produce nasal vowels when the only structure available is CV, and not CVC. Thus, the nasal vowel occupies an open syllable, and not a closed one, as would be expected in the case of the segment status being biphonemic, in which there would be a nasal consonant in addition to the oral vowel.

Articulatory studies using magnetic resonance imaging (MRI) are those by Medeiros and Demolin (2006) and Meireles et al. (2015). In the first study, based on data from a Brazilian participant, the authors observed the position of the soft palate during the production of BP nasal vowels. Data collection included the five BP nasal vowels. Special attention was given to the vowels [ĩ ũ ẽ] since the other vowels behave differently because they constitute diphthongs, especially in word-final position. Comparing the minimal pairs (oral vowel vs. nasal vowel, as in *ata* /ˈata/ ‘record’ and *anta* /ˈãta/ ‘tapir’), results showed that the soft palate is lowered at the beginning of the production of nasal vowels, presenting, in addition, differences in tongue positioning, such as the back of the tongue being higher for [ĩ], flatter for [ũ] and accompanying the movement of the soft palate for [ɐ̃]. The authors emphasize the fact that, according to the literature, the nasal vowel has an oral moment. However, they explain that, through the technique used, which captures only five images per second, it was not possible to observe the non-lowering of the soft palate because in all images the articulator was already lowered. Based on the results presented, the authors defend the existence of full nasal vowels in BP, as they are nasal since the beginning of the production and present articulatory differences in relation to their oral counterpart, being, therefore, distinctive in the language.

In the second study, Meireles et al. (2015) also observed the coordination between tongue and soft palate gestures in the production of nasal vowels in CV syllables using a corpus consisting of four distinct syllables for comparison purposes: Plosive-oral vowel (*pato*, /ˈpato/, 'duck'); plosive-nasal vowel (*panto*, /ˈpãto/); nasal consonant-oral vowel (*mato*, /ˈmato/, 'bush'); and nasal consonant-nasal vowel (*manto*, /ˈmãto/, 'mantle'). For the nasal plosive-vowel constitution, the authors verified that there was a very close synchrony between the onset of the plosive gesture and the onset of the nasal vowel tongue gesture, but that the beginning of the soft palate gesture was in sync with the release of the plosive. In the case of the other three syllabic constitutions (such as *pa*, *ma* and *man*), all the gestures involved presented near-synchrony in their onsets. As reported by the authors, C and V gestures are in phase in CV syllables, according to the Syllable Structure Coupling Hypothesis (Goldstein et al., 2006), unlike what occurs in VC syllables. The gestural coupling between the onset of the velic gesture and the release of the plosive, however, would not configure an antiphase relationship between consonant and vowel. There are two arguments presented by the authors: (i) This type of alignment is not found in the coupling of consonants in antiphase; and (ii) the same gestural coordination was observed by Proctor et al. (2013) in an analysis of French vowels.

Although Meireles et al. (2015) did not mention the consequence of the gestural alignment of the onset of the velic gesture with the release of the plosive for the constitution of the different acoustic moments of nasal vowels, we can infer that the vowel would present an oral phase, since, for a few milliseconds, the plosive and the vowel are being produced without any soft palate movement. However, there are cases where the velic gesture is active from the start and thus in phase with both the plosive consonant gesture and the vowel tongue gesture. In this case, considering the acoustic moments of the nasal vowel, we could argue that there would be a nasal + murmur constitution — as in *manto* 'mantle'.

From the results of Meireles et al. (2015), we can infer that in the absence of an antiphase relationship between the velic gesture and the consonant gesture, we would not have the configuration of a VC syllable for the Portuguese nasal vowels, but the constitution of a full vowel, that is, the monophonemic status of nasality. Such a hypothesis would be corroborated by the observation of the same pattern of gestural coordination found by Proctor et al. (2013) in French, a language about which there are no doubts regarding the status of these segments.

Using vowel nasality perception tests, Marques and Scarborough (2020) investigated how Brazilian Portuguese listeners perceive nasal vowels compared to their oral counterparts. They manipulated acoustic data by removing and including the murmur of nasal vowels in order to verify if this manipulation would interfere in the listeners' perception. In case the manipulation affected perception, listeners would perceive an oral vowel when the murmur was removed, attributing the nasality essentially to the nasal consonant element; if no effect were observed, the vowel would continue to be perceived as nasal in the absence of a murmur. If nasality were associated with the external element, they would be face to face with the biphonemic status, that is, co-articulatory nasality. If this association did not occur, they would be witnessing the monophonemic status. Results showed that the absence of murmur does not prevent the perception of nasality, and that it is, therefore, inherent to the vowel. The murmur, then, would be part of the vowel element, not a consonant, in line with the monophonemic status of nasality.

