
RESEARCH PAPER

Perceptual Compensation of Vowel Nasality in Brazilian Portuguese

Luciana Marques¹ and Rebecca Scarborough²

¹ Department of English, Colorado State University, Fort Collins, CO, US

² Department of Linguistics, University of Colorado, Boulder, CO, US

Corresponding author: Luciana Marques (luciana.marques@colostate.edu)

This study explores the nature of the oral-nasal vowel contrast in Brazilian Portuguese (BP). While vowel nasality is a salient property in the language, scholars differ on whether this property forms the basis of a phonological contrast. The presence of a consonant-like nasal resonance at the right edge of the heavily nasalized vowels (i.e., nasal appendix) leads to an analysis that nasal vowels may be product of a contextual nasalization rule (e.g., Camara Jr 1970, 1971), thus coarticulatory in nature. While most of the literature explores the issue from the perspective of production, the present study analyzes how BP listeners perceive nasal vowels in comparison to oral counterparts. If vowel nasality is coarticulatory, speakers should perceive it as they would other coarticulation; namely, they would perceptually compensate for vowel nasality, attributing the nasality to the nasal consonant element and hearing the vowel as essentially oral (Beddor & Krakow 1999). If the nasality is phonemic, however, it should not induce compensation. A forced-choice comparison task was presented to a group of 43 BP listeners, who had to compare nasality in vowels of paired stimuli with and without the appendix. Results show that participants did not perceptually compensate for vowel nasality. The substance of the contrast lies in the combination of vowel quality changes associated with nasality and the presence of a nasal appendix.

Keywords: vowel nasality; nasal vowel phonemes; perceptual compensation; Brazilian Portuguese

1. Introduction

Along with French, Portuguese is one of the major Romance languages generally considered to have contrastive vowel nasality. While there is very little disagreement that nasal vowels are acoustically, aerodynamically and intuitively nasal, the phonological status of vowel nasality, especially in Brazilian Portuguese, is subject to a long-standing debate among scholars in the field. An overview of the scholarship on the issue shows that nasal vowels can be understood as either phonemic or not; in other words, nasal vowels may be interpreted as either monophonemic or biphonemic (Almeida 1976, as cited in Baptista 1988).

Phonologists following a more formal stance, based in part on the initial proposals of Camara Jr (1971), generally conclude that nasal vowels are not phonemic, but rather, a tautosyllabic sequence of an oral vowel plus a nasal consonant in coda position (or nasal archiphoneme in coda, following Camara Jr's analysis). In other words, they are the product of the application of a sequence of synchronic phonological rules: vowel nasalization and nasal coda deletion. While the first rule is mandatory, the second is optional. When deletion is not applied, a consonant-like nasal resonance, known as nasal appendix or murmur, emerges (e.g., Mateus 1982). When followed by another consonant, the appendix assimilates the consonant's place of articulation. Alternatively, the emergence of nasal vowels can be analyzed as the spread of a nasal autosegment to the vowel in a heavy rhyme (e.g., Mateus & D'Andrade 2000; Wetzels 1997). Consequently, in these analyses,

nasal vowels can be considered to be products of extensive, likely phonologically-specified, coarticulation. Those who argue that nasal vowels are not phonemic, but product of coarticulation, provide as evidence phonological analyses that rely on phone distributions in the language, such as the distribution of the r-allophones (e.g., Camara Jr 1970, 1971), the emergence of latent nasal consonants in certain cases of prefixation (e.g., Mateus 1982) and post-lexical diphthongs (e.g., Bisol 1998).

On the other hand, experimental work has provided evidence based on acoustic and aerodynamic analyses of measurable differences in formant values, nasal and oral airflow, and segment durations between oral and nasal counterparts suggesting that nasal vowels are contrastive in nature (e.g., Medeiros 2007; Seara 2000; Sousa 1994).¹ The way nasality affects vowel quality (Sousa 1994) and nasal airflow differences between nasal vowels and truly nasalized counterparts (where a nasal consonant is the onset of the next syllable), in conjunction with durational differences between the nasal appendix and undisputable oral codas (Medeiros 2011), suggest that nasal vowels are phonemic in nature. More recently, Barlaz et al (2018) demonstrate through rtMRI data that nasal vowels, especially the low ones /a/ and /ẽ/ are articulated differently, which the authors consider to be an enhancement of an underlying phonemic feature. Based on this kind of evidence, nasal vowels are considered phonemic segments, albeit complex, heavily nasal and sometimes qualitatively different from oral counterparts (e.g., Medeiros 2007). The appendix is considered, by some, part of the vowel (Sousa 1994), or by others, a product of nasal consonant gesture misalignment (Medeiros 2011), but not a nasal consonant on its own, given its short and variable duration. Consequently, under the second view, the nasal appendix has no phonological status, but it is “epiphenomenal” (Shosted 2011: 1834).

The positions on the phonemic status of vowel nasality in Brazilian Portuguese cannot easily be reconciled, as this division comprises not only differences in conclusions, but also differences in theoretical stances and methods as well. This lack of conciliation in existing work has left unanswered the fundamental question of what the vowel phonemes are in Brazilian Portuguese. Regardless of stance, though, both approaches examine the issue of vowel nasality contrast through a production lens, focusing on the speaker and the variation that comes from producing coarticulated versus non-coarticulated sounds. Examining listeners’ behavior when perceiving nasal vowels may provide valuable new insight on their nature.

The listener has a key role to play when it comes to understanding and shaping phonological contrasts. A fundamental force shaping phonological systems is the need to minimize “confusion on the part of the listener” (Flemming 2004: 1). In that sense, coarticulation is an important consideration. On the one hand, systematic coarticulation may help with speech signal decoding by providing temporally-distributed perceptual cues for the coarticulating segments (Mattingly 1981). These cues are parsed by the perceiver, who attributes the effects of coarticulation to the context (Fowler & Smith 1986; Mattingly 1981). For example, nasalized vowels are perceived by American English listeners as essentially oral as long as they are heard in the context of a following nasal consonant (Beddor & Krakow 1999). This effect is referred to as coarticulatory compensation. At the same time, however, coarticulation can present ‘parsing problems’ to listeners (Ohala 1993a), especially if they fail to normalize the speech signal, for any reason. Coarticulation is known to lead to changes in the sound system of a language, many times by listeners’ reinterpretation of the signal, when coarticulation is not factored out (e.g., Beddor 2009; Ohala 1993b).

¹ See, however, Cagliari (1977) for an experimental approach that does not consider nasal vowels to be phonemic.

Considering the interplay between coarticulation and speech signal decoding, examining listeners' behavior in perceptual studies gets at something that production studies cannot. It is the listener who first shapes the language by classifying what they hear. Furthermore, querying how listeners interpret a sound sequence and what sound properties are relevant for its identification is a very direct way of assessing the system of contrast that distinguishes one word from another, one segment from another. Thus, a perceptual approach to the study of vowel nasality in Brazilian Portuguese presents a new perspective on the issue of its phonological status. The way Brazilian Portuguese listeners interpret vowel nasality in the acoustic signal could show whether speakers of this language process nasal vowels and their surrounding context in a manner consistent with the perception of other contrasts or in a manner more consistent with the perception of coarticulation.

