PERCEPTION OF VOWEL NASALITY CONTRAST IN BRAZILIAN

PORTUGUESE

by

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Perception of Nasal and Nasalized Vowels in Brazilian Portuguese

Thesis directed by Associate Professor Rebecca Scarborough

Abstract

Vowel nasality is the most controversial phonological aspect of Brazilian Portuguese. Scholars suggest the oral-nasal vowel distinction may not exist. A consonant-like nasal resonance presence at the vowel's right edge (the nasal appendix) might make nasal vowels the product of a contextual vowel nasalization rule. Others suggest that the appendix is a byproduct of a velum lowering gesture misalignment, so, nasal vowels are distinctive due to vowel-inherent differences in nasality and quality. Since two opposing conclusions can be reached by examining nasal vowels production, we seek a new source of evidence in listeners' perception of these vowels.

This dissertation examines how Brazilian Portuguese listeners perceive vowel nasality, to shed light on the phonological status issue. The production study measured oral, nasal and nasalized vowels formants, and acoustic nasality to establish acoustic profiles. The rating perceptual experiment tested whether Brazilian Portuguese listeners treat potentially contrastive vowel nasality as a coarticulatory product of the appendix, i.e., perceptual compensation. The identification experiment tested whether they can identify a word based on vowel alone.

Results show that participants did not perceptually compensate for vowel nasality and identified words based solely on vowels. However, accuracy was much lower than expected. Two factors played a role in accuracy: vowel quality and appendix presence. Accuracy was higher when vowels were different in terms of vowel quality, as attested by differences in the production study; nasal answers increased when vowels were followed by the appendix,

regardless of nasality type. The oral-nasal vowel contrast in Brazilian Portuguese is considered mainly a vowel quality contrast, caused by change in quality due to oral-nasal resonance interactions in nasal vowels. The perceptual distinction is clear in the low and the mid-front vowels, where vowel production shows quality differences, but not in the mid-back or high vowels, where quality differences are small. The appendix increased nasality judgement; it is thought that at least some part of the contrast lies with it. We conclude that vowel nasality in Brazilian Portuguese is phonologized and some vowels are phonemic. However, we cannot say whether phonologization is still ongoing, or whether it is halted by the appendix.

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Introduction

Portuguese is a Romance language spoken as a national language in seven countries, and as a regional language in two others (Ethnologue). It has many varieties, the most spoken of which is the focus in the present study, Brazilian Portuguese. All varieties, though, contain particularly rich vowel inventories with monophthongs, diphthongs, and triphthongs, and among the monophthongs and diphthongs, both oral and nasal counterparts. In addition, oral vowels are subject to allophonic variation, including the nasalization of oral vowels when preceding a heterosyllabic nasal consonant (Silva, 1998).

Nasal vowels are a controversial aspect of (Brazilian) Portuguese phonology. Diachronically, these vowels are hypothesized to have emerged from a process of vowel nasalization, followed by a process of nasal consonant deletion (Sampson, 1999), as they were two phonemes in Latin: an oral vowel followed by a tautosyllabic nasal coda. As the original context for the nasality in the vowel, i.e., the nasal coda, was lost, it is hypothesized that Portuguese speakers attributed the nasality to the vowel and, subsequently they re-categorized these vowels as phonemically nasal. The resulting vowel inventory would be comprised of both oral and nasal vowels at the phonemic level. This process is thought to have finished circa the 13th century. So, when Portuguese first arrived in Brazil in the 14th century, it was probably a language with contrastive vowel nasality.

However, the issue of whether this diachronic process ever finished is far from closed, as scholarship is divided, especially in the case of Brazilian Portuguese. Scholars who hold that nasal vowels in Brazilian Portuguese are full phonemes provide experimental analyses that rely on nasal vowels' formant and duration changes when compared to oral counterparts as proof for their position (Sousa, 1994; Medeiros, 2008; Seara, 2000). Nasal vowels are considered complex

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segments, which may have a nasal appendix (a short consonant-like nasal resonance) at their right edge, but still one segment. Scholars who argue that nasal vowels are not phonemic, but composed of an oral vowel plus a nasal consonant, provide as evidence formal phonological analyses that rely on distributions in the language, such as the distribution of the r-allophones (Camara Jr, 1970, 1971). The vowel that surfaces at the phonetic level is nasalized due to a rule of synchronic vowel nasalization (Mateus, 1982) or nasal autosegment spread (Mateus & D'Andrade, 2000)[1]. The nasal consonant may or may not be deleted depending on factors like immediate context, word boundary and dialect. If not deleted, the consonant will emerge as a nasal appendix.

Much of the issue at hand is part of the old debate between formalism and experimentalism. Both approaches are but one aspect of a much more complex phenomenon. Formal approaches are one part of the scientific analysis of observations; they are an abstract formal model that attempts to account for the observed data. Empirical observations attempt to bring the other side of scientific inquiry, the one where the physical reality of the abstract models is tested. While they should be complementary, with experimental evidence backing up formal theories, in some cases, the conclusions drawn by formal and experimental approaches clash. This is what we see in the case of nasal vowels in (Brazilian) Portuguese[2].

This division in theoretical stances, methods and conclusions have left unanswered the fundamental question of what the vowel phonemes are in Brazilian Portuguese. This division in the field cannot be easily reconciled, however, it is not impossible to find common ground

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[1] While both Mateus (1982) and Mateus & D'Andrade (2000) focus on European Portuguese, their works account for both European and Brazilian varieties.

[2] This issue is possibly the case of French too, the other Romance language with contrastive vowel nasality. Interestingly, however, as far as we know, the issue is quickly dismissed, by classifying the contrast a surface one (e.g Delvaux, 2012). A similar account has been proposed for European Portuguese (Massini-Cagliari, Cagliari & Redenbarger, 2016).

between these two sides. One aspect that these approaches have in common is that they look at the issue of vowel nasality contrast through a production lens, focusing on the speaker and the variation that comes from producing coarticulated sounds. Taking a production standpoint is understandable, since articulation (and acoustics a little later) has been traditionally used to explain sound patterns and even sound change (Hume & Johnson, 2001). However, it is not the only way to explain sound patterns and even sound change, especially when pursuing a production route has proven fruitless. Perhaps, then, it is time to move away from production, and focus on the other end of the communication chain – the listener – to see if the issue vowel nasality and nasal vowel contrasts in Brazilian Portuguese can be better explained.

The listener has a key role when it comes to understanding and shaping phonological contrasts. "Successful communication depends on listeners being able to recover what a speaker is saying" (Flemming, 2004, p.1). In fact, one of the forces shaping phonological systems is the need to minimize "confusion on the part of the listener" (Flemming, 2004, p.1). When the listener does not parse the acoustic signal the way intended by the speaker, confusion in the transmitted message may occur. At the same time, though, confusion may not happen; changes in the sound system may as new sound categories may emerge. (e.g. Ohala 1993a; Beddor, 2009). Consequently, accounts of phonological contrastiveness need to consider the perceptual properties of speech sounds.

Perceptual studies get at something that production studies cannot: how listeners interpret a sound sequence and what sound properties are relevant for its identification. It is the listener who first shapes the language by classifying what they hear. When sound properties change in relevance, or there is a mismatch between what is heard and the speaker's intended utterance, new contrasts can emerge or disappear. Thus, a perceptual approach to the study of vowels in

Brazilian Portuguese would present a different perspective on the matter of the nasal vowel contrast. In line with the relationship between coarticulation and sound change, the way Brazilian Portuguese listeners interpret nasal vowels 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.

This is where the present study fits in. We intend to explain the issue of nasal vowel contrast through how these vowels are perceived. The idea is, first, to compare the perception of allophonic and potentially contrastive vowel nasality with oral counterparts, and second, to evaluate whether the presence/absence of the nasal appendix plays any role in the perception of vowels as nasal in Brazilian Portuguese. Focusing on the listeners, within the scope of this project are questions such as: (1) do Brazilian Portuguese speakers process nasal vowels as phonemes in the language (i.e., do they process nasality as inherent to the nasal vowel), congruent with the experimental analyses, or are these vowels products of a coarticulatory process of nasalization, congruent with the formal analyses? (2) Is nasality in the vowel sufficient for nasal vowel processing, which is an implication of the experimental approaches, or is the nasal appendix also required, an implication of the formal approaches? Two perceptual experiments were conducted to address these questions.

The first perceptual experiment intends to answer question (1). It is a forced-choice rating task that tests whether speakers of Brazilian Portuguese perceive nasal vowels as products of coarticulation, i.e., attribute nasality in the vowel to a following nasal context (appendix or consonant), as in language without nasality contrast such as English (Beddor & Krakow, 1999). In other words, there is perceptual compensation for nasality in the vowel in Brazilian

Portuguese.

Perceptual compensation is a relevant behavior to test for in the context of dubious phonological contrast because it necessarily occurs in the absence of phonemic contrast, as listeners tend to factor out the effect of context on a given segment (e.g. Kawasaki, 1986)[3]. In compensatory perception, the phonetic feature, nasality in this case, is attributed to a nearby conditioning consonant, and the target vowel is perceived as essentially oral (Beddor & Krakow, 1999). While there does not seem to have been, to date, studies explicitly testing for perceptual compensation of a contrastive feature, it is logically expected that, in cases where there is a phonological contrast for a certain feature, the phonetic feature cannot be attributed to a nearby conditioning consonant. Therefore, the phonetic feature must be treated as inherent to the segment rather than coarticulatory; thus, perceptual compensation should not occur. In fact, the failure of perceptual compensation is one of the triggers to sound change (Ohala, 1993; Beddor, Krakow & Lindemann, 2001). Thus, testing for the presence/absence of perceptual compensation of nasality means indirectly testing for its phonemic status in the vowel. We hypothesize that perceptual compensation will not occur when there is a phonemic nasal vowel, regardless of context.

In experiment 1, Brazilian Portuguese listeners are presented a set of stimuli pairs containing oral, nasal and nasalized vowels in different contexts and must answer which vowel they think is more nasal. If Brazilian Portuguese listeners process nasal vowels as phonemes, they should not attribute nasality in the vowel to the appendix. That is because even if there is a nasal appendix present in the signal, it does not cause perceptual compensation, as it has no phonological status

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[3] Originally, perceptual compensation is not a test for phonemic status; it is a test for coarticulation perception, which is why is has never been done in a language with a phonological contrast. To date, this study is the first one to explicitly do it.

in the language.

The perceptual second experiment is an identification task that attempts to answer question (2). It aims at evaluating which features—the degree of nasality in the vowel and/or the presence/absence of the nasal appendix—contribute to Brazilian Portuguese speakers correct identification of words containing nasal vowels. This experiment should be more linguistically meaningful than the first one, as it requests judgments about words rather than explicitly requiring metalinguistic judgments on nasality. We hypothesize that vowel nasality in nasal vowels is the only required feature to correctly identify the word, but not enough to identify nasalized vowels.

In experiment 2, participants hear a stimulus with vowels in the same contexts as experiment 1, and need to identify which word it comes from, given a list of candidates. If nasality from the nasal vowel is sufficient for speakers to identify correctly words where a nasal vowel is expected, then there is evidence that nasal vowels (independent of any nasal appendix) are processed as phonemes in Brazilian Portuguese. If the nasal appendix plays a necessary role in how listeners categorize these vowels in the language, then there would be evidence that the vowel's representation is more complex.

The present investigation is organized as follows. First, a brief description of Portuguese's vowel system is presented, along with an exposition of the controversy on the phonology of nasal vowels in Portuguese so we can understand the origin of the debate. After that, recent studies about the emergence of a contrast, categorization and compensation are summarized, to understand the theoretical and methodological approach taken in this study. Then a summary of what is state of the art in perception of nasality in Brazilian Portuguese is presented, to show what has been done in that regard. The following chapter describes a small-scale production

study designed to mostly describe the stimuli and show degrees of nasality and vowel quality differences that may play a role in the perceptual experiments outlined above. Next, the perception experiments briefly introduced above are presented, and the results analyzed there. Finally, a chapter on how our production and perception results relate to our hypotheses, our theoretical stances, and the controversial issue of vowel nasality contrast in Brazilian Portuguese, with future directions.

Portuguese vowels: a brief description

Most books on Brazilian Portuguese (BP) phonology start with a description of the language's vowel system. Interestingly, not all of them include nasal vowels as separate phonemes, which shows that the status of nasal vowels in BP is indeed a matter of debate. For example, Cagliari (2009) has a section devoted to nasality in general, in which he includes nasal consonants and nasalized vowels. There is no separate section on nasal vowels, as the author does not consider them separate phonemes, but simply the product of a vowel nasalization rule. On the other hand, introductory phonology books such as Silva (1998) make it clear that nasal vowels are phonemes, and treat them in a separate section. Still, other authors, such as Mateus & D'Andrade (2000)[4], have a separate section for nasal vowels in their books, but acknowledge the controversy, and consider these vowels as merely the product of a nasalization rule. In this chapter, a brief description of Brazilian Portuguese oral, nasal and nasalized vowels is provided, with nasal vowels classified as separate entities from nasalized ones. Then, a diachronic explanation of how nasal vowels emerged in Portuguese is given. In addition, a more detailed explanation on the controversy about the phonemic status of nasal vowels is presented under the nasal vowels section.

Oral vowels

Brazilian Portuguese has seven phonemic oral vowels[5], as presented in the following table.

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[4] Notice that Mateus an D'Andrade focus on descriptions of European Portuguese; the authors, however, have a section dedicated to Brazilian Portuguese in regard to vowel nasality.

Table 1. Brazilian Portuguese oral vowels, adapted from Silva (1998).

	Front	Central	Back
High	/i/		/u/
Mid-high	/e/		/o/
Mid-low	/ɛ/		/ɔ/
Low		/a/	

This inventory is identical in all dialects of Brazilian Portuguese, and similar to European

Portuguese varieties. In the European varieties, there is a central mid vowel, /ɐ/, of reduced

occurrence (Massini-Cagliari et al, 2016). Typologically, this vowel inventory is relatively

common, especially across Romance Languages. The back vowels are all rounded, and there is

no length distinction. However, there is a stress-related quality reduction in the inventory. In pre-

stressed syllables, mid-low and mid-high vowels are neutralized, and the actual vowel quality

will depend on dialectal variation. The inventory in this condition is reduced to five vowels. In

post-stressed word final positions, the inventory is reduced to three vowels [ɪ], [ɐ] and [ʊ]. These

vowels are sometimes devoiced (Silva, 1998).

Acoustically, oral vowels are comparable across studies (e.g., Delgado Martins, 1988[6];

Sousa, 1994; Moraes et al, 1996; Seara, 2000; Rauber, 2008). The following plot shows

reference values for first and second formants of the seven stressed oral vowels in non-nasal

contexts based on Barbosa & Madureira (2015). Notice that the back vowels are a little lower

than their front counterparts, reflecting higher F1 values.

Figure 1. Brazilian Portuguese oral vowels example formant values, adapted from Barbosa & Madureira (2015). E = /ɛ/ and O = /ɔ/.

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[6] Delgado Martins (1988) discusses European Portuguese vowels.

Nasal vowels

Despite being controversial, some phonetics and phonology manuals consider the existence of an inventory of nasal vowels. The set of nasal vowels is reduced when compared to the oral ones, also a common typological feature: no language has a bigger nasal vowel inventory than its oral vowel inventory. Brazilian Portuguese has five nasal vowels, as in the table below. This is the same inventory as occurs in European Portuguese (Massini-Cagliari et al, 2016).

Table 2. Nasal vowels in Brazilian Portuguese, adapted from Silva (1998).

	Front	Central	Back
High	/ĩ/		/ũ/
Mid-high	/ẽ/		/õ/
Low		/ã/	

The inventory reduction occurs in the mid region, with mid-low and mid-high vowels neutralizing into mid-high. This neutralization seemed to have already taken place as early as the thirteenth century in Portugal (Sampson, 1999), so it is reasonable to have been well-established by the time the Portuguese people arrived in Brazil, and it is well established across Brazilian Portuguese dialects. Also well-established are some vowel quality changes. The low vowel raises in quality when nasal or nasalized in all Brazilian (e.g., Sousa, 1994) and European Portuguese (e.g., Massini-Cagliari et al, 2016) dialects in comparison with its oral counterpart, becoming a mid-low central vowel. Low vowel raising is a common effect of nasalization, as the nasal formant can perceptually merge with the first formant, lowering its perceived frequency (Beddor, 1983; Maeda, 1993). What is interesting about the Portuguese inventory is that nasalization seems to be very extreme in the low vowel only, while there does not appear to be the same marked nasality effect on the [-low] vowels. Notice that, in the nasal vowel inventory, the mid central vowel /ɐ̃/ is missing. This vowel in its nasal version is missing in both Brazilian and European varieties, and it is hard to say if it is because the low vowel raises when nasal or not,

thus neutralizing low and mid central vowels. However, since /ɐ/ came in relatively late in European Portuguese (Brazilian Portuguese lacks it altogether) and it has a relatively restricted distribution, it likely does not have a nasal counterpart. The mid-high vowels /ẽ/ and /õ/ also change relative to their oral counterparts, but in a different way. These vowels become diphthongs /ẽĩ/ and /õũ/ in some dialects, most notably the Paulista (spoken in São Paulo). The high vowels do not undergo any marked change in quality in any dialect. In addition to changes in quality, it has been said that nasal vowels are longer than their oral counterparts (e.g., Sousa, 1994). However, many of these measurements include as part of the vowel the nasal appendix, a nasal resonance that can emerge at the vowel's right edge, mostly before a heterosyllabic stop. The nature of the appendix is discussed in more detail below, but it is safe to say that, when leaving the appendix out, nasal vowels have roughly the same duration as their oral counterparts (Medeiros, 2011).

There have also been many acoustic descriptions of nasal vowels (e.g., Cagliari, 1977; Sousa 1994; Jesus, 1999; Seara, 2000, for Brazilian Portuguese). The following plot shows reference formant values for the five nasal vowels based on Seara (2000).

Figure 2. Brazilian Portuguese nasal vowels example formant values, adapted from Seara (2000).

Comparing figures 1 and 2, notice that the nasal low vowel's F1 value is about 200 Hz smaller than the oral low vowel's. This big formant change explains the change in quality

reported in the literature. The mid vowels' F1s seem to be higher than their oral counterparts',

especially the mid-front vowel. However, that is not the rule. Sousa (1994) found lower F1

values for both vowels, at around 320Hz. The high vowels F1 do not change much from oral to

nasal.

In addition to changes in average formant values, nasal vowels are also characterized by the

way nasality is implemented over time. Sousa (1994) claims that nasal vowels are composed of

three distinct moments: an oral part, a transitional phase in which nasality is superimposed on the

vowel, and a nasal murmur[7]. This description was later corroborated by other authors (e.g.,

Seara, 2000; Cagliari, 1977; Jesus, 2002; Medeiros, 2007). The nasal phase is the only one

consistently present, while the other two are variable. Nasality, therefore, increases gradually

throughout the vowel, culminating at the nasal appendix. However, the presence of all three

phases in a vowel is not mandatory. For example, the vowels in Sousa (1994) could appear

without the oral phase, being composed of only the nasal phase plus the appendix. Barbosa and

Madureira (2014), state that the only mandatory phase is the nasal, with the appendix being of

variable duration according to the individual and the context. A great proportion of the mid-front,

the high front and the high back vowels instances in Seara (2000) did not have a nasal phase

proper, being composed only of the oral phase and the appendix. Both authors report the

appearance of the nasal appendix, but not consistently.

The nasal appendix is a consonant-like nasal resonance that emerges between a nasal vowel

and an obstruent, notably stops, as well as word finally. It has been reported to have formant

structure (Seara, 2000), with variable nasal formants, and place of articulation cues of the

following consonant if word-medial (Cagliari, 1977), or a palatal-velar place of articulation if

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[7] Sousa calls the nasal appendix nasal murmur.

word-final (Shosted, 2011). It is also of variable duration, and it may even not appear in all productions of nasal vowels, even before stops (Medeiros, 2007). As it will be explained later, it is the presence of the nasal appendix in the acoustic signal, along with a series of phonological patternings and phoneme distribution analyses, that has led many scholars to question the phonemic status of nasal vowels in Brazilian Portuguese (and even in European Portuguese). These scholars (e.g., Mateus, 1982, Bisol, 1998) assert that nasal vowels are underlyingly composed of a sequence of an oral vowel and a nasal consonant and, through a series of phonological rules, the vowel emerges as nasal. On the other hand, there is empirical evidence attesting that the appendix is, as Shosted (2011) puts it, "epiphenomenal" and, thus, without any phonological status by itself. Such a pattern is reported in Southern French by Delvaux *et al* (2012), who concludes that the appendix in this variety of French is a simple prenasalization of the following stop, as it takes some of that consonant's duration.

 Figure 3 below shows an example of a nasal appendix in the word *planto* /ˈplẽⁿtʊ/ "I plant". The annotation tier below the spectrogram shows both the vowel and the appendix.

Figure 3. Example of a nasal appendix in the word *planto*.

 Notice the decrease in resonance amplitudes, as well as a dip in the waveform that signals oral tract closure, and the beginning of the appendix. In this case, the appendix is clearly

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segmentable, with clear left and right boundaries. However, segmentation is not always an easy task. Figure 4 below shows the spectrogram and waveform for the word *tinta* /tʃĩ̃ⁿtɐ/ "paint". Although there is, towards the end of the vowel, a decrease in resonance amplitude, there is no appreciable dip. The appendix, if it exists at all in this example, is not easily segmentable.

Figure 4. Example of a nasal appendix in the word *tinta*.

Aerodynamic descriptions of nasal vowels corroborate the acoustic findings. Medeiros et al (2011) demonstrated that the low and the high front nasal vowels have increasing nasal airflow, meaning nasal vowels become more nasal over time. The high vowel had high nasal airflow from the very beginning, while the low vowel started with relatively low nasal airflow, increasing in nasal airflow more than the high front vowel. Recently, Demeules-Trudel (2015) demonstrated that nasal vowels, in addition to being nasal over their duration, show different profiles of nasality implementation: late-starting increasing, early-starting increase, and plateau, similar to vowel nasality patterns in French (Cohn, 1990).

As for the appendix, Medeiros (2008) states that the increasing nasal airflow that started in the vowel peaks when there is no evidence of the vowel anymore, but there is evidence of oral closure. The appendix takes up some of the consonant's duration. Furthermore, when measuring durations of nasal vowel + appendix + consonant sequences, and comparing them to nasalized

vowel + nasal consonant, and oral vowel + oral coda consonant + consonant sequences, Medeiros (2011) finds that nasal vowel part has comparable duration to the nasalized and the oral vowel in the sequences; the appendix + consonant part has similar duration to the nasal consonant + the oral consonant; and the appendix by itself is much shorter than an oral coda.

A very brief history of nasal vowels

Historically, nasal vowels in Portuguese stem from a coarticulatory process in which a contiguous nasal consonant spread its [+nasal] feature to the vowel (and eventually was deleted). There were three contexts in which vowel nasalization occurred (Moraes, 2013, Sampson, 1999):

Syllable coda, in which a nasal coda spread its [+nasal] feature in a process of regressive assimilation, as in lt. *campo* → *cãmpo* → port. *c[ãᵐ]po*[8]

Syllable onset, in which a nasal consonant spread its [+nasal] feature in a process of regressive assimilation, as in lt. *lana* → *lãna* → *lãa* → port. *l[ã]*[9]

Syllable onset, in which a nasal consonant spread its [+nasal] feature in a process of progressive assimilation, as in lt. *madre* → *mae* → port. *m[ã]e*

This diachronic process is hypothesized to have finished by the beginning of the literary period, around the 13ᵗʰ century in Portugal (Sampson, 1999). However, the variable presence of the nasal appendix in the acoustic signal, as well as some phonotactic patterns, have put into question whether vowel nasalization as in (a) and (b) is indeed finished (or at least unproductive), or if vowel nasalization still occurs synchronically, as it will be seen below. Nasality in context (c) is progressive, and it occurred in very limited cases; it is not clear whether there is an appendix following the nasal vowel in this case.

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[8] Beddor argues that in cases like a and b, instead of a feature spread, we have the nasal gesture overlap with the vocalic gesture, which is gradual.

[9] Sampson (1999) observes that, while nasality in the first vowel occurred, it was only after the final vowel in lana underwent apocope that the nasal consonant became final and was dropped as well.

The problem of Portuguese nasal vowels

While scholars agree that Portuguese nasal vowels are nasal acoustically, aerodynamically and intuitively, there is no agreement on the current phonemic status of these vowels in Brazilian Portuguese (or even in European Portuguese), making this one of the most controversial aspects of Portuguese phonology. There are two competing hypotheses on the issue: the monophonemic hypothesis, which states that nasal vowels are made of one phoneme (in other words, the vowel is contrastively nasal), and the biphonemic hypothesis, which states that nasal vowels are in fact composed of two phonemes, an oral vowel plus a nasal consonant sequence (in other words, the vowel is only contextually nasal). The support for the two views comes from different theoretical standpoints, both formal and experimental; however, most experimental analyses tend to support the first, while most formal phonological analyses tend to support the second.

