Lapierre, Myriam. 2023. Two types of [NT]s in Panãra: Evidence for temporally ordered subsegments. *Glossa: a journal of general linguistics* 8(1). pp. 1–42. DOI: https://doi.org/10.16995/glossa.5739

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Two types of [NT]s in Panãra: Evidence for temporally ordered subsegments

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This paper discusses articulatory and perceptual phonetic data on Panãra (ISO code: kre), a Jê language of Central Brazil, supporting the existence of a previously undocumented phonological distinction between two types of [NT] segments. Panãra exhibits a distinction between partially nasalized consonants arising from two distinct phonological processes: post-oralization of nasal consonants (/m, n, ɲ, ŋ/ → [m^p, n^t, n^s, $ŋ^k$]), and pre-nasalization of oral obstruents (/p, t, s, k/ → [^mp, ^nt, ^ns, ^ŋk]). These [NT]s contrast in surface sequences of the type [ṼNTV], as in the minimal pair /mĩ-ŋrɛ/ → [mĩ$ŋ^k$rɛ] 'caiman egg' vs. /mĩ-krɛ/ → [mĩ^ŋkrɛ] 'caiman burrow.' This novel data provides clear evidence that phonological grammars can and do manipulate subsegmental units. The data is analyzed within the framework of Q Theory, a model of representational phonology which decomposes the segment [Q] into a series of three quantized, temporally ordered subsegments (q^1 q^2 q^3) (e.g., Shih & Inkelas 2019). The tripartite architecture of Q Theory provides the level of granularity necessary to distinguish between post-oralized nasals and pre-nasalized stops, where the former are represented with two nasal subsegments followed by one oral subsegment (m^1 m^2 p^3), and the latter are represented with a single nasal subsegment followed by two oral subsegments (m^1 p^2 p^3). It is shown that, to model the distribution between the two [NT]s in Panãra, the grammar must crucially make use of constraints that reference subsegmental units.

1 Introduction

Nasal stop-obstruent sequences are frequently observed in Panãra, a Jê language spoken in Mato Grosso, Brazil. These [NT]s result from two distinct phonological processes: post-oralization and devoicing of nasal stops before oral vowels and approximants (1a), and pre-nasalization of oral obstruents after phonemically nasal vowels (1b). These two types of [NT]s crucially contrast in surface sequences of the type [ṼNTV], as in the minimal pair /mĩ-ŋɾɛ/ → [mĩŋ^{k}ɾɛ] ‘caiman egg’ vs. /mĩ-kɾɛ/ → [mĩ^{ŋ}kɾɛ] ‘caiman burrow.’ This novel data supports the existence of a previously undocumented phonological distinction, as it has been reported that there is no language that exhibits both post-oralized and pre-nasalized [NT]s within its grammar (Maddieson & Ladefoged 1993; Steriade 1993; Botma 2004). Panãra exhibits a distinction between exactly these two types of [NT]s, arising from the two phonological processes in (1).

(1) a. /m, n, ɲ, ŋ/ → [m^{p}, n^{t}, n^{s}, ŋ^{k}] / $_{\sigma}$[_ {V, w, ɾ, j}
b. /p, t, s, k/ → [^{m}p, ^{n}t, ^{n}s, ^{ŋ}k] / Ṽ _

This finding is particularly relevant to debates on subsegmental representations, as previous models of representational phonology, such as Aperture Theory (Steriade 1993; 1994) and Autosegmental Phonology (Clements 1976; Goldsmith 1976), cannot account for the distinct phonological structures that arise from (1a) and (1b). While these two models are well suited to represent a segment such as [mb], they both predict that a contrast between post-oralized nasals and pre-nasalized stops should not be possible, as both types of [NT]s are represented with the same structure, i.e. a sequence of the distinctive features [+nasal] [–nasal].

I argue on the basis of Panãra for a tripartite model of subsegmental representations, such as Q Theory (Inkelas & Shih 2016; 2017; Shih & Inkelas 2014; 2019). Q Theory proposes a model of subsegmental representations with three distinct phases, where the large [Q] represents the segment, and the smalls q’s (q^1 q^2 q^3) represent temporally ordered subsegments. Q Theory’s architecture provides the level of granularity necessary to distinguish between post-oralization (1a) and pre-nasalization (1b), where the former is represented with two nasal subsegments followed by one oral subsegment (2a), and the latter is represented with a single nasal subsegment followed by two oral subsegments (2b). I further show that, to model the distribution between [N, T, N^{T}, ^{N}T] in Panãra within a Maximum Entropy Harmonic Grammar (MaxEnt HG; e.g. Goldwater & Johnson 2003; Wilson 2006; Hayes & Wilson 2008), the grammar must crucially include constraints that reference q subsegments.

(2) a. Post-oralized nasals b. Pre-nasalized stops

[m^{p}] [^{m}p]

↓ ↓

(m^{1} m^{2} p^{3}) (m^{1} p^{2} p^{3})

The results of two phonetic experiments support the proposed Q-theoretic representations. The first is a production experiment showing that Panãra speakers systematically produce the two types of [NT]s differently (Lin & Lapierre 2019). The second is a perception experiment showing that native Panãra listeners can reliably identify a given [NT] as arising from either post-oralization or pre-nasalization (Lapierre & Lin 2019). Taken together, the results of these experiments show that native speakers of Panãra systematically produce the two types of [NT]s distinctly and are further able to perceptually differentiate between the two structures.

This article is structured as follows: §2 provides background on Panãra and the phonological patterns that give rise to the two types of [NT]s; §3 summarizes the results of recent production and perception experiments; §4 presents the proposed Q-theoretic analysis; §5 models the data within MaxEnt HG, showing that the grammar must crucially make reference to subsegments; §6 discusses how alternative models of phonological representations cannot capture the relevant pattern; §7 discusses some consequences of the proposed model; and §8 concludes.

2 Background on Panãra

Panãra (ISO code: kre) is a Jê language spoken by approximately 630 people on the border between the Brazilian states of Pará and Mato Grosso. The language has an extensive segmental inventory with 45 phonemes, including 17 consonants and 28 vowels. Panãra's consonant inventory is provided in **Table 1**, and its vowel inventory in **Table 2**. For a detailed description of the phonological grammar of the language, see Lapierre (2023a; 2023b).

	Bilabial	**Alveolar**	**Palatal**	**Velar**
Singleton obstruent	p	t	s	k
Geminate obstruent	pː	tː	sː	kː
Singleton nasal	m	n	ɲ	ŋ
Geminate nasal	mː	nː		
Approximant	w	ɾ	j	

Table 1: Consonant phonemes.

Short oral			Short nasal		
i	ɯ	u	ĩ	ɯ̃	ũ
e	ɤ	o	ẽ	ɤ̃	õ
ɛ	a	ɔ			
Long oral			**Long nasal**		
iː	ɯː	uː	ĩː		
eː	ɤː	oː	ẽː	ɤ̃ː	õː
ɛː	aː	ɔː			

Table 2: Vowel phonemes.

In addition to its extensive phonemic inventory, Panãra also exhibits a large number of segmental alternations, resulting in a highly complex (sub)segmental phonology. The contrast for nasality is highly productive for both vowels and consonants throughout the language's lexicon, and is further complicated by a number of subsegmental alternations that result from local nasal and oral assimilation. Notably, Panãra exhibits a distinction between two types of [NT] sequences, which arise from two distinct phonological processes. The first is a categorical process whereby nasal consonants /N/ are post-oralized and devoiced [N^{T}] before approximants[1] or oral vowels (2a, 3). Plain nasal stops [N] are only observed immediately before contrastively nasal vowels (2b, 4).