The present study investigates the status of vowel nasality in Brazilian Portuguese from a perceptual point of view, with the ultimate goal of understanding listeners' behavior with respect to oral and nasal vowels. A forced-choice comparison experiment tested whether BP listeners hear nasality as inherent to nasal vowels, or whether they attribute the nasality they hear in the vowel to a nasal element outside the vowel, i.e., the nasal appendix. If nasality in the vowel is attributed to the consonantal nasal element as in languages such as English, where vowel nasality is coarticulatory, it can be inferred that the nasality in BP is coarticulatory as well and not inherent to the vowel. In other words, the main research question of this study is, do Brazilian Portuguese listeners perceptually compensate for vowel nasality? A finding of perceptual compensation would provide perceptual evidence that nasal vowels in Brazilian Portuguese are treated as coarticulatory in nature, and thus should not be considered distinct phonemes in the language. A lack of perceptual compensation, on the other hand, would provide evidence that, despite the presence of the nasal appendix, nasal vowels are treated as distinct units in the language.

2. Coarticulation and perceptual compensation

At the core of the contrastiveness question is whether a phonetic feature in the acoustic signal is treated as inherent to a segment (presumably, part of the underlying representation of that segment) or the product of coarticulation by a neighboring segment (where the relevant feature is part of that neighbor's representation instead). A phonemic contrast between two segments is due to differences in inherent features, i.e., features specified in the underlying representation. Coarticulated features, on the other hand, are not part of the underlying phonological representation of a segment in a language, though they can be grammatically specified and constrained, based on the kinds of phonemic contrasts a language has (e.g., Cohn 1988; Manuel 1990), in order to ensure the maintenance of those contrasts. Further aiding the maintenance of perceptual distinctions is the fact that, upon perceiving the result of coarticulation in the speech signal, listeners *compensate* for the coarticulatory effects by attributing them to the coarticulating source segment. If compensation occurs and the coarticulatory effects on a segment are factored out, then the information contained in the coarticulation can actually be used by listeners without hindering perception. For example, in cases of anticipatory coarticulation, the coarticulatory effect can provide information that predicts the upcoming segment in the signal without obscuring cues for the segment on which the cues are temporally realized (e.g., Beddor et al 2013; Lahiri & Marslen-Wilson 1990 for English vowel nasality).

Beddor & Krakow (1999) demonstrate perceptual compensation for coarticulatory vowel nasality in American English. For native listeners, nasalized vowels between two nasal consonants were perceived as less nasal than the same vowels in isolation or between two oral consonants. At the same time, nasalized vowels between two nasal consonants were

identified as essentially the same as oral vowels in isolation or between two oral consonants. Nasalized vowels in isolation and in between two oral consonants were accurately perceived as the same. Thus, when English listeners encounter vowel nasality, which in English is coarticulatory and occurs in the context of nasal consonants, they perceive that nasality as part of the context and *not* part of the vowel. Crucially, though, compensation cannot occur where the relevant feature is phonemic because compensation requires the presence of the conditioning segment. Perceptual compensation, then, is a predicted and useful behavior, dependent on the system of phonemic contrasts a language has.

If perceptual compensation occurs when the target feature is coarticulatory, failure to perceptually compensate for a phonetic feature in the presence of an apparent conditioning segment would mean that listeners treat that feature as non-coarticulatory. In other words, that feature could be interpreted as inherent to the target segment and not to the context. Thus, perceptual compensation can provide a novel framework to test for phonemic status of apparently coarticulated segments. Beddor & Krakow (1999) suggest this possibility through their interpretation of the fact that their participants did not compensate in about 25% of the cases, despite the presence of the conditioning context. The authors suggest that the lack of compensation could be attributed to nasality in the vowel being partially phonologized in English. Thus, one should expect, if a phonetic feature is inherent to a given segment, that compensation should not occur.

A similar hypothesis could be made in the case of Brazilian Portuguese. If vowel nasality is strictly contextual and rule-governed (i.e., coarticulatory), then participants should compensate for vowel nasality, attributing it to the nasal appendix which, in turn, can be considered a conditioning consonant. However, if vowel nasality is not coarticulatory but inherent, then participants should not compensate for vowel nasality despite the presence of the appendix. Nasal vowels, in this case, can be considered phonemic, and the appendix is not an independent conditioning consonant.

3. Experiment

To test for perceptual compensation effects of vowel nasality in Brazilian Portuguese, a forced-choice comparison task was designed. Native speakers of Brazilian Portuguese were asked to select, from a pair of stimuli, the stimulus with the more nasal vowel. If compensation occurs, listeners should never select a nasal vowel in the context of the appendix as more nasal.

3.1. Stimuli creation

Twenty word and non-word disyllabic tokens were recorded by two native speakers of Brazilian Portuguese. The tokens conformed to one of the following patterns: 'CVCV or 'CVC̃V. The crucial difference between 'CVCV and 'CVC̃V tokens is vowel nasality (plus the presence of a nasal appendix). In all tokens, the penultimate syllable is stressed (bold syllables on **Table 1**). Disyllabic tokens were selected to increase the likelihood

Table 1: Tokens recorded for stimulus creation.

	'CVCV	'CVC̃V
/a/	Capa	Campo
/e/	* Teto	Tento
/i/	Tita	Tinta
/o/	Popa	Pompa
/u/	* Tutu	* Tunta

of nasal appendix emergence and facilitate segmentation. The nasal appendix has been reported to have variable nasal formants (Seara 2000), and place of articulation cues of the following consonant if word-medial (Cagliari 1977). If word-final, its closure might not always occur (Shosted 2011), and its place of articulation can be palatal-velar (Shosted 2006). The appendix is also of variable duration, and it may even not appear in all productions of nasal vowels (Medeiros 2007). There are, however, instances in which a nasal appendix is more likely to emerge. Particularly, the nasal appendix has been shown to consistently occur between nasal vowels and stop consonants, due to consonantal oral tract closure occurring before velopharyngeal port closure, creating, aerodynamically, an increase in nasal airflow that peaks after oral tract closure. This *gestural misalignment* creates a more consonant-like appendix at the vowel's right edge (e.g., Medeiros 2008, 2011), with nasal resonances but no vowel resonances, especially in non-low nasal vowels (see **Figure 2** for an example of this kind of appendix at the vowel's right edge). This specific quality of the nasal appendix, along with its immediate context of a vowel to the left and a voiceless stop consonant to the right visually facilitates appendix identification and segmentation, which cannot be done as easily with other consonants such as fricatives (Medeiros 2008).

Table 1 presents the tokens recorded; note that the orthographic nasal consonant is not expected to be pronounced. The starred token is not a real word in Brazilian Portuguese.²

Stimuli were created by using only the first part of each recorded token. For CVCV tokens, the first part consisted of the initial C and the first vowel; for CVCV tokens, the first part consisted of the initial C, \tilde{V} and the nasal appendix. **Figure 1** below shows the word *capa* 'cape' as produced by speaker 1. The highlighted portion shows the part of the word that was used to create stimuli for the low vowel, the first consonant [k] and the first vowel [a].