Formal approaches to the study of nasal vowels in BP comprise traditional, broadly generative phonological analyses. They do not use phonetic experiments in the sense of collecting, measuring and using information from the acoustic or aerodynamic signal in their analyses, but rely on phoneme and allophone patterning in the language for their arguments. In these approaches, it is argued that at the UR, nasal vowels are composed of V+N sequence, where V stands for any oral vowel and N stands for a nasal consonant. Nasal vowels, then, are conditioned allophones of oral vowels in the language. The evidence for this claim comes from such phenomena as the distribution of /ɾ/ and /r/[10] (Camara Jr, 1970, 1971, 1977). The tap /ɾ/ cannot occur after closed syllables, only after open syllables, while /r/ occurs everywhere, including after closed syllables. If syllables with nasal vowels were composed only of the nasal vowels, then one should expect /ɾ/ to occur after them, because they would be considered open

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[10] Strong-r, as this phoneme is called, has different phonetic realizations depending on the dialect of Portuguese, ranging from the trill /r/ to a glottal fricative /h/.

syllables; however, what we see in Portuguese is that after these syllables, only /r/ can occur, as in /õⁿ.ʁɐ/ *honra* "honor". Thus, this suggests that the syllable containing the nasal vowel is closed, composed of an oral vowel and a nasal coda.

An additional argument is the case of the latent a nasal consonant that emerges in certain contexts. We can see in the example provided by Mateus (1982) that a latent nasal consonant appear in alternations with the prefix *in-*:

[ĩpuˈsivɛl] *impossível* "impossible"

[inakɑˈbadu] *inacabado* "unfinished"

The nasal consonant appears when the prefix is added to a word beginning with a vowel, so the consonant becomes the onset for the following syllable. By analyzing these and other words' cases, Mateus (1982) concludes that their underlying representation must include a nasal consonant.

What we see in the surface form is described to be the result of vowel nasalization and subsequent nasal consonant deletion rules as in (1) and (2) below (Mateus, 1982):

(1) V → [+nas] / ___ [C +nas]

(2) [C +nas] → Ø / [V +nas] ___

Other studies describe nasal vowels in terms of the attachment of a nasal autosegment to an oral vowel (Mateus and D'Andrade, 2000). Here the nasal autosegment does not get to be fully realized because it does not warrant its own timing slot, so it transfers its nasality to the vowel.

One problem with these formal approaches is that they normally do not take into account phonetic detail, such as the gradual implementation of nasality in the vowel over time, or the presence of a nasal appendix in the signal. When they do, the solutions are often cumbersome. For example, Mateus (1982) proposes different rules for the various degrees of nasality

implementation; Bisol (1998) proposes that the appendix will occur as offglides in some environments, and as consonants in other. This inability of formal approaches to account for phonetic detail is where experimental studies pick up.

Experimental approaches to the study of nasal vowels in BP comprise mostly acoustic and aerodynamic production studies, with or without a theoretical framework behind. These studies came after the first formal analyses of nasal vowels became known, with the idea to provide empirical substance to either support or refute those analyses. As a result, there have been plenty of acoustic and aerodynamic studies describing oral vs. nasal vs. nasalized vowels.

As already briefly described above, experimental studies (e.g., Sousa (1994) and Medeiros (2007; 2011)) show that nasal vowels are complex segments, with nasality implemented gradually, and resonance interactions that can cause changes in vowel quality[11]. Because the presence and duration of the nasal appendix[12] is variable in relation to the neighboring sounds, it is not described as a fully specified nasal consonant. For example, acoustically, the appendix does not emerge before fricatives. These studies describe the nasal appendix as either part of the vowel (e.g. Sousa 1994) or part of the following consonant (e.g. Medeiros, 2008), as product of how nasality is implemented through the velum lowering gesture, but never its own segment. Sousa (1994) claims the appendix is part of the vowel because it has no place of articulation cues neither can it be easily segmented from the vowel. Medeiros (2008) claims the appendix is part of the following consonant because it occurs after the following consonant had already started, taking some of its duration, like a form of prenasalization. The author concludes, from an Articulatory Phonology theoretical standpoint, that the nasal appendix is simply the velum

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[11] These occur in only some vowels, most notably the low vowel.
[12] Unlike the biphonemic accounts, the monophonemic accounts hardly use the words consonant or coda when applied to nasals because, in this approach, there is no nasal consonant or coda in Brazilian Portuguese.

lowering gesture misaligned with the vowel gesture, overlapping the following consonant's closure gestures[13].

Interestingly, these acoustic and aerodynamic results parallel acoustic results from studies of French nasal vowels (Cohn, 1990; Delvaux et al, 2012). Cohn (1990) shows that French nasal and nasalized vowels will have different patterns of nasality implementation to their different phonological status. Nasality in nasal vowels is implemented mostly in a plateau-like fashion, while it is more restricted to the end in nasalized vowels. A plateau-like profile for nasal vowels and a more restricted to the end profile for nasalized vowels for Brazilian Portuguese was found in Medeiros (2008; 2011) and in Desmeules-Trudel (2015). Delvaux et al (2012) show that nasal vowels in Southern French are different from nasal vowels in Northern French in terms of velum lowering gesture timing organization. The results are comparable to those by Medeiros (2008, 2011), in that the nasal appendix must be part of the consonant, as it takes some of its duration.

Delvaux et al (2012) take this as evidence that nasal vowels in French are monophonemic in the underlying representation, but differ in the implementation. If the representation were biphonemic, there would have to be a longer nasal gesture to account for the duration of the nasal coda. However, formal phonological accounts such as Shane (1970) contend that, just like Portuguese, French nasal vowels are underlyingly a sequence of oral vowel + nasal consonant. Interestingly, despite also having contradictory accounts, it is undisputed, despite variation in the signal implementation, that there is a clear surface contrast between oral and nasal vowels in French (Delvaux, 2012). Perhaps this clarity is due to the fact that French nasal vowels are, in addition to being nasal, of different quality when compared to their oral counterparts. That way,

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[13] There are, of course, experimental studies that do support the biphonemic interpretation of nasal vowels, such as Cagliari (1977) and Moraes and Wetzels (1992)

differences in nasality implementation could be less relevant in terms of production and perception than the presence of nasality or the difference in quality.

While the issue of vowel nasality contrastiveness is less controversial in French, the same cannot be said of these vowels in Portuguese. The fact that different studies come up with different conclusions reflects their assumptions about what an analysis should be and what counts as evidence. As stated in the introduction, it appears that formal models and the experimental tests clash where they should complement each other. That means we need to keep searching other corners to test for the physical reality of the abstract model, or to find that the model is not sustained the way it currently is. Thus, we turn to perceptual experimentation. But what do we know about perception in Portuguese?

Perception of nasal vowels

While there have been extensive study of how nasal vowels are produced, even if they lead to different conclusions, the study of how nasal vowels are perceived is still in its first steps. There is much variation in scopes, goals and conclusions among the few studies on nasal vowel perception, probably because of there are so few of them. However, all try to understand, to different extents, whether nasal vowels can be perceived as distinct segments in the language.

The oldest perception study involving Brazilian Portuguese nasal vowels is Brito (1975), which demonstrated that Brazilian Portuguese listeners can perceive nasal vowels as independent segments most of the time, but not conclusively. Six native speakers of Brazilian Portuguese participated in an identification task on word medial, syllable final sounds, which were oral, nasal or nasalized vowels. They had to classify what sound they heard, if an oral, nasal or nasalized vowel, or a nasal consonant. In the case of nasal vowels, such as in *tempo* /tẽᵐpʊ/ "time", participants labeled the last sound as a nasal vowel about 52% of the time. While it is not

a low number, the author expected that, if the vowels were uncontroversially nasal, this response rate would have been much higher. Accurate perception depended on vowel quality, with low nasal vowel stimuli being more consistently perceived as a nasal vowel than the non-low nasal vowel stimuli, which were perceived to have a nasal consonant-like resonance most of the time[14]. The author attributes this difference in accuracy to differences in spelling between the low and non-low vowels. Low vowels tend to be spelled with a tilde most of the time, as in *lã* /lɐ̃/ "wool", while non-low vowels are always spelled with a nasal consonant afterwards, as in *bom* /bõ/ "good". Thus, in this study, it is difficult to separate spelling from vowel quality effect, but a quality effect cannot be discarded.

Seara (2000) isolated and manipulated nasal vowels in an attempt to understand which cues were most helpful in perceiving these vowels as nasal. The author attenuated F1 amplitude of oral vowels, a change commonly associated with nasality (Hawkins and Stevens, 1985), deleted the nasal appendix that followed nasal vowels and spliced the nasal appendix to same-quality oral vowels. She then presented the resulting stimuli to five native speakers of Brazilian Portuguese, who had to rate the orality/nasality of the vowel on a scale of 1-6, with 1 being oral and 6 being nasal. The results show that attenuating F1's amplitude made only the low and the high back vowel sound nasal; other vowels were all perceived as oral. The nasal appendix's absence did not affect the participants' perception of the nasal vowels as such, except for the high front vowel, which was not conclusive, and the mid vowels were judged less natural, probably because of a change in quality when nasal[15]. This result, along with the fact that F1

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[14] There were also cases in which participants classified a nasal vowel as a vowel and consonant at the same time. Brito considers these as problems of inadequate expression, rather than inaccurate perception. If those who could not properly express how they classify the vowel were joined with those who accurately classified the vowel as nasal, accuracy would reach about 60%.
[15] It seems likely that the author might have cut some of the mid vowels' diphthongal ending

amplitude attenuation did not produce the expected effect, shows that there is more to nasality than just formant amplitude changes, and the appendix is not required to the perception of vowels as nasal, but it helps it. These results would be in line with the monophonemic hypothesis, as they show that participants can perceive and classify vowels as nasal, as opposed to oral vowels with or without the nasal appendix, but only indirectly. Perceiving a nasal vowel in isolation as such is not much informative of its phonemic status: vowels with nasality, especially if it is a high level of nasality, may sound differently because of how nasality affects vowel quality. It would be interesting to see what participants' perception of nasal vowels would be if the appendix had been included. The results also show cross-vowel differences, perhaps related to the fact that some vowels have quality changes in addition to nasality when going from oral to nasal. Thus, vowel quality change is an issue that may play a role when perceiving nasal vowels, and it must be accounted for if we are to understand the role of vowel nasality – and only of nasality – in the perception of nasal vowels.

Moraes (2013), reporting on a study from 2003, attempted to understand how nasal vowels are phonemically represented – mono or biphonemic – and the perceptual prominence the appendix has through two experiments with spliced stimuli. The first evaluated if the nasality in coarticulatorily nasalized vowels would be enough to be perceived as the nasality from a phonemic nasal vowel[16]. The author spliced the first syllable from words like *cama* [kɐ̃mɐ] "bed" into the context of *capa* [kapɐ] "cape", and presented it to 25 participants.

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[16] Interestingly, the author does not test nasal vowels. It would have made sense to test them to at least have a comparative baseline of whether participants can accurately perceive nasal vowels as nasal. This is especially true in light of the difficulty in perceiving high nasal vowels found in our own experiments.

Table 3. Nasalized vowels in oral context, adapted from Moraes (2013). The percentage to the left represents the percentage of oral responses, and the percentage to the right represents the percentage of nasal responses to the stimuli.

Percentage	Oral	Nasal	Percentage
4%	Caba	Camba	96%
28%	Seda	Senda	72%
0%	Soda	Sonda	100%
84%	Cida	Cinda	16%
76%	Suga	Sunga	24%

The results (presented in table 7 divided by vowel quality) show that nasalized vowels in the context of oral vowels were perceived as nasal around 62% of the time, regardless of quality. The low and the mid vowels were mostly perceived as nasal, while, high vowels were mostly perceived as oral. The author interprets these results as possible evidence of a sound change underway, or perhaps just a greater difficulty in perceiving nasalization in high vowels.

In the second experiment, Moraes deleted the oral stop or oral fricative from words like *mando* [ˈmɐ̃(ⁿ)dʊ] "I command", in which the nasal vowel occurs at the end of the first syllable followed by the appendix, then presented the resulting "word" to the same 25 participants. His goal was to see whether participants would perceive the nasal appendix as a full heterosyllabic consonant, as in *mano* [ˈmɐ̃nʊ], or just as nasality in the vowel, as in *mão* [ˈmɐ̃ʊ].

The results show that participants perceived the new word as *mano* virtually 100% of the time, especially in cases where the original word contained an oral stop. The author concludes that the nasal appendix is phonologically strong, suggesting that it could be considered a syllable coda, which resyllabifies, becoming an onset. Such an interpretation highlights its importance and favors the biphonemic hypothesis. However, that is not without reserve. If we consider that the appendix is some form of stop prenasalization, then it should have consonantal place cues from that stop in the vowel. So, while still not having any phonological status, the appendix can be perceived as a consonant-like sound, which can explain Moraes's results.

These three perceptual attempts to understand the phonemic status of nasal vowels are very different, but also have some aspects in common. There is great agreement in how the low nasal vowel is perceived: always nasal, with good accuracy rates. That can be because of the great quality difference between the oral and the non-oral low vowels. There is less agreement in how the non-low nasal vowels are perceived, except for the high front vowel, which is normally perceived as oral. The mid vowels have great variation, likely because of the difference in quality that separates the nasal vowel from their oral and nasal counterparts. These differences in how these vowels are perceived can mean many things, from a non-phonemic status to a sound change in progress. Thus, there is the need to further investigate how these vowels are perceived.

Nasalized vowels

While the oral – nasal vowel contrast when considering nasal vowels is very controversial, there is more consensus that nasalized vowels are not contrastive in any variety of Portuguese. The oral - nasal vowel contrast, assuming there is one, is considered only partial in Brazilian Portuguese, because it is neutralized before a heterosyllabic nasal consonant[17]. The resulting vowel nasalized vowel[18] is the product of the influence of the heterosyllabic nasal consonant in onset position of the next syllable, for example *ca.ma* /kɐ̃.mɐ/ "bed". The rule can be described as rule (1) of vowel nasalization above for nasal vowels; however, rule (2) of nasal consonant deletion never applies. This kind of vowel nasalization varies according to syllable stress (Quicoli, 1995). In stressed syllables, it occurs obligatorily in Brazilian Portuguese, while in pre

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[17] In European Portuguese, however, vowel nasalization in stressed syllabled does not occur (Massini-Cagliari et al, 2016), so that the vowel in this variety is phonetically oral.

[18] Nasalized vowels can also occur with a tautosyllabic nasal consonant in onset, similar to the diachronic (c) cases above. Nasalization in this case is much lighter in terms of degree and is prone to stress influences as carry-over nasalization.

and post-stressed conditions it varies depending on the dialect (Abaurre and Pagotto, 1982). Thus, nasalized vowels are phonologically oral vowels that are phonetically nasalized[19].

There is not an inventory of nasalized vowels in Brazilian Portuguese because, in principle, every oral vowel can be nasalized when in the proper context. Thus, the nasalized vowels in Brazilian Portuguese could be described as in table 3.

Table 4. Nasalized vowels in Brazilian Portuguese.

	Front	Central	Back
High	[ĩ]		[ũ]
Mid-high	[ẽ]		[õ]
Mid-low	([ɛ̃])		([ɔ̃])
Low		[ã]	

While there is clear inventory reduction in the mid vowel domain for nasal vowels, it is hard to say the same for the nasalized ones, at least as far as the resulting vowel quality is concerned. The number of nasalized vowels is also reduced to five, as the contrast in the mid vowel domain ceases to exist; however, the resulting vowel quality can vary depending on dialect. The most southern dialects tend to favor the mid-high vowels, while northeastern dialects tend to favor the mid-low ones (Abaurre & Pagotto, 1982).

There have been some acoustic analyses of nasalized vowels in Brazilian Portuguese, but in a much smaller scale than acoustic analyses of nasal vowels, perhaps because nasalized vowels are much less controversial than nasal vowels in terms of their phonological status. Most studies about nasalized vowels focus on the difference between nasalized vowels and their nasal counterparts, especially when it comes to their duration. For example, Campos (2009) found that nasalized vowels are as long as their oral counterparts, but shorter than nasal ones. At the same

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[19] Some studies will say that nasalized vowels in stressed position in Brazilian Portuguese are phonologized; i.e., nasality is an intended part of the vowel (Moraes, 2013). It is not clear how nasalized vowels are different from nasal ones in this case, as this difference depends on what stance the author takes in relation to nasal vowels, if phonemic or allophonic.

time, Medeiros (2011) found that nasalized vowels can be as long as nasal counterparts if we exclude the appendix from the nasal vowels.

In terms of formant values, the low nasalized vowel tends to be similar to the low nasal vowel with respect to F1 and F2 values, while the high nasalized vowels are similar to both nasal and oral high vowels. Jesus (2002), for example, examined F1 and F2 values for the low and high oral, nasal and nasalized vowels. She found that nasalized vowels are more variable in formant values depending on vowel quality. The low nasalized vowel is no different from the nasal counterpart, while the high vowels are closer to their oral counterparts, becoming more like the nasal ones towards the end. The mid nasalized vowels are not diphthongal, unlike their nasal counterparts, but it is harder to tell if their formant values change considerably from oral vowels as scholars normally do not analyze mid vowels.

Aerodynamically, Medeiros (2011) shows that nasalized vowels have increasing mean values of nasal airflow throughout their duration, like nasal vowels, but the mean amount of airflow is smaller, indicating that nasalized vowels are not as nasal as their nasal counterparts, which points to a difference in how nasality is implemented between these two types of vowels. Desmeules-Trudel (2015) shows that, in addition to being shorter in duration, nasalized vowels have in general less nasal airflow, being either minimally nasalized throughout their duration, or increasing nasal airflow much later in the vowel when compared to their nasal counterparts.

However, intuitively, nasalized vowels are very similar to nasal vowels in terms of how nasal they sound (Brito, 1975, Souza & Pacheco, 2012). Thus, perceptually, nasalized vowels are not much different from nasal vowels, at least not in the amount of perceived nasality[20].

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[20] Studies in the perception of nasal and nasalized vowels do not normally contemplate the mid vowels, because of the difference in quality between nasal and nasalized mid vowels. We suspect, however, that a study comparing these vowels at the mid quality would yield considerable differences not due to nasality, but due to the inherent quality differences between them.

The phonological process of vowel nasalization is a synchronic process, as the phonological rule is applied at the time of speaking. However, we can make a parallel between the synchronic process and the diachronic processes outlined earlier. The synchronic process of allophonic nasalization occurs in the same (b) context where diachronic vowel nasalization is said to have occurred, i.e., preceding a heterosyllabic nasal consonant. The difference is that the heterosyllabic consonant in the synchronic process does not disappear, at least not yet. That demonstrates how much productive vowel nasalization still exists in Portuguese. We can infer, if the language history teaches us anything, that, if the synchronic process is the continuation of the diachronic process, the nasal consonant may at some point fall.

Vowel nasality in Portuguese, in special Brazilian Portuguese, is pervasive and very likely distinctive. However, at the same time, it has been so challenged that we find it difficult to support a strong claim of phonological contrast based on the current literature. In this debate, a bigger question emerges: if it is so difficult to sustain that a well-known distinction exists, how did it come to be? Why would scholars say that it exists? Although it seems like it should be a trivial pursuit to establish whether a well-known segment or feature is indeed phonemic, demonstrating that it is the case turns out to be very difficult. How do we know a contrast exists in first place? We attempt to address this question in the next chapter.

How do we know when we have a phonological contrast?

We can see that formal and experimental approaches to the study of nasal vowels in Brazilian Portuguese come to different – and even opposing – conclusions as to the status of these vowels, leaving open the fundamental question of which are the vowel phonemes in the language. Given the phonetic and phonological observed behavior, how do we know whether nasal vowels are phonemes or product of coarticulation in Brazilian Portuguese? More generally, how do we know when there is a contrast between two sounds in a language or how these two sounds are two conditioned allophones of the same phoneme? To answer that, we need to think about certain aspects of the interaction between phonetics and phonology, more specifically, when phonetics becomes phonology, or when coarticulation becomes contrast. Let us start by considering what coarticulation is, then move to how segments cease to be coarticulated to become contrastive. Finally, we consider how perceptual compensation can be a way to demonstrate a phonological contrast.

Coarticulation

Coarticulation plays a great role in how we produce and perceive speech contrasts. The term refers to "the fact that a phonological segment is not realized identically in all environments, but often apparently varies to become more like an adjacent or nearby segment" (Kühnert & Nolan,1999, p.7). The human vocal tract's physiology itself does not allow us to produce sounds in isolation; moving from one articulatory sequence to another requires a transition period. However, that does not mean we cannot control the amount of coarticulation between segments.

Coarticulation can be controlled depending on phonological constraints, such as the number and type of contrasts a language makes. Too much coarticulation can make two distinctive phonemes too similar, hindering accurate perception and erasing a contrast. Thus, to maintain

contrasts, speakers may constrain coarticulation of the gestures relevant to the contrast. Manuel (1990) analyzed vowel-to-vowel coarticulation in languages with vowel systems differing in size, and concluded that coarticulation is constrained depending on the number and quality of contrastive vowels a language has. The author measured the first and second formant values at the middle and end of the first vowel in /Vpɑ/ sequences in Ndebele, Shona and Sotho to measure the amount of anticipatory coarticulation of /ɑ/ on the target vowel. Ndebele and Shona have a 5-vowel system /i e ɑ o u/, while Sotho has 7 /i e ɛ ɑ ɔ o u/. The results show that coarticulation of the vowel /ɑ/ on the first vowel is indeed more extensive in Ndebele and Shona than it is in Sotho. That is argued to be because Sotho has a more crowded vowel space than the other two languages, so there is less space for variation. Therefore, if the language wanted to keep the existing contrast, coarticulation would need to be constrained.

Bringing Manuel's study to the issue of vowel nasality, we might expect coarticulatory nasality to be constrained depending on whether vowel nasality is contrastive in a language. If nasality is not contrastive, then nasality coarticulation will not be controlled in vowels, while it should be controlled in cases in which vowel nasality is contrastive. In the first case, coarticulation should be more pervasive. In the second case, nasal coarticulation in the vowel should be more restricted, so speakers do not confuse it with nasality inherent to the vowel, so that, in the end, a language with contrastive vowel nasality will have two patterns of nasality implementation. What is left to know is what exactly these two patterns are.

Cohn (1990) investigates how nasality is implemented in a language with vowel nasality contrasts, French, and in a language without the contrast, English. The author measured nasal airflow of phonemic nasal vowels in French and nasalized vowels both in French and English. The author shows that nasality can be implemented in two ways: gradient and categorical,

gradient being phonetic and categorical being phonological. Phonetic gradient nasality is coarticulatory in nature, and results in a gradual increase of nasal airflow approaching a nasal consonant, reflecting the feature's phonological underspecification. Phonological categorical nasality is characterized by a plateau in nasal airflow, reflecting a steady-state signal of the implementation of a specified phonological feature. Because French has both phonemic and coarticulatory vowel nasality, nasality is implemented in either way depending on the phonemic status of the vowel, while English needs to be gradient, as nasality is considered phonetic.

The author shows that English has essentially two patterns of nasal coarticulation: gradual increase and plateau. When comparing these patterns of nasal airflow in coarticulated vowels to French patterns of vowel nasality in phonemic and coarticulated vowels, Cohn noticed that the English words of the CVN kind have the same pattern of nasality as French coarticulatorily nasalized vowels, while the CVNC kind showed the same pattern of nasal airflow as French phonemic nasal vowels.

When considering both Manuel's and Cohn's studies, we can hypothesize that French nasalized vowels have the gradient pattern of nasal air flow because it aids in contrast maintenance. Phonemic nasality occurs throughout the vowel, starting early and being stable, consistent with a categorical implementation of a phonological feature; coarticulatory nasality starts later, then increases, restricted to the vowel's end, which is consistent with a gradual implementation of a phonetic feature. If there was no oral – nasal vowel phonemic contrast, we should expect coarticulation to be pervasive, starting at the beginning of the vowel, but it is hard to say whether it would be plateau-like or gradient.

The way coarticulation can restrained to maintain phonological contrasts, along with the way vowel nasality can be implemented depending on whether it is phonemic or coarticulatory

can shed light on how phonological contrasts can emerge in a language. The lack of constraints in how a feature is phonetically implemented may lead to pervasive coarticulation. If left unconstrained, coarticulation might affect a segment in a context, to the extent that it may become part of the segment itself. When that happens, coarticulation has become phonologized. Hyman (2001, p. 143) argues that, "[…] once such natural phonetic process is 'phonologized', they enter into the realm of grammar and are subject to different principles." That means the coarticulated phonetic feature becomes an intended part of a segment, and may lead to the emergence of new phonemes. Evidence for phonologization can be seen in diachronic processes of sound change.