3. Method

In this section, we will present the method used in the present study, which focuses on BP nasal vowels ([ɐ̃], [ẽ], [ĩ], [õ], [ũ]) produced by five adult speakers. The variables analyzed were the amplitude of the global and nasal acoustic signals. From them, we can verify the beginning and the end of the nasal vowels' constitutive acoustic moments. Furthermore, from the nasal acoustic signal, we can observe the propagation of nasality in view of the preceding context.

3.1. Participants

The speech samples were obtained from five adult participants, two men and three women, aged between 25 and 52 years. They were all born in the city of Florianópolis, in the state of Santa Catarina, Brazil, and had completed post-secondary education in different areas. At the time of data collection, participants length of residence in Paris ranged from one week to two months. They were all there for professional reasons. Participants did not present perceptually evident articulatory alterations. Altogether, they were a consistent group of informants. They gave consent to take part in the study and to have their pictures shared. The recordings were approved by the Ethics in Research Board at the Federal University of Santa Catarina under number 2057 (FR 434924).

3.2. Corpus

The corpus of this research consists of 75 carrier phrases containing pairs of trisyllabic, paroxytone pseudowords, elaborated with the objective of presenting the distinctive vowel nasality. The carrier phrase used was *Digo* ______ *baixinho* ("I say ______ quietly"). The five nasal vowels ([ɐ̃], [ẽ], [ĩ], [õ], [ũ]) and their oral counterparts ([a], [e], [i], [o], [u]) were inserted into the pseudowords that constituted the carrier phrases, as shown in Table 1. The target vowels were in stressed or unstressed syllables, preceded by stops, and followed by plosives [p, t, k] or fricatives [f, s, ʃ']. Some examples are shown in Table 1.

Oral vowel	Nasal vowel	Preceding context	Following context	Unstressed syllable	Stressed syllable
[a]	[ɐ̃]	[p t k]	[p t k f s ʃ]	papapa-pampapa	papapa-papampa
[e]	[ẽ]	[p t k]	[p t k f s ʃ]	teta-tentata	tateta-tatenta
[i]	[ĩ]	[p t k]	[p t k f s ʃ]	quicaca-quincaca	caquica-caquinca
[o]	[õ]	[p t k]	[p t k f s ʃ]	pofapa-pomfapa	papofa-papomfa
[u]	[ũ]	[p t k]	[p t k f s ʃ]	tuchata-tunchata	tatucha-tatuncha

Table 1. Oral and nasal vowels, their preceding and following consonant contexts, and some examples of the pseudoword pairs recorded in stressed and unstressed syllables.

Each speaker read the 75 carrier phrases three times, producing a total of 225 sentences each. These sentences were randomly presented. Due to noise and unclear visualizations of the spectrogram, portion of dataset was not included in the analysis, resulting in different numbers of productions among the speakers: 124 for Speaker 1; 118 for Speaker 2; 122 for Speaker 3; 114 for Speaker 4; and 120 for Speaker 5. Thus, the total number of instances investigated in this study was 598.

3.3. Instruments and data collection

The recordings were made in an acoustic booth at the *Laboratoire de Phonétique et Phonologie*, at *Université Paris III - Sorbonne Nouvelle* (Paris, France). Due to the instruments used for data collection, individual sessions were held with each participant, with an average duration of one hour. The sentences were presented with Microsoft Office PowerPoint. The following instruments were used to record the data analyzed in the present study, as shown in Figure 2: (i) A SONY MDR-EX15AP nasal microphone, (ii) a piezoelectric vibration transducer for the NAS, and (iii) a MicroMic C520L acoustic microphone coupled close to the oral air outlet in order to capture the global acoustic signal. All instruments were coupled to a preamplifier (40dB) and to an external acquisition board (*Motu Ultralite, mk3, hybride*), and recorded in three channels.

In the present study, we based our investigations on the NAS obtained through the nasal microphone as well as on the acoustic signal obtained through the global microphone.