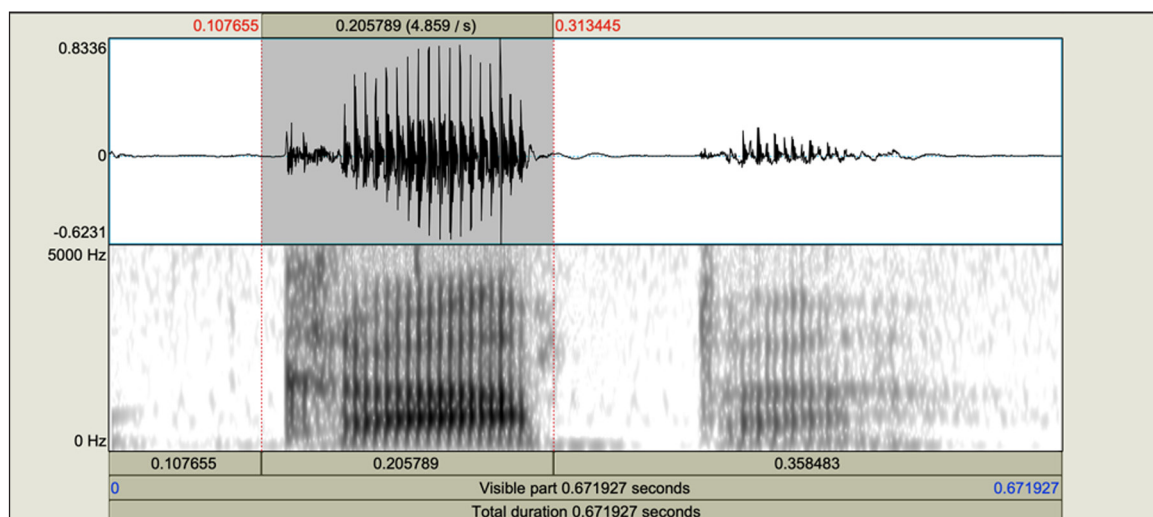


Figure 1: Waveform and broadband spectrogram for speaker 1 production of *capa*. The highlighted portion corresponds to the consonant [k] and vowel [a].

² In this phonological context, the mid-low front unrounded vowel / ϵ / is expected. / ϵ / has a very distinct quality, which would pose problems for the experiment. Instead, a non-word was selected to match more closely the nasal vowel quality. As for the high back vowel /u/, non-words were selected because it was difficult to find words that match the phonological requisites for this vowel quality (disyllabic, penultimate stress, voiceless stop at the right edge of vowel). A simple search in the *Corpus do Português* (Davies 2016) shows that, among the first 1000 words, none fit the requisites.

Figure 2 below shows the word *campo* ‘field’ as produced by speaker 1. The highlighted portion shows the part of the word that was used to create stimuli for the low vowel, the first consonant [k] and the first vowel [ẽ]. The nasal appendix can be seen at the vowel’s right edge, after the formants abruptly end. Two distinct nasal resonances can be observed, one very low at around 252Hz, and another broader one at about 2600 Hz. The end of these resonances signaled the end of the appendix.

Stimulus creation involved cutting the oral (V) and nasal (Ṽ) vowels for a given vowel quality from their original contexts and splicing them into each other’s contexts: C_# (isolation) for oral and C_#^N (appendix) for nasal vowels. This resulted in three relevant stimuli for each word pair of a given vowel quality: CV#, C̃V#, C̃V#^N.³ **Table 2** below presents the stimuli created by the method described above using the words *capa* and *campo* with the low vowel.

Stimuli were paired in different conditions according to context and vowel nasality. **Table 3** presents stimuli pairs divided by the relevant contexts for analysis. In all, there were 6 stimuli pairs per vowel quality (3 pairs * 2 speakers), yielding 30 relevant pairs in total.

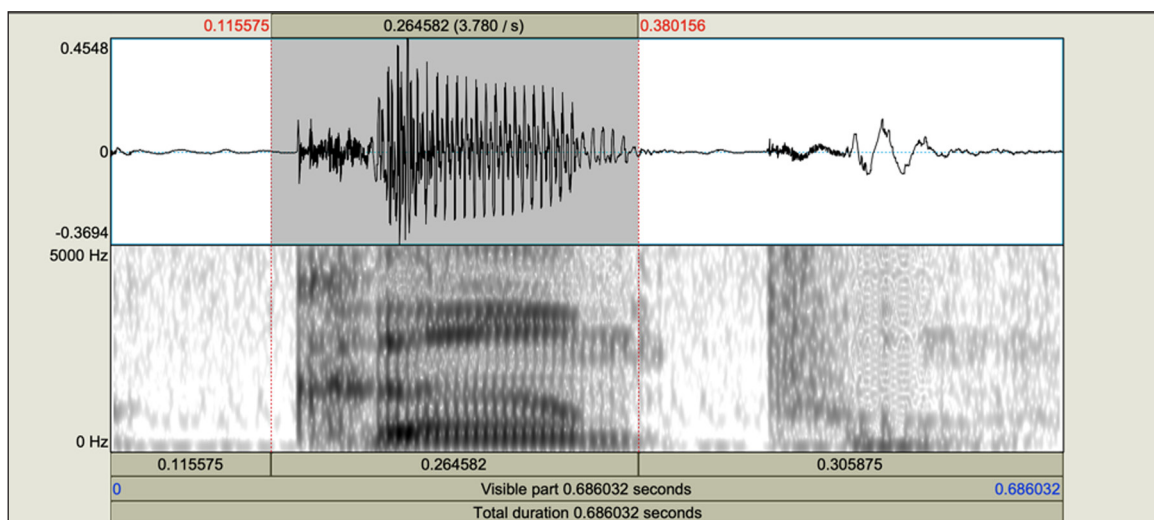


Figure 2: Waveform and broadband spectrogram for speaker 1 production of *campo*. The highlighted portion corresponds to the consonant [k] and vowel [ẽ] with the appendix.

Table 2: Stimuli created based on the words *capa* and *campo*.

	k_#	k_# ^m
a	[ka]	[ka ^m]
ẽ	[kẽ]	[kẽ ^m]

Table 3: Stimuli pairs divided by relevant contexts.

Stimulus type	Pair
Type 1: Different context, same vowel nasality	C̃V#-C̃V# ^N
Type 2: Different context, different vowel nasality	CV#-C̃V# ^N
Type 3: Same context, different vowel nasality	CV#-C̃V#

³ The fourth possibility, CV^N, was not analyzed since such structures with an oral vowel and a nasal appendix do not occur naturally in Brazilian Portuguese. Furthermore, the literature on compensation does not make clear predictions about CV^N because there is no nasality in the vowel to be compensated for (Beddor et al 2001).

3.2. Participants and procedure

43 participants took part in the experiment. Participants were undergraduate students at the Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil, and were native speakers of Brazilian Portuguese who used the language daily. They were paid for their participation. As all participants were majors in Portuguese language and literature, they were familiar with the concept of nasality and nasal vowels.

The experiment was conducted in a sound booth at the Laboratório de Fonética e Psicolinguística (LAFAPE) at UNICAMP. For the task, an experimental routine was created in PsychoPy (Peirce 2007) and presented to the listeners on a computer screen and over headphones. First, participants were presented with instructions for the task, given in Brazilian Portuguese. They were asked to focus on the vowel sounds. Upon listening to a pair of parts of words, participants were told to answer, by pressing a key on a computer keyboard as quickly as possible, which vowel they thought was more nasal: the first (left arrow), the second (right arrow), or if the two were the same (down arrow). The first vowel corresponded to the vowel in the first stimulus and the second vowel corresponded to the vowel in the second stimulus.