(2) a. /m, n, ɲ, ŋ/ → [m^{p}, n^{t}, n^{s}, ŋ^{k}] / $_{\sigma}$[__{V, w, ɾ, j}
    b. → [m, n, ɲ, ŋ] / $_{\sigma}$[__Ṽ

(3) a. /mɯ/ → [ĩm^{p}ɯ] 'man/penis'
    b. /na/ → [ĩn^{t}a] 'rain'
    c. /nɤ̃ɲo/ → [nɤ̃n^{s}o] 'mouse'
    d. /ŋɤ/ → [ĩŋ^{k}ɤ] 'parliament'
    e. /ŋjẽ/ → [ĩŋ^{k}jẽ] '1.SG.ABS'
    f. /swɤmɾõ/ → [swɤm^{p}ɾõ] 'tapioca bread'

(4) a. /mɤ̃-mɯ̃n/ → [mɤ̃mɯ̃ŋ] 'come.IMP'
    b. /nõpjõ/ → [nõpjõ ~ nõ^{m}pjõ] 'few'
    c. /ɲɤ̃sɯ/ → [ɲɤ̃sɯ ~ ɲɤ̃^{n}sɯ] 'deer'
    d. /ŋɤ̃ː/ → [ŋɤ̃ː] 'yes'

[1] Approximants do not contrast for nasality in Panãra: They are phonologically specified as oral, and always surface as phonetically oral as well.

This phenomenon, termed *environmental shielding* by Herbert (1986), is widespread in Jê and across Amazonia more broadly. The phonological process causes a nasal consonant to undergo coarticulatory oralization, triggered by an immediately following contrastively oral vowel, where the velum is fully raised before the oral constriction (e.g. lip closure) of the underlying nasal consonant is released. Shielding is argued to be a contrast-preserving mechanism that renders oral and nasal vowels maximally distinct, as raising the velum after the oral release of the nasal consonant would induce some coarticulatory nasalization from the nasal consonant to the oral vowel (/NV/ → [N$^{\tilde{V}}$V]), thus reducing the contrast between phonemic oral and nasal vowels in the context of nasal consonants (Hyman 1975; Herbert 1986; Stanton 2017; 2018; Wetzels & Nevins 2018).

Panãra differs from other languages with environmental shielding in that the result of nasal consonant post-oralization further includes devoicing of the oral portion of the stop. Post-nasal devoicing in Panãra is categorical, and articulatory data suggests that vocal fold vibration is actively suppressed when the velum is maximally open. According to acoustic measurements (Lapierre, in press), the average duration of a post-oralized [N^{T}] is longer than that of a simple [N] or [T], but shorter than the combined duration of [N] and [T]. Panãra's post-oralized [N^{T}]s result from a direct sound change from ND > NT, likely motivated by a functional pressure to increase the perceptual salience of the oral stop release of the underlying nasal consonant (Lapierre, in press).

Surface [NT]s also arise in Panãra as the result of another phonological process, whereby oral obstruents /T/ are optionally pre-nasalized [^{N}T] following contrastively nasal vowels (5–6). This process causes an oral obstruent to become pre-nasalized as the result of coarticulation triggered by an immediately preceding contrastively nasal vowel, where the velum is raised after the oral constriction (e.g. lip closure) of the underlying oral consonant is achieved.

(5) a. /p, t, s, k/ → [^{m}p, ^{n}t, ^{n}s, ^{ŋ}k] / Ṽ_
b. → [p, t, s, k] / V_

(6) a. /kjɤ̃pɔ/ → [kjɤ̃pɔ ~ kjɤ̃^{m}pɔ] 'beiju'
b. /sõtɔ/ → [sõtɔ ~ sõ^{n}tɔ] 'tongue'
c. /ɲɤ̃seɾ/ → [ɲɤ̃seːɾi ~ ɲɤ̃^{n}seːɾi][2] 'play'
d. /kjɤ̃-kĩɲ/ → [kjɤ̃kĩɲ ~ kjɤ̃^{ŋ}kĩɲ] 'intelligent'

This phenomenon, commonly referred to as a *nasal appendix*, has been documented for several varieties of French (Léon 1983; Delvaux et al. 2008; Delvaux 2012; Coquillon & Turcsan 2012; Carignan 2013; Desmeules-Trudel & Brunelle 2018), as well as for Brazilian Portuguese (de

[2] Panãra exhibits a ban on word-final oral consonants. The presence of final oral consonants in the underlying representation of a word gives rise to two phonological processes: Word-final [i] epenthesis, and penultimate vowel lengthening (Lapierre 2023b).

Medeiros et al. 2008; Desmeules-Trudel & Brunelle 2018). Nasal appendices have also been described for another Jê language, Kaingang (Wiesemann 1972).

Pre-nasalization is optional, observed on average 72.6% of the time in /ṼT/ sequences (Lapierre & Lin 2018; items (e, f, m, o) in **Table 3**). Speakers vary in the frequency at which they pre-nasalize, where female speakers pre-nasalize at a slightly higher rate (79%) compared to male speakers (62%). Pre-nasalization also seems to occur more frequently in the onset of a prosodically strong syllable, e.g. one bearing stress or appearing in word-initial position.

Table 3 presents an exhaustive list of all possible linear orderings of nasal-oral segments in Panãra, including input-output mappings and relevant examples. Note that all nasalization and oralization processes in Panãra are strictly local, and long-distance nasal harmony is not attested.

Linear ordering		**Example**		**Gloss**
Input	**Output**	**Input**	**Output**	
a. /ṼNV/	[ṼN^{T}V]	/nɤ̃ɲo/	[nɤ̃n^{s}o]	‘mouse’
b. /VNṼ/	[VNṼ]	/kɾɛ-nõ/	[kɾɛnõ]	‘shallow water’
c. /ṼNṼ/	[ṼNṼ]	/kjã-ɲĩ/	[kjãɲĩ]	‘brain’
d. /VNV/	[VN^{T}V]	/paː-nɔ/	[paːn^{t}ɔ]	‘toe’
e. /ṼTV/	[ṼTV ~ Ṽ^{N}TV]	/sõtɔ/	[sõtɔ ~ sõ^{n}tɔ]	‘tongue’
f. /VTṼ/	[VTṼ]	/pikõ/	[pikõ]	‘proper name’
g. /ṼTṼ/	[ṼTṼ ~ Ṽ^{N}TṼ]	/sõ-tõ/	[sõtõ ~ sõ^{n}tõ]	‘their sibling’
h. /VTV/	[VTV]	/kuka/	[kuka]	‘sand’
i. /ṼNRV/	[ṼN^{T}RV]	/nãŋjɔ/	[nãŋ^{k}jɔ]	‘hot’
j. /VNRṼ/	[VN^{T}RṼ]	/swɤmɾõ/	[swɤm^{p}ɾõ]	‘tapioca bread’
k. /ṼNRṼ/	[ṼN^{T}RṼ]	/nõmɾẽ/	[nõm^{p}ɾẽ]	‘obsolete’
l. /VNRV/	[VN^{T}RV]	/ɾa-ŋɾɛː/	[ɾaŋ^{k}ɾɛː]	‘I danced’
m. /ṼTRV/	[ṼTRV ~ Ṽ^{N}TRV]	/nãpjuː/	[nãpjuː ~ nã^{m}pjuː]	‘blood’
n. /VTRṼ/	[VTRṼ]	/ka-kjã/	[kakjã]	‘your head’
o. /ṼTRṼ/	[ṼTRṼ ~ Ṽ^{N}TRṼ]	/nõpjõ/	[nõpjõ ~ nõ^{m}pjõ]	‘few’
p. /VTRV/	[VTRV]	/kukɾɛ/	[kukɾɛ]	‘house’

Table 3: Input-output mappings of possible sequences of nasal and oral segments.

Post-oralization and pre-nasalization are not simply the result of phonetic implementation: They must crucially be encoded in the phonological grammar of Panãra. Evidence for this comes from the fact that other phonological patterns in the language are sensitive to these derived structures. Crucially, post-oralized [N^{T}]s are often repaired when they occur in word-initial position. A word-initial epenthetic nasalized [ĩ] is categorically observed before a stem-initial nasal consonant, when the relevant stem is monosyllabic (Lapierre 2023b). When the nasal-initial stem is monosyllabic, a word-initial epenthetic [ĩ] vowel is categorically observed (7). When the relevant stem has two or more syllables, variation is observed between forms with initial [ĩ] epenthesis, initial [N^{T}], and denasalization of [N^{T}] (8), where the frequency of word-initial [ĩ] seems to decrease as the number of syllables in the stem increases (Lapierre 2023b). Post-oralized [N^{T}]s are never repaired word-internally.