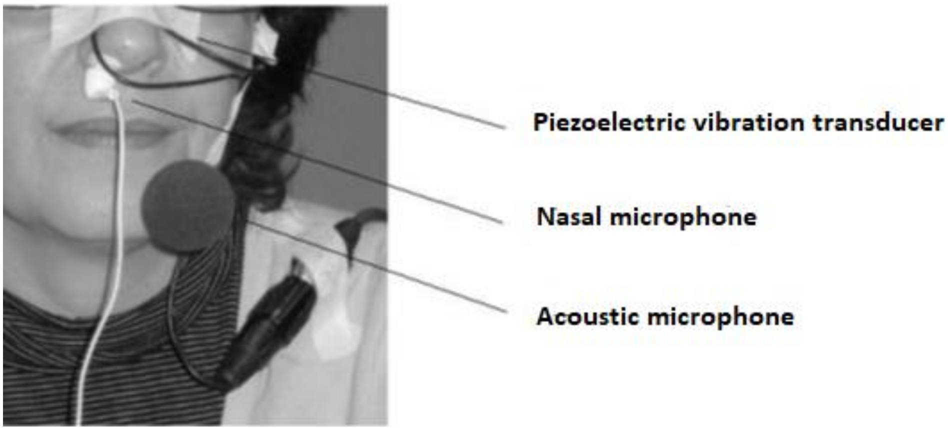

Figure 2. Instruments used for data collection. Source: Photo archive of one of the authors.

3.4. Acoustic treatment of the data

The acoustic signals from the oral and nasal microphones were analyzed in stereo format, that is, in two channels synchronized in time. Thus, it was possible to observe the spreading of the NAS from the nasal vowel and from the surrounding segments. Using *Praat* version 6.1.14, the nasal vowel of the recorded pseudowords was initially submitted to auditory and visual inspection.

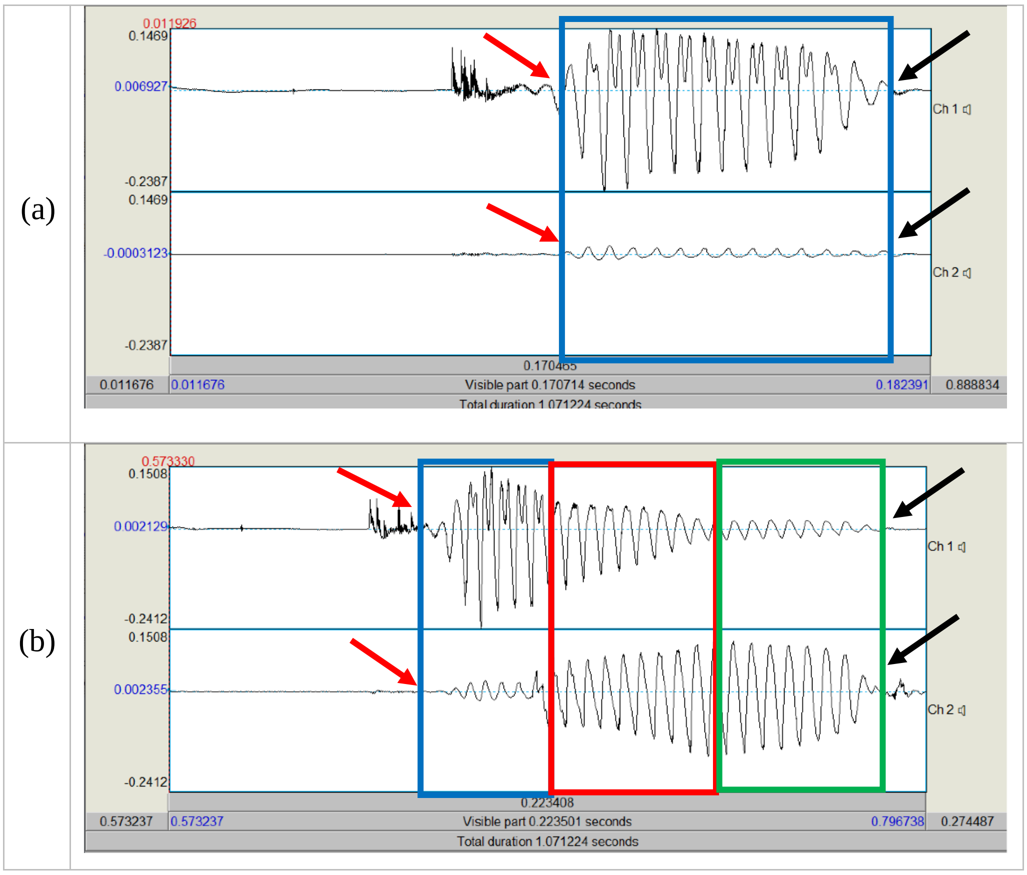

Figure 3. Example of visual inspection, using *Praat*, of the vowels [e] (panel (a)) and [ẽ] (panel (b)), present in the pair of pseudowords *quecaca-quencaca* produced by Speaker 2. The waveforms of the global and NAS signal are in the windows corresponding to Channel 1 and 2 respectively: The red arrow indicates the onset and the black arrow indicates the offset of the vowels [e] and [ẽ]. The blue frame on panel (a) indicates that the vowel at issue is oral, and on panel (b) it shows the oral portion of the nasal vowel. The red frame on panel (b) highlights the nasal portion of the nasal vowel, while the green frame corresponds to its murmur.