A practice block was presented first to familiarize participants with the task. No test stimulus pairs were used in the practice block. Then, participants completed five test blocks, one for each vowel quality. Each block contained all of the possible stimulus pair combinations for a given vowel quality. The experiment lasted around one hour. All procedures were performed in accordance with the Declaration of Helsinki and approved by the University of Colorado's Institutional Board Review under protocol number 15-0204.

3.3. Interpretation

The guiding hypothesis for the experiment is that if nasality in nasal vowels is coarticulatory in nature, nasal vowels before an appendix should be judged to be less nasal than the nasal vowels in isolation ($C\tilde{V}\# > C\tilde{V}^N$), and nasal vowels before the appendix would be judged to be the same as oral vowels in isolation ($CV\# = C\tilde{V}^N$). In other words, participants should compensate for vowel nasality by attributing it to the neighboring nasal appendix if nasal vowels are the product of coarticulation in Brazilian Portuguese. However, if nasality is contrastive, context should be ignored, and vowels in $C\tilde{V}\#-C\tilde{V}^N$ pairs should be perceived as the same ($C\tilde{V}\# = C\tilde{V}^N$), while vowels in $CV\#-C\tilde{V}^N$ pairs should be perceived as different, with the nasal vowel considered more nasal than the oral one ($C\tilde{V}^N > CV\#$). Interpretations are presented in **Table 4** below.

A further implication would be that the appendix, in the first case, could be considered a consonant with a clear phonemic status, as suggested in the more formal analyses; in the second case, it would be considered a simple byproduct of gestural misalignment, with no phonemic status of its own, as suggested in more experimental analyses.

Table 4: Interpretation of results.

Stimulus pair	Compensation scenario	Non-compensation scenario
Type 1: $C\tilde{V}\#-C\tilde{V}^N$	$C\tilde{V}\#$ more nasal	vowels are equal
Type 2: $CV\#-C\tilde{V}^N$	vowels are equal	$C\tilde{V}^N$ more nasal
Type 3: $CV\#-C\tilde{V}\#$	N/A	N/A

3.4. Analysis

The results were analyzed statistically using logistic mixed effect models on accuracy, or how well participants were able to respond veridically that the vowels were the same in type 1 pairs ($C\tilde{V}\#-C\tilde{V}^N$), and how well participants were able to respond veridically that the second vowel was more nasal in type 2 pairs ($CV\#-C\tilde{V}^N$). Type 3 pairs ($CV\#-C\tilde{V}\#$) were also tested to see if participants could differentiate oral and nasal vowels based solely on differences in nasality within the vowel; the expected correct answer is that the second vowel is more nasal. Thus, we can think of the dependent variable as a binary variable with two levels, *correct* and *incorrect*, defined relative to veridical perception, or the identification of actual acoustic differences between vowels. Consequently, the appropriate model for analysis is a logistic mixed model, because it allows the dependent variable to be non-continuous. The statistical function used was the *glmer* from the *lme4* package (Bates et al 2015) in R (R Core Team 2013). First, answers to all stimulus pairs were analyzed together.⁴ Then, each stimulus pair type was analyzed separately based on the established hypotheses. Speaker was a random explanatory variable for all stimulus pairs analyses. Independent variables varied depending on the analysis. Stimulus pair had three levels: type 1, 2 and 3 and was used in the overall analyses. Vowel quality had five levels: low, mid-front, mid-back, high front, high back and was used in each stimulus pair type analysis.

4. Results

There were in total 2579 responses, 1290 of which are of the relevant stimulus pair types 1, 2 and 3 from **Table 2**. Overall, participants were able to correctly identify the nasal vowel as more nasal (or as the same in the case of type 1 stimulus pairs) 64% of the time. When dividing correct answers by stimulus pair type, it is easy to notice that accuracy varies. Answers by stimulus pair type are presented in **Figure 3** below.

The stimulus pair with the most correct answers is type 2, $CV\#-C\tilde{V}^N$, at 88.37% accuracy, i.e., the second vowel was judged more nasal about 89% of the time. It is clear that perceptual compensation did not occur for this stimulus pair, otherwise the

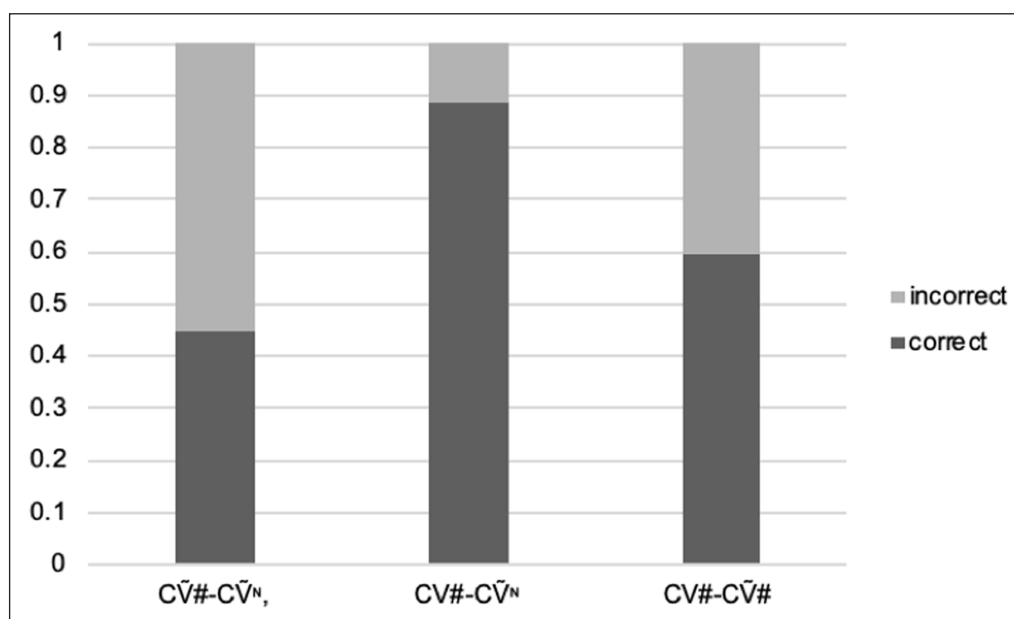


Figure 3: Overall accuracy by stimulus pair type.

⁴ The statistical function used in R for this analysis is: `glmer(correct ~ pair + (1 + pair|Speaker), family = binomial, data = responseDF)`.

second vowel would not have been judged more nasal. Stimulus pair type 3, CV#-C \tilde{V} # yielded 59% of correct second-vowel-is-more-nasal answers, which shows participants can distinguish vowels based on their difference in nasality. However, accuracy was much lower than in type 2 stimulus pairs, while still above the chance level of 33%. The difference in accuracy between type 3 and type 2 pairs is significant (est = -2.1847, $p < 0.0005$). Stimulus pair type 1, C \tilde{V} #-C \tilde{V} ^N, yielded the lowest veridical rates, i.e., vowels were judged to be the same only 45% of the time, which is significantly less than type 2 (est = -2.8546, $p < 0.0005$) and type 3 pairs (est = -0.6699, $p > 0.005$), despite being above chance level.