(7) a. /nɔ/ → [ĩn^{t}ɔ] 'eye'
b. /ŋo/ → [ĩŋ^{k}o] 'water'

(8) a. /mɔ-ɲĩ/ → [ĩm^{p}ɔɲĩ ~ m^{p}ɔɲĩ ~ pɔɲĩ] 'beef'
b. /nɔ-pɤ̃ː/ → [ĩn^{t}ɔpɤ̃ː ~ n^{t}ɔpɤ̃ː ~ tɔpɤ̃ː] 'small hole'

Crucially, monosyllabic stems that begin with a plain obstruent /T/ or nasal /N/ are optionally realized with word-initial [i] epenthesis (9), but this epenthetic vowel is ungrammatical if the relevant stem has two or more syllables (10).

(9) a. /tu/ → [tu ~ itu] 'stomach'
b. /pẽː/ → [pẽː ~ ipẽː] 'language'

(10) a. /paː-kɤ/ → [paːkɤ], *[ipaːkɤ] 'shoe'
b. /nɤ̃ɲo/ → [nɤ̃n^{s}o], *[ĩnɤ̃n^{s}o] 'mouse'

Key evidence that the distinction between post-oralization and pre-nasalization must be encoded in the phonological grammar of Panãra comes from the observation that these two types of [NT]s contrast in surface sequences of the type [ṼNTV], such as in the (near-)minimal pairs in (11–15). **Figure 1** presents spectrograms of a female speaker's production of the [ṼNTV] sequences from the words in (15), namely /mĩnɔ/ → [mĩn^{t}ɔ] (left), and /mĩtɛ/ → [mĩ^{n}tɛ] (right).

(11) a. /ŋjẽ-ma/ → [ĩŋ^{k}jẽm^{p}a] 'my liver'
b. /ŋjẽ-pa/ → [ĩŋ^{k}jẽpa ~ ĩŋ^{k}jẽ^{m}pa] 'my arm'

(12) a. /kjɤ̃-ɲi/ → [kjɤ̃n^{s}i] 'big head'
b. /kjɤ̃-si/ → [kjɤ̃si ~ kjɤ̃^{n}si] 'skull'

(13) a. /mĩ-ŋɾɛ/ → [mĩŋ^{k}ɾɛ] 'caiman egg'
b. /mĩ-kɾɛ / → [mĩkɾɛ ~ mĩ^{ŋ}kɾɛ] 'caiman burrow'

(14) a. /tõ-nɔ/ → [tõn^{t}ɔ] 'sibling's eye'
b. /sõtɔ/ → [sõtɔ ~ sõ^{n}tɔ] 'tongue'

(15) a. /mĩ-nɔ/ → [mĩn^{t}ɔ] 'caiman eye'
b. /mĩ-tɛ/ → [mĩtɛ ~ mĩ^{n}tɛ] 'caiman leg'

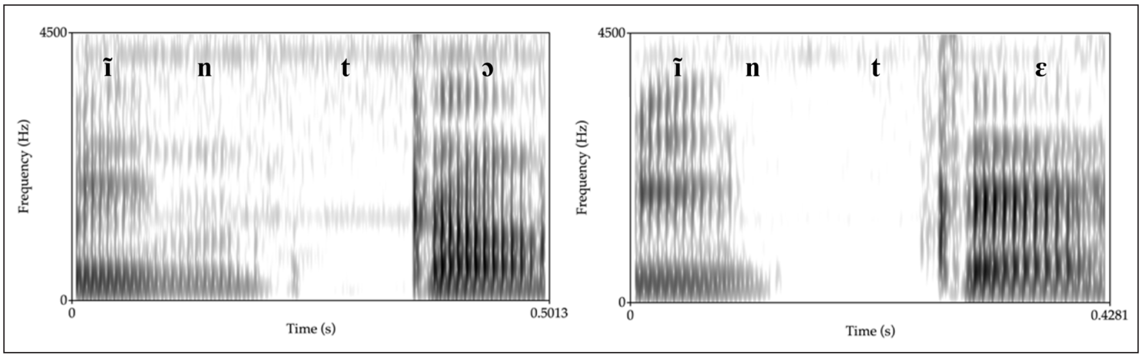

Figure 1: Spectrograms from the production of the [ṼNTV] sequences in the words /mĩnɔ/ [mĩn^{t}ɔ] ‘caiman eye’ (post-oralization, left), and /mĩtɛ/ [mĩ^{n}tɛ] ‘caiman leg’ (pre-nasalization, right).

This finding is important to the typology of nasality, as it supports the existence of a previously undocumented phonological distinction. In their overview paper on partially nasalized consonants, Maddieson & Ladefoged (1993; 283) note that, “[t]here […] seem to be several ways in which […] ‘post-stopped’ nasals differ from pre-nasalized stops in the phonetic domain, […] but it is less clear that distinct phonological structures are involved. We know of no language in which these two classes of sounds contrast with each other.” Given a lack of evidence at the time that these two types of [NT]s require distinct structures within the grammar of a single language, the authors state that post-oralized nasals and pre-nasalized stops should have the same phonological representation. As presented here, however, Panãra exhibits a distinction between exactly these two types of [NT]s, resulting from two distinct phonological processes: post-oralization of nasal consonants, and pre-nasalization of oral obstruents.

This data poses an interesting challenge for current models of representational phonology. As discussed below, this data cannot be accounted for by a purely segmental model of representation, nor can it be accounted for by several models of subsegmental representations that have been proposed in the literature, including standard Autosegmental Phonology (Clements 1976; Goldsmith 1976), and Aperture Theory (Steriade 1993; 1994). On the one hand, Aperture Theory allows for a maximum of two phases per segment, with no internal timing distinctions. On the other hand, Autosegmental Phonology allows for an unbounded number of changes between nasal and oral within a segment (assuming a binary feature [+/–nasal]), but cannot express a contrast involving a sequence of two oral or nasal features due to the Obligatory Contour Principle (Leben 1973; Goldsmith 1976; Odden 1986).

In the following section, phonetic data from two experiments (Lin & Lapierre 2019; Lapierre & Lin 2019) are discussed. The goal of the first experiment is to show that there exist systematic differences in the production of the two types of [NT]s. The goal of the second experiment is to show that native speakers of Panãra can perceptually differentiate between the two types of

[NT]s. Taken together, the results show that native speakers of Panãra systematically produce the two types of [NT]s distinctly and are further able to perceptually differentiate between the two structures, thus supporting the need for distinct phonological structures to account for post-oralized nasal stops and pre-nasalized obstruents in Panãra.

3 Experimental evidence

3.1 Evidence from production

Lin & Lapierre (2019) conducted a production experiment, designed to test whether Panãra speakers produce [NT]s arising from post-oralization and pre-nasalization differently. Acoustic recordings, along with oral and nasal airflow data, were collected from 7 native speakers of Panãra (3 female) during the production of both types of [NT]s. The results of the experiment show that Panãra speakers do indeed systematically produce these two types of [NT]s distinctly with respect to three articulatory measures.

These articulatory measures were obtained by calculating the time interval between two articulatory landmarks from the acoustic and airflow data. A total of five articulatory landmarks were identified for each [NT] token in the data,[3] all of which are marked for one token of a post-oralized nasal stop (left) and a pre-nasalized stop (right) in **Figure 2**: (i) offset of vocal fold vibration (dotted black line), (ii) achievement oral cavity constriction (right pointing orange arrow), (iii) oral constriction release (left pointing orange arrow), (iv) onset of velic closure (right pointing blue arrow), and (v) achievement of velic closure (left pointing blue arrow). As described in Lin & Lapierre (2019), offset of vocal fold vibration in each [ṼNTV] token was determined by using Praat's PointProcess object (Boersma & Weenink 2008). Articulatory landmarks relating to velic movement and oral cavity constriction were operationalized by identifying the inflection points (i.e. local minima and maxima of the second derivative) in the nasal and oral airflow curves, respectively. The achievement of velic and oral constriction was operationalized as the inflection point with negative slope and zero nasal and oral airflow, respectively. Onset of velic and oral release was operationalized as the inflection point with negative slope and non-zero nasal and oral airflow, respectively.