The amplitude of the oral vowel NAS is used as a reference for the observation of the presence of the nasal vowels' oral acoustic moment. For the visual inspection of the nasal vowel, in (b), we consider the presence of nasality when the amplitude of Channel 2 is higher than that of Channel 1, and, based on the similarities and differences in the amplitudes in the two channels, we can also observe the different acoustic moments of the nasal vowels, in addition to verifying the spreading of nasality in preceding and following contexts. For a better understanding of the criteria used for visual inspection, see Figure 3. In this figure, the global acoustic signal (Channel 1) and the NAS (Channel 2) of the oral vowel [e] (on panel (a)) and of the nasal [ẽ] (on panel (b)) are displayed. In the production of the oral vowel [e], the amplitude of the NAS must be quite incipient since it is an oral vowel and, according to Amelot (2004), it is not just any movement in the nasal acoustic signal that triggers the perception of nasality. It takes time for the soft palate to lower and, consequently, the spreading of nasality also takes time to become strong to the point of being acoustically detected.

Thus, in Figure 3 we see that, in the onset of the nasal vowel [ẽ] (blue frame in (b)), the NAS curve (Channel 2) has a higher amplitude than the global signal curve (Channel 1), so that it is not in sync with the onset of the nasal vowel production. In this portion, [ẽ] NAS curve (Channel 2, blue frame in (b)) resembles the [e] NAS curve (Channel 2, blue frame in (a)). This indicates the presence of the oral moment of the nasal vowel [ẽ]. Next, we observe that the amplitude of the [ẽ] NAS (Channel 2, red frame in (b)) has greater magnitude than the amplitude of the global signal (Channel 1) of the vowel [ẽ]. This portion exemplifies the nasal acoustic moment of the vowel [ẽ]. In the nasal vowel offset (green frame in (b)), we notice that there is an increase in the NAS amplitude (Channel 2), while there is a decrease in the amplitude of the global acoustic signal of the nasal vowel [ẽ], indicating the presence of murmur.

The results of the acoustic inspection were tabulated in an Excel spreadsheet in order to organize the data and observe the acoustic moment constitution of nasal vowels. It was then possible to analyze and observe all the variables involved in the experiment: Vowel, stress, context, and speaker.

4. Results and discussion

Table 2 presents a summary of the occurrence of each nasal vowel constitutive acoustic moment, in percentage, obtained from the synchronization of global and nasal acoustic signals (NAS), as explained in the methodological procedures. We emphasize the fact that this work does not include inferential statistics due to the low number of data points related to the category Oral+Murmur, as shown below, although we recognize its importance for future research.

	Stressed			Unstressed		
Vowel	**Oral + Nasal + Murmur**	**Nasal + Murmur**	**Oral + Murmur**	**Oral + Nasal + Murmur**	**Nasal + Murmur**	**Oral + Murmur**
[ĩ]	42%	45%	13%	28%	51%	22%
[ẽ]	60%	33%	7%	56%	32%	12%
[ɐ̃]	77%	21%	2%	73%	24%	3%
[õ]	72%	23%	6%	53%	35%	12%
[ũ]	40%	44%	16%	26%	67%	8%
Mean	58%	33%	9%	47%	41%	12%

Table 2. Mean percentage of acoustic moment occurrence in stressed and unstressed nasal vowels.

We will initially analyze the occurrence of different types of nasal vowel constitutions with reference to their acoustic moments. Considering the hypothesis of the monophonemic status of BP nasal vowels, we expected to find a higher percentage of vowels composed by the Oral+Nasal+Murmur (O+N+M) and Nasal+Murm (N+M) moments than by the Oral+Murmur (O+M) moment. In our dataset, we observed the expected behavior, that is, O+N+M and N+M constitutions figure in 91% of the stressed syllables and in 88% of the unstressed syllables.