4.1. Stimulus pair type 1: C \tilde{V} #-C \tilde{V} ^N

For stimulus pairs type 1, vowels should be judged as the same if perceptual compensation did not occur, or the first one should be judged more nasal if compensation did occur. In the latter case, that is because participants should attribute nasality in the second vowel to the appendix, which would cause them to perceive the second vowel as less nasal despite being acoustically the same as the first vowel in the pair. **Figure 4** below presents the results for stimulus pair type 1.

Upon listening to a type 1 stimulus pair, participants correctly judged the vowels to be the same about 45% of the time, while only choosing the vowel in C \tilde{V} # as more nasal 5% of the time. These results suggest that compensation did not occur. However, the patterns of response for this stimulus pair reveal one curious finding: most participants mistakenly judged the second vowel in this pair to be more nasal, which was considered more nasal about 50% of the time. While a 5% difference is not particularly high, the presence of the appendix increases nasality ratings. Thus, in type 1 stimulus pairs, either the participants ignored the appendix altogether, or it contributed to nasality judgements. They very rarely used the appendix in the expected perceptual compensation manner. In that sense, the role of the appendix appears to be different from the one played by nasal consonants in languages like English; the appendix at least in this study does not seem to be a consonant that triggers compensation, and vowel nasality is not simply a product of coarticulation. In fact, it is as if the appendix is instead considered to be (an optional) part of the vowel.

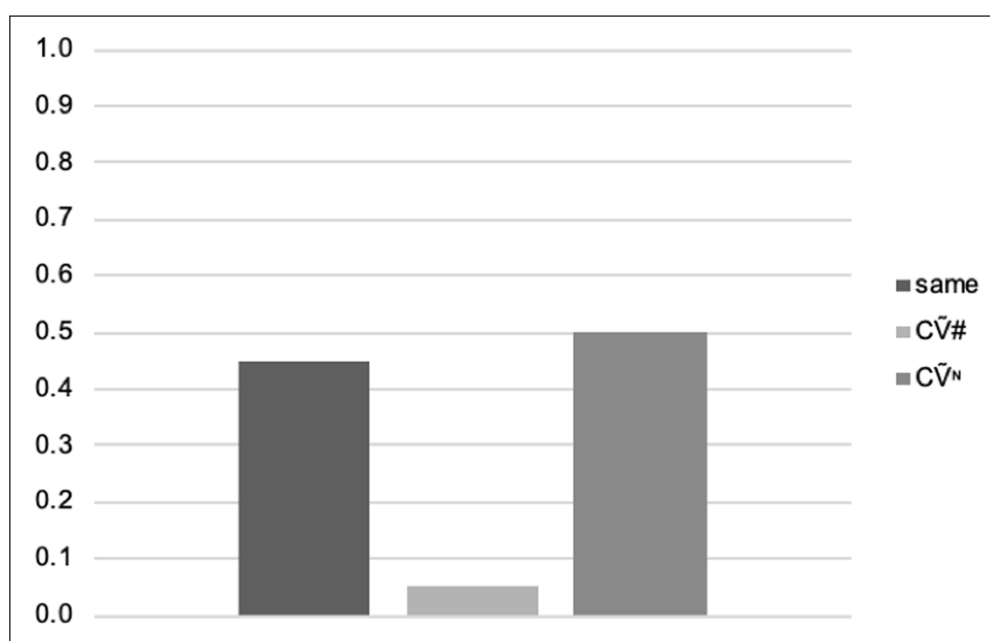


Figure 4: Rating responses for stimulus pairs type 1.

4.2. Stimulus pairs type 2: CV#-C \tilde{V} ^N

For type 2 stimulus pairs, if perceptual compensation occurs, vowels should be judged as being the same, since nasality heard in the second vowel should be attributed to the appendix. On the other hand, if nasality is contrastive, the second vowel should be judged as more nasal. **Figure 5** below presents the answers for type 2 stimulus pairs divided by all possible answers: same, CV# and C \tilde{V} ^N.

In this context, the correct answer (C \tilde{V} ^N) was chosen at around 88% of the time, versus only 6% of the time for each of the other two possible responses. It is clear that, in this stimulus pair type, perceptual compensation did not occur either; nasal vowels followed by the appendix were perceived as more nasal than oral vowels in isolation. Moreover, the appendix seems to have played a similar role in type 2 stimulus pairs as in type 1 stimulus pairs. Thus, it seems clearer that the appendix not only does not trigger compensation, and so cannot be considered a consonant, but it aids in the perception of nasality. When considering the pattern of answers in type 1 stimulus pairs, the great number of correct answers show that vowel nasality and the appendix work together as percept for nasality.

4.3. Stimulus pair type 3: CV#-C \tilde{V} #

Stimulus pairs of type 3 are not part of the hypothesis *per se*, as there is no context for perceptual compensation to occur in this case, but the lack of compensation context means listeners had to rely strictly on acoustic differences between vowels in a stimulus pair, be it vowel nasality or vowel quality. If participants can distinguish between the vowels in these pairs, then there is evidence that they can pay attention to vowel nasality, and that nasality itself is perceptually salient enough; further, it would mean that the addition of the appendix to a nasal vowel, while it may reinforce the perception of nasality, is not the only source of nasal perception. When judging vowel nasality of stimulus pairs of this type, the expected correct answer is C \tilde{V} #, since the vowel in this stimulus is acoustically nasal. **Figure 6** presents the data combined for all vowel qualities.

Participants correctly judged the second vowel as more nasal 50% of the time. Vowels were considered the same 45% of the time. While the difference of 5% is small, it seems that participants are able to distinguish vowels based solely on acoustic differences, even without further context.

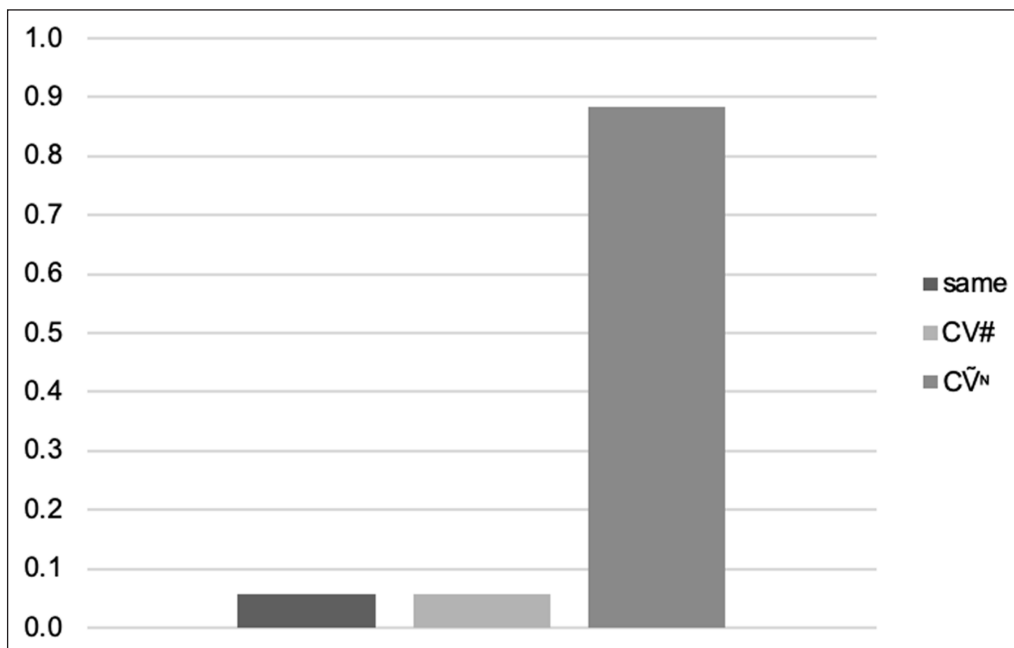


Figure 5: Rating responses for stimulus pair type 2.