From these articulatory landmarks, oral lag, velum raising, and voicing lag were calculated as follows:

i. oral lag = onset of velic closure – achievement of oral constriction;

ii. velum raising = achievement of velic closure – onset of velic closure; *and*

iii. voicing lag = achievement of velic closure – offset of vocal fold vibration.

[3] The data presented for pre-nasalized stops is for the subset of /ṼT/ tokens where pre-nasalization did occur, i.e. for all tokens that surfaced as [Ṽ^{N}T].

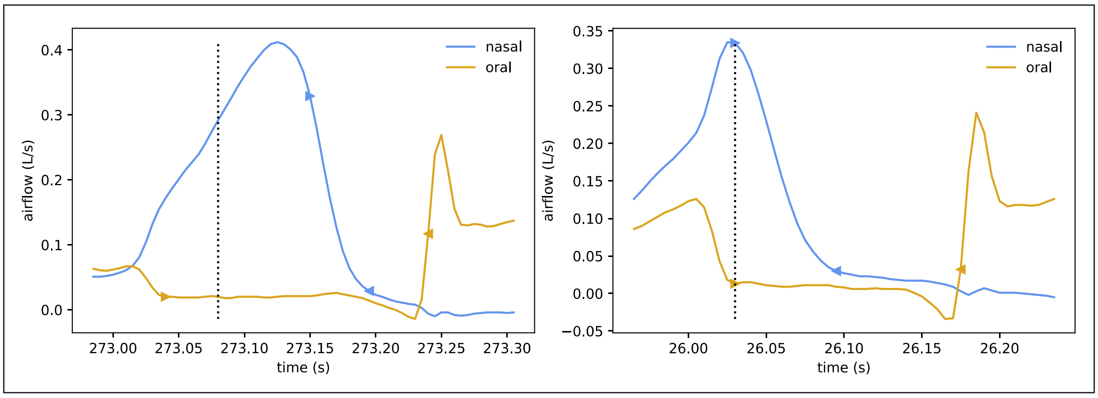

Figure 2: Oral (orange) and nasal (blue) airflow channel during the production of the [ṼNTV] sequences in the word /mĩnɔ/ [mĩn^{t}ɔ] 'caiman eye' (post-oralization, left), and /mĩtɛ/ [mĩ^{n}tɛ] 'caiman leg' (pre-nasalization, right).[4] The dotted black line indicates the offset of voicing.

Results of Lin & Lapierre's experiment show that post-oralized nasals and pre-nasalized stops significantly differed according to all three articulatory measures. Oral lag, velum raising, and voicing lag were all found to be significantly greater for post-oralized nasals relative to pre-nasalized stops. **Table 4** presents a summary of the estimated durations for each of the articulatory measures from Lin & Lapierre's statistical model.

	Post-oralized nasals [N^{T}]	**Pre-nasalized stops [^{N}T]**
Oral lag	100 ms	27 ms
Voicing lag	78 ms	43 ms
Velum raising	83 ms	51 ms

Table 4: Articulatory measures' estimated duration from Lin & Lapierre's statistical model.

The authors' results show that the onset of velum raising happens significantly later after the achievement of oral closure in post-oralized nasals vs. pre-nasalized stops. Likewise, the onset of the velum raising gesture happens significantly later after the offset of vocal fold vibration in post-oralized nasals; and the velum raising gesture is realized significantly more slowly. Furthermore, the achievement of oral constriction, the onset of velic closure, and the offset of vocal fold vibration all happen at roughly the same time during the production of pre-nasalized stops, while these three gestures are sequential with respect to one another during the production of post-oralized nasals. For the latter, the oral closure is always achieved first, followed by the offset of vocal fold vibration, and the onset of velic closure. In **Figure 3** (reproduced from the original article), the relevant articulatory gestures are represented as gestural scores to

[4] Reproduced from Lin & Lapierre (2019).

schematize the alignment between the oral, nasal, and glottal gestures in pre-nasalized stops (left) and misalignment of these same gestures for post-oralized nasals (right), where each box represents a gesture's total duration.

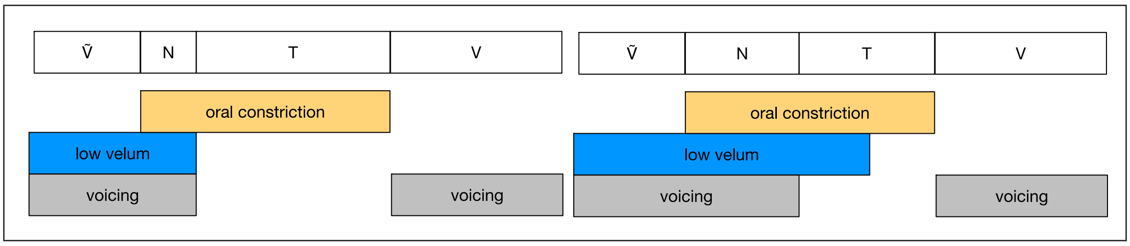

Figure 3: Gestural scores for a pre-nasalized stop (left) and post-oralized nasal (right).[5]

In sum, the data from the production experiment suggests that Panãra speakers systematically produce [NT]s arising from post-oralization and pre-nasalization distinctly. As such, the contrast between underlying /T/ and /N/ is retained in surface structures, providing strong evidence in favour of the need for the two types of [NT]s to be mapped to different representational structures within the phonological grammar of Panãra.

3.2 Evidence from perception

Lapierre & Lin (2019) also conducted a perception experiment, designed to test whether native Panãra listeners can perceptually distinguish between the two types of [NT]s and identify a given [NT] as arising from either post-oralization or pre-nasalization. This experiment further tested which acoustic cues speakers of Panãra rely on in identifying a given [NT] as arising from post-oralized /N/ or pre-nasalized /T/.

The authors conducted a four-option forced choice task involving a minimal quadruple of the shape /TV, TṼ, NV, NṼ/ (16). Each token was presented auditorily, embedded within the carrier phrase [kjẽhẽ kasũ X] *I say the word X*, where X is the target word. This carrier phrase crucially places the target consonant immediately after a nasal vowel, generating the phonotactic environment required for pre-nasalization to occur. The stimuli for this experiment were created by synthesizing original recordings of these words by a male native speaker of Panãra. The following acoustic cues were manipulated: (i) relative duration of the nasal murmur and oral stop closure duration; (ii) quality of the nasal murmur, (iii) presence or absence of an oral stop burst, and (iv) oral or nasal quality of the vowel immediately following the target [NT]. Only the results of the experiment relating to the first three manipulations are discussed here. Please refer to the original article for a full discussion of the results.

[5] Reproduced from Lin & Lapierre (2019).

(16)	a.	/pa/ → [pa ~ ^{m}pa]	‘arm’
	c.	/ma/ → [m^{p}a]	‘liver’
	b.	/pã/ → [pã ~ ^{m}pã]	‘owl’
	d.	/mã/→ [mã]	‘rhea’

The authors collected perception data from 36 Panãra listeners between the ages of 16 and 40 (mean = 25), including 21 females. Experimental results show that listeners’ perception of the acoustic stimuli varied as a function of the relative duration of the nasal murmur and oral stop components of the [NT]s. As seen in **Figure 4**, as the relative duration of the nasal murmur in the [NT] sequence increases, so do the proportion of /N/ responses. This suggests that those differences that are observed in the production of post-oralized and pre-nasalized [NT]s in Panãra also serve as acoustic cues to the distinction between the two phonological structures in speech perception.

Results also show that listeners’ perception was affected by the quality of the nasal murmur. All else being equal, listeners are more likely to categorize a given [NT] token as arising from /N/ than /T/ if the nasal murmur is of greater amplitude (orange lines), compared to nasal murmur of lower amplitude (blue lines). The authors also found that the presence of a stop burst increased /T/ responses: Listeners required a greater proportion of nasal murmur to perceive /N/ when a burst was present (solid lines) than when it was absent (dashed lines).