When looking at the percentage of constitution occurrence among all participants, we see that the vowel quality, especially with regard to height, is relevant for the emergence of different acoustic moment constitutions. Just like in Seara (2000), vowels [ĩ] and [ũ] presented a distinctive behavior in both stressed and unstressed positions when compared to other nasal vowels. However, this behavior differs from that presented by the author, since in the present data the N+M and O+N+M constitutions are the most frequent for high vowels, while in Seara (2000) the constitutions are less systematic. However, it is noteworthy that the acoustic moments observed by the author were based on acoustic parameters such as oral and nasal formants and antiformants. Furthermore, we emphasize the fact that the vowels increased their percentage of N+M constitution when in unstressed syllables, with the exception of [ẽ]. This may be related to the position of the nasal vowel in the word: Initial position for unstressed nasal vowels, in our corpus; and medial position for stressed ones. This behavior corroborates the findings of Lovatto et al. (2007), who pointed to a significantly higher percentage of anticipation of the soft palate movement when the nasal vowel was in word-initial position, although there was no consonant preceding the nasal vowel in Lovatto et al. (2007). For medial and final positions, the anticipation was lower. The constitution of nasal vowels in our data set is presented in the histograms shown in Figure 4 (a) and (b).

As shown in Figure 4 (a) and (b), the O+N+M constitution is more frequent for mid and low vowels. This holds true in both stressed and unstressed positions. Thus, confirming our hypothesis regarding the monophonemic status, we found a high percentage of occurrence of nasal vowel constitutions of the N+M and O+N+M types. As previously reported, according to Sousa (1994), most likely the oral moment of the O+N+M constitution is due to the slowness of the soft palate, which requires some time until the gesture is actually performed and its nasalance is detected. In addition, studies such as Montagu (2004) have shown that the French nasal vowels also present a non-nasalized initial part, which leads us again to observe similarities between the BP nasal vowels and those of French in relation to their constitution. This comparison is interesting since, in French, nasal vowels are phonological. This means that the initial non-nasalized part of BP nasal vowels would not be a counter-argument to its monophonemic status.

In their analysis based on data from a fiberscope, Lovatto et al. (2007) observed that, in the pseudoword *pimpa* produced by a Brazilian speaker, the soft palate was lowered due to the production of /p/ before the nasal vowel, although this was not observed acoustically. Furthermore, the look-ahead model of anticipatory nasality (Henke, 1966) predicts that any oral vowel followed by a nasal consonant would be fully nasalized in a language that lacks phonological nasal vowels. Thus, the results obtained by Lovatto et al. (2007) and in the present study, as shown in Table 2 and Figure 4 (a) and (b), provide evidence in favor of the monophonemic status, since BP nasal vowels are not totally nasalized, presenting high percentages of the O+N+M constitutions, for example, which, according to Henke (1966), would be a clue to refute the biphonemic status.

In Figure 4 (c), the constitution of nasal vowels according to vowel height is presented. It is evident the importance of vowel quality. Although we observe occurrences of O+M for all vowel heights, the low vowel [ɐ̃] is the one with the lowest frequency of occurrence of the O+M constitution. The highest frequency of occurrence is in high vowels (see percentages in Table 1). This is likely due to physiological and articulatory issues. Considering that the tongue position for [ɐ̃] is low and that the palatoglossus muscle connects the tongue to the soft palate, an articulatory consequence is the lowering of the soft palate to a greater degree, allowing greater escape of nasal air (Carton, 1974, p.18). Maeda (1993) also points out the need for a greater magnitude of nasal coupling for the low vowel to be perceived as nasal. Hence, physiologically, it was expected that the most frequent constitutions for [ɐ̃] would be N+M or O+N+M. Likewise, Marques and Scaborough (2020) observed a greater air leak for the BP low vowel, based on perception tests with the pair [a]/[ɐ̃], unlike what happened for other pairs, such as [o]/[õ].