Sound change

Theories of sound change (e.g., Ohala, 1993a; Ohala, 1993b; Hajek, 1997) posit that a contrast emerges when the conditioning environment for a low-level phonetic variation (i.e. coarticulation) is lost or becomes weak, in other words, when we cannot see what context conditions an allophone at the SR. Sound change is initiated by the listeners who cannot factor out the contextual influence anymore, as they should despite the speech signal being variable, and listeners turned speakers start to produce what was originally the conditioned allophone as the default allophone, attributing phonological significance to the product of coarticulation. Ohala (1993a) calls this hypocorrection, as listeners do not correct the contextually conditioned variant to what the expected phoneme should be. He argues that sound change needs to be consistent with known properties of the speech production mechanism, i.e., based on speech organs constraints, and it needs to be spread through the speech community. Ohala cites in his work nasal vowels as a clear case of sound change in which listeners failed to factor out the

original conditioning environment, as the nasal consonant was either lost or weakened to the point of become imperceptible.

Nasality is particularly interesting in the case of Romance languages, where the phenomenon can clearly be traced back to the mother language (Hajek, 1997). Nasal vowels are said to have emerged from the loss of the nasal consonant that conditioned coarticulatory vowel nasalization in early Romance. When aiming at producing /VN/ a speaker may produce [Ṽ], maybe due to gestural overlap between the vowel and the nasal gestures, or aerodynamic constraints depending on the context (e.g. Beddor, 2009). A listener, when hearing [Ṽ], may not be able to reconstruct /VN/ from the acoustic signal, as there is no [N]. The end product then would be /Ṽ/ instead of /VN/. A further development of this process would be re-categorization, in which [Ṽ] becomes /Ṽ/.

This diachronic process is hypothesized to have occurred in in the history of Portuguese, as mentioned in chapter 2 (Sampson, 1999). However, some phonological distribution patterns and the existence of the nasal appendix in the acoustic signal may be evidence against the completion of such a sound change process (even though some experimental evidence arguably supports it). So, how can we demonstrate, synchronically, whether such a historical process took place, i.e., how can we demonstrate whether there is indeed a contrast between nasal and oral vowels in Portuguese?

Perceptual compensation

Synchronically, a way to tell if a language has a contrast between two sounds such the oral – nasal vowel contrast is through how listeners perceive and interpret a segment or sound sequence upon hearing it. Our phonological system of contrast influences the way we perceive speech, and vice-versa (Hume and Johnson, 2001). Entering the realm of speech perception experimentation,

we are mostly familiar with categorization studies, whereby listeners of a language with a given contrast draw a sharp boundary in a stimulus continuum (VOT, nasality, place of articulation vowel formant cues). However, categorization experiments seem to work very well for consonants, but less so for vowels, perhaps due to the more variable nature of vowel production versus the more precise articulation of consonantal gestures, especially obstruents (for a brief review, refer to Beddor & Strange, 1982[21]). Thus, we need to find another way of getting at a phonological contrast. Another possible (and likely novel) way to see if a language has a phonological contrast is through perceptual compensation studies, even though they are not commonly used that way.

Perceptual compensation is one of the ways our phonological system influences speech perception. As exposed above, coarticulation has an important role when it comes to perceiving speech. Listeners may use coarticulation to foresee upcoming sounds in the speech stream. For example, they may use lip rounding in stop consonants to anticipate that a rounded vowel is coming (Bell-Berti & Harris, 1981). While informative of an upcoming sound, coarticulation is normally factored out when a listener is interpreting the acoustic signal, as it is not part of the grammar. Therefore, we can say that listeners, upon hearing the acoustic consequences of lip rounding in the consonant, will attribute it to the upcoming vowel due to coarticulation, rather than interpret it as inherent to the consonant. In other words, they will compensate for the effect of lip rounding in the consonant.

Perceptual compensation can occur with any phonetic feature that is not contrastive in a language, i.e., not part of the segment's phonological constitution. In fact, compensation is

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[21] However, in this study, Beddor and Strange are able to obtain categorization responses consistent with a categorical perception for vowel nasality in Hindi, a language with contrastive vowel nasality, but only after an initial unsuccessful attempt.

expected to occur whenever the mapping between the acoustic signal and the linguistic representation occurs. In terms of coarticulatory vowel nasality, perceptual compensation occurs when nasality occurring on the vowel is factored out by the listener and attributed to a vowel-adjacent nasal consonant, most commonly a consonant following the vowel. Conversely, in cases when a listener cannot attribute nasality in the vowel to a coarticulatory source, for example when the nasal consonant cannot be perceived, perhaps because it is very short, weak, or not present, nasality enters the realm of grammar, as explained above, because the listener will likely attribute it to the vowel and consider nasality an inherent vowel feature.

Kawasaki (1986) tests the idea of failing to factor out nasality from the vowel when the context is not perceptible by showing that, while speakers can normally factor out "commonly encountered perturbation of one segment by another" (p. 87), if the perturbing segment cannot be detected, then the perturbation cannot be dismissed as coarticulation, and it is consequently included in the segment's phonological interpretation. The author performed identification and discrimination tasks in which CVC syllables containing nasalized vowels flanked by nasal consonants were manipulated so that the consonants' amplitudes were attenuated in five different steps. These manipulated syllables were presented to native speakers of English, who had to judge the degree of vowel nasality in each stimulus, or judge which vowel was more nasal out of a pair. Her results supported the hypothesis: most subjects judged a vowel as more nasal when it was between two attenuated consonants, while most vowels between non-attenuated consonants were judged as (relatively) oral. These results show that nasality in a nasalized vowel is attributed to the context, but not when the context is not present. In other words, listeners perceptually compensate for vowel nasality when the context is present. (When subjects failed judge the vowel as nasal between two attenuated nasal consonants, mostly in the identification

task, they reported the vowel to be more oral. The author does not delve into why that could happen.)

Beddor & Krakow (1999) report on an experiment where American English speakers partially compensate for vowel nasalization in the appropriate context. The authors spliced oral vowels into nasal (N__N) and oral (C__C) contexts and presented the resulting stimuli, along with isolated oral (V) and nasalized (Ṽ) vowels, in pairs to American English speaking participants. Their task was to choose which vowel was more nasal, the first or the second, relative to one another. In cases where the vowel was nasalized, but occurred in stimulus pairs with different contexts (for example, CṼC–NṼN), participants answered that the vowel in the oral context was judged as more nasal than the vowel in the nasal context (or in isolation). In cases where a nasalized vowel in a nasal context was compared with an oral vowel either in isolation or in an oral context, participants judged that they were judged to be essentially the same in terms nasality (although not necessarily oral). These results demonstrate that American English speakers compensate for nasality in the vowel, attributing this property to the context, a nearby nasal consonant in this case. However, in about 25% of the cases participants chose the nasal vowel in nasal contexts as more nasal than an oral vowel, which indicates that compensation is not complete. Beddor *et al.* (2001) interpret these findings in light of sound change. Participants' partial difficulty in detecting nasal vowels in the nasal contexts, suggests that nasal vowels may emerge in contexts where nasalization was at some point coarticulatory, which is consistent with theories of sound change.

An implication of compensation studies such as the ones above is the assumption that listeners know that some phonetic aspects of the target sound do not have phonemic status in the language. That is the reason listeners should attribute the phonetic feature on the target segment

to the context. In the current study, the assumption of lack of phonemic status is turned around. What happens with compensation when it is unclear whether a phonetic feature is coarticulatory? Using the premises of perceptual compensation studies, it is possible to see if they consider a sound they hear a phoneme in their language or not, by showing whether they compensate for the acoustic effects of coarticulation. If listeners of a target language fail to compensate for a certain sound property in the target sound, it could indicate that the target sound is perceived as a phoneme in the language. This idea is consistent with sound change theories cited above, where a phoneme emerges exactly because a listener fails to factor out the effect of coarticulation in a sound.

Beddor, Krakow & Goldstein (1986) is a good example of what happens when there is no coarticulatory context to which listeners attribute nasality in the vowel in a language that has no contrastive nasal vowels. The authors attempt to link perceptual compensation failure to sound change in a study where the effect of vowel nasalization on vowel quality, height to be more specific, is examined in phonological, acoustic and perceptual data. Their hypothesis is that vowel nasalization affects perceived vowel height, but only when the listener cannot attribute nasality in the vowel to a neighboring nasal consonant, such as in cases where the conditioning nasal consonant is missing. In these contexts, speakers fail to compensate for nasalization in the vowel and attribute its effect to vowel quality.

When presented with words containing synthesized /ɛ/, /æ/, /ɛ̃/ and /æ̃/ between [b___d], American listeners reported hearing more /æ/ when the vowels were nasal than when vowels were oral, due to lack of coarticulatory context. The authors believe that listeners interpreted the effect of nasalization as tongue body lowering, creating a low vowel with a high F1 (Krakow *et al*., 1988). However, when there is appropriate phonological context, i.e., the presence of a nasal

consonant after the vowel, the appropriate height should be perceived. To demonstrate this claim, the authors presented to the same participants stimuli where the same vowels were in a [b___nd]. They found that listeners reported hearing /ε/ when the vowel was nasalized in this latter context in much the same way as they heard /æ/ when the vowel was oral in the [b___d] context. This result indicates that listeners compensate for nasalization in the vowel when the phonological context is appropriate for English, but do not when the context is inappropriate. English listeners resolve inappropriate vowel nasality in terms of vowel quality. This effect only occurs because English has no contrastive vowel nasality, however, based on the history of languages with contrastive vowel nasality such as French, we can hypothesize that a similar effect might have occurred, as oral and nasal counterparts have different vowel qualities in addition to nasality.

Going back to the implication that perceptual compensation assumes lack of phonemic contrast and the question of what happens with compensation when it is not clear if a phonetic feature is contrastive or coarticulatory, we should expect, in a language that has contrastive nasal vowels, non-compensatory responses in the context of a nasal consonant and accurate vowel quality identification. In the case of Brazilian Portuguese, we should expect non-compensatory and accurate vowel quality identification, if nasal vowels are contrastive. Because of the way perceptual compensation tests work, we can test for the phonemic status of nasal vowels as opposed to oral vowels by testing listener for perceptual compensation effects. Also, we indirectly can test for the phonological role the nasal appendix has[22]. If vowel nasality is coarticulatory and triggered by the nasal appendix, we should expect that Brazilian Portuguese listeners attribute the effects of vowel nasalization to the nasal appendix, in other words, that they compensate for the effect of nasalization in the vowel. Therefore, it would be implied that

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[22] Remember from the chapter about description of Brazilian Portuguese vowels that some scholars believe the nasal appendix is the surface realization of an underlying nasal consonant that nasalized the preceding vowel.

nasal vowels are not phonemes in the language. However, if vowel nasality is contrastive, then perceptual compensation should not occur in nasal vowels followed by the appendix. There would be no inappropriate vowel nasality or context, and listeners would not resolve for those by saying the vowel has a different vowel quality than what it actually has.

Goodin-Mayeda (2011) attempted to test for vowel nasality perceptual compensation effects in Brazilian Portuguese. Like Beddor & Krakow (1999), the author investigated the effect of nasalization on the perception of vowel height in Spanish and Portuguese, asking if listeners could accurately perceive vowel height both in and out of the context of a nasal consonant. In a language that has both phonemic and allophonic nasality, like Portuguese, at least according to Goodin-Mayeda, it is expected that listeners should be able to identify accurately vowel height regardless of context, due to their experience with both kinds of nasality. In a language that has no such contrast, and very little coarticulatory nasality like Spanish, however, it is expected that listeners should not be able to perceive accurately vowel height regardless of context. This is unlike English, which has heavy contextual vowel nasalization, and in which vowel height only be accurately perceived in the context of a nasal consonant (Krakow *et al*, 1988).

The author presented to native speakers of Spanish and Portuguese pseudo-words[23] with synthesized high and mid-high back vowels in a continuum from high to mid-high, oral to nasal in two different contexts: with and without a nasal consonant[24] at the vowel's right edge. The task was to identify the vowel height: [u] or [o]. Spanish speakers heard [u] more often in both contexts when compared to an oral vowel in a no-nasal consonant context. This means that Spanish speakers were unable to factor out nasality in the vowel even in the appropriate context,

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[23] The pseudo-words were all in the form of [gVs] and [gVns], where V is one of the manipulations the author made.

[24] The author never tested the nasal appendix, because Spanish does not have it.

attributing its effects to vowel height, as an effect of nasality in mid vowels is to raise its perceived quality. That is, two vowels with the same F1 value were considered both [u], even though one of them was [õ]. Portuguese speakers, on the other hand, did not hear [u] when presented with [õ] more often in the nasal context than in the no-nasal consonant context, which means they were able to correctly identify vowels, not attributing differences in nasality to height, regardless of whether a vowel was followed by a nasal consonant or not. The author explains that this difference in how vowels were perceived is due to the differences in nasal vowels' phonemic status as well as differences in amount of coarticulatory nasality in the vowels between the two languages. Thus, this study demonstrates, at least partially[25], the expectations of what happens with perceptual compensation in Portuguese, assuming the oral-nasal contrast exists: accurate vowel perception regardless of context.

Returning to the title question of how we know a language has a phonological contrast, it is safe to say that it is not a simple matter. There are issues with coarticulation control, coarticulation perception, phonologization and sound change, and these issues are not exhaustive. A combination of different angles of investigation are required to establish the presence of absence of a contrast, especially when the evidence is not conclusive. In Brazilian Portuguese, that is the case. Approaching the issue of vowel nasality from the listener point of view through perceptual compensation could provide new evidence for the phonemic status of nasal vowels. That is what we set out to do in the next chapters.

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[25] We say partially because the methodology used in this study was different from the methodology used in perceptual compensation experiments. Goodin-Mayeda (2011) uses a categorization experiment paradigm. An experimental paradigm for perceptual compensation should include direct stimuli comparison in different contexts. That is not to say, however, that Goodin-Mayeda's experiment is not valid.

Production study

While the focus of this project is on the perception of nasal and nasalized vowels, a small production study was performed on oral, nasal and nasalized vowels to establish a profile in terms of formant values, degree of nasality and the phonetic realization of the nasal appendix to relate production to perception findings. This study will also evaluate the claim stated elsewhere in the literature (Brito, 1975, Souza & Pacheco, 2012) that there is no difference between phonemic nasal and coarticulatory nasalized vowels in Brazilian Portuguese in terms of degree of nasality and formant values, despite a possible duration difference (Campos, 2009). One important contribution of this production study to the literature about nasal and nasalized vowels is the inclusion of mid vowels in the analysis. Few of the many studies include mid vowels due to the perceptible diphthongization mid vowels undergo when nasal (but not when nasalized). These findings are consistent with the formant value measurements performed by Jesus (2002), who has also found the same pattern for the high back vowel. However, the high front vowel /i/ showed differences between the coarticulatory nasalized and the phonemic nasal vowels, the former being closer to the oral vowel /i/ in terms of formant values. There were no values whatsoever for the mid vowels, however Sousa (1994) and Seara (2000) show that the mid vowels are also influenced by nasality, so that the nasal vowel becomes lower and more fronted when compared with their oral counterparts. Therefore, it is important to describe the acoustic properties of these vowels before jumping to how they are perceived by native speakers of Portuguese.

Methods

A total of 30 words and pseudo-words were recorded by 6 native speakers of Brazilian Portuguese from different regions of Brazil, all living in Boulder at the time of collection. The

words and pseudo-words are presented on table 5. The vowels were flanked by an oral stop at the left, and by either an oral or nasal stop at the right edge. These words are divided according to vowel quality and type of nasality: oral, nasal and nasalized.

Table 5. Tokens recorded for stimuli creation. C=oral stop; N=nasal stop; V=oral vowel; Ṽ1=nasal vowel; Ṽ2=nasalized vowel.

	C1VC2V	C1Ṽ1C2V	C1Ṽ2NV
/a/	Capa	Campo	Cama
	Jato	Janto	Janio
/e/	*Deto	Dente	Denis
	*Teto	Tento	Tenis
/i/	Tita	Tinta	Tina
	Pita	Pinta	Pino
/o/	Popa	Pompa	Pomo
	*Toto	Tonto	Tona
/u/	Juta	Junto	Juno
	*Tutu	*Tuntra	*Tunu

Once recorded, first and second oral formants (F1 and F2), two measures of nasality, A1-P0 and A1-P1 (Chen, 1997), were measured in each word at 10 sequential time points to observe how formant values and nasality in the vowels unfolded over the vowels' duration. These measurements were done semi-automatically through a script routine created at the University of Colorado Phonetics Lab (Nasality automeasure). Corrections were made based on the visual inspection of each token's spectral slice. For formant analysis, time points 4 and 5 were averaged to find the most stable part of the vowels, which were used in a statistical analysis.

For acoustic nasality analysis, time points 1 and 10 were removed due to the proximity with right and left segment boundaries and consequent undesirable consonant place coarticulatory interferences, so that time points 2 to 8 were used to present results visually. Time points 2-3, 4-5-6, and 7-8-9 were averaged in three groups, so that there were three different averaged time points (early, mid, and late), which were used in the statistical analysis.

Formant and nasality statistical analyses were separately carried out using linear mixed-effects models. First and second formants were continuous dependent variables in the first analysis; A1-P0 and A1-P1 were continuous dependent variables in the second; vowel nasality (oral, nasalized, nasal) and vowel quality (/a/, /e/, /i/, /o/, /u/) were categorical independent variables in both analyses, with three and five levels respectively; averaged time point was a categorical independent variable in the nasality analysis; participant (tokens in table 2) was treated as random variable in both analyses.

While formant analysis is well known in the literature and does not require further explanation, nasality analysis through A1-P0 and A1-P1 analysis does. These are indirect ways to measure how nasal a vowel is in the acoustic signal (Chen, 1997). They are expressed by the difference between the amplitude of the first formant A1 spectral peak and the amplitude of a low-frequency nasal peak P0, or a peak around 950Hz P1. The acoustic consequences of velopharyngeal coupling in the spectrum are reduction of first formant F1 amplitude, and the increase in amplitude of a low-frequency peak in the spectrum of a nasal vowel (and also a peak around 950Hz). The difference between amplitudes is the indirect measure of nasality; it is a relative measure always compared to the amplitudes of the oral counterpart's same peaks for a given speaker. A consequence for nasal (and nasalized) vowels, then, is that A1-P0 and A1-P1 should be relatively small; for oral vowels, they should be larger. Figure 5 below illustrates this point.

Figure 5. Spectral slices from oral and nasal vowels. The peaks used in A1-P0 and A1-P1 measures are labeled.

Chen applied this method to English and French, with good results. In English, the comparison was made between oral and nasalized vowels. A1-P0 for low vowels had a significant difference, ranging from 6 to 8 dB difference, between oral and nasalized. The remaining higher vowels had better results with A1-P1, with oral-nasalized differences ranging from 10 to 15 dB difference. For French, Chen measured contrastive nasal vowels at different points to observe the effects of the increase in velopharyngeal port opening, in other words, the decrease in amplitude differences across time. Her results showed that A1-P0 and A1-P1 values at the beginning and at the end of the vowels were significantly different, ranging from 3 to 9dB difference for A1-P0 and 9 to 12 dB difference for A1-P1.

In the current study, in addition to formant analysis and A1-P0 and A1-P1 analyses, all words with nasal vowels were inspected for the presence of the nasal appendix (through visual inspection of the spectrogram and waveform), its duration was manually measured, and it was compared with the duration of the following nasal consonant in words containing nasalized vowels.

Figure 6. Nasal appendix duration measurement in *dente* "tooth", represented by the letter "n" in the textgrid tier vowel.

Figure 7. Nasal consonant duration measurement in *Denis*, represented by the letter "N" in the textgrid tier vowel.

The nasal consonant was quite easily spotted due to its acoustic characteristics of nasal resonances, one at low frequencies, one at around 1100 Hz and two others above 2000 Hz. Most importantly, though, there is a great drop in amplitude between the two vowels, due to a closed oral tract, which created sharp boundaries between the consonant and the vowels.

The nasal appendix, however, was more difficult to pinpoint, for a couple of reasons. First, the expected amplitude drop due to oral tract closure was not always very drastic. Second, the extent of the appendix is highly variable among subjects, being sometimes non-existent (see also Barbosa & Madureira, 2015). Still, drop in amplitude, formant changes in the spectrogram

(including formant loss), and changes in waveform were the guides for measuring the duration of the nasal appendix (Kelm, 1989).

Predictions

While this production study is more exploratory than analytical, we can make some predictions based on the literature:

1. Oral vowels will be less nasal than either their nasal or nasalized counterparts, regardless of vowel quality. That means non-high oral vowels will have higher A1-P0 values when compared to the other two; high oral vowels will also have higher A1-P1 values.

2. Nasal vowels will not be significantly more nasal than their nasalized counterparts, regardless of vowel quality. That means non-high nasal vowels will not have higher A1-P0 values than nasalized vowels; high vowels will not have higher A1-P1 values than nasalized ones either.

3. The nasal appendix is expected to emerge in words with ostensible nasal vowels, and its duration should be short, especially when compared to nasal consonants.

These predictions are also related to predictions pertaining to the perceptual experiments, explained in the perception experiments.

With respect to formant values, it is well known in the literature that they change from oral to nasal and nasalized vowels (e.g., Sousa, 1994). There is a change in vowel quality associated with nasality that can potentially affect the way Brazilian Portuguese speakers perceive nasality. However, the change in vowel quality is more appreciable in the low and the mid vowels; the high vowels are reported not to change in quality. It is possible that vowel quality might

influence the patterns of response in the perceptual experiment, which is why a formant analysis

is included here.

Analysis

Formant Analysis

First and second oral formants are treated as dependent variables, each with its own separate

linear mixed-effect model, with vowel quality and nasality as independent factors, and speaker

and word as random factors for both. This is a standard formant analysis procedure in the

literature, with perhaps a difference in the addition of random variables to account for speaker

differences. Formants are treated as continuous variables, and the levels of the independent

variables are shown in table 6.

Table 6. Independent variables used in the linear mixed effects analysis for formants; bold indicates reference level.

Variable	Levels
Vowel nasality	**oral**, nasal, nasalized
Vowel quality	**a**, e, i, o, u

These variables both predict changes in formant values due to changes in resonances in the

oral and nasal tracts. This analysis shows that there is an effect of vowel quality and type of

nasality with the interaction vowel quality and nasality being significant for F1 but not for F2.

This demonstrates that there is an interaction between these two factors, which is expected given

the literature on the relationship between vowel nasality and change in quality.

Table 7. Linear mixed effect analysis for F1. Values in bold are statistically significant.

Dependent variable: F1	Estimate	Std. Error	t-value	p-value
(Intercept)	913.42	34.86	26.2	**< 0.0001**
nasality: nasal	-348.14	31.49	-11.056	**< 0.0001**
nasality: nasalized	-365.21	31.49	-11.598	**< 0.0001**
vowel: e	-512.67	33.06	-15.505	**< 0.0001**
vowel: i	-605.7	31.49	-19.236	**< 0.0001**
vowel: o	-435.81	31.49	-13.841	**< 0.0001**
vowel: u	-441.7	31.49	-14.028	**< 0.0001**
nasality: nasal; vowel: e	419.15	45.66	9.18	**< 0.0001**
nasality: nasalized; vowel: e	393.37	45.66	8.615	**< 0.0001**
nasality: nasal; vowel: i	425.77	44.53	9.561	**< 0.0001**
nasality: nasalized; vowel: i	398.36	44.53	8.946	**< 0.0001**
nasality: nasal; vowel: o	473.22	44.53	10.627	**< 0.0001**
nasality: nasalized; vowel: o	424.59	44.53	9.535	**< 0.0001**
nasality: nasal; vowel: u	332.19	44.53	7.46	**< 0.0001**
nasality: nasalized; vowel: u	364.98	44.53	8.196	**< 0.0001**

Table 8. Linear mixed effect analysis for F2. Values in bold are statistically significant.