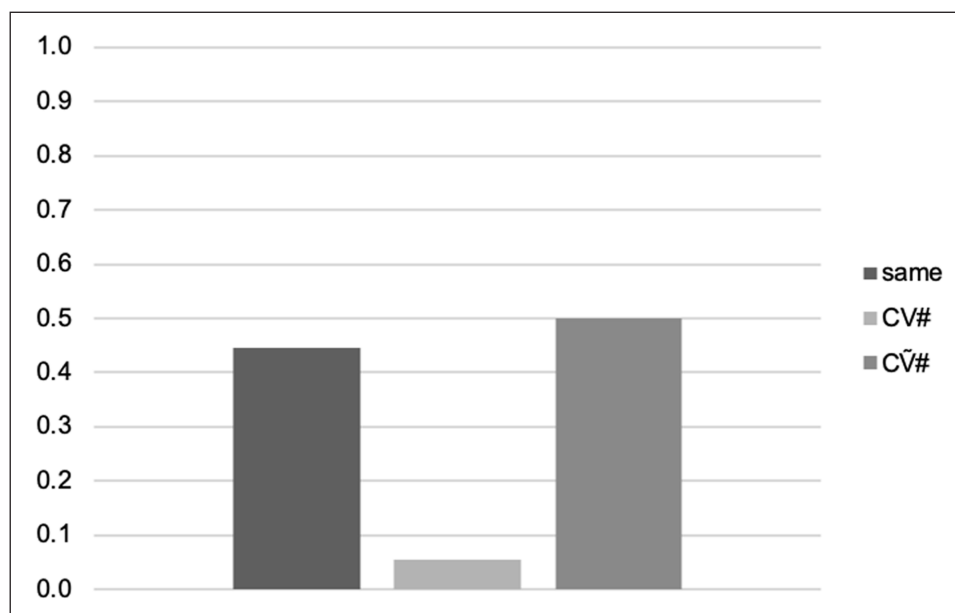


Figure 6: Rating responses for stimulus pairs type 3.

When considering the results, correct and incorrect, for all three stimulus pair types, the effect of vowel nasality and the appendix can be better appreciated. Clearly, perceptual compensation did not occur in any case. It also seems clear that vowel nasality can be perceived on its own. The appendix does not hinder veridical nasality perception; rather, it enhances it. Particularly, adding the appendix increases correct answers, from type 3 to type 2 (the only change being the presence of the appendix in type 2 pairs), by 29%. Thus, the results do not support any of the hypotheses directly, but rather they seem consistent with the idea that vowel nasality is inherent to the vowel and that the appendix is not a consonant in itself, but part of vowel.

4.4. Effects of vowel quality

One interesting aspect of vowel nasality in Brazilian Portuguese is the interaction with vowel quality, in terms of production. All the nasal vowels are very nasal phonetically, with similar degrees of acoustic nasality per vowel quality, as demonstrated elsewhere (Marques & Scarborough 2017). However, nasal vowels also, in some cases, differ in vowel quality. To illustrate, **Figure 7** below shows formant values for oral and nasal vowels of the vowels used in the stimuli, all measured at their midpoints.

Separate linear mixed-effects models for each vowel quality with F1 and F2 as dependent variables, nasality as independent variable, and speaker as random independent variable, were fitted.⁵ **Table 5** below shows which formant differences (oral minus nasal vowel formant values) were statistically significant.

Statistically, only the low vowel's F1 is significantly different between oral and nasal vowels (the mid-back vowel is only marginally significant, so it will be paired with the non-low vowels). The low nasal vowel F1 is indeed much lower than its oral counterpart, making /ã/ a much higher vowel than /a/, as can be seen in **Figure 7**. Thus, there is a vowel quality difference associated with the nasality distinction, especially for the low vowels. This quality difference for the low vowel in Portuguese has been described before (e.g., Sousa 1994), and it can be explained acoustically at least in part by the interactions between oral and nasal resonances that tend to raise low vowels and lower high vowels

⁵ The function used in R for this analysis is: `lmer (Formant ~ nasality + (1 + nasality|speaker), data = formantDFV)`. The function was used for each vowel formants separately.

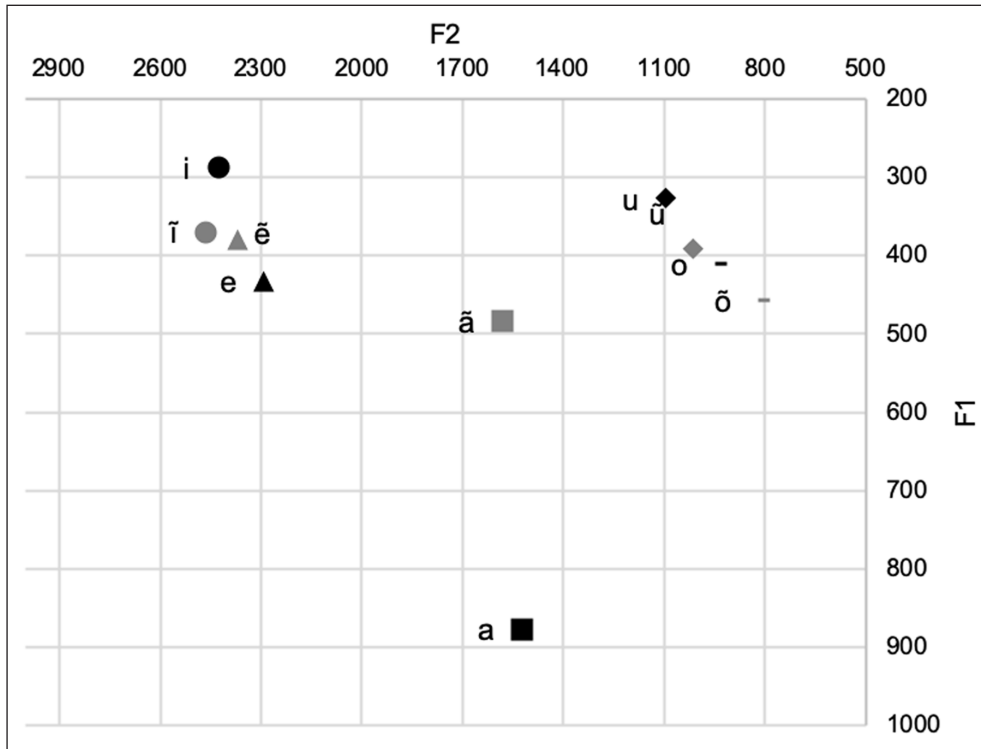


Figure 7: F1 by F2 plot for oral and nasal vowels in the stimuli.

Table 5: Formant differences and p-values for oral-nasal vowel differences.