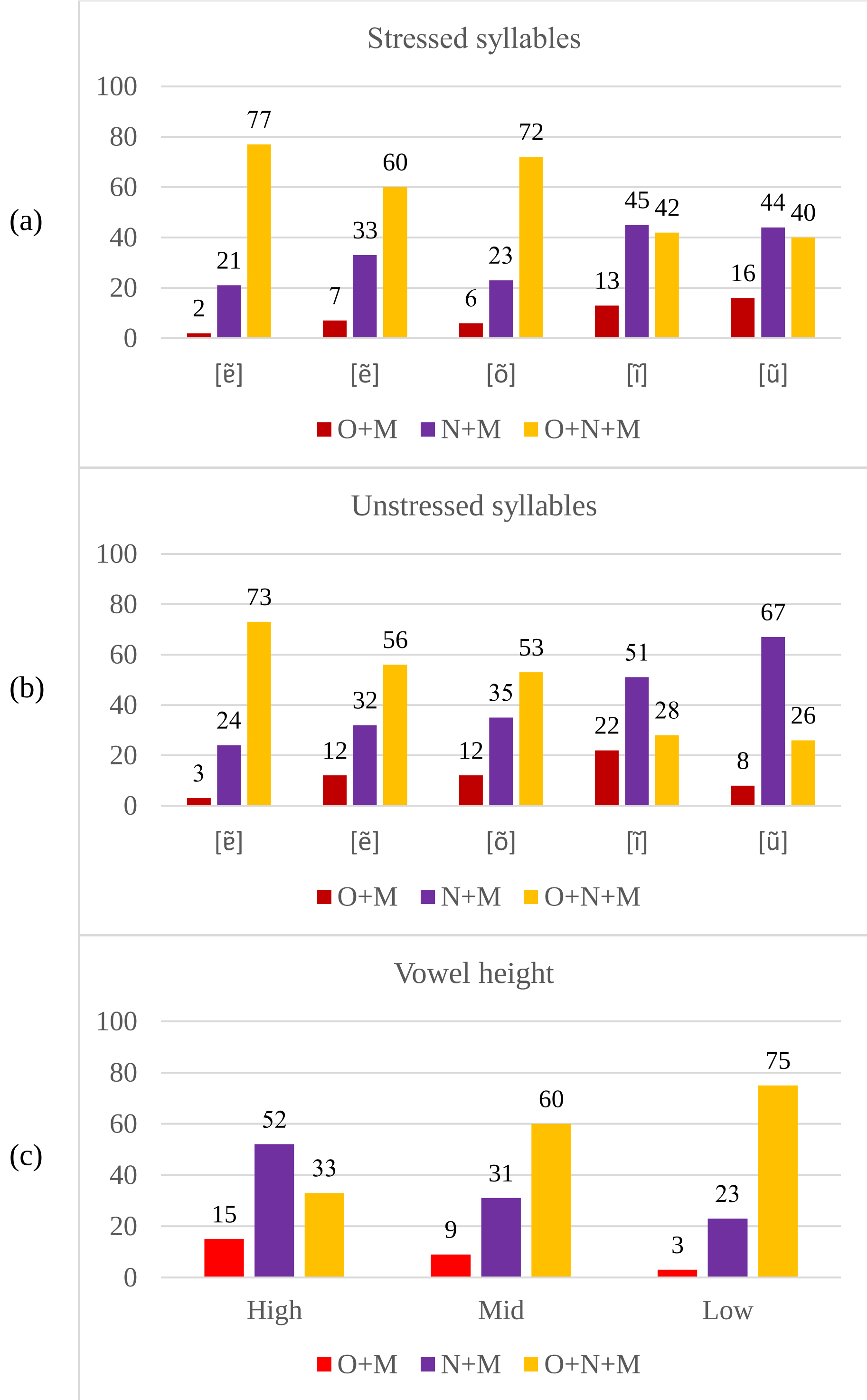

Figure 4. Percentage of occurrence of (a) nasal vowel constitutions in stressed syllables; (b) nasal vowel constitutions in unstressed syllables; (c) nasal vowel constitutions as a function of vowel height.

Another result that leads us to confirm the monophonemic status for BP nasal vowels is related to the behavior of coarticulatory nasality spreading in nasalized vowels. In this case, we will look at the findings of Mendonça (2017) and Mendonca and Seara (2015), which focus on nasalized vowels and the spreading of the nasal consonant NAS curves over the vowels that precede them. According to the authors, the more posterior the point of articulation of the following consonant, the greater the nasal spread. That is, there is greater spreading of nasality on vowels that precede palatal nasal consonants (about 75%) than on bilabial ones (about 25%); and those that are followed by alveolar consonants (about 50%) present less spreading when compared to palatal consonants, but greater spreading than bilabials. Therefore, for comparison purposes, we used Mendonça's (2017) nasality propagation data for nasalized vowels and observed whether or not there was the same behavior in nasal vowels. If that was the case, we could confirm the biphonemic hypothesis, in which a consonant is responsible for nasalization. To confirm the monophonemic status, we expected the NAS curve in nasality spreading in vowels nasalized by nasal consonants in adjacent syllables to be different from the NAS curve found in BP nasal vowels.

To measure nasality spreading over the nasal vowel, we used the equation presented in (1):

(1) % of nasality in the nasal vowel = total vowel duration – oral moment duration*100

Regarding the vowels with the N+M constitution, nasality spreading over the nasal vowel was present in 100% of the cases. Thus, the vowels followed by the velar consonant should present a higher percentage of the N+M constitution. This occurs because velar consonants are the most posterior and, thereby, responsible for the greater spreading of nasality; the more posterior the point of articulation of the following consonant, the greater the spread of nasality. See Figure 5.