Dependent variable: F2	Estimate	Std. Error	t-value	p-value
(Intercept)	1537.8	82.34	18.677	**<0.0001**
nasality: nasal	46.09	110.04	0.419	0.6758
nasality: nasalized	77.1	110.04	0.701	0.4845
vowel: e	690.06	115.5	5.975	**<0.0001**
vowel: i	886.51	110.04	8.057	**<0.0001**
vowel: o	-627.57	110.04	-5.703	**<0.0001**
vowel: u	-319.48	110.04	-2.903	**0.0042**
nasality: nasal; vowel: e	20.99	159.52	0.132	0.8955
nasality: nasalized; vowel: e	-22.11	159.52	-0.139	0.8899
nasality: nasal; vowel: i	-254.55	155.61	-1.636	0.1038
nasality: nasalized; vowel: i	-146.93	155.61	-0.944	0.3465
nasality: nasal; vowel: o	192.8	155.61	1.239	0.2171
nasality: nasalized; vowel: o	49.08	155.61	0.315	0.7528
nasality: nasal; vowel: u	109.34	155.61	0.703	0.4833
nasality: nasalized; vowel: u	-46.87	155.61	-0.301	0.7636

The reason why these results, especially F1, are all significant is the low vowel. Recall that

this vowel, when nasal or nasalized, undergoes an extreme change in vowel quality, being

considered not a low vowel anymore, but a central vowel. This great change in quality can be

seen in figure 8 below, where a scatterplot of speaker-averaged formant values at the averaged

mid (4-5) time points is presented. Each different group of data points represent a vowel quality.

Notice how low the oral low vowel (diamond) is.

Figure 8. Vowel first and second formant scatterplot based on our measurements.

The oral low vowel being so low in the graph when compared to the other vowels shows that

it has, in this sample, a very high F1 value. Taking that vowel as reference for a statistical

analysis, therefore, would likely cause all the other vowels' F1 to be significantly different from

it, as we see in the analysis. It is as if the low vowel behaved like an outlier in the dataset. F2

shows a different pattern, but also predictable based on the low vowel's horizontal position in the

graph above. No interaction is significant, only main vowel effects, showing that front and back

vowels are different from the central ones as groups, but individual vowels are not by themselves

any different[26]. This very general model, while informative, is very predictable, as expected,

since vowels are inherently different from one another in at least one formant. However, it does

not capture key differences between oral, nasal and nasalized vowels for a given vowel category.

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[26] When the low vowel is removed from the dataset and the high front vowel is used as the reference, then no interaction for F1 is significant, only main vowel quality effects. For F2, only the interaction of nasality and back vowels is significant, but that is expected since the high front vowel has a very high F2, regardless of nasality.

Therefore, it makes sense to divide the data by vowel quality, so that a better examination of the effects of vowel nasality could be performed[27].

The most striking feature in the chart above concerns the low vowel (diamonds), as the vertical distance (F1) between the low oral vowel and the other two shows a big difference in terms of vowel quality, with the nasal and nasalized vowels being essentially mid-central. This difference is statistically significant, with nasal and nasalized F1 values at the averaged mid-point (time points 4 and 5) decreasing by about 348Hz and 365Hz respectively ($t(36) = -14.01$, $p < 0.005$; $t(36) = -14.69$, $p < 0.005$). This big difference between oral and non-oral vowels for the low vowels is expected, though, as it has been clearly attested in the literature. The difference between nasal and nasalized low vowels, however, is not significant ($t(36) = -0.687$, $p = 0.497$), showing that the nasal and the nasalized low vowel have similar heights. In terms of F2, the low vowel presented no difference between the different types of nasality, with the nasal and nasalized vowel being slightly more fronted than the oral one by 46Hz and 77Hz respectively ($t(36) = 1.449$, $p = 0.6758$; $t(36) = 2.423$, $p < 0.05$). Nasality affects the low vowel more by making it higher in the vowel space than by making it more fronted.

The other vowels, however, do not appear to show very accentuated formant differences based on the vowel plot above. The mid-front vowel category shows a significant difference in terms of F1 only between the oral and the nasal vowel by about 73Hz ($t(34) = 3.773$, $p < 0.005$), but not between the oral and the nasalized vowel ($t(34) = 1.585$, $p = 0.1231$). The nasal and nasalized vowels are different from one another ($t(34) = -2.309$, $p = 0.0291$). For F2, both nasal and nasalized vowels are a little more fronted than the oral vowel, with the nasal vowel being about 71Hz more fronted than the oral vowel ($t(34) = 2.338$, $p < 0.05$), and the nasalized vowel

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[27] The mixed model function for each formant value was lmer(freq_f1 ~ nasality*vowelq+(1|speaker), prod), lmer(freq_f2 ~ nasality*vowelq+(1|speaker), prod). The functions for each vowel quality followed the same pattern.

being about 59Hz more fronted (t(34) = 1.942, p = 0.06). The nasal and nasalized vowels are, again, not different (t(34) = -0.418, p = 0.6794). Thus, in the case of the mid-front vowels, the nasal vowel is different from the oral and the nasalized ones.

The mid-back vowel also shows a more marked difference between the oral, the nasal and the nasalized vowels for F1. The nasal vowel has an significantly F1 higher than the oral vowel by 125Hz (t(36) = 5.082, p < 0.0005); the nasalized vowel is also higher than the oral by 59Hz (t(36) = 2.413, p < 0.05). The nasal and nasalized vowels are marginally different from each other by 65 Hz (t(34) = -2.669, p = 0.125). Only the nasal vowel's F2 is significantly different from the oral's, by about 238Hz (t(36) = 3.056, p < 0.005), while the nasalized F2 is 126Hz higher (t(36) = 1.614, p = 0.1161). The nasalized vowel's F2 is lower than the nasal's by 112 Hz, but that difference is not significant (t(34) = 1.442, p = 0.1605). As with the mid-front vowel, the nasal mid-back vowel is the most different from the three, being lower and more fronted than the oral.

The high front vowel shows a significant difference between the oral and the nasal vowels, but not between the oral and the nasalized vowels in terms of F1. The nasal vowel is about 77Hz higher than its oral counterpart (t(36) = 2.52, p < 0.05), while the nasalized is about 33Hz higher, but not significantly (t(36) = 1.076, p = 0.2895). The same goes for F1 difference between the nasal and the nasalized high front vowels, with the nasalized vowel being a bit lower than the nasal counterpart by 77hz, but the difference is not significant (t(34) = -1.444, p = 0.1598). In terms of F2, the same pattern repeats. The nasal vowel is significantly different from the oral vowel, being more retracted by 208Hz (t(36) = -2.19, p < 0.05), while the nasalized vowel is not, still being more retracted by about 69Hz (t(36) = -0.735, p = 0.4675). The nasalized vowel is a bit more forward than the nasal counterpart by 122 Hz (t(34) = 1.459, p = 0.1555). When

compared to the oral, therefore, we can say that the nasal and nasalized vowels are lower and backer than the oral vowel, but only the nasal vowel is indeed different.

Finally, the high back vowel, none of the vowels are significantly different from the oral. Nasal F1 is about 15Hz smaller than oral F1, and nasalized F1 is about 0.22Hz smaller, none of which are significant differences (t(36) = -0.413, p = 0.6824; t(36) = -0.006, p = 0.9953, respectively). Nasal F2 is about 155Hz greater than oral F2, and nasalized F2 is 30Hz smaller. These differences are not significant (t(36) = 1.546, p = 0.1315; t(36) = 0.301, p = 0.7655), and so are not the difference between the nasal and nasalized vowels (t(34) = 0.407, p = 0.687 for F1 and t(34) = -1.246, p = 0.233 for F2). While being a little bit higher and more fronted in the vowel space, the nasal and nasalized high back vowels are essentially not different from the oral one, neither from each other.

In summary, we can see that nasality affected mostly the first formant in all vowel qualities, but not the second formant, which is consistent with the literature. More specifically, it seems that, at least when it comes to F1, the nasal vowels tended to be more centralized relative to their oral counterparts, while the nasalized ones did not, at least not significantly. Therefore, oral and nasalized vowels, except for the low vowel, are very similar to each other, while the nasal vowels are not as similar to either the oral or the nasalized vowels, at least in terms of formant values at the vowels' mid-points[28]. Perhaps this centralization can be used to enhance contrast between oral and nasal vowels, if we consider that there is one, so that it aids in the perception of vowel nasality.

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[28] Notice that the analysis did not reveal significant difference between nasal and nasalized mid vowels, likely because the difference between these two lies in the diphthogization towards the end, not at the mid-point.

A1-P0 and A1-P1

There are two dependent variables in this analysis: A1-P0 and A1-P1. A1-P0 measures the

amount of acoustic nasality in non-high vowels /a/, /e/ and /o/. A1-P1 measures the amount of

acoustic nasality in high vowels /i/ and /u/. These variables will be treated in two different linear

mixed effects analyses. The independent variables are: vowel nasality, time point and vowel

height. These variables are all categorical with different levels, as explained in table 9 below:

Table 9. Variables used in the acoustic nasality linear mixed effects analysis.

Variable	Levels
Vowel nasality	**oral**, nasal, nasalized
Time point	**early**, mid, late
Vowel quality A1-P0	**a**, e, o
Vowel quality A1-P1	i

It is known that vowel quality affects the degree of nasality due to requiring different

degrees of velopharyngeal port opening. Low vowels normally need more nasality to be

perceived as nasal because they are produced with bigger velopharyngeal port opening even

when they are oral, while high vowels need little nasality to be perceived as nasal. Therefore, it is

expected that, despite overall differences in nasality regardless of vowel quality, the low vowel

will be the most nasal, since nasality affects this quality quite heavily.

Figure 9 below shows how speaker-averaged A1-P0 values (y-axis) unfold over time for the

low and mid vowels across 8 different time points (x-axis), from the vowels' left boundary with

a stop, to the vowels' right boundary with either a stop, a nasal consonant or the nasal appendix.

The lines with triangles represent the oral vowels; the lines with diamonds represent the nasal

vowels; the lines with squares represent the nasalized vowels.

Figure 9. A1-P0 values for the low (upper left), mid-front (upper right) and mid back (lower center) vowels for all three vowel nasality types.

The arrows represent the direction in which acoustic nasality increases, evidencing the inverse relationship between A1-P0 and acoustic nasality. The bigger A1-P0 is, the less nasal a vowel is. Conversely, the smaller A1-P0 is, the more nasal the vowel. In the graph, then, more nasal values translate in the A1-P0 line being lower visually. In figure 3, A1-P0 for oral vowels are the highest in the graph when compared to the other two lines, indicating they are the least nasal vowels of the three. The nasal vowels are represented by the lowest lines in the graph, at least towards the end, indicating that these vowels are the most nasal of the three. The nasalized vowels' lines are of intermediate height in the graph, but closer to the nasal vowels, indicating intermediate A1-P0 values, and therefore intermediate nasality for these vowels. The fact that the lines for nasalized vowels are closer to the lines for nasal vowels than to the oral vowels, regardless of vowel quality, show that these vowels are already very nasal, consistent with the profile of nasality found in the literature.

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Overall, it seems clear that non-high nasal and nasalized vowels are different from the corresponding oral vowels in terms of amount of acoustic nasality. A linear mixed effects analysis[29] for these vowels shows that these differences are statistically significant, as presented on table 10 below.

Table 10. Linear mixed effect analysis for non-high vowels. Bold indicates significance levels < 0.05.

Independent variable: A1-P0	Estimate	St. Error	t-value	p-value
(Intercept)	11.623	2.071	5.613	<0.0001
nasality: nasal	-4.185	1.120	-3.736	**<0.0001**
nasality: nasalized	-4.012	1.120	-3.582	**<0.0001**
vowel: e	-2.053	0.997	-2.060	**0.040**
vowel: o	-2.166	0.997	-2.174	**0.031**
timepoint: late	-0.448	0.627	-0.715	0.475
timepoint: mid	1.324	0.626	2.113	**0.035**
nasality: nasal; vowel: e	1.316	1.409	0.934	0.351
nasality: nasalized; vowel: e	1.493	1.409	1.059	0.290
nasality: nasal; vowel: o	3.829	1.409	2.717	**0.007**
nasality: nasalized; vowel: o	3.024	1.409	2.145	**0.033**
nasality: nasal; timepoint: late	-3.479	0.886	-3.926	**<0.0001**
nasality: nasalized; timepoint: late	-1.018	0.886	-1.149	0.252
nasality: nasal; timepoint: mid	-2.138	0.886	-2.412	**0.016**
nasality: nasalized; timepoint: mid	-1.100	0.886	-1.241	0.215

The analysis shows that nasal and nasalized vowels' A1-P0 are overall lower than oral vowels' by around 4dB (t(324) = -3.736, p < 0.005 for nasal vowels; t(324) = -4.012, p < 0.005 for nasalized vowels), from the average of 11.6dB for oral vowels. There is also a difference in vowel quality as expected, with the mid vowels being less nasal overall than the low vowel by around 2dB (t(324) = -2.060, p < 0.05 for mid front; t(324) = -2.74, p < 0.05 for mid back). We can also see that A1-P0 in the middle of the vowels is higher than at the beginning (t(324) = 2.113, p < 0.05), suggesting that the vowels are less nasal in the middle than at their beginning;

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[29] The mixed model function for A1-P0 is lmer(a1po~nasality*vowel+nasality*timepoint + (1|speaker), nasalitynonhigh).

A1-P0 is lower towards the vowels' end but this difference is not significant ($t(324) = -0.715$, $p = 0.475$).

The most important feature in the analysis is an interaction of vowel nasality and time point, presented in the last four lines of table xx. The interactions show that the curves of A1-P0 profiles for different nasality conditions differ across time points. Nasal vowels become more nasal more quickly than their oral counterparts, both in the mid ($t(324) = -2.412$, $p < 0.05$) and late ($t(324) = -3.926$, $p < 0.05$) time points. These results are consistent with the visual inspection of the graphs in figure 3, in which we can see that the lines with diamonds corresponding to nasal vowels decrease more rapidly than the lines with triangles corresponding to oral vowels. Nasalized vowels, although being overall lower in A1-P0 when compared to their oral counterparts, do not become more nasal over time, as attested by the lack of significant interaction difference between oral and nasalized vowels at the mid and late points ($t(324) =-1.018$, $p=0.252$; $t(324) =-1.100$, $p=0.215$, respectively); however, the decrease is not statistically significant from mid to late points; nasalized vowels have essentially the same curve profiles than oral vowels in the graphs, only with overall lower A1-P0 values.

What about the difference between nasal and nasalized vowels? Post-hoc linear mixed models including just nasal and nasalized vowels show that there is no overall difference between nasal and nasalized vowels ($t(216) = 0.233$, $p = 0.815$) across time points. However, there is a time point effect, with the late portion of both nasal and nasalized vowels being more nasal from their early portions by about 3dB ($t(216) = -8.037$, $p < 0.05$), while there were not significant differences in their mid-portions. There is, more importantly, an interaction between vowel nasality and time point, with the late portion of nasalized vowels being less nasal than

nasalized vowels by about 2dB ($t(216) = 3.563$, $p < 0.05$), and the nasal vowels' A1-P0 values decreasing more rapidly than nasalized vowels' A1-P0.

Turning to the analysis of high vowels, figure 5 below shows speaker-averaged A1-P1 (y-axis) values for the two high vowels, as it unfolds across time points (x-axis), from the vowels' left boundary with a stop, to the vowels' right boundary with either a stop, a nasal consonant or the nasal appendix. The lines with triangles represent the oral vowels; the lines with diamonds represent the nasal vowels; the lines with squares represent the nasalized vowels. The black arrow represents direction acoustic nasality increase.

Figure 10. A1-P1 values for the high front (left), high back (right) vowels at different time points, for all three types of vowel nasality.

As with A1-P0, A1-P1 differences are bigger the less nasal a vowel is; conversely as the difference decreases, the vowel is more nasal acoustically. The arrows in the figure also represent the inverse relationship between A1-P1 and acoustic nasality, so that as A1-P1 decreases, acoustic nasality increases.

In figure 10, the left panel shows the high front vowels. All the lines are visually close to each other, but we can see the same pattern as for low and mid vowels: the oral vowel has higher A1-P1 values than the other two, indicating that the oral vowels are the least nasal of the three. Next, the nasalized vowel is of intermediate A1-P1, and the nasal vowel has the lowest A1-P1, showing that this vowel has the greatest nasality overall. While all lines are close to each other,

we can see that the lines for nasal and nasalized vowels present a steeper decline than the oral vowel line, showing that these vowels become more nasal over time.

The right panel in figure 10 shows the high back vowels. Unlike all other vowels seen so far, A1-P1 values for the back vowel all seem to be close to each other, so it is hard to say whether these vowels have any differences in nasality or not. There is no discernable trend here; moreover, the oral vowel seems to become more nasal over time, while the nasal vowel seems to become less nasal. The nasalized vowel is the only one that seems to become more nasal from time point 6 on. There are some possible reasons for this confusing result. High back vowels are more difficult to measure, due to the proximity of F1, F2 and the various nasal resonances (Jesus, 2002). So, a possibility is that there is an acoustic interaction or at least a very close proximity between F1, F2 and P1 in the back vowels in the data. Remember, P1 is around 950Hz, a region where F2 for the high back vowel is found. Thus, the measurement script may not have consistently measured P1 but F2 instead; or maybe F2 and P1 could not be discerned in the signal, so that the script measured a combination of these resonances instead. An alternative possibility is that the back vowel is simply not nasal. However, such possibility is very unlikely, given the body of literature attesting to the difference between oral and nasal(ized) high back vowels (e.g., Sousa, 1994), so that the more reasonable explanation for the lack of patterns is issues with resonance identification. Therefore, the high back vowel will be removed from further analysis, so that only the high front vowel will be interpreted in the statistical analysis presented below.

Table 11. Linear mixed effect analysis for high-front vowels. Bold indicates significance levels < 0.05.

Independent variables: A1-P1	Estimate	Std. Error	t-value	p-value
(Intercept)	30.0067	2.1625	13.876	0
nasality nasal	-3.3825	1.5578	-2.171	**0.0323**
nasality nasalized	-1.15	1.5578	-0.738	0.4621
timepoint late	-0.3233	1.3935	-0.232	0.817
timepoint mid	0.9517	1.3935	0.683	0.4962
nasality nasal: timepoint late	-4.5175	1.9707	-2.292	**0.024**
nasality nasalized: timepoint late	-3.2467	1.9707	-1.647	0.1026
nasality nasal: timepoint mid	-3.3175	1.9707	-1.683	0.0954
nasality nasalized: timepoint mid	-1.1675	1.9707	-0.592	0.5549

The analysis of A1-P1 in high front vowels shows that the nasal vowels have indeed lower A1-P1 values than oral vowels by about 3 dB (t(108) = -2.171, p < 0.05), while the nasalized vowels are not significantly different from their oral counterparts (t(108) = -0.738, p = 0.462). So, nasalized vowels, while appearing to be of intermediate nasality in the graph, are not more nasal than an oral high front vowel.

The important time point variable, which shows how nasality unfolds over time, has no significant main effect in high vowels. However, there is an interaction between time point and nasality, with the nasal vowel presenting smaller A1-P0 values at the later time point than the nasalized vowel when compared to the oral vowel (t(108) = -2.292, p < 0.05 for the nasal vowel; t(108) = -1.647, p = 0.102 for the nasalized vowel), a pattern not found in the mid portion of either vowel when compared to their respective early time points. So, we can see that the nasal vowels become significantly more nasal over time, when compared with the oral vowel, while the nasalized vowel does not.

Post-hoc linear mixed model analysis considering only nasal and nasalized vowels shows that A1-P1 for the late time point in the nasal high front vowel is significantly different from its early time point (t(72) = -4.422, p < 0.05), but not for the nasalized counterpart. This is evident

in the graph, where the line for oral /i/ and the line for nasal /ĩ/ are relatively far apart. When comparing nasal and nasalized vowels, these are only different towards their end in terms of acoustic nasality.

Overall, A1-P0 in low and mid vowels is fairly consistent: oral vowels have the highest values, followed by nasalized and then by nasal vowels (though the nasalized vs. nasal difference was not found to be statistically significant). This means oral vowels are the least acoustically nasal vowels, followed by nasalized vowels; nasal vowels are the most acoustically nasal ones. Such a pattern was expected since oral vowels have little to no velopharyngeal port opening, while nasal and nasalized vowels do. A1-P1 values, however, were not as clear: the high front vowel obeys the same oral-nasal-nasalized patterns as the non-high vowels (despite the lack of statistical significance between nasal and oral vowels), but the high back vowel does not.

When comparing nasal and nasalized vowels, what is notably different between these two kinds of vowels is the profile of nasality; nasal vowels have overall steeper A1-P0 lines as they approach the vowels' right edge than their nasalized counterparts, so that the most marked difference in nasality between these vowels is towards the end. This pattern of nasality was unexpected, but not completely unreasonable given the body of research. Nasal airflow profiles in Medeiros *et al* (2008) show that the nasal vowels can have a steep nasal airflow increase, with vocalic nasal airflow starting relatively early or late in some words. Similar results were found by Desmeules-Trudel (2015), in which some participants presented an increasing nasal airflow profile of vowel nasality for both nasal and nasalized vowels, with the difference being that nasal airflow in nasal vowels started earlier than in nasalized counterparts. However, both authors show that these are just two possible profiles for these vowels, and that nasality implementation may vary from individual to individual.

Nasal appendix and nasal consonant

Duration of the nasal element (appendix or consonant) is the dependent continuous variable in this analysis, motivated by the literature, especially when it comes to the appendix. The independent variables are nasal element, vowel quality, all factors. Speaker is a random variable to account for variability among speakers in how long their appendices and consonants are, described in more detail below.

Table 12. Independent variables for the appendix and consonant analysis.

Variable	Level
Nasal element	**appendix**, consonant
Vowel quality	**a**, e, i, o, u

It was expected that the appendix would appear in all nasal vowels' right edges, regardless of quality, which happened in all but two instances. It was also expected that the appendix would be much shorter than the nasal consonant, consistent with the literature findings. Figure 11 below shows average appendix and consonant duration across speakers.

Figure 11. Average appendix and nasal consonant duration in seconds.

In our data, the appendix is on average 0.06 s long and the consonant is 0.07 s. The appendix is significantly shorter than the nasal consonant by about 0.01s (t = -6.76, p < 0.005)[30], which is consistent with the prediction. However, this difference in our data is much smaller than the

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[30] The function in R is: lmer(duration~ nasal + (1|Speaker), nasalduration).

differences found in the literature. For example, Medeiros (2008) found in her aerodynamic measurements that the appendix is on average 0.04 s, while the consonant is 0.07, with a difference of 0.03s. Our appendices are on average 50% longer than Medeiros's. A possible reason for such discrepancy is the difficulty in segmenting the appendix in the signal. Sometimes, there was no "dip" in the waveform, or the change in resonance amplitudes was not as obvious. Thus, it is possible that a part of the vowel was segmented with the appendix in our measurements, which can make the appendix longer than it is in fact.

The literature on the nasal appendix says that it should be very short and variable in duration, depending on factors such as context and speaker. Therefore, we should expect differences in duration variability between the appendix and the consonant, with the appendix being more variable. In our data, standard deviation for the appendix is 0.03 and 0.02 for the consonant, which shows the appendix to be a little more variable than the consonant, as expected. When considering speaker as a likely cause for this variability is the speaker, it was found that one speaker's appendices were considerably shorter than the consonants, as evidenced in figure 12 below. Interestingly, this speaker is the only one from northeast Brazil, a dialectal area known for being overall more nasal than the southernmost varieties (Abaurre & Pagotto, 1983).

Figure 12. Average appendix and consonant durations in seconds by speaker.

The goal of this chapter was to perform an acoustic analysis of oral, nasal and nasalized vowels, and a duration analysis of the appendix and nasal consonant, to provide a measure of production to perception comparison. Here, we found that oral, nasal and nasalized vowels differ in terms of vowel formants and acoustic nasality, and we found that these are not completely related. Some vowels are different in terms of nasality, but not in terms of formants, as it is the case of nasalized vowels. Nasal vowels are different from oral vowels in both formants and nasality, but when compared to nasalized vowels, patterns are different. The appendix is shorter and more variable than the consonant, but not by a lot. All these differences are likely to play a role in how the vowels are perceived, however, it is not clear how, especially in the light of the dubious phonological status of nasal vowels. Our approach, in this sense, is a novel one, and we hope to contribute to the issue of the phonemic status of nasality in Brazilian Portuguese and whether the appendix has any status at all by examining how listeners perceive and classify vowels when near the appendix.

Perceptual Experiment 1 – Forced-choice Rating

The first experiment consists in observing whether Brazilian Portuguese listeners attribute the nasality they hear in the vowel of a stimulus in a pair to an upcoming nasal consonant or not, i.e., if there is perceptual compensation. It has been demonstrated that listeners make judgments based on the coarticulatory context, and perceptual compensation for vowel nasalization is one particularly well-explored effect, at least in English (Beddor & Krakow, 1999; Krakow *et al*, 1988). The implication for the phonological status of nasal vowels in Brazilian Portuguese is that, given that compensation should occur only when nasality is not a vowel inherent feature, compensation should not occur when it is. We can test whether nasal vowels are phonemic in the language by showing whether or not there is compensation in purported nasal vowel contexts. Thus, the question is: *Do BP listeners compensate for vowel nasalization?*

If BP listeners attribute vowel nasality in nasal and nasalized vowels to the context, namely the nasal appendix or the nasal consonant, these vowels should be perceived as (nearly) oral, even though they are phonetically nasalized. Phonologically, these vowels would be oral at the phonemic level. We could infer that the context triggers vowel nasalization. This would imply that vowel nasalization is a systematic phonological process, but nasal vowels are not phonemic, neither phonologized, since nasality is considered coarticulatory in nature. However, if the presence (or absence) of a nasal consonant or appendix at the vowel's the right edge does not influence its perception as nasal, these vowels would be considered phonologically nasal, at the phonemic level.