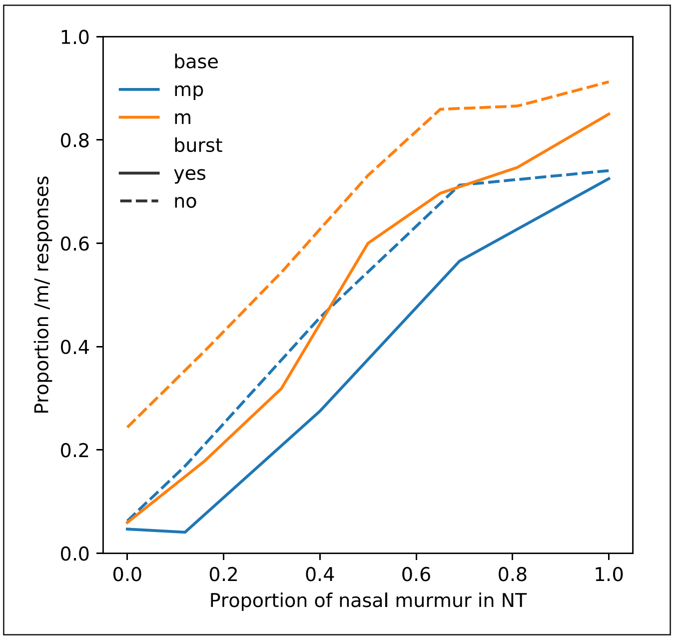

Figure 4: Proportion of /m/ responses by relative duration of nasal murmur to oral stop closure, and by quality of nasal murmur and presence of stop burst.[6]

[6] Reproduced from Lapierre & Lin (2019).

In sum, the data from the perception experiment suggests that native Panãra listeners can reliably identify a given [NT] token as arising from either post-oralization or pre-nasalization. All experimental manipulations had a significant effect on listeners' responses to the stimuli, where the following acoustic cues increase the proportion of /N/ response: (i) longer relative duration of the nasal murmur compared to the oral stop closure; (ii) nasal murmur with higher amplitude and more regular periodicity; and (iii) absence of an oral stop burst. As such, the contrast between underlying /T/ and /N/ is retained in surface structures, in both the articulatory and perceptual domains, providing strong evidence in favour of the need for the two types of [NT]s to have distinct phonological representations structures in Panãra's grammar.

4 A Q theoretic subsegmental analysis

4.1 Background

Q Theory is a model of representational phonology which decomposes the segment [Q] into a series of quantized, temporally ordered subsegments (q) (Shih & Inkelas 2014; 2019; Inkelas & Shih 2016; 2017). Q Theory builds on Aperture Theory (Steriade 1993; 1994) by proposing that the canonical short segment is represented with three subsegments (q^1 q^2 q^3) roughly corresponding to the onset, c-center (mid-point of gestural plateau), and release of a gesture. Segments may deviate from this canon by possessing more or fewer subsegments (Inkelas & Shih 2017; Garvin et al. 2018; 2020; Schwarz et al. 2019).

Q Theory assumes much of the same machinery as the Sound Pattern of English (SPE, Chomsky & Halle 1968), namely the quantization of the temporal dimension of speech into phonological units made up of feature bundles that can be manipulated by the grammar. Following Shih & Inkelas (2019), each q subsegment is a representational unit consisting of a canonical feature bundle, and subsegments are featurally uniform, meaning that for any given phonological feature [+/–F], a subsegment may not possess more than one value. For the feature [nasal], Q Theory assumes the possible discretization [+nasal], [–nasal], or [∅nasal]. Since Q Theory allows for the phonological grammar to operate on temporal units smaller than the segment, this gives rise to more fine-grained distinctions in phonological representations than could be afforded by SPE, Autosegmental Phonology, and Aperture Theory.

Clear evidence of a need for a tripartite division of the segment comes from the existence of segments consisting of triple tone contours, triphthongs, and pre-nasalized affricates, as in (17) (examples from Shih & Inkelas 2019).

(17)		Segment	Subsegment	Example
	a.	â̌	(L H L)	Mende contour mbâ̌, 'companion' (Leben 1978: 186)
	b.	e̯ai̯	(e a i)	Romanian triphthong cite̯ai̯, 'read.IND.IMPF.2SG' (Dindelegan 2013: 12)
	c.	ndz	(n d z)	Pre-nasalized affricate, (e.g. Steriade 1993)

In addition, some languages provide evidence from crucial contrasts which require a tripartite representation of the segment. Dinka and Shilluk (Remijsen 2013; Remijsen & Ayoker 2014) present a contrast between early falling vs. late falling HL tone contours, mirroring the pattern observed for post-oralized and pre-nasalized [NT]s in Panãra. Similarly, Pycha (2009; 2010) showed that the Hungarian affricates /ts/ and /tʃ/ differ in their internal relative timing: the frication portion of /ts/ is longer than that of /tʃ/. Inkelas & Shih (2017) propose the Q theoretic representations for the Dinka and Shilluk pattern in (18), and for Hungarian affricates in (19).

(18) a. Early falling (H L L) b. Late falling (H H L)

(19) a. /ts/ (t s s) b. /tʃ/ (t t ʃ)

4.2 Proposal

The combined results of the production and perception experiments presented in §3 suggest a robust distinction between post-oralized nasals and pre-nasalized stops in Panãra. If the two types of [NT]s shared the same phonological representation, this would predict that they should be phonetically implemented in the same way. However, this is not the case: The two structures are systematically articulated distinctly, and native Panãra speakers can reliably differentiate between them. As such, the phonological representations of the two types of [NT]s must be distinct.

The novel typological pattern observed in Panãra poses a challenge to traditional models of phonological representations that assume that segments are the smallest timing units in the phonological grammar. Given that a segmental analysis cannot capture the distinction between post-oralized nasals and pre-nasalized stops in Panãra, this data provides clear evidence that phonological grammars can and do manipulate subsegmental units.

On the basis of Panãra, I argue for a tripartite model of subsegmental representations, such as Q Theory. Q Theory's architecture provides the level of granularity necessary to distinguish between post-oralized nasals and pre-nasalized stops, where the former is represented with two [+nasal] subsegments followed by one [–nasal] subsegment, and the latter is represented with a single [+nasal] subsegment followed by two [–nasal] subsegments, as in (20). As will be argued in §6, previous models of phonological representations are not sufficient to capture the distinction between post-oralized nasals and pre-nasalized stops in Panãra.

(20) a. **Post-oralized nasals** b. **Pre-nasalized stops**

a.
$$\begin{array}{ccc} & [^{m}p] & \\ & \downarrow & \\ (m^{1} & p^{2} & p^{3}) \\ \begin{bmatrix} +\text{nasal} \\ -\text{cont.} \\ \dots \end{bmatrix} & \begin{bmatrix} -\text{nasal} \\ -\text{cont.} \\ \dots \end{bmatrix} & \begin{bmatrix} -\text{nasal} \\ -\text{cont.} \\ \dots \end{bmatrix} \end{array}$$

b.
$$\begin{array}{ccc} & [^{m}p] & \\ & \downarrow & \\ (m^{1} & p^{2} & p^{3}) \\ \begin{bmatrix} +\text{nasal} \\ -\text{cont.} \\ \dots \end{bmatrix} & \begin{bmatrix} -\text{nasal} \\ -\text{cont.} \\ \dots \end{bmatrix} & \begin{bmatrix} -\text{nasal} \\ -\text{cont.} \\ \dots \end{bmatrix} \end{array}$$

The goal of this article proposes a grammar of subsegmental representations which provides enough granularity to account for the full range of typological phenomena involving pattens of local nasalization and oralization, while at the same time not providing more detail than is strictly necessary. In other words, the goal is to articulate a model that encodes a minimal but sufficient amount of information to derive both contrastive and distinctive structures. The following section provides a MaxEnt HG grammar of Panãra [NT]s, showing how the use of constraints that make reference to q subsegments is crucial for modeling the relevant pattern.

5 A grammar of subsegments

5.1 Constraints

The distinction between post-oralized $[N^{T}]$ and pre-nasalized $[^{N}T]$ in Panãra provides clear evidence that phonological grammars can and do manipulate subsegmental units. I follow current work in phonology by modeling the observed distribution between $[N, T, N^{T}, {}^{N}T]$ and deriving the patterns of local nasal and oral assimilation observed in consonants within the framework of Agreement-by-Correspondence (ABC; Walker 2000; Hansson 2001; 2010; Rose & Walker 2004). Recent work within ABC has extended the mechanism of feature agreement to account for processes of local assimilation (Wayment 2009; Shih & Inkelas 2014; Sylak-Glassman, Farmer, & Michael 2014; Shih & Inkelas 2019). In this way, all local and long-distance assimilation processes can be derived via feature agreement, driven by correspondence relationships. The innovation of ABC + Q (Agreement-by-Correspondence + Q Theory; Shih & Inkelas 2019) further allows for feature agreement between *sub*segmental units. ABC + Q is particularly well suited to modeling patterns of local nasal and oral assimilation, as it partial segmental assimilation is elegantly captured by the simple generalization that linearly adjacent edges of segments often share the same value for the feature [nasal].