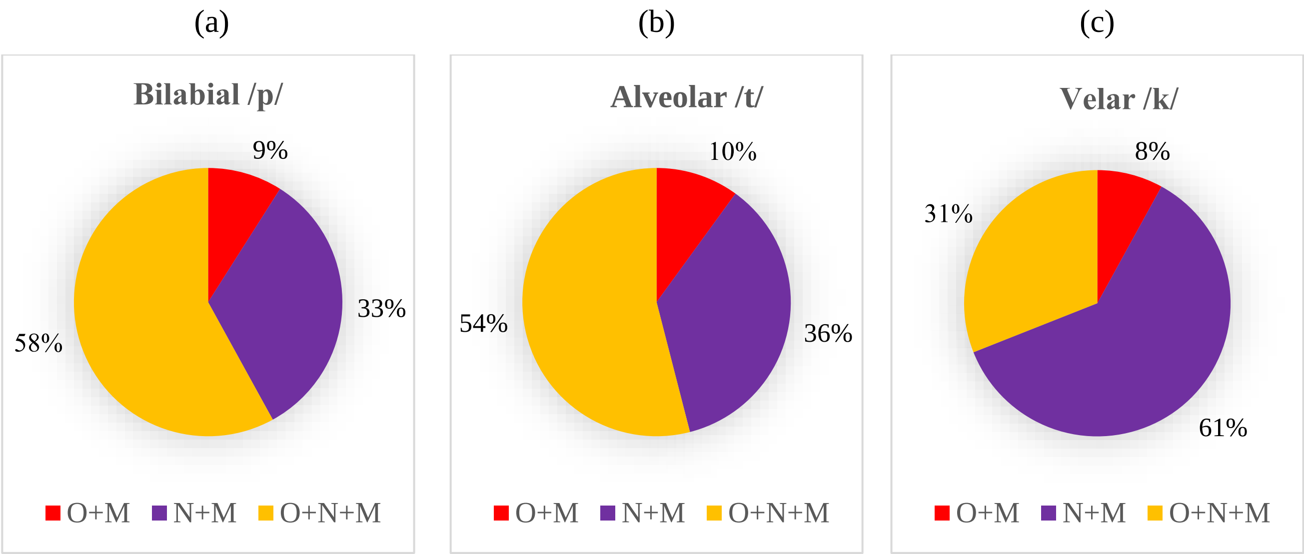

Figure 5. Percentage of acoustic moment constitutions considering the stop that follows the nasal vowel: (a) bilabial, (b) alveolar, or (c) velar.

In Figure 5, we observe that nasal vowels followed by a velar consonant present a higher percentage of the N+M constitution type, that is, 61% of nasal vowels followed by a velar consonant have 100% of nasality spreading. This fact seems to refute our hypothesis for the monophonemic status, since its behavior is similar to that of nasalized vowels. However, for the most anterior place of articulation, i.e., bilabial and alveolar, 100% nasality also occurs in 33% and 36%, respectively. Once again, considering that nasality spreading increases the more posterior the place of articulation is, the fact that there was 100% nasality spreading on a percentage of nasal vowels followed by bilabial and alveolar consonants does not seem to advocate in favor of the biphonemic status. The lack of systematicity in the spreading of anticipatory nasality in view of the following context — unlike what was observed by Mendonça (2017) for vowels nasalized by bilabial, alveolar and palatal consonants — supports the monophonemic status for these segments.

It is important to highlight the very low rate of the O+M constitution in the analyzed data, varying between 9%, 12%, and its absence — as in the case of the low nasal vowel in the context of [k] — and, in many cases, with only one occurrence of the O+M constitution. This finding may indicate that this is not the expected pattern for BP nasal vowels. We also emphasize that a single speaker produced most of these instances. Therefore, these data points were not included in the temporal evaluation of the acoustic moments.

Now focusing on the data referring to the acoustic moments O+N+M, it was necessary to examine the duration of the oral moment relative to the total vowel duration to verify the percentage of nasality spreading using the formula presented in (1). As stated by Bouchard and Chang (2014), the extent of nasal coarticulation is under the speaker's control and depends on the phonemic repertoire of the language. Thus, this analysis is of paramount importance. See, in Table 3, the relative duration values of the oral acoustic moment referring to each following context in the O+N+M constitution.