Finally, there is also the predicted difference between the expected effects of a nasal consonant vs. the nasal appendix. The appendix should not trigger any form of perceptual compensation in nasal or nasalized vowels, as it should not have any perceptual salience, since it

should not be a separate consonant, while the nasal consonant should be more likely to do so, especially with nasalized vowel (and nasal vowels as well, assuming nasal vowels not phonemes).

Stimuli Creation

30 word and non-word disyllabic tokens were read twice by two of the five native speakers of Brazilian Portuguese who took part in the production experiment. The words, taken from the production experiment, conformed to one of the following patterns: C1VC2V, C1Ṽ1C2V or C1Ṽ2NV (where V = oral vowel, Ṽ1 = phonemic nasal vowel, Ṽ2 = coarticulatorily nasalized vowel, C1 = any viable BP onset, C2 = voiceless stop /p/ or /t/, N = nasal consonant with the same place of articulation as C2). Altogether, there were 5 vowel qualities (i, e, a, o, u) x 3 nasality conditions (oral, nasal, nasalized) x 2 tokens per vowel per nasality x 2 speakers. Table 13 presents the tokens recorded (the tokens that have a star are not words in Portuguese).

Table 13. Tokens recorded for stimulus creation.

	C1VC2V	**C1Ṽ1C2V**	**C1Ṽ2NV**
/a/	Capa	Campo	Cama
	Jato	Janto	Janio
/e/	*Deto	Dente	Denis
	*Teto	Tento	Tenis
/i/	Tita	Tinta	Tina
	Pita	Pinta	Pino
/o/	Popa	Pompa	Pomo
	*Toto	Tonto	Tona
/u/	Juta	Junto	Juno
	*Tutu	*Tuntra	*Tunu

Only the first part of each token was used in the creation of the stimuli. For C1VC2V tokens, C1V was used; for C1Ṽ1C2V tokens, C1Ṽ1 was used, up until the end of the nasal appendix (which systematically appears in the acoustic signal); for C1Ṽ2NV tokens, C1Ṽ2N until the end of the nasal consonant was used. After each part of interest was selected, the vowel was excised from its original context, and spliced into the other two contexts. For example, in the

syllable /ka/ from /ˈkapɐ/ "capa", the vowel /a/ was spliced into the contexts from /ˈkẽ^mpʊ/

"campo", /ˈkẽmɐ/ "cama" and the second token of /ˈkapɐ/ "capa", forming the stimuli [ka^m],

[kam] and [ka], respectively. The resulting stimulus frames, showing nasality condition and

context combination, are presented in table 14.

Table 14. Resulting stimuli for both experiments. V = oral vowel, Ṽ1 = nasal vowel, Ṽ2 = nasalized vowel; # = no segment after the vowel, ᴺ = nasal appendix, N = nasal consonant.

	C___#	**C___ᴺ**	**C___N**
V	CV#	CVᴺ	CVN
Ṽ1	CṼ1#	CṼ1ᴺ	CṼ1N
Ṽ2	CṼ2#	CṼ2ᴺ	CṼ2N

This resulted in 180 stimuli (5 vowels x 3 nasality conditions x 3 contexts x 2 words per

vowel x 2 speakers). Splicing was done in all stimuli, even the ones that should occur naturally,

to eliminate the chance of a stimulus being chosen because it was not manipulated.

Method

For experiment 1, only 90 of the original 180 stimuli generated from the frames in table 14

and the tokens[31] from table 13 were used (5 vowel qualities x 3 nasality conditions x 2 speakers x

1 token). The stimuli were paired up in all possible combinations, resulting in a total of 360

stimulus pairs (36 possible pairs x 5 vowels x 2 speakers per vowel). Table 15 below presents the

stimulus pairs for the low vowel /a/, from the tokens *capa*, *campo*, *cama*, as an illustration of

what the stimulus pairs look like. The row stimuli were presented first in a pair; the column

stimuli were presented second.

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[31] Only the first set of tokens for each vowel quality was used; for example, for the low vowel, only the *capa, campo, cama* set was used.

Table 15. Stimulus pairs for the vowel /a/ or /ɛ̃/. a = oral vowel; ã1 = nasal vowel; ã2 = nasalized vowel; ^{m} = appendix, M = nasal consonant.

	ka	kã1	kã2	ka^m	kã1^m	kã2^m	kaM	kã1M	Kã2M
ka		ka-kã1	ka-kã2	ka-ka^m	ka-kã1^m	ka-kã2^m	ka-kaM	ka-kã1M	ka-kã2M
kã1			kã1-kã2	kã1-ka^m	kã1-kã1^m	kã1-kã2^m	kã1-kaM	kã1-kã1M	kã1-kã2M
kã2				kã2-ka^m	kã2-kã1^m	kã2-kã2^m	kã2-kaM	kã2-kã1M	kã2-kã2M
ka^m					ka^m-kã1^m	ka^m-kã2^m	ka^m-kaM	ka^m-kã1M	ka^m-kã2M
kã1^m						kã1^m-kã2^m	kã1^m-kaM	kã1^m-kã1M	kã1^m-kã2M
kã2^m							kã2^m-kaM	kã2^m-kã1M	kã2^m-kã2M
kaM								kaM-kã1M	kaM-kã2M
kã1M									kã1M-kã2M
kã2M									

There were 40 participants who 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 BP 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. Instructions and questionnaire were all in Brazilian Portuguese.

For the task, an experimental routine was created in Psychopy (Peirce, 2007). First participants were presented with instructions to the task. They were asked to focus on the vowel sounds. Upon listening to a pair of parts of words, participants had to answer by pressing a key 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). Next, a practice block was presented 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. Figure 13 below

shows the screen participants saw continuously when listening to stimulus pairs. It was a

reminder of what keys participants should press to give their answers[32].

PRIMEIRA   IGUAIS   SEGUNDA
ESQUERDA   ABAIXO   DIREITA

Figure 13. Experiment 1 Psychopy test screen.

Immediately after each response, participants listened to the next stimulus pair, until the

block was finished. Participants could take a break between blocks if they wanted to.

Predictions

Table 16 presents specific predicted outcomes for each type of stimulus pair. While in the

statistical analysis correct answers were based on vowels being acoustically equal, the predicted

outcomes considering the review of the literature and our research questions are based on

whether the two vowels are perceived as different or not, due to two factors:

1. Whether perceptual compensation occurs.

2. The type of resulting vowel nasality (after compensation occurs).

We expect perceptual compensation to occur only in coarticulatory contexts, i.e., when there

is a vowel preceded by nasal consonant. When there is an appendix, compensation should not

occur. This is assuming nasal and nasalized vowels are not phonemic. As a result, some vowels

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[32] The screen reads, in English, "first, left; same, down; second, right".

will be perceived as different or the same because they are inherently different and/or there is no

context for compensation to occur; some vowels will be perceived as different or the same

because compensation occurred.

Table 16. Predictions for each stimulus pair-wise comparison. V = oral vowel, Ṽ1 = nasal vowel, Ṽ2 = nasalized vowel; # = no segment after the vowel, ^{N} = nasal appendix, N = nasal consonant.

	CV#	CṼ1#	CṼ2#	CV^{N}	CṼ1^{N}	CṼ2^{N}	CVN	CṼ1N	CṼ2N
CV#		**Y**	Y	*N/A*	Y	Y	*N/A*	N(Y)	**N**
CṼ1#			N	*N/A*	**N**	N(Y)	*N/A*	Y(N)	Y
CṼ2#				*N/A*	N(Y)	N	*N/A*	Y(N)	**Y**
CV^{N}					Y	Y	*N/A*	*N/A*	*N/A*
CṼ1^{N}						N(Y)	*N/A*	Y(N)	Y
CṼ2^{N}							*N/A*	Y(N)	Y
CVN								N	N
CṼ1N									N
CṼ2N									

"Y" indicates that vowels are discriminable. Participants can tell that the vowels are

different because they differ in terms of type of nasality, acoustically or perceived after

compensation occurred. For example, CV#-CṼ1# (in bold) is discriminable because V and Ṽ1

are expected to sound different due to acoustic differences, such as amount of nasality and vowel

formants; CṼ2#-CṼ2N (in bold) is discriminable because Ṽ2 in isolation is expected to sound

different from the same vowel in consonant context for the participants, as perceptual

compensation should occur in these cases.

"N" indicates that vowels are not discriminable. Participants can tell the vowels are the same

because they have the same perceived degree of nasality. As in the discriminable pairs, e.g.,

CṼ1#-CṼ1^{N} (in bold) is not discriminable because Ṽ1 in isolation should be perceived as the

same as Ṽ1 in the appendix context, as the appendix is not expected to trigger compensation;

CV#-CṼ2N (in bold) is not discriminable because Ṽ2 is expected to sound like V for the

participants, as they are expected to attribute nasality in Ṽ2 to the consonant.

"N/A" (not applicable) indicates that there is no prediction for this pair. Only 240 of the original 360 stimuli pairs have predictions, because perceptual compensation does not make clear predictions about oral vowels in nasal contexts (Beddor *et al*, 2001).

Similar compensation effects are predicted for both Ṽ1 (nasal vowels) and Ṽ2 (nasalized vowels). Both vowels have approximately the same degree of acoustic nasality as attested by our production study and in the literature (e.g., Moraes, 2013), which makes them phonetically similar. Notice, however, that there are quality differences between some nasal and nasalized vowels, as attested by our production study. Also, for some vowel qualities, nasal and nasalized vowels do have different degrees of vowel nasality. In addition, if we consider that nasal and nasalized vowels have different phonological status, it is possible the nasal vowels would not lend themselves to compensatory effects, as nasality in inherent to the vowel, while nasalized vowels, which are phonemically oral, would lend themselves to compensation. Thus, while nasal and nasalized vowels are grouped, there are certain differences that may play a role in how nasal and nasalized vowels are perceived. The "Y" and "N" in parentheses in the table reflect this potential phonological difference and provide predictions based on this distinction.

While the nasal appendix is generally not expected to trigger any compensation, if it does (because it is considered a residual consonant by some scholars, e.g., Bisol, 1998), it would be expected to behave like other coarticulatory contexts as, historically, vowel nasalization occurred whenever there was a nasal consonant at the right edge of the vowel (Sampson, 1999).

For the sake of statistical analysis, while our predictions are given in terms of discriminability, the stimulus pairs will be divided into subsets according to the following criteria:

1. Different context, different vowel nasality

2. Different context, same vowel nasality

3. Same context, different vowel nasality

Within each subset, we analyze the effect vowel nasality, quality and context have on the perception of vowel nasality and then relate the results back to the predictions. Different context, different nasality pairs will join the effects of vowel nasality with the context, while the other two subsets tease apart the effects of each variable separately. However, the main reason to divide the analysis by these criteria is that the expected "correct" answers vary depending on the type of vowel nasality in the pair. As it will be seen later, the expected answer for the different context, different vowel nasality and same context, different vowel nasality subsets is that the second vowel should be more nasal; the expected answer for different context, same nasality subset is that the vowels are same.

Analysis

Data analysis was performed on accuracy (correct/incorrect answers, using logistic mixed effects models) for each stimulus pair grouped in three different subsets. The reason to use a mixed effects model is because each participant had a total of 360 answers in the whole experiment. Therefore, we cannot say that the observations are independent, which calls for a mixed model analysis (Johnson, 2008; Baayen 2008).

Accuracy in this case means whether participants succeeded or failed in correctly rating the target vowels as the same or different, depending on whether the vowels are acoustically the same or not (in the study, a correct was based on vowels being acoustically the same or different, not based on whether compensation should occur; that is because compensation is measure by the failure in rating the vowels as acoustically the same of different). This is a binary variable with the levels "correct" and "incorrect", which calls for a logistic regression analysis. The

explanatory variables include context, vowel nasality and vowel quality with levels as shown in

table 17 below. A variable called Speaker was used as a random explanatory variable.

Table 17. Variables and their levels in the logistic regression models. Default levels are in bold.

Variable	Level
Accuracy	correct; **incorrect**
Vowel quality	**a**; e; i; o; u
Comparison 1 – different nasality, different context	
Context	C_#-C_^{N}; **C_#-C_N**
Vowel nasality pair	V-Ṽ1; **V-Ṽ2**
Comparison 2 – same nasality, different context	
Context	C_#-C_^{N}; **C_#-C_N**
Vowel nasality	nasal; **nasalized**
Comparison 3 – different nasality, same context	
Context	**C_#**; C_^{N}; C_N
Vowel nasality pair	**V-Ṽ1**; V-Ṽ2

The variables context, vowel nasality (pair) are theoretically motivated based on the research

questions. Context intends to verify the effect of context in participants' answers, whether N (and

to some extent n) lower participants' accuracy or not. Notice that there are three different kinds

of contexts. Vowel nasality (pair) intends to verify the effect of type of vowel nasality in

participants' answers, i.e., whether they are more accurate in nasal vowel (Ṽ1) cases than in

nasalized vowel (Ṽ2) cases. There are two kinds of vowel nasality pairs, with two levels each.

Vowel quality is not pertinent to the research questions per se, but is motivated by the

observations that there are vowel quality differences between the different vowel heights. The

low vowel becomes centralized when nasal; the mid vowels may become diphthongized; no

change occurs with the high vowels, as presented in chapter 2. The variables were all dummy

coded (0 and 1), with the default level being chosen based on preliminary data exploration. The

default levels are in bold on table 12 above.

The function[33] used to do all the mixed effect analyses is glmer from the lme4 (Bates and

Sarkar, 2007) package in R (R Core Team, 2013). This function belongs to the GLM family, and

adds the random component to the function glm(). It works almost like the lmer() function from

lme4 package for mixed effects models (Bates *et al*, 2015), but it does not use a set of statistical

assumptions that normally do not hold for non-continuous dependent variables, such as

following a normal distribution (refer to Johnson, 2008 and Baayen, 2008 for further details on

the difference between linear and generalized linear models).

The model output includes an "estimate", which shows how much difference the change

from the intercept to a given level makes, and whether that change is statistically significant or

not. If the estimate is positive, then there is an increase in change, i.e., a tendency to answer

correctly; if it is negative, then there is a decrease in change, i.e., a tendency to answer

incorrectly. This change is given in terms of log odds, which are the log transformations of the

odds ratio, or the probability of a factor occurring. The log odds themselves are rather difficult to

interpret; if we exponentiate them, we can find the probability of the dependent variable's level

change from the intercept. However, for our work, this probability is not very useful; we are

more interested in understanding which factors influence accuracy outcomes, in our case, correct

vowel nasality rating answers, and for that, all we need is to find which factors are statistically

significant.

Table 18. Sample of an output table for a mixed-effects logistic regression analysis.

	Estimate	Std. Error	Z value	Pr(>|z|)
(Intercept)	0.003476	0.2366	0.15	0.9882
context C_-C_^{N}	1.5128	0.3616	4.184	2.87e-05

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[33] The actual function in R for this example is: glmer(correctness ~ context*nasalityv1*Vowel + (1|Speaker), family = "binomial", data = pred1f). The dependent variable is correctness; the explanatory variables are context, nasality and vowel; we also proposed an interaction between context and nasality based on my hypotheses. This model changes in the part 2 of the experiment.

Table 18 above shows a sample of a logistic linear mixed effects model. Here, we can see that the estimate is positive, which means that accuracy, i.e., correctly rate vowel nasality, increases when the context is C_#-C_ᴺ. This context is significant, which means that this level of the context independent variable significantly influences correct answers. Now, it is time to present the analysis, starting with different vowel nasality, different context subset.

Different vowel nasality, different context

Let us start with the pairs with different vowel nasality and different contexts, described in table 19. The vowels in these pairs are as different from each other as possible: oral vowel in isolation context vs. non-oral vowel with some nasal context.

Table 19. Stimulus pairs composing the first subset.

	C$\tilde{\text{V}}$1ⁿ	C$\tilde{\text{V}}$2ᴺ	C$\tilde{\text{V}}$1N	C$\tilde{\text{V}}$2N
CV	CV-C$\tilde{\text{V}}$1ⁿ	CV-C$\tilde{\text{V}}$2ᴺ	CV-C$\tilde{\text{V}}$1N	CV-C$\tilde{\text{V}}$2N

Since the vowels are acoustically different, an acoustically accurate response is that the second vowel in the pair is more nasal. However, if perception compensation occurs as predicted, vowels should be mistakenly identified as being the same in the CV–C$\tilde{\text{V}}$1N and CV–C$\tilde{\text{V}}$2N pairs. Compensation effects should not be observed in any other pair as they have a nasal appendix, which should not trigger compensation.

Figure 14. Choice by stimuli pair for different vowel, different context subset.

Based on figure 14, we can see that the correct "second" answer was the most chosen answer for the pairs in question, between 91% for CV-C$\tilde{\text{V}}$1N, and 84% for CV-C$\tilde{\text{V}}$2$_N$. There were very few incorrect "first" and, most importantly, few "same" answers. Thus, we can say that participants were able to perceive the differences in nasality between the two vowels. Compensation did not occur in any pair type, even in the most possible pair, CV-C$\tilde{\text{V}}$2N. Brazilian Portuguese speakers do not attribute nasality they hear in the vowel to context. This is very different from English, where nasality in the vowel is thought to stem from the context, as attested by the fact that English listeners consider nasalized vowels in nasal consonant contexts to be the same as oral vowels in isolation contexts (Beddor & Krakow, 1999). BP speakers seem to consider vowel nasality to belong to the vowel, regardless of whether this vowel is phonemically nasal or coarticulatorily nasalized, and regardless of context.

A logistic mixed model analysis[34] shows that, despite the lack of compensation, type of vowel nasality does have some effect on accuracy. Accuracy decreases when the pair contains a nasalized vowel when compared to a pair containing a nasal vowel. This difference is significant ($p < 0.005$). Therefore, participants tended to correctly identify the more nasal vowel when one of the vowels in the stimulus pair is nasal than when it is nasalized. This reflects the greater oral-nasal vs. oral-nasalized vowel quality and nasality differences presented in the production experiment.

Accuracy decreases a bit when the context is a nasal appendix as compared to a nasal consonant, but that decrease is not significant ($p = 0.2306$), which means there is no reliable

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[34] The function used in this analysis was: glmer(correctness ~ context+pairV+Vowel+(1|Speaker), family = "binomial", data = diffvdiffc). Notice that no interactions between the factors were included in the final model because they were not significant.

difference[35]. Nevertheless, this lack of effect is interesting, because we should have expected the

nasal appendix to induce fewer mistakes than the nasal consonant in nasality perception as it is

not a full consonant, and therefore should not have any perceptual influence on vowel nasality

(participants were correct 87% of the time in consonant vs. 83% of the time in appendix context).

These seem to show that amount of context, but not type of context, *aids* in accurate vowel

nasality perception rather than hinder it. The longer the nasal element (consonant or appendix),

the more nasal a vowel is perceived to be.

Same vowel nasality, different context

Let us examine now stimulus pairs with the same type of vowel nasality, but different

contexts as shown in table 20 below[36]. Since the vowels are acoustically the same in each pair,

nasal or nasalized, an acoustically accurate answer would be that the vowels are the same. If

perception compensation occurs, we should see low accuracy rates in nasal consonant contexts

with nasalized vowels, where these would be perceived as less nasal than the same vowel in

isolation context. Therefore, accuracy should be higher in nasal appendix cases than in nasal

consonant cases.

Table 20. Stimulus pairs to which the vowel was the same acoustically. V = oral vowel, Ṽ1 = nasal vowel, Ṽ2 = nasalized vowel; # = no segment after the vowel, ᴺ = nasal appendix, N = nasal consonant.

	C_# - C_ᴺ	**C_# - C_N**
Ṽ1	CṼ1 - CṼ1ᴺ	CṼ1 - CṼ1N
Ṽ2	CṼ2 - CṼ2ᴺ	CṼ2 - CṼ2N

Figure 15 below presents accuracy for each context and each vowel nasality type.

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[35] Based on these results only we cannot say whether any context matters or not; we can only say that there is no evidence that one context matters more than the other. We need to compare presence versus absence of context to see if context matters or not.

[36] While participants were exposed to oral vowels in these contexts, as well as all vowel nasality in C_ᴺ - C_N contexts, for the purposes of statistical analysis and ease of interpretation, oral pairs and C_ᴺ - C_N pairs are left out for now.

Figure 15. Percentage of correct answers by context and vowel nasality for same vowel, different context subset.

Participants performed similarly well with nasalized and nasal vowels. Nasal vowels were correctly rated as the same around 43% of the time; nasalized vowels were also rated as the same bout 43% of the time (similar to the 49% accuracy rate in Beddor & Krakow (1999)), as evidenced in figure 15 above. There was no statistically significant difference between nasal and nasalized vowels ($p = 0.916$)[37], which means participants were as good in identifying nasal vowel stimulus pairs as the same as they were in identifying the nasalized vowel stimulus pairs as the same. Interestingly, this number is already above chance level of 33%, but it is much lower than the accuracy rates in the previous analysis.

As for context, participants could rate the vowels as the same 38% of the time in C_#-C_N contexts, and 49% of the time in C_#-C_ᴺ regardless of type of vowel nasality. This difference between contexts is significant ($p < 0.05$), showing that the nasal consonant interferes more with accurate vowel perception than the nasal appendix.

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[37] The logistic model function used for the statistical analysis of this subset in RStudio is: glmer(correctness ~ context+nasalityv1+Vowel+(1|Speaker), family = "binomial", data = pred1f). Notice that no interactions were included in this model. Examining, figure 15, it is clear that there is an interaction: accuracy in nasal vowels in appendix context is higher than accuracy in nasalized vowels in consonant context. However, accuracy is higher in the appendix context overall, which is a more relevant finding for the research. That is why the interaction was omitted from the analysis.

We also examine what kinds of mistakes participants committed for this subset, because failing to correctly identify the vowels in a stimulus pair as the same alone does not show perceptual compensation for nasality in the vowel. The vowel in a pair's first stimulus (in which there was no nasal consonant or appendix after the vowel) needs to be chosen as more nasal over the second (in which there was either a nasal consonant or appendix after vowel). That is because participants should attribute the nasality they hear in the vowel of the second stimulus in the pair to the context, making the vowel perceptually less nasal. A comparison of each answer for each context and vowel nasality is presented in Figure 16.

Figure 16. Responses for C_#-C_N and C_#-C_ᴺ; right column is nasal, left is nasalized vowel. # = isolation, ᴺ = nasal appendix, N = nasal consonant. In this subset, "first" is the response corresponding to the stimulus presented first, and "second" corresponds to the stimuls presented second.

Recall from the methods section that "first" is the vowel in C_#, or isolation, context and "second" is the vowel in the C_N or C_ᴺ contexts. "same" answers in figure 16 are the correct answers presented in the previous figure, and are here just for reference. We see that, in misjudging a vowel's relative nasality, participants answered that the vowel in the second stimulus, C_N or C_ᴺ contexts (56% and 46%, respectively), was more nasal than the same vowel in C_# context (which was around 5% of the time for both contexts). Moreover, the incorrect "second" answer is selected much more often than the correct answer for C_#-C_N, (43% correct "same" answers vs. 56% incorrect "second" answers) while for C_#-C_ᴺ, the answers were about the same (43% "same" vs. 46% "second"). This pattern of mistakes is not

consistent with the prediction that participants would, if perceptually compensating for nasality in the vowel, answer that the first vowel is more nasal than the second for C_#-C_N cases, but not for C_#-C_^{N}. However, this pattern of mistakes is similar to the pattern of answers found in the previous subset, where the stimulus with the nasal consonant in a pair was judged as more nasal than the stimulus with the appendix.

There is still one context not discussed in this analysis: the appendix vs. consonant cases, C_^{N}-C_N. In table 16, we predicted that participants should discriminate between these vowels because the full consonant should trigger perceptual compensation, despite the vowels being acoustically the same. The vowel followed by the nasal consonant should be rated as less nasal than the vowel followed by the appendix. If compensation does not occur, then the vowels should be rated the same, as they are the same vowel.

Table 21. Remaining same vowel, different context pairs appendix vs. nasal consonant.

	C_^{N} - C_N
Ṽ1	CṼ1^N - CṼ1N
Ṽ2	CṼ2^N - CṼ2N

Figure 17. Percentage nasal and nasalized vowel correct answers for C_^{N}-C_N context. ^{N} = nasal appendix, N = nasal consonant. In this subset, "first" is the response corresponding to the stimulus presented first, and "second" corresponds to the stimuls presented second.