Vowel quality	F1 difference (Hz)	F2 difference (Hz)	p-value significance
a	393	-58	F1 only
e	52	-80	none
i	83	-39	none
o	-46	129	marginal F1 only
u	-64	81	none

(e.g., Beddor 1983). Articulatory differences in oropharyngeal configuration have been found in nasal vowels as well, for example a higher tongue blade position and a wider hyperpharyngeal region for /ã/ relative to /a/ (Barlaz et al 2018). In both cases, the result is a higher vowel quality. In fact, Barlaz et al (2018: 94) argue that the articulatory differences “enhance the effects of nasalization on the acoustic output” in Brazilian Portuguese. Indeed, F1, tongue height and nasality are integrated in the perception of nasal vowels (e.g., Beddor et al 1986; Krakow et al 1987).

Importantly, though, the difference in vowel quality has implications for the perception of vowel nasality. This finding shows that the greatest difference in quality, and the only statistically significant difference, is with the low vowels. This means that for the low vowels in the current experiment, participants potentially had this vowel quality difference to rely on in addition to nasality when making judgements about which vowel is more nasal. This allows for a prediction that more correct answers, regardless of context, should be yielded for low vowel stimulus pairs over other vowel qualities. **Figure 8** presents the proportions of accurate answers, regardless of stimulus type, divided by vowel quality.

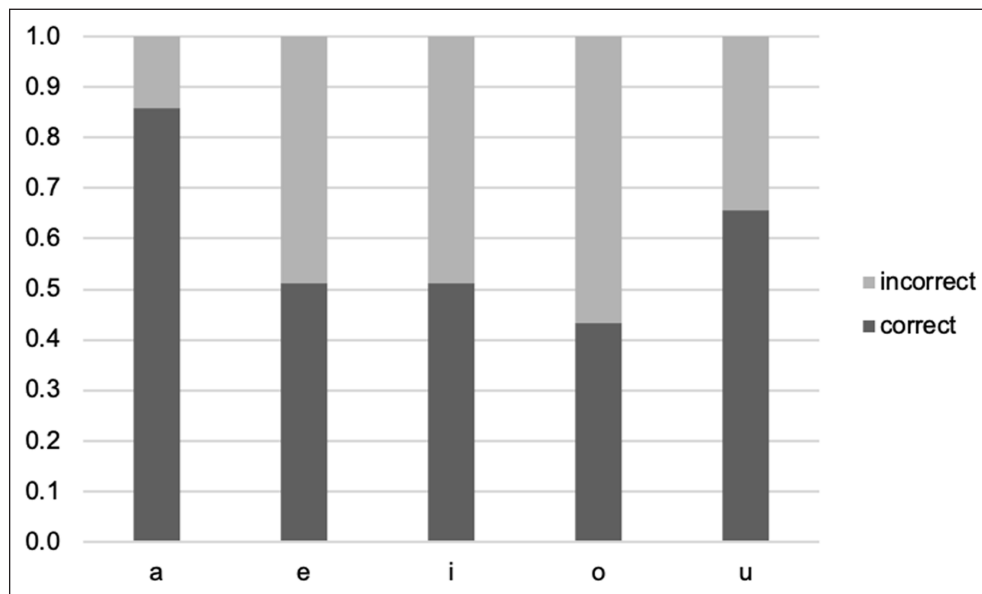


Figure 8: Overall ratings accuracy by vowel quality.

The low vowel stimulus pairs yielded more veridical answers (86%) when compared to all other vowel qualities, consistent with the observed acoustic differences in vowel quality. A logistic mixed-linear effect model on correct answers by vowel quality and speaker as a random independent variable shows that the likelihood of having a correct answer is significantly lower in all the non-low vowels when compared to the low ones (all *p*-values less than 0.0005).⁶ On average, participants were able to accurately evaluate the non-low more nasal vowels about 53% of the time only, and there is much variation in response patterns. The mid and high front vowels have as many incorrect as correct answers; the mid-back vowel yielded about 57% incorrect answers. Thus, the lack of significant acoustic vowel quality differences between oral and nasal counterparts corresponds almost directly to difficulty in differentiating oral and nasal vowels. Interestingly, the high-back vowel did not pattern with the other non-low vowels, as participants seemed to have been able to correctly identify the more nasal vowels about 67% of the time, despite the non-significant formant value differences. While oral and nasal high back vowels are not statistically different acoustically, Barlaz et al (2018) found that these vowels are articulated slightly different, with a lower tongue blade for /ũ/, which could explain why F1 for this vowel is higher than the oral counterpart and also why participants were able to identify the more nasal high back vowel in the present study.⁷ All in all, it seems clear, from this analysis, that vowel quality differences associated with nasality may function as a reliable perceptual nasality cue.

Given that the appendix also influenced nasality responses, a more detailed analysis of responses by vowel quality and context is needed. **Figure 9** presents the proportion of correct/acoustically veridical answers by stimulus pair type, divided by vowel quality.

The proportions of correct answers for stimulus type 3, CV#-C̃V#, show that participants can distinguish oral from nasal vowels even in the absence of context, as already mentioned above. However, there seems to be a clear effect of vowel quality in

⁶ The function used in R for this analysis is: `glmer (accuracy ~ vowel + (1 + vowel|speaker), family = binomial, data = response2DF)`.

⁷ Barlaz et al (2018: 92) also found slight differences in articulation between oral and nasal high front counterparts; however, these were more variable, with “a slightly lower tongue blade position and a more constricted hyperpharyngeal region for /i/”. This difference explains the non-significant F1 differences found; however, it does not explain the low accuracy rates for these vowels in our experiment.

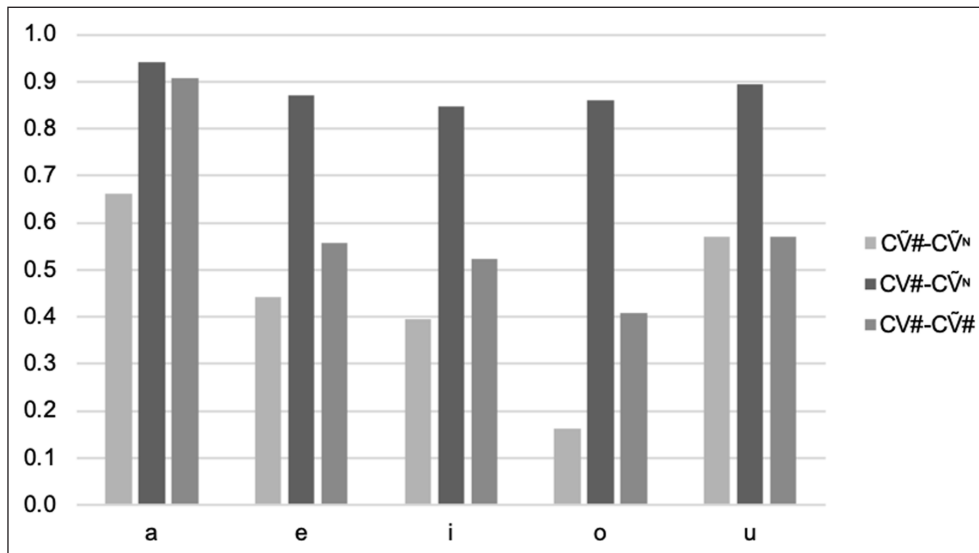


Figure 9: Overall accurate answers by vowel quality.

this stimulus pair type. The low nasal vowel is perceived as more nasal 91% of the time, versus the average 52% accuracy for other vowel qualities (notice the particularly low proportion of correct answers for the mid-back vowel). A logistic mixed-effect model with accuracy as dependent variable and vowel quality as independent variable shows that the differences in accuracy by vowel quality are all statistically significant, with all non-low vowels veridical answers less correctly identified (all p -values are less than 0.005).⁸ Given that the low vowel quality is the only one in which there are appreciable acoustic vowel quality differences between the oral and nasal counterparts, it is clear that these vowel quality differences influence nasality perception, over and above nasality in the vowel *per se*. In other words, the acoustic consequence of nasal coupling on the vowel's formant profile, along with any adjustment of the oral articulation, works as a perceptual cue for vowel nasality. When those quality differences are absent, as in the case of non-low vowels, then accuracy decreases.