O+N+M constitution						
Vowels	**Bilabial context [p]**		**Alveolar context [t]**		**Velar context [k]**	
	O	**N+M**	**O**	**N+M**	**O**	**N+M**
[ɐ̃]	31	69	24	76	33	67
[ẽ]	27	73	29	71	23	77
[ĩ]	23	77	19	81	13	87
[õ]	30	70	22	78	26	74
[ũ]	20	80	25	75	26	74
Mean	27	73	25	75	26	74
Median	24	76	25	75	21	79

Table 3. Mean and median of the relative duration (%) of the oral acoustic moment (O) and of the nasal acoustic moments (N) + murmur (M) in the O+N+M constitution, in relation to the total vowel duration in the following bilabial [p], alveolar [t] and velar [k] context.

As shown in Table 3, there are no major differences in the relative duration of the oral acoustic moment of the vowels, regardless of the following context. Therefore, for nasal vowels preceded by bilabial, alveolar and velar consonants, nasality spreading covers more than 70% of the vowels, which indicates that the oral moment of nasal vowels with the O+N+M constitution corresponds to 30%, on average, of the nasal vowel. These values are only similar to those of Mendonça (2017) for velars, since vowels nasalized by bilabial or alveolar consonants do not present such overlap, remaining, on average, below 50%. We believe that this finding, differently from what occurs with nasalized vowels, may also provide evidence of the monophonemic status of BP nasal vowels.

Considering the absolute duration of the oral acoustic moment in the O+N+M constitution, we performed an exploratory analysis of the data variability. This analysis allowed us to investigate whether there are similarities or differences between the data that refer to the time for the beginning of the soft palate lowering, which, according to Amelot et al. (2008), would be 30 to 40 ms for French. The mean time until the beginning of the soft palate lowering (37.83 ms), considering all vowels, is close to the values presented by Amelot et al. (2008). See Table 4.

Vowel	**Dur. of the acoustic moment (O) (ms) O+N+M constitution**	
	Mean	**Median**
[ɐ̃]	43.41	44.00
[ẽ]	39.09	32.50
[ĩ]	27.95	26.00
[õ]	40.44	36.00
[ũ]	30.48	26.00
General	37.83	33.00

Table 4. Mean and median of the absolute duration (in ms) of the oral acoustic moment in the nasal vowel O+N+M constitution.

Thus, considering that the mean duration values are close to the values presented in the study by Amelot et al. (2008), we can infer that the time of the oral acoustic moment corresponds precisely to the slowness of the soft palate, the main articulator for the production of a nasal. Therefore, the oral gesture would not be planned by the speaker; rather it would be a consequence of the articulator movement, which, in our view, is another argument in favor of the monophonemic status of nasality of BP vowels.

5. Final remarks

The present work aimed to investigate vowel nasality in Brazilian Portuguese from the analysis of (i) the acoustic moments that constitute BP nasal vowels, and (ii) the spreading of the nasal acoustic signal (NAS). Through laboratory experiments, we support the hypothesis that the configuration of the nasal vowel acoustic moments reveals its phonemic status in this language. The detailed description of the acoustic moments provided for the BP nasal vowels included data referring to the nasal acoustic signal. It was possible to infer the movements of the soft palate through a non-invasive technique that is also more accessible to research laboratories in Brazil.

Our findings point towards the monophonemic nasality in Portuguese considering: (i) The predominance of vowels composed by the Oral+Nasal+Murmur (O+N+M) and Nasal+Murmur (N+M) moments than by the Oral+Murmur (O+M) moment; (ii) the absence of a co-articulatory nasality spreading pattern observed for nasalized vowels, with no considerable differences in the relative duration of the vowel oral acoustic moment, regardless of the following place of articulation; and (iii) the similarities between the time for the beginning of the soft palate lowering observed by Amelot et al. (2008) for French monophonemic vowels and our results.

Although we have presented arguments that we believe support the monophonemic status, as done by other scholars in the field (Lüdtke, 1953; Pontes, 1972; Couto, 1978; Tláskal, 1980; Callou & Leite, 1990; Costa & Freitas, 2001), we cannot see this issue as solved. For the moment, we seek to add this work to the scarce literature that looks at vowel nasality from an experimental perspective, so that it helps ground the complex discussion about its phonological status. The frequency of the acoustic moment constitutions presented tell us a lot about the configuration of the tract and the gestural interrelationships during the production of a BP nasal vowel. The exercise of considering mental meaning from a physical point of view, that is, from the articulation of sounds to the mind, from the outside to the inside, is necessary (Albano, 2020) and needs to be widely adopted so that we can better understand phonological discussions such as the one we proposed.

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