Participants performed better on nasal than on nasalized vowels in these pairs, 74% vs. 64% respectively, with an increase of 0.52 log odds (p < .005). However, the high accuracy regardless of vowel nasality already shows compensation did not occur in this case. What is remarkable

about these pairs is that accuracy here is much higher than accuracy for pairs that include an isolation condition: 69% averaged accuracy between nasal and nasalized vowels in appendix – nasal consonant context (C_^{N}-C_N) vs. 38% average accuracy for isolation-nasal consonant (C_#-C_N) and 49% for isolation-appendix (C_#-C_^{N}). When comparing these correct answers with the mistakes from the isolation – nasal element contexts, we can see why. If the presence of a consonant or an appendix increases the chances of a vowel being perceived as nasal, then the addition of a context in both stimuli should increase nasality perception and, therefore, increase accuracy.

In summary, in the analysis of stimulus pairs with the same vowel nasality, but different contexts:

1. participants performed better when the second stimulus contained a nasal appendix than when it contained a nasal consonant;

2. participants performed slightly better when the vowel is nasal than when the vowel is nasalized, but the difference is not significant;

3. participants' mistakes lean toward interpreting stimuli with either a nasal consonant or a nasal appendix as more nasal.

The results seem at first pass to be consistent with a perceptual compensation hypothesis, due to the fact that participants failed perceive that the vowels in all the stimulus pairs were the same in C_#-C_N contexts. However, mistakes show a different tendency than predicted by a compensation hypothesis (Beddor & Krakow, 1999), or the finding that vowels in English are perceived as more nasal when the context is attenuated (Kawasaki, 1986). While nasal and nasalized vowels were accurately perceived above chance, the presence of a nasal context aided in accurate perception. It seems participants needed to have some kind of nasal element after the

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vowel to consider it definitely nasal, indicating that a context might be required for accurate perception of nasality. In addition, the fact that nasal and nasalized vowels yielded similar results shows that vowel nasality may itself play little role in identification, being only consistently differentiated when a nasal element follows.

Different nasality, same context

Next, we examine stimulus pairs in which vowel nasality is different, but context is the same, as shown in table 22 below.

Table 22. Different vowel nasality stimulus pairs. V = oral vowel, Ṽ1 = nasal vowel, Ṽ2 = nasalized vowel; # = no segment after the vowel, ᴺ = nasal appendix, N = nasal consonant.

	C_#	C_ᴺ	C_N
V-Ṽ1	CV-CṼ1	CVᴺ-CṼ1ᴺ	CVN-CṼ1N
V-Ṽ2	CV-CṼ2	CVᴺ-CṼ2ᴺ	CVN-CṼ2N

The comparison in this case is an oral vowel in the first stimulus vs. a nasal or a nasalized vowel in the second stimulus. Since vowels are acoustically different this time, the accurate answer is that the second vowel in the pair is more nasal regardless of context. If perceptual compensation occurs, however, vowels in the nasal consonant context (C_N) should be perceived as being like their oral counterparts, yielding a mistaken "same" answer for these stimuli, which would lower accuracy.

The figure below presents the average correct responses for all the oral-nasal (V-Ṽ1) and oral-nasalized (V-Ṽ2) pairs in the three contexts. Percentages are based on the total answers for a given context and vowel pair (430 total).

Figure 18. Number of correct responses per vowel per context, for same context, different vowel nasality. # = isolation, n = nasal appendix, N = nasal consonant.

Average accuracy across contexts and vowel pairs range from 40-70%, which is above chance (since for each stimulus pair, participants had three possible alternatives, making chance level 33%), as presented in figure 18. Therefore, participants were able to make distinctions regardless of type of vowel nasality and context. However, participants were more accurate when judging stimulus pairs that contained a nasal vowel (V-Ṽ1) than when it contained a nasalized vowel (V-Ṽ2), regardless of context. Participants were about 72% correct for V-Ṽ1 (oral-nasal) pairs and 62% for V-Ṽ2 (oral-nasalized) pairs. The difference was significant ($p < 0.05$)[38].

When it comes to context, participants fared best in nasal appendix (C_ᴺ) contexts (61% accuracy), followed by the consonant (C_N) context (56% accuracy), and then isolation (C_#) context (50%). Those differences are statistically significant ($p < 0.005$). This finding is unexpected given the prediction as the coarticulatory context should hinder correct nasality perception, not help it. However, it is consistent with the previous subsets results.

Again, it is important to analyze the kinds of mistakes participants made. Because the correct response in this case is the second vowel stimulus, the relevant pattern of mistakes in this

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[38] The function used for this logistic analysis in RStudio was: glmer(correctness ~ context+pairV+Vowel+(1|Speaker), family = "binomial", data = pred2f). No interactions were significant in this model, so they are not reported here.

case would be a "same" answer, meaning participants would think that the vowels have the same degree of nasality in C_N context, which would be consistent with a perceptual compensation hypothesis. In other contexts, especially C_#, answering "same" means participant failed to perceive the vowels as acoustically different. "first" answers in this subset are difficult to interpret, and the first vowel is always oral; there is no prediction in the literature about how oral vowels in nasal contexts behave. However, considering the results of the production experiment's acoustic nasality and how similar some oral vowels are to nasalized, and even nasal vowels, it makes sense to have some oral vowels in nasal consonants to be considered more nasal, as we can see in figure 19 below.

Figure 19. Number of responses for nasal and nasalized vowels in different vowel, same context subset. # = isolation, n = nasal appendix, N = nasal consonant. In this subset, "first" is the response corresponding to the stimulus presented first, an oral vowel, and "second" corresponds to the stimuls presented second, either a nasal or a nasalized vowel.

In Figure 19, we see that participants, when misjudging the stimuli's nasality, often considered the vowels to be the same, regardless of context (average of 20% for oral-nasal, 30% for oral-nasalized pairs). When analyzing oral-nasal vowel pairs, we can see that the difference between the correct answer and "same" is large, 72% vs. 20%, which shows that oral and nasal vowels are perceptually very different for the participants. This could be because of nasal vowels' greater difference in nasality and quality from oral vowels, as reported in the production

experiment, which might reflect their different phonemic status. This pattern seems to hold across context, indicating that the nasal consonant did not, in fact, trigger any compensation.

When it comes to nasalized vowels, even though correct answers were given about 62% of the time, the error "same" answer might appear to be partially consistent with a perceptual compensation hypothesis. However, we see that oral and nasalized vowels were considered the same in all contexts, not just C_N. In fact, the coarticulatory context yielded the smallest number of "same" mistakes (35% vs. 38% for C_^{N} and 48% for C_#). Because it occurs regardless of context, including isolation, this pattern of mistakes is unlikely to be due to context alone, but is more likely due to failure to perceive differences in between oral and nasalized vowels. These vowels, as presented in the production experiment, tend to be more similar to each other in terms of degree of nasality and quality than oral and nasal vowels are.

The final set of pairs in this subset, Ṽ1-Ṽ2 pairs in any context, are presented in table 23. These pairs were not included in the analysis above because, while the accurate answer in the statistical analysis is the second stimulus should be more nasal, the expected correct answer here is that these vowels are the same, since there is little difference in degree of acoustic nasality between these two vowels. These vowels have been reported elsewhere to be like each other in terms of nasality (Moraes, 2013), which is mostly true in our acoustic analysis as well[39]. The only way to differentiate these vowels here is if participants treated them differently somehow, maybe due to differences in vowel quality and/or differences in phonological status.

Table 23. Ṽ1-Ṽ2 pairs in isolation, appendix and nasal consonant contexts. Ṽ1 = nasal vowel, Ṽ2= nasalized vowel.

	Ṽ1-Ṽ2
C_#	CṼ1-CṼ2
C_^{N}	CṼ1^N-CṼ2^N
C_N	CṼ1N-CṼ2N

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[39] Notice, however, that, as explained in the production experiment, nasal and nasalized vowels do have quality and nasality differences depending on the vowel, which may influence participants' perception of nasality here.

Figure 20. Responses for same context, different vowel subset; left column is "same", middle is "first", right is "second" vowel; Ṽ1 = nasal vowel; Ṽ2 = nasalized vowel. In this subset, "first" is the response corresponding to the stimulus presented first, a nasal vowel, and "second" corresponds to the stimuls presented second, a nasalized vowel.

Figure 20 above shows that participants considered the vowels the same most of the time, regardless of context (58% for C_# and C_N, and 55% for C_ᴺ). This means that nasal and nasalized vowels were perceptually the same for participants in most cases, as predicted in table 16. These results do not tell us whether these are equally nasal or equally oral, i.e., whether compensation occurred or not, but they do tell us that vowels do not seem to be treated differently due to quality or phonological status differences.

Despite the overall low rate of mistakes, notice that the pattern of mistakes changes depending on the context. In C_# and C_ᴺ contexts, the nasal vowel (Ṽ1) is mistakenly perceived to be more nasal than the nasalized vowel (27% for C_# and 26% for C_ᴺ), while in the nasal consonant context, the nasalized vowel (Ṽ2) is perceived to be more nasal than the nasal vowel (29%). This shows that the context when both vowels in a pair have some sort of nasality can have an effect over perceived nasality, but this effect is not as strong as the effect of nasality itself.

These results so far seem to show that:

1. participants can differentiate between oral and non-oral vowels (oral-nasal and oral-nasalized) regardless of context most of the time;

2. participants fared better on oral-nasal than on oral-nasalized vowels;

3. participants performed worst in C_# contexts and best in C_N contexts;

4. participants' mistakes lean towards "same", regardless of context.

The results partially confirm the discrimination predictions for the vowels in this subset presented in table 16, as vowels in C_N contexts were quite discriminable, behaving like vowels in C_# or C_ᴺ context. The only time the nasal and nasalized vowels were rated the "same" in C_N (in any context, to be fair) is when they occurred in the same stimulus pair. Thus, compensation did not occur in C_N, contrary to the prediction. Interestingly, context has the opposite effect of the expected. The presence of a nasal context, either the appendix or the consonant helps perception, as attested by the worst performance in C_# and the best performance in C_N, again suggesting that both vowel nasality and context are required for accurate nasality perception.

Vowel quality analysis

While the results so far seem clear enough, it is important to examine the effects vowel quality have on the responses. There are appreciable quality differences between different types of nasality for a given vowel, as presented in the production experiment. In addition, vowel as a factor was always significant in the statistical analyses, with accuracy in non-low vowels being lower than in the low vowels. Thus, for each subset, vowel quality influences will be examined. Let us start with different vowel, different context.

Different vowel, different context

Figure 21 below shows responses for the different vowel, different context subset divided by vowel quality. While the overall context nasality influence is expected to continue, and perceptual compensation did not occur, we may be able to see vowel quality effects that reflect similarities found in chapter 4, the production experiment.

Figure 21. Choice by stimuli pair for different vowel, different context subset divided by vowel quality. In this subset, "first" is the response corresponding to the stimulus presented first, an oral vowel, and "second" corresponds to the stimuls presented second, either a nasal or a nasalized vowel.

While the overall answer trends persist when compared to the subset not divided by vowel quality, small trends to appear. We can see that for the non-low vowels, the oral and the nasalized vowels in the appendix context are confused with each other quite often (26% for the mid-back, 21% for the high front and high back vowels); for the non-low front vowels, the same occurs in the consonant context (23% for the mid-front, 19% for the high back vowels). These patterns of confusion are a clear effect of similarities in vowel quality, since nasal and nasalized vowels have different degrees of acoustic nasality, as attested in chapter 4, the production

experiment. The same can be said of the low vowel, where confusion was minimal overall; the striking differences in vowel quality between the oral and the non-oral vowels for this quality (along with the presence of the context nasality) explain the patterns of response found.

Same vowel, different context

Next, let us examine the patterns of response in the same vowel, different context subset. Again, while the overall trend found for this subset is expected to persist, patterns of confusion that reflect the acoustic similarities found in chapter 4 are also expected to emerge. Figure 22 show the pattern of responses for this subset divided by context and vowel quality.

Figure 22. Responses for C_#-C_N and C_#-C_ᴺ, divided by vowel quality; right column is nasal, left is nasalized vowel. In this subset, "first" is the response corresponding to the stimulus presented first, and "second" corresponds to the stimulus presented second, both the same vowel, either nasal or nasalized.

In this subset, it is harder to see vowel quality effects because the vowels in each stimulus pair are exactly the same. However, we can see that the patterns of response are different depending on the vowel quality, which shows that these are treated differently. For example, there were much more correct "same" stimulus answer for the low vowels than for any other vowel (for example, 67% "same" answers for the low nasal vowel in both contexts), which reflects the inherent differences in quality when these vowels are not oral. On the other end, we have the high front vowel, with a great number of "second" stimulus answers (for example, 78% for the high front nasalized vowel in the appendix context). Context nasality seems to be required for high front vowels to be perceived as nasal. Considering the small difference in formant and acoustic nasality measurements for these vowels, oral, nasal and nasalized vowels can be considered the same. So, it makes sense that listeners would use the context nasality information to make nasality judgements. The mid-front vowels show a split number of "same" and "second" answers. This finding is surprising, especially for the nasal vowel, since it is the most different from the three. The high-back vowel shows a bigger influence of context nasality in the patterns of answers, with the appendix triggering more "same" answers than the consonant.

Different vowel, same context

Finally, let us examine patterns of responses in the different vowel, same context subset. Since vowels are acoustically different in this subset, and there is no perceptual compensation, "same" answers can be attributed to similarities in vowel quality. Figure 23 below shows patterns of response for each vowel quality.

Figure 23. Number of responses for nasal and nasalized vowels divided by vowel quality in different vowel, same context subset. In this subset, "first" is the response corresponding to the stimulus presented first, an oral vowel, and "second" corresponds to the stimuls presented second, either a nasal or a nasalized vowel.

In this subset, it is quite easy to see vowel quality influences. There were very few "same" or "first" answers for the low vowel, with the correct "second" answer reaching over 90% of the times. This is clearly due to the differences in quality between oral and non-oral low vowels (although in this case, the patterns of answers here could be due to nasality, since the comparison is always between an oral and a non-oral vowel). The response pattern differences between the

nasal and the nasalized the mid-front vowels is also consistent with difference in quality rather than nasality. When the comparison involved the nasal vowel, the listeners correctly answered "second" more often, reaching 66% in the C_N context (although there is some interesting confusion in the C_# context). In this case, both quality and nasality could be this reason for the pattern of responses. When the comparison involved the nasalized vowel, a more confusing pattern emerges. In isolation, oral and nasalized mid-front vowels are thought to be the same about 69% of the time. When a context nasality is present, accuracy increases, but never to reach the same levels as the nasal vowel. Since oral and nasalized vowels are different in terms of nasality, the only possible explanation for the patterns of confusion found for the mid-front vowels is their similarity in quality. The mid-back and high-front vowels show very similar patterns of responses, in that participants were quite confused between the vowels being the same and the second vowel being more nasal (they almost never say that the first vowel is more nasal). From these two vowels, we can clearly say that participants did not use vowel nasality as the primary perceptual cue, and the lack of differences in quality only contributed to the overall confusion. Finally, the high back vowel showed an interesting pattern. While we do not know whether there is any acoustic difference between the oral, nasal and nasalized high back vowels, it seems clear that listeners were able to distinguish the nasal vowel, but not the nasalized, from the oral counterpart, even though it is clear that the context aids in accurate perception of vowel nasality.

Preliminary conclusions

Let us put all the three subsets together and draw common conclusions from experiment 1. Participants are very good at differentiating oral from non-oral vowels regardless of context, but not nasal from nasalized vowels. This means that vowel nasality already seems to work as a

distinctive feature, at least for some vowel qualities. In fact, vowel quality seems to be a better correlate to perceived nasality than nasality by itself, since the bigger the difference in quality for a given vowel, the more accurate responses were. Also, adding a nasal context makes a non-oral vowel sound more nasal. This means that participants treat the context as relevant to the evaluation of vowel nasality, regardless of whether it is the appendix or a nasal consonant. Compensation not only does not seem to occur, but the context aids in nasality perception.

A comparison task like experiment 1 is, by itself, not enough to establish how listeners perceive a given sound sequence. All we know is that participants can tell if vowels are different from each other in terms of phonetic nasality. We need to know as well how listeners' perception of nasality reflects their grammatical structure, i.e. how they use this information, if they use it at all. Listeners may be sensitive to nasality in stimuli, but can they interpret it in a more linguistically meaningful task? That is where a complement to a rating task like this comes into play: a word identification task using nasality.

Perceptual Experiment 2 – Word Identification

Experiment 2 investigated whether it is possible to identify words with an oral, a nasal or a nasalized vowel based on the nasality in the vowel, and the presence or absence of a nasal context, either the nasal appendix or nasal consonant. This is a more phonological task than the discrimination task that targets how listeners use nasality in the vowel and its surrounding context in a linguistically meaningful way, and in linguistically natural environments. The main question we are trying to answer with this experiment is: *Can Brazilian Portuguese listeners identify a word containing a nasal vowel based on the vowel alone?*

If listeners can identify a word containing a nasal vowel based on the vowel alone, i.e., not confuse it with a word containing either an oral or nasalized vowel, this would suggest that nasal vowels are phonemic in BP, as they should be sufficient alone generate lexically meaningful distinctions. This would mean that participants attribute nasality in the vowel to the vowel itself, at least until they have more information about the context (as in Bengali in Lahiri & Marslen-Wilson (1991)).

On the other hand, if listeners cannot identify the word containing a nasal vowel based on the stimulus vowel alone, then nasal vowels are likely not phonemic. There must be something else that helps them distinguish these vowels: perhaps the presence of a nasal appendix or a full nasal consonant, or even vowel quality.

Method

The same 180 stimuli generated by splicing, based on table 14 in the previous chapter, were presented in random order to the same 40 undergraduate students from UNICAMP. Unlike in experiment 1, however, the stimuli were not presented in pairs. Listeners heard just the beginning of one token, and were asked to answer which word the stimulus they heard came

from. Also, in this experiment, all the 180 resulting stimuli were used, since they were presented in isolation, resulting in 180 responses per participant. The listeners were presented with three word possibilities on a computer screen, as shown in table 24 below, and had to press the key corresponding to the word to which they think the stimulus belongs. For example, listeners were presented with the possible words *capa* ("cape"), *campo* ("field") and *cama* ("bed") in the screen, and, upon hearing the stimulus [ka], they had to choose, among the three words, which one they think the stimulus [ka] came from.

Table 24. Portuguese words available for listeners to choose from in experiment 2 – identification.

	C1VC2V	**C1Ṽ1C2V**	**C1Ṽ2NV**
/a/	Capa	Campo	Cama
	Jato	Janto	Janio
/e/	Dedo	Dente	Denis
	Telha	Tento	Tenis
/i/	Tita	Tinta	Tina
	Pito	Pinta	Pino
/o/	Popa	Pompa	Pomo
	Todo	Tonto	Tona
/u/	Juta	Junto	Juno
	Tudo	Tundra	Tunel

Notice that these words are the same as the words used for stimuli creation, with the exception of four: *telha, todo, tudo* and *tundra*. In order to maintain the same context across tokens in the stimuli creation, non-words were used: *teto*, *toto*, *tuto* and *tunto* (refer to table 13 in the previous chapter). In this experiment, however, listeners were given actual Brazilian Portuguese words to choose from.

As with experiment 1, an experimental routine was created in Psychopy (Peirce, 2007). First participants were presented with instructions and then a practice block. Then, participants completed five test blocks, one for each of the five vowel categories. Figure 24 below shows an example screen that participants were presented with when listening to a stimulus. The screen

changed every time the target word set changed, which was random within vowel quality. For example, for /a/ blocks, word sets would alternate between "capa – campo – cama" and "jato – janto – janio"[40].

Figure 24. Experiment 2 Psychopy test screen.

Immediately after each response, participants listened to the next stimulus, until the block was finished. Participants could take a break between blocks if they wanted to.

Predictions

Table 25 below presents specific predictions for each stimulus.

Table 25. Predictions for each stimulus identification.

Stimulus	C1VC2V	C1Ṽ1ᴺC2V	C1Ṽ2NV
CV	1		
CṼ1		1	
CṼ2		1	
CVᴺ		2	
CṼ1ᴺ		2	
CṼ2ᴺ		2	
CVN			3
CṼ1N			3
CṼ2N			3

"1": Identification if the vowel is enough to correctly identify the word.

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[40] The screen reads, in English: *gato, left; sugar cane, down; corner, right*.

Participants in these stimuli only have the vowel as cue to word identification. Stimuli with nasal and nasalized vowels should equally identify the same word, as there is little nasality difference between them, according to the production experiment results and the literature. The identified word should always be the one with a nasal vowel (except for CV stimuli), as the premise is that nasality is inherent to the nasal vowel. Since both vowels are phonetically nasalized, listeners would not have enough information to distinguish nasal from nasalized vowels, thus they should consider nasality in either vowel as phonemic. This is the prediction that most directly addresses the research question in this experiment. However, if they can identify words containing nasal as opposed to words containing nasalized vowels, then these vowels are differentiated by aspects other than nasality.

"2": Identification if the appendix is required for perception of vowel nasality.

Nasal and nasalized vowels should be identified with words containing nasal vowels, as the appendix is not expected to trigger compensation or be treated as a consonant. This should be true even in the case of an oral vowel, if nasality in the vowel is not the most relevant perceptual cue for vowel nasality. However, if participants can separate nasal and nasalized vowels, then there is evidence that type of nasality matters in vowel nasality perception, and likely these vowels are differentiated by aspects other than nasality.

"3": Identification if there is a compensatory response, as the nasal context is a consonant; the non-oral vowels should not be perceived as nasal.

The presence of the full nasal consonant in the stimuli should trigger perceptual compensation in non-oral vowels (provided vowel nasality is not phonemic). Type of vowel nasality should equally identify the same word, as nasal and nasalized vowels are acoustically similar, according to the results of our production experiment. However, if participants can

identify nasal and nasal vowel separately, then there is evidence that nasal vowels are treated differently from nasalized vowels, likely these vowels are differentiated by aspects other than nasality. The context does not interfere with accurate perception.

Notice that all predictions do not take into account differences in vowel quality, as it is expected that there should be no appreciable difference in vowel quality between oral, nasal and nasalized vowels of the same height and "backness" (with perhaps the exception of the [+low] vowel).

Analysis

Analyses of accuracy and reaction time were performed via mixed effects modeling, linear and logistic, using glmer() function in R. The reason for choosing mixed effects modeling in this experiment is the same as in experiment 1.

Accuracy is the dependent variable with two levels. The correct answer in this case is always the word where the vowel comes from. For example, for a stimulus like [ka] (C_# context, oral vowel), the correct answer would be *capa*; for [kẽ] (C_# context, nasal vowel), the correct answer would be *campo*; for [kaᵐ] (C_ᴺ context, oral vowel), the correct answer would be *capa*. The explanatory variables include context and vowel nasality both with three levels (listed in Table 26), and vowel quality, with five levels, one per vowel quality. Speaker was included as a random explanatory variable.

Table 26. Independent variables in the logistic regression models for the identification experiment.

Variable	Level
Accuracy	correct; **incorrect**
Context	**C_#**; C_ ᴺ; C_N;
Vowel nasality	**oral**; nasal; nasalized
Vowel quality	**a**; e; i; o; u

The variables Context and Vowel nasality are theoretically motivated based on the research questions. Context intends to verify the effect of context in participants' answers, whether presence and absence of N (and to some extent ᴺ) lower participants' ratings or not. Vowel nasality intends to verify the effect of degree of nasality in participants' answers, whether they are more accurate in oral (V), nasal (Ṽ1) or nasalized vowel (Ṽ2) cases. Vowel quality is not pertinent to the research questions per se, but is motivated by the observations that there are vowel quality differences between oral and nasal, depending on vowel height. The low vowel becomes centralized when nasal; the mid vowels may become diphthongized; no change occurs with the high vowels. The variables were all dummy coded (0 and 1), with the default level being chosen based on preliminary data exploration.

The logistic mixed effects model[41] shows that there is an influence of context, vowel nasality and vowel quality on accuracy, as well as an interaction between context and vowel nasality. Table 27 below presents the main fixed effects in more detail.

Table 27. Logistic mixed model analysis for experiment 2. Estimate is given in log odds.