The first set of constraints needed are those that establish crucial correspondence relationships between adjacent subsegments across a segment boundary. Defined in Q-theoretic terms (Shih & Inkelas 2019), the first CORRESPONDENCE constraint establishes correspondence and drives agreement[7] between any two adjacent q subsegments separated by a Q segment boundary and requires that they agree in the feature [+/–nasal] (21). This constraint accounts for the overwhelming cross-linguistic tendency for edges of segments to agree in nasality or orality (see also Pulleyblank 2002; and Mahanta 2007; 2009 on banning sequences of the type [+F][–F]).

(21) **Corr-q:Q:q**: Assign one violation for every consecutive pair of subsegments (q_i, q_j) if
- i. q_i and q_j are not in a surface correspondence relationship;
- ii. q_i and q_j are immediately adjacent;
- iii. q_i and q_j are separated by no more and no less than one Q segment boundary; *and*
- iv. q_i and q_j do not agree in the feature [+/–nasal].

In addition to the general constraint in (21), the derivational grammar of Panãra requires a more specific constraint establishing cross-segment subsegmental correspondence, which targets sequences in which the first subsegment is a consonant and the second subsegment is a vowel. This more specific Correspondence constraint establishes correspondence and drives agreement between any consonant subsegment immediately followed by a vowel subsegment, if they are separated by a Q segment boundary, and requires that they agree in the feature [+/–nasal] (22). This additional constraint is needed given that the processes of post-oralization and pre-nasalization are not observed at the same frequency, where the former is a categorical process, and the latter applies variably, with an average rate of application of 72.6%.

(22) **Corr-c:Q:v**: Assign one violation for every consecutive pair of subsegments (q_i, q_j) if
- i. q_i and q_j are not in a surface correspondence relationship;
- ii. q_i and q_j are immediately adjacent;
- iii. q_i and q_j are separated by no more and no less than one Q segment boundary;
- iv. qi is a consonant and qj is a vowel; *and*
- v. q_i and q_j do not agree in the feature [+/–nasal].

Because both of the constraints in (21) and (22) are active within Panãra's grammar, input sequences of the type /NV/ that surface without post-oralization are penalized by both constraints, while input sequences of the type /ṼT/ that surface without pre-nasalization are only penalized by the general constraint in (21). Taken together, the constraints in (21) and (22) capture the fact that /NV/ input sequences are repaired more frequently than /ṼT/ input

[7] Recent work within ABC has shown that formally separating Correspondence and Output-Output Identity constraints has little utility, and suggests combining them into a single conflated constraint (Hansson 2014; Walker 2015; Shih & Inkelas 2019). Following these conventions, I conflate them under the label of Correspondence. This simplified machinery allows for a smaller set of constraints while incurring no costs on the accuracy or efficacy of the grammatical model.

sequences. In the case of Panãra, this can be explained by the fact that post-oralization is phonologically motivated by the categorical need for shielding, whereas pre-nasalization is due to a more gradient coarticulatory phenomenon, resulting from the biomechanical fact that the velum raises slowly.

In order to derive the correct patterns of local nasal and oral assimilation observed in Panãra, the model additionally requires a subtype of CORRESPONDENCE constraint which establishes a correspondence relationship between any two adjacent q subsegments contained within the same Q segment. The second type of CORRESPONDENCE constraint accounts for the fact that, when all of the subsegments in a segment agree in nasality or orality, this has the consequence of enhancing the cues to the perceptibility of that contrast in a particular class of segments. Following Stanton (2017; 2018), for a contrast in vowel nasality to be sufficiently distinct, phonemically oral vowels must be realized as fully oral, and phonemically nasal vowels must be realized as fully nasal. Stanton's proposal formalizes this using a MINIMUM DISTANCE constraint (Flemming 2002; 2004), which is evaluated by looking at the proportion of a vowel's raw duration that is oral or nasal. Here, I use a CORRESPONDENCE constraint that is evaluated against abstract representational units, namely q subsegments. This constraint establishes a correspondence relationship between pairs of adjacent vowel subsegments contained with the same Q segment and requires that they agree in the feature [+/–nasal] (23), effectively achieving the same goal as a MINIMUM DISTANCE constraint.

(23) **CORR-(VV)**: Assign one violation for every consecutive pair of subsegments (q_i, q_j) if
- i. q_i and q_j are not in a surface correspondence relationship;
- ii. q_i and q_j are immediately adjacent;
- iii. q_i and q_j are not separated by a Q segment boundary;
- iv. q_i and q_j are vowels; *and*
- v. q_i and q_j do not agree in the feature [+/–nasal].

The addition of (23) in the grammar effectively forces any modification in nasality or orality between the input and the output to be realized on consonants, rather than vowels. While (21) only requires that edge subsegments agree in the feature [+/–nasal], it does not specify whether a vowel should agree with an adjacent consonant, or whether a consonant should agree with an adjacent vowel. As such, when taken together, the two constraints in (21) and (23) effectively force changes to occur to consonant subsegments rather than vowel subsegments, thereby prioritizing faithfulness to vowels over faithfulness to consonants.

The notion of faithfulness, however, is contingent on the presence of an active constraint in the grammar of Panãra which ensures that output subsegments match the feature matrix of their respective input subsegments. The necessary faithfulness constraint in this particular case evaluates changes in the input-output mappings of subsegments for the feature [+/–nasal] (24).

(24) **IDENT-IO-q [F] :** Assign one violation for every q subsegment in the input whose output correspondent does not match in its value for the feature [F].

Finally, the last constraint needed is one that penalizes output [TN] sequences, but not [NT] sequences (25).

(25) ***TN:** Assign one violation for every consecutive pair of subsegments (q_i, q_j) if q_i is a voiceless oral obstruent and q_j is a nasal consonant.

This markedness constraint is needed, as both /NV/ and /ṼT/ input sequences result in an output [NT] sequence, but neither /TṼ/ nor /VN/ input sequences result in an output [TN] sequence (see **Table 3**). In other words, all sequences of the type [+nasal][−nasal] are repaired within the grammar of Panãra, regardless of whether the relevant segments are consonants or vowels, but sequences of the type [−nasal][+nasal] are never repaired. In practice, this constraint penalizes all segments of the shape (T N N), (T T N), or (T N T). This pattern observed in Panãra follows from the general markedness of [TN] segments cross-linguistically justifying its formulation as a markedness constraint. Complex segments of the type [NT] combine the most perceptually salient portions of both an oral and a nasal stop, while segments of the type [TN] combine the least perceptually salient portions of both oral and nasal stops (see §7.1). This perception-based explanation provides a functional motivation for the greater cross-linguistic frequency of [NT], as well as the presence of [NT] segments but not [TN] segments in Panãra's grammar more specifically.

5.2 A MaxEnt Harmonic Grammar of subsegments

I model the distribution of Panãra [NT]s within MaxEnt HG[8] (e.g. Goldwater & Johnson 2003; Wilson 2006; Hayes & Wilson 2008). MaxEnt HG is a probabilistic variant of Harmonic Grammar (Legendre et al. 1990) in which constraints are weighted, and candidates within a candidate set are assigned a probability value. This component of the MaxEnt Grammar crucially allows for modeling the non-categorical behaviour of pre-nasalization in Panãra. For each candidate, a $\mathscr{H}$armony score is calculated from constraint weights and the candidate's constraint violations. This $\mathscr{H}$armony value is translated into an output probability for a given candidate, roughly representative of its relative frequency, where the total summed probability of all candidates in the set is 1. The relative probability of two (or more) candidates is dependent on the difference between their harmony scores, where candidates with lower harmony scores (i.e. closer to negative infinity) are observed more frequently.