The high proportions of correct answers for stimulus pair type 2, CV#-C~Vⁿ, across vowels confirms that the appendix does not trigger compensation, and it aids in vowel nasality perception for all vowels. However, the size of the benefit varies by vowel quality. The biggest benefit over the no-context comparisons happened in non-low vowel stimulus pairs. There was an average increase in accuracy for non-low vowels of 35%, from an average 52% in type 3 to an average 87% in type 2 stimulus pairs, versus only a 4% increase for the low vowel. Thus, in the absence of an appreciable acoustic difference between oral and nasal counterparts, participants appeared to have relied more on the appendix to evaluate a vowel as more nasal. The appendix seems to function as a locus of nasality perception, hence the substantial increase in accuracy.

The proportions of correct answers for stimulus pairs of type 1, C~V#-C~Vⁿ, seem consistent with this idea. While all the accuracy proportions for this stimulus pair type are lower than type 2 pair accuracy, the low number of correct *same* answers, especially for the mid and high-front vowels, demonstrates a higher reliance on the presence of the nasal appendix for nasality ratings. If the appendix did not play any role on the perception of nasality, accurate *same* ratings would be higher, perhaps close to type 2 pairs, as the presence of the appendix would be ignored.

⁸ The function used in R for this analysis is: `glmer (accuracy ~ vowel + (1 + vowel|speaker), family = binomial, data = response2DF)`

5. Discussion and conclusions

The present study examined the way nasal vowels are perceived by native speakers of Brazilian Portuguese, with the ultimate goal of elucidating their phonological status. A perceptual approach to the issue was adopted because most of the debate around the phonological status of nasal vowels in BP comes from a production perspective. However, listeners also play a role in shaping the grammar of a language, creating and deleting categories based on how the acoustic input is perceived and interpreted. From a perceptual point of view, contrastive and coarticulatory nasality should be processed differently. If nasal vowels are not phonemic, but rather a contextually-conditioned product of coarticulation, listeners of Brazilian Portuguese would be expected to perceptually compensate for nasality in the vowel, when presented with nasal vowels followed by a nasal appendix. However, if nasal vowels are phonemic, perceptual compensation should not occur. A perceptual experiment was designed to test this hypothesis. The experiment required listeners to select the more nasal vowel from stimulus pairs with different contexts, with and without the appendix.

Results showed that participants did not compensate for vowel nasality. Most of the time, participants were able to accurately identify which vowel was more nasal. This suggests that nasality is indeed perceived as inherent to the vowel and that the appendix should not be considered a conditioning consonant. In fact, our results showed that the appendix seemed to have aided in the perception of vowel nasality. However, accuracy rates were different depending on the type of stimulus pair, which indicated that there is more than just vowel nasality at play in listeners' evaluations. Accuracy changed depending on vowel quality: when oral and nasal counterparts differed significantly in their formant values, reflecting differences in vowel quality, accuracy increased. When they did not, accuracy was, in general, not as high. This is particularly salient in the case of the low vowel, where a considerable quality difference between the oral and nasal counterparts aided in nasality perception. Thus, we can conclude that vowel quality changes associated with nasality, not just vowel nasality itself, work as perceptual cues to nasality.

Extensive nasality has been shown elsewhere as well to be associated with changes in vowel formants, changing the acoustic dimension related to vowel height e.g., Beddor and Hawkins 1990). In particular, nasality is associated with lowering of F1 frequency in low vowels and increasing of F1 frequency in high vowels. Krakow et al (1986: 39) show that heavily nasalized /ε/ without appropriate context is perceived by native speakers of American English as having a lower vowel quality when compared to oral or nasalized /ε/ in the appropriate context, presumably due to increased F1 frequency in the nasalized vowel. The authors conclude that, since American English does not have phonemically nasal vowels, any acoustic change due to heavy nasalization is perceived as a change in vowel quality.

In languages with phonemic nasality, vowel quality changes are associated with nasality as well. For example, in French, nasal vowels are different in quality from their oral counterparts; this difference can be attributed to nasal-oral resonance interaction, as well as to articulatory differences (Delvaux et al 2002). Thus, what historically started as a clear process of extensive coarticulation appears has led to the emergence of a new contrast in more than one dimension (Sampson 1999). Nasal vowels tend to have, in addition to nasality, changes in articulation that reflect this difference in phonemic status. The same process appears to be reflected in the case of the Brazilian Portuguese low vowel: the change in quality associated with acoustic consequences of nasality can itself realize the difference in phonemic status. And parallel to the French case, differences in the oral articulation of the low vowel between the nasal and oral counterparts in Brazilian Portuguese may serve to enhance nasal vowel quality differences e.g., Carignan 2011;

Barlaz et al. 2018). Perceptually, it is clear that this difference between oral and nasal counterparts is phonologically useful.

In the current study, when there were not significant differences in quality, as in the high-front vowel, the nasal appendix played a bigger role in vowel nasality rating. The lack of quality change led listeners to confuse oral and nasal vowels in most non-low vowels, and participants relied more heavily on the presence of the appendix to make nasality judgements, even in type 1 stimulus pairs ($C\tilde{V}\#-C\tilde{V}^N$). In other words, nasality can be signaled by the appendix, making it the perceptual cue for nasality when formant quality cues are missing. The idea that the appendix can be considered a locus of nasality is much less studied. It is only hinted at by Oliveira et al (2012), who found through MRI scans that high nasal vowels in European Portuguese are not articulated differently from oral counterparts, similarly from Barlaz et al (2018), who found that the degree of difference in articulation between oral and nasal high vowels is much less pronounced. Both studies found that the nasal appendix emerges with the high vowels and consider that the appendix can either be the locus of nasality or a strategy to enhance the contrast between the oral and nasal vowels. The idea is not far-fetched. Given that extensive nasality affects the percept of vowel height (and articulation as well), one might infer that, for vowel quality to be maintained in spite of extensive nasality, nasality might need to move elsewhere. Moving the locus of nasality to the appendix would allow vowels to be perceived as nasal, while still maintaining their qualities. This pattern would seem to serve a similar purpose to compensation, but for contrastive features rather than coarticulatory ones, allowing for both nasality and quality information to be well-perceived. Further research needs to be conducted to examine this possibility further.

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Competing Interests

The authors have no competing interests to declare.

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