Dependent variable: accuracy	Estimate	Std. Error	Z-value	Pr(>|z|)
(Intercept)	3.50376	0.470587	7.446	9.66E-14
context C_N	-3.334854	0.495465	-6.731	1.69E-11
context C_ᴺ	-2.961872	0.497704	-5.951	2.66E-09
nasality nasal	-3.672138	0.495541	-7.41	1.26E-13
nasality nasalized	-2.518135	0.501763	-5.019	5.21E-07
vowel e	-2.635236	0.499911	-5.271	1.35E-07
vowel i	-2.548165	0.500914	-5.087	3.64E-07
vowel o	-1.426312	0.531348	-2.684	0.00727
Vowel u	-2.361374	0.503692	-4.688	2.76E-06
context C_N:nasality nasal	3.309559	0.543509	6.089	1.13E-09
context C_ᴺ:nasality nasal	4.372658	0.554931	7.88	3.28E-15
context C_N:nasality nasalized	4.488069	0.583044	7.698	1.39E-14
context C_ᴺ:nasality nasalized	3.288653	0.561827	5.853	4.81E-09

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[41] glmer(correctnessv ~ context*nasalityv*vogal+(1|Speaker), family = "binomial", data = exp2). Only the context by vowel nasality interaction was significant, so this interaction is the only one reported.

In regard to vowel nasality, participants' accuracy significantly increases when the vowel is either nasal or nasalized, rather than oral ($p < 0.05$ for both nasal and nasalized vowels). In figure 25 below, the words identification responses by stimulus vowel nasality type are presented. "oral", "nasal" and "nasalized" indicate the type of vowel the response word contained. When the stimulus vowel is oral (rightmost bar group), participants correctly answered "oral", about 50% of the time (lightest gray bar in the group); when the stimulus vowel is nasal (leftmost bar group), participants correctly answered "nasal" (right bar in the group), about 60% of the time; when the stimulus vowel is nasalized (middle bar group), participants correctly answered "nasalized" also about 60% of the time (darkest gray bar in the group). These results show that, regardless of context, participants can correctly identify the vowel. Patterns of mistakes show that oral vowels can be confused with nasalized vowels, as participants answered "nasalized" for oral vowel stimuli a bit over 30% of the time (darkest bar in the rightmost bar group). Nasalized vowels can be confused with nasal vowels, as participants answered "nasal" for nasalized vowel stimuli about 60% of the time (rightmost bar in the middle bar group). Nasal vowels were confused with nasalized ones a bit over 30% of the time (darkest bar in the leftmost bar group). These results, correct answers and mistakes, show that participants can separate oral from non-oral vowels, and nasal from nasalized vowels relatively well, but nasalized vowels can

be classified as nasal quite often, which leads us to believe that nasality is treated as inherent to nasal vowels.

Figure 25. Identification responses by type of vowel nasality in the stimulus. Total number of responses is 7740, 2580 answers per stimulus.

In terms of context effects, participants' accuracy decreases when the context is a nasal consonant, C_N, which is statistically significant ($p < 0.05$). Accuracy slightly increases when the context is the nasal appendix, but this increase is not statistically significant ($p = 0.269265$). In other words, when a fully realized nasal consonant is present, speakers are less likely to say that the stimulus they heard is from the actual target word. Vowels in isolation and vowels followed by the appendix seem to be equally well identified.

We split the data by context to analyze the relationship between context and type of vowel nasality, since there was an interaction between these two factors. Splitting the data this way follows closely the prediction listed on table 25.

C_# contexts

The C_# context allows us to more directly test our research question addressed by this experiment, which translates into prediction "1". In other words, it allows us to test if the vowel is sufficient to correctly identify words, at least the difference between oral vs. non-oral (nasal or nasalized) vowels.

A logistic linear mixed effects model considering only C_# context shows that accuracy is lower for nasal and nasalized vowels, relative to oral vowels (-3.6694, p < 0.005 for nasal vowels; -2.5175, p < 0.005 for nasalized vowels), showing that participants are not as good in identifying words based on vowel nasality alone as the initial results in figure 25 above seemed to indicate. These results can be visualized in figure 26 below.

Figure 26. Number of responses by stimulus divided by vowel nasality type in C_# (isolation) contexts. Total number of responses is 2580, 860 per vowel condition.

In Figure 26, "oral", "nasal" and "nasalized" indicate the type of vowel the response word contained. So, for example, if a participant heard a /ka/ stimulus (C_# and oral vowel), they could choose between *cama* ("nasalized"), *campo* ("nasal") or *capa* ("oral").

Broken down by stimulus type for C_# context, accuracy is high for stimuli with oral vowels (80%), as expected, since there is neither context nor nasality in the vowel to confound participants. For nasal vowels in C_# context, the most frequent answer is the correct response "nasal" (44%). "nasalized" answers for a nasal vowel stimulus are not infrequent, at around 34%. For nasalized vowel stimuli, "nasalized" and "oral" answers are essentially the same, 43% and 42% respectively. These results partially confirm prediction 1 above, as nasalized vowel stimuli correctly triggered "nasalized" responses. However, the most interesting finding is that

participants' capacity of identification based on the vowel alone is not very good for C_#, except when they must identify oral stimuli.

Overall, when there is some kind of phonetic nasality in the vowel, accuracy decreases, as there is much confusion between nasal and nasalized responses. If the stimulus vowel is nasal, the answers can be either "nasal" or "nasalized"; if the stimulus vowel is nasalized, the answers can be either "nasalized" or "oral". It seems that, when participants heard a nasal vowel, they knew that the vowel is not oral; when they heard a nasalized vowel, they knew that the vowel is not nasal. This difference in response confusion patterns may be due to slight differences in degree of nasality in between nasal and nasalized vowels, with nasal vowels becoming slightly more nasal than nasalized ones, as shown in our production experiment, even though these vowels were considered essentially the same. In the production experiment, we can see that, while nasal and nasalized vowels are very similar and start with essentially the same level of acoustic nasality, they have different nasality profiles: nasal vowels increase in nasality faster than their nasalized counterparts. Perhaps, then, participants attend both to the similar levels of nasality that nasal and nasalized vowels have in common, and to the difference in nasality profile that nasalized and oral vowels have in common (while different depending on vowel quality, A1-P0 and A1-P1 profiles for these vowels do not change over time). An alternative explanation, explored in more detail later, is that vowel quality changes associated with nasality play a role in the response patterns presented in this section. In any case, it is clear that the vowel alone may not provide enough information for accurate perception of vowel nasality, and prediction 1 holds only partially.

C_ᴺ contexts

What happens when listeners are exposed to the nasal appendix? The prediction for this context (prediction 2 above) was that participants would identify the stimulus with the nasal appendix as the word containing a nasal vowel, regardless of vowel nasality, if nasality in the vowel were not a sufficient perceptual cue for correct word identification. The prediction is especially relevant now, based on the finding that nasality in the vowel alone confuses participants in C_# contexts.

A mixed-effect logistic model shows a slight increase in accuracy when the vowel is nasal (0.7028, p < 0.005) or nasalized (0.7729, p < 0.005), when compared to the oral vowel. When compared to C_# context, we see that the addition of context increases accuracy for vowels with some type of nasality, as evidenced in figure 27.

Figure 27. Number of answers by stimulus divided by vowel nasality type in C_ᴺ (nasal appendix) contexts. Total number of responses is 2580, 860 per vowel condition.

When we have an oral vowel with a nasal appendix, accuracy decreases. 40% of the time, participants answered "oral" for these stimuli, vs. 80% oral vowel word answers in C_#. Thus, context itself plays an important role in perceiving a vowel as nasal. Of course, phonotactics could also contribute to that decrease in accuracy since we do not find phonetically oral vowels with a nasal resonance of any kind afterwards in Brazilian Portuguese; vowels in this context are

always phonetically nasal. So, it makes sense that participants would choose word with some kind of nasal resonance as the answer for CV^N stimuli (25% nasal vowel word and 34% nasalized vowel word), even though the vowel itself had no nasality, maybe thinking that either "nasal" or "nasalized" answers would be a better fit in for this stimulus than an "oral" answer. However, it is interesting that participants still chose "oral" as the most frequent answer for oral vowel stimuli, which shows that the appendix is likely not very salient in the acoustic signal. Interestingly, the fact that participants chose nasalized vowel words for oral vowel stimuli so often is consistent with the pattern of confusion found in the C_# contexts, where nasalized vowels were thought to be oral quite often. Perhaps the similarity in nasality profile or vowel quality was the cue participants used to make their choices.

For a nasal vowel in a nasal appendix case, participants overwhelmingly answered "nasal" 72% of the time, as expected. There were very few answers for the other two cases: 24% for nasalized vowel words and 3% for oral vowel words. For nasalized vowels, participants answered "nasalized" most of the time (59%), followed by nasal vowel word (29%) and oral vowel word (12%).

Therefore, while the logistic mixed-effects test presented in table 27 show a small increase in overall accuracy when the context is $C\_^N$, it is clear that the presence of the nasal appendix increases accuracy in both nasal and nasalized vowel words only, consistent with the context and vowel nasality interaction in the statistical model. When compared to the relatively poor performance for nasal and nasalized vowels in the C_# (isolation) context, we can see that the appendix seems to be necessary for a vowel to be correctly perceived as either nasal or nasalized. Therefore, prediction 2, that participants would answer "nasal" regardless of type of vowel nasality, is not confirmed, as the addition of appendix helped listeners choose the correct

answer for nasal and nasalized vowel stimuli. The addition of the appendix helped participants to choose the correct answer when compared to C_#, which means that a combination of vowel plus some resonance is required to correctly identify a vowel as nasal or nasalized. It is important to notice that the appendix it helps with correct identification both nasal and nasalized stimuli. Does that mean that more context increases accuracy?

C_N contexts

For C_N contexts, we expect that the nasal consonant will aid in the identification of nasalized vowel words, and that type of nasality in the vowel should not influence participants' answers (prediction 3). In other words, all answers would be "nasalized".

A logistic mixed-model shows that accuracy increased when the vowel stimulus was nasalized (1.9602, $p < 0.005$), and it decreased when the vowel was nasal, but not significantly (-0.3599, $p = 0.1007$), when compared to oral vowels. This pattern is likely due to the large number of nasalized vowel word answers regardless of type of nasality, as presented in figure 28 below.
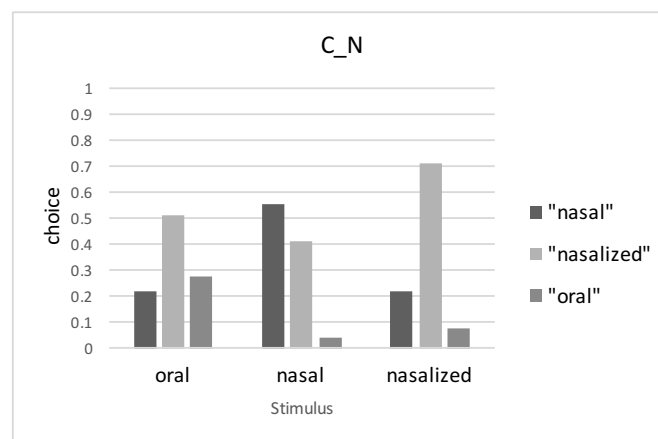

Figure 28. Number of answers by stimulus divided by vowel nasality type in C_N (nasal consonant) contexts. Number of responses is 2580, 860 per vowel condition.

Analyzing the oral vowel stimuli in C_N contexts, we can see that participants' most common answer was "nasalized" (50%). We see effect of context on oral vowels here, whereby the presence of a nasal consonant influences participants, similar to the presence of the appendix effect in C_ᴺ contexts. In this context, the nasal consonant exerts so much influence that, "nasalized" answers surpass "oral" answers, unlike C_ᴺ, showing that the nasal consonant is salient enough in the acoustic signal. Answering "nasalized" instead of "nasal" for this stimulus may be due to the similarity between oral and nasalized vowels' nasality profiles (but not overall degree of acoustic nasality) and is consistent with findings in the C_# context, where nasalized and oral vowels were confused by participants.

Nasal vowels in this context show an interesting trend, with the most frequent answer being "nasal" (55%), followed by "nasalized" (41%). Nasalized vowel stimuli yielded 70% "nasalized" answers, the highest of all, followed by "nasal" at 22%. These results partially contradict our prediction 3, that nasal and nasalized vowels would be identified as nasalized, due to phonetic similarity. Just like the in C_ᴺ contexts, where the appendix helped participants choose the correct answer for nasal and nasalized, the presence of a nasal consonant also helped participants choose the correct answer for both nasal and nasalized vowels.

In summary, when considering the identification results of all three contexts, while participants were mostly accurate in identifying words based on vowel alone (C_# context, prediction 1), it is clear that some form of context is required in addition to the vowel to help participants identify the word when the vowel is either nasal or nasalized (C_ᴺ and C_N contexts). Predictions 2 and 3 were not completely confirmed, as adding a nasal element, be it the appendix or the nasal consonant, to nasal and nasalized vowels helped participant identify nasal vowel stimuli as "nasal" and nasalized vowel stimuli as "nasalized". In other words,

addition of a nasal element helped with correct phonological identification despite acoustic nasality similarity between these vowels. It seems, based on the identification results, that vowel nasality type by itself is not a very salient perceptual cue, but the combination vowel and nasal element, either the appendix or the consonant, is (even though the statistics were not significant). These results are consistent with the results from experiment 1, in which participants always considered nasal and nasalized vowel stimuli followed by either a nasal appendix or a nasal consonant to be more nasal than stimuli not followed by a nasal element.

Vowel quality analysis

While context and vowel nasality type appear to be important factors, differences in vowel quality across Brazilian Portuguese oral, nasal and nasalized vowels may also account for some of the patterns of response presented earlier. In fact, as presented in the initial statistical analysis, we find vowel quality main effects; accuracy is lower in every other vowel quality when compared to the low vowel. Thus, vowel quality seems to play a role in participants' responses. In fact, it is possible that differences in vowel quality could be causing this pattern of response, *rather than* patterns of nasality profile. Recall that low vowels are raised when nasal or nasalized and mid vowels are diphthongized when nasal (but not nasalized). Since phonemic nasality can alter vowel quality, as is also the case with French (e.g., Sampson, 1999), we re-analyze the pattern of responses by vowel quality. The graphs in figures 29 and 30 show responses for vowel nasality stimuli divided by vowel quality regardless of context.

Figure 29. Percentage word identification answers divided by vowel quality for low and mid vowels across contexts.

For low vowels, we can see that, for oral stimuli, the most frequent response was "oral", as expected (71%). When the stimulus was nasalized, the most frequent response was "nasalized", also as expected (80%). However, the nasal stimuli yielded similar "nasal" (55%) and "nasalized" (44%) responses, suggesting that there is something about the nasal low vowel that caused confusion, regardless of context.

The mid front vowels show accurate answers for the nasal stimuli only, as expected (72%). There was confusion in responses for oral and nasalized stimuli, with similar percentage answers for each: "oral" for oral stimuli (43%) and "nasalized" nasalized stimuli (42%). This result is explained when we recall that the nasal vowel stimuli were diphthongized, but not the other the oral or nasalized stimuli. In fact, this shows that vowel quality was a stronger perceptual cue than vowel nasality for the mid front vowels, as both nasal and nasalized stimuli yielded similar responses.

The mid back vowels in figure 29 show mostly accurate responses for all three stimuli: "oral" for oral (48%), "nasal" for nasal (59%), and "nasalized" for nasalized (65%) stimuli. The oral stimuli were confused with nasalized vowels (39%), as well as the nasal stimuli (29%). Here, a vowel quality effect is less apparent. Like its front counterpart, the mid-back vowel is also reported to be diphthongized when nasal, so it would be expected that the nasal vowel stimuli would yield higher correct responses than the other two, but that is not the case here. The difference in vowel quality between nasal and nasalized mid-back vowels does not seem to affect accuracy (both nasal and nasalized vowels have similar degrees of acoustic nasality); however, the difference in degree of nasality between oral and nasalized vowels (which are not different in quality) affects accuracy.

Figure 30. Percentage word identification answers divided by vowel quality for high vowels across contexts.

The left graph in figure 30 shows responses for the high front vowels. All the high front stimuli triggered correct responses above chance: "oral" for oral stimuli (42%), "nasal" for nasal stimuli (44%) and "nasalized" nasalized stimuli (43%). However, there is relatively high confusion among all three types of stimuli. Nasal stimuli yielded as much "nasalized" as "nasal" responses (42%), and there was a small percentage of "oral" confusion (14%). Oral stimuli yielded slightly lower "nasalized" responses than "oral" responses (36% vs. 42% respectively). Nasalized stimuli were confused with both oral and nasal stimuli, with around 30% responses

each. Overall, we can see that all the high front vowels were confused with each other, likely due to an interaction between similar nasality and lack of marked vowel quality differences among high vowels, as attested by the production experiment.

The right graph shows the responses for the high back vowel. There are more accurate responses for the nasal (54%) and the nasalized stimuli (58%) than for the oral one (41%), but all of them are accurate above chance. The oral high back vowel was confused with the nasalized vowel about 44% of the time, while the nasal high back vowel was confused with the nasalized 33% of the time. Interestingly, the nasalized vowel was not confused with the other two vowels often. It is difficult to explain, based on our acoustic nasality and formant measurements in the production experiment why the nasal and nasalized high back vowels were accurately perceived, since there seems to be little difference between the types of nasality in terms of vowel formants, and the acoustic nasality measurements were uninterpretable since the proximity between the nasal formants and the first two oral formants makes it difficult to tease apart their values.

Preliminary conclusions

Our predictions for the identification experiment fared relatively well. Participants were able to correctly identify words based on vowel alone, albeit not as accurately as expected. There was confusion between nasal and nasalized vowels, and between nasalized and oral vowels. The addition of the appendix and the nasal consonant increased accuracy for nasal and nasalized vowels, showing that the extra nasal context aids in nasality perception. There was, however, an effect of vowel quality that better explains the patterns of identification, both accurate and inaccurate, than vowel nasality alone, in particular the low and mid-front vowels. These results show that, in a linguistically significant task, listeners use vowel quality and context as perceptual cues to lexically meaningful differences in nasality.

Both this experiment and Experiment 1 aimed at testing whether Brazilian Portuguese listeners treat vowel nasality as inherent to the vowel or as a product of coarticulation. Experiment 1 showed that perceptual compensation did not occur, but accuracy was higher when there were considerable vowel quality differences, and nasal context (the appendix or the nasal consonant) aided in the perception of vowel nasality. Experiment 2 showed that the vowel by itself was enough for participants to correctly identify the word containing the vowel, but accuracy was higher when there were considerable vowel quality differences, and the nasal context (appendix and nasal consonant) aided in correct word identification. The next chapter discusses these findings in light of the relevant literature on vowel nasality and quality perception, as well as theories of phonologization and sound change.

Discussion

Now that we know how Brazilian Portuguese listeners respond to vowel nasality in different contexts, what do we make of it? In this chapter, we discuss the experiments' results considering the hypotheses laid out in the production experiment. Then, we consider the results in light of theoretical points of view on compensation, vowel quality issues, and phonologization.

Research questions revisited

There were two questions we aimed to answer with the rating and the identification experiments:

Do BP listeners compensate for vowel nasalization?

Hypothesis: BP listeners will not compensate for vowel nasalization when the vowel is phonemically nasal, but they may compensate when the vowel is allophonicaly nasalized.

Can BP listeners identify a word containing a nasal vowel based on the vowel's nasality alone?

Hypothesis: yes, BP listeners can identify a word containing a nasal vowel based on the vowel's nasality alone.

Let us address each one in turn.

The first question was addressed by experiment 1, the rating experiment. The vowel discriminability predictions for this experiment were based on the general assumption that perceptual compensation would occur whenever the appropriate context presented itself, i.e., a nasalized vowel in a nasal consonant context. The idea was that, since vowel nasality before a nasal consonant in a language without vowel nasality contrast is traditionally considered not to be phonemic, upon hearing a vowel with some type of nasality in a nasal consonant context, participants would attribute such vowel nasality to the context, making them interpret the vowel

as not nasal(ized). This compensatory effect would result in vowels being judged more or less nasal than the other vowels in the pair depending on the specific pair being judged; for example, if the two stimuli in a pair had the same nasal vowel, but one vowel was followed by a nasal consonant, then this vowel would be considered perceptually less nasal than the vowel without the consonant. Thus, and following experiment 1 hypothesis, compensation effects were not expected to occur if the vowel is phonemically nasal, regardless of context. The nasal vowel would always be judged as more nasal than other vowels.

It is safe to say at this point that perceptual compensation in experiment 1 did not occur in any context, expected or not. Participants could differentiate oral from non-oral vowels quite reliably regardless of context and type of nasality (not just in the cases of purportedly phonemic nasal vowel), even though in some non-oral cases accuracy rates were lower than expected (especially, if we compare them to oral vowel accuracy). This finding alone suggests that nasality is perceived as an inherent vowel feature. Furthermore, participants' equally successful judgment of nasal and nasalized vowels suggests nasality in both types of vowel is perceived as at least phonological, i.e., mandatory and part of the vowel's phonological makeup. Thus, hypothesis one is confirmed for nasal vowels, but not for nasalized vowels. It is as if nasalized vowels have already a different phonological status than oral vowels.

When investigating the rating experiment results more deeply, however, we see that there is more than just nasality playing a role in vowel rating. Participants were more accurate in differentiating oral from non-oral vowels depending on vowel quality. Upon further investigation and comparison with the production experiment, it was found that accuracy was relatively higher in cases where oral, nasal and nasalized vowels for a given vowel quality differed in terms of vowel formants, regardless of degree nasality, suggesting that participants associated certain

vowel quality changes with nasality. For example, participants rated the mid-front nasal vowel as more nasal than the oral counterpart more often than they rated the nasalized vowel against the oral one. Both the nasal and the nasalized mid-front vowels have similar degrees of nasality, but differ in vowel formant trajectories (the nasal vowel is diphthongized, while the nasalized vowel is not.) However, both nasalized and oral mid-front vowels have similar vowel formants, differing in degree of nasality. If nasality were the main perceptual cue, nasalized and oral mid-front vowels would be rated as different more often. Furthermore, the high vowels, with less vowel formant value differences between oral, nasal and nasalized counterparts (which leads to less vowel quality changes), showed considerable confusion, despite differences in degree of nasality. If nasality were the main perceptual cue, we should have expected a more marked difference between at least the oral vs. non-oral vowels. It seems that vowel quality change from oral to non-oral played a stronger role in this rating task than degree of nasality, which leads to the conclusion that participants paid attention first to differences in vowel quality, then differences in nasality. Therefore, nasality seems to be a secondary perceptual cue for nasality contrasts, and vowel quality changes associated with nasality, the primary cue.

The identification experiment addressed the second question presented above. The predictions for this experiment were based on the idea that if a feature such as nasality is inherent to the vowel, then that feature's presence in the segment alone should be sufficient for word identification. The hypothesis, then, is that nasality in the vowel should be sufficient for a vowel to be perceived as nasal. Participants would be able to correctly identify the word based on vowel nasality alone, especially in the oral and nasal vowel cases. If nasality in the vowel were not enough for correct identification of the word, then there must something else that is required for identification, such as context nasality. The identification experiment yielded similar results

to the rating experiment. Participants could identify nasal vowels, and nasalized vowels to a certain extent, quite reliably, although not as reliably as oral vowels, regardless of context. These results suggest that vowel nasality is perceived as inherent rather than coarticulatory.

The identification experiment results also yielded vowel quality effects. When there were greater vowel formant differences between oral, nasal and nasalized vowels of a given quality, accurate identification increased. Taking the mid vowel again as example, the greater formant trajectory differences between the nasal and the other two vowels seems to have aided in correct word identification, while the similarities in formant trajectories between the oral and the nasalized vowel only caused the nasalized vowel to be confused with the oral (interestingly, the oral vowel was rarely confused with the nasalized). Vowels with no appreciable difference in quality among the types of nasality, such as the high ones, yielded identification responses almost at chance level, suggesting that participants were not sure whether the vowel they heard was oral, nasal or nasalized, especially in the case of the nasal vowel stimuli.

Based on these results, we can conclude that participants paid more attention to changes in vowel quality as a reflection of nasality rather than to nasality by itself. When nasal vowels were not qualitatively different from their oral counterparts, it was difficult for participants, without further context, to rate and identify a vowel as nasal, as nasalized, and, in some cases, even as oral. It seems, thus, that vowel nasality by itself is not a very strong perceptual cue, at least not as strong as vowel quality. This can be explained by how nasal resonances from the nasal tract interact with oral tract resonances, as explained next.

Vowel quality as a cue to nasality

Changes in quality due to nasality effects, and their effects on vowel perception, have been extensively documented in the literature. Nasal resonances interact with oral resonances in a

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vowel's F1 region, causing changes in perceived vowel quality, especially in perceived height. For low vowels, the addition of nasal resonances around F1 makes a low vowel sound higher, as the new perceived F1 is lower in frequency; for high vowels, the opposite happens, raising perceived F1, making the high vowel sound lower. For example, Beddor and Hawkins (1990) presented nasal – oral vowel pairs to American English listeners, who had to judge their similarity. Listeners judged oral vowels that had similar F1 to the nasals' averaged FN (nasal resonance) and F1 (the average called center of gravity) as more similar than oral vowels that had the same F1 as the nasal. They conclude that this FN and F1 averaging affected the perception of vowel height. This effect of nasal vowel height centralization is typologically common across languages, where high vowels can be considered lower, and low vowels can be considered higher than their oral counterparts (Beddor, 1983). This change in perceived vowel height is only true when nasality is strong enough to introduce FN, and merge it with the vowel's F1 (Carignan, 2011.). Moderate nasality will not change perceived vowel height, as it will not lower F1 for low nasal vowels.