[8] The model presented here uses a version of the MaxEnt equation that takes the exponential of the negative harmony score.

The MaxEnt Grammar Tool (George et al. 2006) was used to learn constraint weights and compute the probability of all candidates. **Tables 5–8** below exhaustively present the input data provided to the learning algorithm. All four constraints were given default initial weights of $\mu = 0$, and a prior of $\sigma^2 = 100{,}000$, which remained constant after optimization. The average error per candidate was 0.001%, which is particularly low, meaning that the model was able to match the input frequencies remarkably well. Constraint weights have been rounded to the second decimal point for ease of exposition, and all changes from the input have been underlined in the output.

Table 5 presents the Tableau for an input /ṼNV/ sequence. In Candidate (a), the underlying nasal consonant is post-oralized before a phonemically oral vowel. Candidate (b) is fully faithful, meaning that there is no change between the input and the output. In Candidate (c), the first q subsegment of the underlying oral vowel is nasalized following a phonemically nasal consonant. In Candidate (d), all three subsegments of the underlying oral vowel have been nasalized following the nasal consonant. The model was able to reproduce the observed frequency of each one of the candidates with nearly perfect accuracy. Candidate (b) is predicted to surface with exceedingly low probability because it violates both of the constraints requiring agreement of adjacent subsegments across a segment boundary for the feature [+/–nasal], namely CORR-q:Q:q and CORR-c:Q:v. Candidate (c) is likewise predicted to occur with exceedingly low probability because it incurs a violation of the IDENT-IO-q constraint, in addition to a violation of the CORR-(vv) constraint, which requires adjacent vowel subsegment contained within the same segment to agree for the feature [+/–nasal]. Candidate (d) is also predicted to occur with exceedingly low frequency because it incurs three violations of IDENT-IO-q. The optimal candidate, that is, the candidate with the highest predicted frequency, is Candidate (a), which incurs only a violation of the IDENT-IO-q constraint.

Table 6 presents the Tableau for an input /ṼTV/ sequence. In Candidate (a), the underlying oral obstruent is pre-nasalized after a phonemically nasal vowel. Candidate (b) is fully faithful. In Candidate (c), the last q subsegment of the underlying nasal vowel is oralized before the oral consonant. In Candidate (d), all three subsegments of the underlying nasal vowel have been oralized preceding the oral consonant. As in the Tableau above, the model was able to reproduce the observed frequency of each candidate with nearly perfect accuracy. Candidate (c) is predicted to surface with extremely low probability because it incurs a violation CORR-(vv), in addition to a violation of the IDENT-IO-q constraint. Candidate (d) is likewise predicted to surface with very low probability because it incurs three violations of IDENT-IO-q. Candidate (a) is predicted to surface most frequently at 72.6% of the time, as it incurs only a violation of IDENT-IO-q. Finally, Candidate (b) is predicted to surface 27.4% of the time, as it only incurs a violation of the more general constraint penalizing pairs of corresponding adjacent subsegments separated by a segmented boundary which do not agree for the feature [+/–nasal], CORR-q:Q:q.

/ṼNV/ (Ṽ^1 Ṽ^2 Ṽ^3)(N^1 N^2 N^3)(V^1 V^2 V^3)	**Corr-(vv)**	***TN**	**Corr-q:Q:q**	**Ident-IO-q**	**Corr-c:Q:v**	**ℋarmony**	**Observed frequency**	**Predicted frequency**
	15.12	**15.12**	**8.83**	**7.86**	**6.04**			
a. [ṼN$^{\underline{T}}$V] (Ṽ Ṽ Ṽ)(N N <u>T</u>)(V V V)				1		7.86	1	1
b. [ṼNV] (Ṽ Ṽ Ṽ)(N N N)(V V V)			1		1	16.69	0	0
c. [ṼN$^{\underline{\tilde{V}}}$V] (Ṽ Ṽ Ṽ)(N N N)(<u>Ṽ</u> V V)	1			1		22.98	0	0
d. [ṼN<u>Ṽ</u>] (Ṽ Ṽ Ṽ)(N N N)(<u>Ṽ Ṽ Ṽ</u>)				3		23.58	0	0

Table 5: Tableau for /ṼNV/ input sequence

/ṼTV/ (Ṽ^1 Ṽ^2 Ṽ^3)(T^1 T^2 T^3)(V^1 V^2 V^3)	**Corr-(vv)**	***TN**	**Corr-q:Q:q**	**Ident-IO-q**	**Corr-c:Q:v**	**ℋarmony**	**Observed frequency**	**Predicted frequency**
	15.12	**15.12**	**8.83**	**7.86**	**6.04**			
a. [Ṽ$^{\underline{N}}$TV] (Ṽ Ṽ Ṽ)(<u>N</u> T T)(V V V)				1		7.86	0.726	0.726
b. [ṼTV] (Ṽ Ṽ Ṽ)(T T T)(V V V)			1			8.83	0.274	0.274
c. [Ṽ$^{\underline{V}}$TV] (Ṽ Ṽ Ṽ)(T T T)(V V V)	1			1		22.98	0	0
d. [<u>V</u>TV] (<u>V V V</u>)(T T T)(V V V)				3		23.58	0	0

Table 6: Tableau for /ṼTV/ input sequence.

Table 7 presents the Tableau for an input /VNṼ/ sequence. In Candidate (a), the underlying nasal consonant is pre-oralized after a phonemically oral vowel. Candidate (b) is fully faithful. In Candidate (c), the last q subsegment of the underlying oral vowel is nasalized before the nasal consonant. In Candidate (d), all three subsegments of the underlying oral vowel have been nasalized preceding the nasal consonant. The model was again able to reproduce the observed frequency of each one of the candidates. Candidate (a) is predicted to occur at an exceedingly low frequency because it incurs a violation of the *TN constraint, as well as of IDENT-IO-q. Candidate (c) is likewise predicted to occur at an exceedingly low frequency because it incurs violations of both the CORR-(vv) and IDENT-IO-q constraints. Candidate (d) is also predicted to occur with a very low frequency because it incurs three violations of IDENT-IO-q. The candidate with the highest predicted frequency, Candidate (b), only incurs a violation of the more general constraint penalizing pairs of corresponding adjacent subsegments separated by a segmented boundary which do not agree for the feature [+/–nasal], CORR-q:Q:q.

Finally, **Table 8** presents the Tableau for an input /VTṼ/ sequence. In Candidate (a), the underlying oral obstruent is post-nasalized before a phonemically nasal vowel. Candidate (b) is fully faithful. In Candidate (c), the first q subsegment of the underlying nasal vowel is oralized after the oral obstruent. In Candidate (d), all three subsegments of the underlying nasal vowel have been oralized following the oral consonant. As in the Tableaux above, the model was able to reproduce the observed frequency of each one of the candidates. Candidate (a) is predicted to occur at an exceedingly low frequency because it incurs violations of both the *TN and IDENT-IO-q constraints. Candidate (c) is likewise predicted to occur at an exceedingly low frequency because it incurs violations of both the CORR-(vv) and IDENT-IO-q constraints. Candidate (d) is also predicted to occur at a very low frequency because it incurs three violations of IDENT-IO-q. IDENT-IO-q. The candidate with the highest predicted frequency, Candidate (b), incurs violations of two lowly-weighted constraints, CORR-q:Q:q and CORR-c:Q:v, which require corresponding subsegments separated by a segmented boundary which do not agree for the feature [+/–nasal].

The MaxEnt HG analysis presented here demonstrates the need for tripartite subsegmental representations to be included in the phonological grammar in order to model the observed distribution of fully nasal [N], fully oral [T], post-oralized [N^{T}] and pre-nasalized [^{N}T] consonants in Panãra. This was implemented by making use of five constraints that crucially make reference to q subsegments: CORR-q:Q:q, CORR-c:Q:v, CORR-(vv), IDENT-IO-q[F], and *TN.