This change in perceived vowel height can have phonological consequences, such as initiating a phonological contrast. For example, modern French has four nasal vowels /ɑ̃ ɔ̃ ɛ̃ (œ̃)/. These vowels are very different in quality from their oral counterparts, and noticeably, French lacks high nasal vowels. However, early Old French possessed a full set of nasal vowels. The high nasal vowels in French underwent lowering around the 13th century (Sampson, 1999), so that they ceased to exist. The author states that one possible reason for this is the perceptual effect of nasality on high vowels: nasal and oral resonance interactions led listeners to perceive

and later articulate nasal vowels as lower than their oral counterparts[42], deleting them from the phoneme inventory.

Because a change in the first formant (responsible for vowel height) can be correlated to either jaw lowering/rising or increased nasal coupling (Krakow, Beddor and Goldstein, 1988), changes in perceived vowel height may lead to changes in the oral articulation of nasal vowels. In the end, then, the contrast between oral and nasal vowels does not rest solely on the velum lowering. In French, nasal vowels are articulated differently from their oral counterparts (Delvaux et at, 2002; Carignan, 2011). For example, in comparison with their oral counterparts (/a/, /ɛ/, /ɔ/), French nasal vowels /ã/ and /ɛ̃/ tend to have a more lowered and retracted tongue body position, while /ɔ̃/ is more raised and fronted. This translates into higher F1 values for /ã/ and /ɛ̃/, meaning these vowels are lower in quality than their oral counterparts, and lower F1 for /ɔ̃/, meaning this vowel is higher than its oral counterpart. Shosted *et al* (2012) show that Hindi nasal vowels also undergo articulatory changes when compared to their oral counterparts, but the direction of change is a bit different. For example, /ɛ̃/ is articulated with a tongue body higher than its oral counterpart, which causes a decrease in F1 frequency; consequently, the vowel sounds higher in quality. Interestingly, this change in height happens with the whole front series, including the high front vowel, which goes against the tendency for high nasal vowels to lower. The authors suggest that the changes in articulation, and the acoustic consequences due to nasality, can be understood as a clockwise chain shift[43]. Thus, it seems that, due to nasal and oral resonances interactions leading to change in perceived vowel height, new articulatory targets can happen, ending in the emergence of new contrasts.

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[42] Sampson states, however, that perceived lowering must not have been the sole cause for the lowering of French high nasal vowels, as high nasal vowels are maintained in other languages, Portuguese included.
[43] The same chain shift, the authors say, can be observed in Quebecois French (Carignan, 2011).

In Brazilian Portuguese, vowel quality changes due to nasality are seen in the low and mid-front nasal vowels. Our formant analysis in chapter the production experiment shows that the low vowel has lower F1 than its oral counterpart, causing it to be higher in quality, going from low to central. The mid-front vowel is considerably diphthongized, going from mid to high. These are likely caused by resonance interactions in the F1 region. These same oral-to-nasal quality changes are found elsewhere (Sousa, 1994, Seara, 2000), showing that they are systematic, and may result from FN and F1 interactions.

Furthermore, there is evidence that nasal vowels in Portuguese are articulated differently, even if just slightly. Oliveira *et al* (2012), reporting the results of an MRI study for European Portuguese, notice that the low nasal vowel is fronted and raised when compared to the oral counterpart; the mid front nasal and oral vowels had the same articulation; two of three speakers produced a more fronted and lowered mid back nasal vowel; the high front vowels were very similar; and the high back vowel was slightly lowered in comparison with the oral counterpart. They conclude that the differences in oral articulation between oral and nasal vowels are subtle, especially when it comes to the high vowels. Teixeira *et al* (2003) report, based on EMMA studies, that the low nasal vowel is higher than its oral counterpart; that the mid nasal vowels are lower than their oral counterparts; and that the high vowels have similar heights compared to their oral counterparts. For Brazilian Portuguese, Medeiros and Demolin (2006) report, based on MRI scans of one subject, that the "posterior part of the tongue seems to follow the velum movement" (p. 137, our translation); the tongue front is raised for the high front nasal vowel, and the high back vowel's tongue body is "flatter" (p. 138, our translation). The authors do not explain whether these articulatory adjustments lead to any change in vowel quality, but we can think that they do not, except for the low vowel. None of the Brazilian or the Portuguese authors

attempt to explicitly relate the changes in articulation observed to changes in the acoustic signal. However, it is reasonable to say, given our knowledge of the relationship between vowel articulation and acoustic output, that these changes in vowel articulation cause changes in vocal tract configuration, which, in turn, causes changes in the vowels' resonance patterns. The result must be a vowel of different quality, at least for the low and mid vowels.

The patterns of confusion found for high vowels can be explained by their lack of marked change in vowel quality, i.e., the high nasal and nasalized vowels do not sound much different from their oral counterparts. Neither nasal nor nasalized vowels were judged to be much different from their oral counterparts, despite being more acoustically nasal, as shown in chapter 4. The results of our acoustic formant measurements in chapter 4 show that the high nasal and nasalized vowels /ĩ/ and /ũ/ are not significantly different from their oral counterparts either. Similar results are found in the literature (Sousa, 1994; Seara, 2000; Jesus, 2002). Therefore, in terms of vowel quality, neither high nasal or nasalized vowel is different from the respective oral counterpart; thus, they are not discriminable. The question is now, why would oral and nasal high vowels not be different enough from each other, while the low and mid-front are, despite all having differences in degree of nasality?

There are two possible reasons. First, if we assume that, to be perceived as nasal(ized), a vowel needs to be nasal enough to cause vowel quality changes, as it seems to be the case for the low and mid-front nasal vowels (and also all the French nasal vowels), then perhaps the current levels of nasality in these vowels are not sufficient to make the quality distinct from their oral counterparts. Second, if we think that, for a nasal vowel to be perceived as such, it needs to have articulatory adjustments, then perhaps a lack of articulation difference between oral and nasal

vowels could be at play. Unfortunately, our measurements do not provide enough evidence for either of these explanations.

To understand whether the current levels of nasality in the high vowels are enough for the nasal (and nasalized) vowels to be perceived as different from oral counterparts, we would need to manipulate different levels of nasality (however we do that: F1 attenuation, introduction of nasal poles and zeroes) to find out the nasality threshold for Brazilian Portuguese for these vowels, and compare the thresholds to the levels of nasality in our stimuli. We would expect, based on our perceptual results, that, due to the relationship between nasality and vowel quality, the threshold would need to change the perceived vowel quality, so it would need to interact with the oral vowels' resonances, probably causing high vowel lowering. Any nasal vowel with nasality above the threshold would cause listeners to differentiate the oral and nasal high vowels, increasing accuracy in a rating experiment such as ours, as well as in an identification experiment. Unfortunately, we are not aware of any rating or identification experiments in Brazilian Portuguese that manipulate degree of vowel nasality with a setup like ours. The perception studies reported in chapters 2 either do not manipulate degree of nasality (Brito, 1975; Moraes, 2003), or they do not elicit a rating based on comparison or word identification (Seara, 2000). Goodin-Mayeda (2011, 2014) manipulates degree of nasality in a categorization task, and finds that Brazilian Portuguese listeners perceived vowel nasality categorically, but does not provide the F1 threshold.

As for articulatory adjustments, while it seems clear based on the formant measurements in the production experiment 4 that there are articulatory adjustments when producing nasal and nasalized vowels for some qualities, we would need to have articulatory measurements to see Brazilian Portuguese speakers adjust their articulation of high nasal vowels when compared to

their oral counterparts, including EMMA and/or MRI, to either enhance the acoustic consequences of nasality to increase the perception of the oral-nasal contrast. However, we know, based on the literature, that high nasal vowels in Portuguese are not articulated much differently from their oral counterparts, as described by Teixeira *et al* (2003), Oliveira *et al* 2012, and Medeiros and Demolin (2006). If these articulatory changes were quantified, then we could relate them to changes in the acoustic signal and rating/identification tasks.

The effect of the context nasality[44]

One of the main points of disagreement among phoneticians and phonologists of Brazilian Portuguese is the phonological role the nasal appendix has in the language. The usual conclusions are either that it is a nasal consonant or that it is a byproduct of vowel articulation or gestural misalignment. While scholarship never questions the fact that nasal and nasalized vowels are phonetically nasalized, formal approaches consider the appendix a consonant, while the experimental approaches do not. In the present study, there is evidence that the appendix is relevant to the perception of vowel nasality, and not a separate consonant.

In experiment 1, the rating task, we tested the idea that the appendix and the nasal consonant would trigger perceptual compensation. What we found that is that neither triggered compensation. In fact, they seemed to aid in the perception of nasality, which was unexpected given the literature (Seara, 2000). When participants in our rating experiment failed to correctly rate the more nasal vowel, they would almost always choose the stimulus with the appendix (or the nasal consonant) as the more nasal. In the identification task, stimuli with the appendix (or the nasal consonant) yielded more accurate identification results than stimuli without it. It seems

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[44] We will not comment on the nasal consonant effects because they were the same as the appendix's effects on accuracy. In fact, it appears that participants treated the consonant as an appendix.

that the context nasality is relevant (but perhaps not necessary) to the perception of a vowel as nasal(ized).

This finding could mean that the context nasality is part of the vowel. This possibility is consistent with some of the acoustic analyses in the literature, such as Sousa (1994). The author claims that the appendix must be part of the vowel since it does not appear to have any consonantal features. While the justification seems questionable, since it has been found elsewhere that the appendix has a place of articulation (e.g Shosted 2006), perceptually, grouping the context nasality with the vowel seems to make sense here, especially if we think that having nasality outside the vowel aids in the perception of some nasal vowels.

The presence of the context nasality was particularly helpful when there was no difference in quality between oral and non-oral vowels, i.e., the high vowels (and the mid-back vowel). So, it is possible that nasality can be signaled by the presence of the appendix, regardless of whether it is part of the vowel or the following consonant, especially when vowel quality change is missing, making it the perceptual cue when quality is missing. This possibility is just hinted at by Oliveira *et al* (2012), in the case of high vowels, and it definitely calls for further investigation. The locus of nasality for these vowels could be in the nasal appendix.

The idea of moving the locus of nasality to the appendix can explain why high vowels do not change quality despite being more nasal than their oral counterparts. Perhaps high nasal vowels in isolation are not nasal enough to make them perceptually different from their oral counterparts; moreover, they cannot be made nasal enough, otherwise they would change in quality, which could erase the high – mid nasal vowel contrast (like what happened with French, where high nasal vowels were lost, Sampson, 1999). So, to maintain the high – mid vowel contrast, but at the same time make the high vowels sound nasal, moving nasality from the vowel

to the following consonant, creating the appendix as a result of gestural overlap, could be an alternative. If that is the case, then we can think of the appendix as serving the purpose of halting a process of phonemicization of nasal vowels through vowel quality changes. We will touch on this subject more in the section below.

Phonologization

The bigger question we wanted to answer in this study is if the way listeners perceive vowel nasality in Brazilian Portuguese would give us any insight into the phonological status of nasal vowels, in an attempt to weigh in on the controversy of whether nasal vowels are made of one or two phonemes. The driving idea was that two sounds need to be different enough in the acoustic signal for listeners to perceive them as different.

The evidence we brought to bear on the issue shows that participants could accurately rate the vowels or identify the word based on the vowel alone a considerable number of times. So, there was no perceptual compensation. However, it was only when the nasal vowel is qualitatively different from the oral (and the nasalized) counterparts that listeners could more accurately perceive vowel differences, regardless of context. This means that nasality per se is not the perceptual cue they used. We proposed that it is the change in quality, height to be more specific, that causes changes in vowel perception, not nasality itself, based on the comparison of our acoustic analysis and perceptual experiment results with what we observe in the literature. This change in quality is caused by nasality. So, nasality has an indirect role in perception of vowel nasality. The question now is: does the change in vowel quality mean that nasality is distinctive in Brazilian Portuguese? We think so. Are all nasal vowels different segments? We think not (yet), but some are.

Theories of phonologization and sound change argue that a new segment emerges when coarticulatory features on a segment become part of its phonological structure. That is because the coarticulated feature becomes so perceptible that listeners think it a property of the segment, and start to use it systematically. Ohala in his work (1993a, b) argues that sound change only happens after the original conditioning environment is lost/attenuated; listeners cannot factor out the contextual influence anymore and will use the feature as an intentional part of the target segment. Hyman (1976) proposes that the original environment need not be lost, but what was an "intrinsic", or unintentional coarticulation product regulated by universal phonetic principles must become "extrinsic", or intentional and controlled by the speaker for a new contrast to emerge. At this phase, the original conditioning context is still present, but listeners do not associate the coarticulated feature to it anymore: the feature has been *phonologized*. Only after the conditioning context is fully lost is that we can call a segment *phonemicized*. So, the author considers that sound change occurs in three stages: intrinsic-phonetic → extrinsic-phonological → distinctive-phonemic (p. 34).

When bringing this approach to vowel nasality, we can think of nasal vowel emergence the same way:

Stage 1: Intrinsic vowel nasalization

Stage 2: Extrinsic vowel nasalization with the nasalizing context still present

Stage 3: Phonemic nasal vowels without the nasalizing context

This appears to have been the case with French nasal vowels, at least in some dialects. The intrinsic vowel nasalization changed vowel quality because of low restrictions in the amount of coarticulatory nasality (Stage 1), leading listeners to attribute the change to the vowel itself and produce nasal vowels with the different quality (Stage 2); finally, the nasal consonant was lost,

leaving just nasal vowels (Stage 3). This seems quite simple, if not simplistic, but it is not an unreasonable account. In modern French, it seems that the sound change process of vowel nasalization is halted, maybe due to the different way nasality is implemented in the acoustic signal in nasalized vowels (Cohn, 1990).

Can we propose a similar account for Portuguese? Based on our results for production and perception, we can certainly propose that Portuguese is in Stage 2.

Stage 1: intrinsic vowel nasalization. While intrinsic vowel nasalization occurs throughout the language (Abaurre & Pagotto, 1982), especially in carryover contexts (Moraes 2013), when it comes to nasal vowels, Brazilian Portuguese is past this stage. In fact, we can argue that the same is true for some nasalized vowels, specifically the low vowel, since they yielded similar results in both the rating and identification tasks. The other nasalized vowels seem to be at this stage, since they are confused with oral counterparts quite a lot, but not because they trigger compensation.

Stage 2: extrinsic vowel nasalization with the nasalizing context still present. We can say that nasality in Brazilian Portuguese is phonologized. The vowels are much nasal, to the point of changing some vowels' quality. The fact that participants can accurately rate and identify nasal vowels as opposed to oral vowels shows that nasality is inherent to the vowel. The same case applies to the low nasalized vowel. However, the context issue is harder to precise, because of the controversial status of the appendix[45], i.e., whether it is a consonant, a part of the vowel, or simply a prenasalization process due to gestural misalignment. In our data, the appendix was always present and was used by participants to rate and identify correctly both the nasal and the nasalized vowels. A typically phonologized process would, in principle, not rely on the context

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[45] While the heterosyllabic nasal consonant has a full consonantal phonemic status, we believe participants treated it as a long appendix, reinterpreting CV.N as CV^N, since CVN is not an allowed sequence in Brazilian Portuguese (as per out theoretical stance), and both the appendix and the consonant in our data have roughly the same duration.

in any way. While we cannot specify what role the appendix has, we can certainly say it does not hinder perception. Thus, nasality in Brazilian Portuguese is phonologized, both in nasal and nasalized vowel cases. Nasalized vowels seem to be halted in stage 2, since the nasal consonant does not show signs of being deleted any time soon. Nasal vowels, on the other hand show signs of moving into stage 3.

Stage 3: phonemic nasal vowels without the nasalizing context. If we consider that, to be classified as nasal, a vowel needs to have its quality changed, the fact that some, but not all, vowels change quality is a good indication that nasal vowels are not phonemes (yet) in Brazilian Portuguese, but may be in the process of becoming phonemic. The change seems to be occurring in a predictable way, in accordance with the Vowel Height Parameter, or VHP (Hajek &Maeda, 2000), in which "distinctive nasalization process occurs preferentially in the context of low vowels before spreading gradually to mid and then finally to high vowels when adjacent to nasal consonants (p.1)." While the VHP hypothesis is by no means universal, and many of its predictions are not empirically demonstrated, Brazilian Portuguese seems to be following it, at least when considering low vs. non-low vowels.

Furthermore, since nasal vowels tend to be followed by an appendix, it is difficult to argue for a phonemic status[46] in the idea that all associated features of a phoneme must be contained within it. However, the fact that the appendix helps with nasality instead of preventing it shows that it cannot be a typical consonant, even in a phonologized stage. It seems that there is no contextual consonant anymore and the vowels are perceived as oral or nasal (and, to a lesser extent, as nasalized) regardless of what is on the right edge. Thus, we can think of the appendix as something else, part of the vowel or a prenasalization. Given the VHP tendency to be true, and

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[46] Of course, the same would apply to some French dialects whose nasal vowels are also complex segments.

that the appendix is something other than a consonant, then we could envision a time when all the nasal vowels will change quality to keep their status.

At the same time, though, it seems that listeners relayed the percept of nasality to the appendix in some cases, changing the locus of nasality perception to this nasal resonance at the vowel's right edge. Thus, we can argue that, especially in the cases where vowel quality change is not very pronounced, the appendix may work as a perceptual cue substitute for vowel quality. Perhaps moving the locus of nasality somewhat helps maintain high nasal vowels as high in quality. High degrees of vowel nasalization would likely lower high vowels, maybe to the point of merging the with the mid vowels. If we want to maintain the high – non-high vowel contrast in Brazilian Portuguese, it is crucial to maintain the high vowels as high. If that is the case, then we can infer that the presence of the appendix may halt nasal vowel phonemicization in the most common way, i.e., through nasality in the vowel, but may allow the contrast to exist in a different way. This, of course, needs to be better investigated in future endeavors.

In conclusion, our hypotheses regarding the perception of phonemic and allophonic nasality fared well, but not in the expected way. Nasality is not the strongest perceptual feature used in recognizing nasal vowels; rather vowel quality is, showing that these vowels are distinctive, and in a process of phonemicization. The context (appendix or consonant) increases perceptual accuracy, showing that it has an important role in vowel nasality perception, maybe to the point of being the locus of nasality perception for some vowels. Similar results were obtained for the nasalized vowel, showing that these vowels are already phonologized in the language, but cannot become phonemic.

There are many limitations to this study. The biggest issue is methodological. The stimuli in the perception experiments could have been interpreted as syllables, which could cause problems

to nasal consonant stimuli, as these consonants are always heterosyllabic in Brazilian Portuguese. The nasal consonant could have been interpreted as a long nasal appendix in both experiments, which could cause nasalized vowels to be perceived as nasal vowels. If that is the case, then there is no way to know if the nasal consonant could trigger perceptual compensation, as it could have been treated like the appendix by the listeners. In addition, nasal and nasalized vowels in Brazilian Portuguese are considered very nasal, but it is difficult to quantify how much nasal a vowel must be in Brazilian Portuguese to be perceived as such. A categorical perception study is still necessary to measure the threshold of nasality, especially in cases where nasality does not alter vowel quality to see if the levels of nasality are enough for vowels to be perceived as such. Finally, the issue with the appendix and the nasal consonant aiding in perception needs to be investigated further, especially in light of the possibility of being an important perceptual cue to nasality when there are no vowel quality differences, and whether it halts the process of nasal vowels phonologization. Some may think it is trivial to measure what appears to be a well-established contrast, but, given the less conclusive perceptual results, it is clear further experimentation is needed.

Conclusions

Scientific inquiry is made of two parts: abstract modeling and testing for physical reality of those models. A complete scientific account of any phenomenon should include both, which complement each other. Linguistic inquiry is no different. Experimentation is essential to corroborate the formal model. When they do not, we may end up with unresolved and debatable issues. It also means that further and new research is needed. The phonological status of vowel nasality is among the most debated phonological questions about Portuguese, especially the Brazilian. Variation in theoretical approaches, methodologies and conclusions have made a uniform account of the issue very difficult. With the present work, we attempted to bring evidence that could shed light on the issue through perception.

First, a small-scale production study was conducted to identify differences in patterns of acoustic nasality, potential vowel quality and appendix vs. consonant duration differences that could have played a role in the perception studies. Here, it was found that oral vowels are less acoustically nasal than the non-oral vowels, with the difference decreasing depending on vowel quality. Nasal and nasalized vowels were not very different from each other except towards the end, showing that nasal vowels become more nasal over time than nasalized counterparts. There were some vowel quality changes depending on type of nasality, especially the low and mid-front vowels, but not the other three. Finally, the appendix and the consonant duration were not so different from each other, but for the appendix being more variable. These results correlated to some of the patterns found in the perception experiments.

The rating perceptual experiment tested for perceptual compensation effects of vowel nasality, to show whether nasality in vowel is interpreted by listeners as coarticulatory or as contrastive. Our hypothesis was that they would not compensate for nasal vowels. The

identification experiment tested whether nasality in the vowel, nasal or nasalized, was sufficient to cause accurate word identification. Our hypothesis was that nasality is enough. Furthermore, we expected that, if not triggering compensation, the appendix would not have any role in how participants perceived nasal and nasalized vowels.

Results were not completely as expected. Clearly there was no perceptual compensation. Nasal and nasalized vowels were perceived as such more often than chance. However, overall accuracy for non-oral vowels was not as high as that for oral vowels, showing that there is some difficulty in perceiving vowel nasality. It was found that accuracy was higher when the difference between the three types of vowels corresponded to a marked difference in quality (in terms of vowel formants), which leads us to believe that the strongest perceptual cue in our experiments was vowel quality, not vowel nasality or context nasality. The response pattern is consistent with the literature on the interaction of oral and nasal resonances and with the literature of sound change regarding the emergence of new contrasts. We proposed that the acoustic consequence of nasality in the vowel, rather than simple presence of nasality in the vowel, is the best perceptual cue to make nasal and oral vowels contrast in Brazilian Portuguese. We also found that, unlike the expectation, context nasality aids in accurate vowel nasality perception, with answers increasing when context nasality was present.

There was no perceptual compensation, indicating that, vowel nasality is not coarticulatory. Based on the experimental results, we propose that vowel nasality in Brazilian Portuguese is phonologized, and that nasal vowels are phonemic, at least for the low and mid-front vowel qualities. It is difficult to make the same claims for the mid-back and the high vowels, as at least the high vowels retain their quality despite differences in nasality. Phonologization includes nasalized vowels, as much of their perception is similar to nasal vowels', but only in Brazilian

Portuguese[47]. It also seems clear that the context nasality is considered part of the vowel. Thus, when it comes to shedding light to the issue of vowel nasality contrast in Brazilian Portuguese, we can say that vowel nasality is phonological in Brazilian Portuguese, and phonemic to a certain extent.

Saying that nasality is phonemic just for some qualities implies the possibility of a sound change in progress. While we cannot tell for sure that this is the case, it is undeniable that the current state of vowel nasality in Brazilian Portuguese is consistent with theories of sound change and vowel quality, especially vowel height. Understanding whether there is a sound change in progress is a topic for further systematic investigation, just as the possibility of the nasal appendix halting the process of sound change by preventing high vowel lowering is.

In addition to sound change issues, our work opens other questions related to vowel nasality production and perception that need to be investigated in the future. We need to investigate more systematically how perceptual compensation works in languages where a phonetic feature is undeniably phonemic and allophonic in similar contexts, so see if listeners can compensate in the latter, but not in the first case. Furthermore, it is necessary to investigate whether compensation can occur across syllable boundaries or if it only occurs within syllables. since we believe listeners in our experiments may have tread the nasal consonant as a longer nasal appendix, an experimental paradigm needs to be designed to separate syllable boundary effects in a future perceptual compensation experiment. Also, we need to further investigate the claim that nasality is only perceptually salient when it affects vowel quality. While it explains the emergence of nasal vowels in languages such as French, and the big difference between low oral and nasal/nasalized vowels, this hypothesis needs to be explicitly tested before any conclusive

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[47] European Portuguese does not have nasalized vowels, as reported in Massini-Cagliari et al (2016).

statements can be made. Another important question that needs further investigation is whether the locus of nasality could have been transferred to the appendix, halting the process of vowel quality change in high vowels in Brazilian Portuguese.

Most importantly, despite the large body of study dedicated to production of nasal vowels and vowel nasality in general, there is still the clear need for well-rounded and unified methodologies when it comes to the study of perception of vowel nasality in languages with the contrast. We hope to keep contributing to this field in the years to come.

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