6 Alternative models of subsegmental representations

In this section, I show that previous models of phonological representations are unable to account for the distinction between post-oralization and pre-nasalization in Panãra. §6.1 considers classic models of segmental representation (Chomsky & Halle 1968; Anderson 1976); §6.2 considers

/VNṼ/ (V^1 V^2 V^3)(N^1 N^2 N^3)($\tilde{V}^1$ $\tilde{V}^2$ $\tilde{V}^3$)	**Corr-(vv)**	***TN**	**Corr-q:Q:q**	**Ident-IO-q**	**Corr-c:Q:v**	**ℋarmony**	**Observed frequency**	**Predicted frequency**
	15.12	**15.12**	**8.83**	**7.86**	**6.04**			
a. [V^{T}NṼ] (V V V)($\underline{\text{T}}$ N N)(Ṽ Ṽ Ṽ)		1		1		22.98	0	0
b. [VNṼ] (V V V)(N N N)(Ṽ Ṽ Ṽ)			1			8.83	1	1
c. [V^{Ṽ}NṼ] (V V $\underline{\tilde{\text{V}}}$)(N N N)(Ṽ Ṽ Ṽ)	1			1		22.98	0	0
d. [$\underline{\tilde{\text{V}}}$NṼ] ($\underline{\tilde{\text{V}}\ \tilde{\text{V}}\ \tilde{\text{V}}}$)(N N N)(Ṽ Ṽ Ṽ)				3		23.58	0	0

Table 7: Tableau for /VNṼ/ input sequence.

/VTṼ/ (V^1 V^2 V^3)(T^1 T^2 T^3)($\tilde{V}^1$ $\tilde{V}^2$ $\tilde{V}^3$)	**Corr-(vv)**	***TN**	**Corr-q:Q:q**	**Ident-IO-q**	**Corr-c:Q:v**	**ℋarmony**	**Observed frequency**	**Predicted frequency**
	15.12	**15.12**	**8.83**	**7.86**	**6.04**			
a. [VT^{N}Ṽ] (V V V)(T T $\underline{\text{N}}$)(Ṽ Ṽ Ṽ)		1		1		22.98	0	0
b. [VTṼ] (V V V)(T T T)(Ṽ Ṽ Ṽ)			1		1	14.87	1	1
c. [VT^{V}Ṽ] (V V V)(T T T)($\underline{\text{V}}$ Ṽ Ṽ)	1			1		22.98	0	0
d. [VT$\underline{\text{V}}$] ($\underline{\text{V V V}}$)(T T T)(V V V)				3		23.58	0	0

Table 8: Tableau for /VTṼ/ input sequence.

non-linear accounts of Autosegmental Phonology (Clements 1976; Goldsmith 1976) and Feature Geometry (e.g. Durvasula 2009); §6.3 discusses Aperture Theory (Steriade 1993; 1994); and finally, §6.4 considers gestural frameworks, including Articulatory Phonology (Browman & Goldstein 1989; 1992) and Gestural Coordination Theory (Gafos 2002).

6.1 Segments are not enough

Many of the basic tenets of SPE are still widely used in modern phonology, in particular the idea that the phonological grammar manipulates temporally quantized elements, namely segments, where each segment is made up of a matrix of distinctive features defining its articulatory-acoustic content. Segments are phonological units that appear in a linear sequence in the input and output phonological representations of morphemes, and they are the grammatical unit that phonological rules manipulate. In this framework, nasality is generally analyzed as a binary feature with possible positive [+nasal] and negative [–nasal] values.

Despite its transformative consequences for the field, SPE falls short of accounting for all phonological patterns observed in the world's languages. For instance, SPE's notion of a uniform segment cannot account for complex segments, such as affricates (e.g. [tʃ]) and complex nasals (e.g. [mb]). In particular, SPE cannot straightforwardly account for temporal misalignment between the onset and offset of oral and nasal gestures, as feature matrices apply to whole segments. Given that the smallest unit of representation is the segment, SPE is unable to account for the occurrence of partially nasal segments, such as [mb, bm]. The challenge that SPE faces in representing complex segments was discussed by Anderson (1976), who argued that contour nasal segments provide evidence that the phonological grammar is able to manipulate units smaller than a segment, i.e. subsegments. Anderson pushed the basic mechanics of segmental features to their limits by introducing the feature [+/–prenasal] in an attempt to model languages with a three way /b, mb, m/ contrast. According to this possible analysis, which the author later rejects, the phonemes /b, mb, m/ would have the feature matrices in (26).

(26)	a.	/b/	= [–prenasal, –nasal]
	b.	/mb/	= [+prenasal, –nasal]
	c.	/m/	= [+prenasal, +nasal]

As Anderson argues, however, the nature of the feature [+/–prenasal] defies the basic architecture of distinctive feature theory, which was designed to apply wholesale to segments. A feature which, by definition, only applies to the first portion of a segment, is a challenge to the *a priori* validity of this theory. Furthermore, even if one were to assume that such a feature does exist, we would still be faced with the obvious challenge of needing to account for the existence of segments of the type [bm] and, more challenging yet, [bmb] (see §7.1). Given this logical conclusion, Anderson compellingly argues that the introduction of the [+/–prenasal] feature fails to capture crucial generalizations about the temporal sequencing of the [+/–nasal] feature, and that complex nasal segments provide clear evidence in favour of subsegmental units.

Over the last few decades, a body of literature has shown converging evidence that segmental representations are insufficient to capture the range of phonological patterns observed across the world's languages (e.g., Clements 1985; Sagey 1986; Steriade 1993; 1994; Clements & Hume 1995). Speakers encode very detailed phonetic knowledge that applies to much more fine-grained structures than can be captured by segmental models (e.g. Kingston & Diehl 1994; Johnson 1997; Pierrehumbert 2001). In response to these important findings, phonologists have begun to move beyond the classic idea of contrastive phonemes and to posit various ways of representing subsegmental units within the phonological grammar.

6.2 Non-linear approaches are not enough

Autosegmental Phonology (Clements 1976; Goldsmith 1976; see also Hyman 1982; Piggott 1988) was developed, in part, to account for the behaviour of long-distance vowel-consonant nasal harmony[9] and complex nasal segments [mb, nd, ŋg] in Paraguayan Guaraní (Paraguay, ISO code: gug). Within this framework, the representation of each segment is divided into two parts: its feature matrix, and the timing tier, a sequence of skeletal units schematizing the temporal representation of the string to which feature matrices are linked. This machinery allows for multiple timing units to be linked to the same feature matrix, thus accounting for phenomena such as long-distance nasal harmony, and for a single timing unit to be simultaneously linked to multiple feature bundles. This latter tenet of Autosegmental Phonology makes it particularly well equipped to account for the representation of complex segments, such as partially nasalized consonants (e.g. [mb]).

Autosegmental Phonology does not, however, provide the representational machinery necessary to distinguish between phonological structures that differ in the relative timing of oral and nasal gestures, such as the post-oralized nasals and pre-nasalized stops of Panãra. Crucially, the phonological representations of both post-oralized and pre-nasalized segments would have the same structure, neutralizing the distinction between these two types of complex segments (27a). Autosegmental Phonology's neutralizing problem extends beyond its failure to capture the distinction between Panãra's two types of [NT]s because feature matrices associated to a given timing slot have no internal structure. While two nasal features [+nasal] and [–nasal] may be ordered with respect to one another on the feature tier; linear sequencing of two such features

[9] Long-distance nasal harmony is a process whereby a [+nasal] segment causes nasalization of a non-adjacent segment. In analytical terms, this process is sometimes termed 'unbounded' or 'iterative' harmony.

is not possible on a single segment. As such, not only does the architecture of Autosegmental Phonology neutralize the contrast between pre-nasalized [^{N}T] and post-oralized [N^{T}] in Panãra, but it also neutralizes these two types of complex nasal segments with both post-nasalized and [T^{N}] and pre-oralized [^{T}N] segments, as in (27b).

(27) a. [mb] /\ [+nasal][–nasal] = b. [bm] /\ [+nasal][–nasal]

Autosegmental Phonology also faces the well-known problem of many-to-one mapping, according to which segments may be associated to any number of feature matrices (Inkelas & Shih 2016; 2017; Shih & Inkelas 2019). This results in the pathological prediction that complex nasal segments of the type [mbmb] should occur (**Figure 5**), with the sequenced features [+nasal][–nasal][+nasal][–nasal]. Such complex nasal segments are unattested. Furthermore, while Autosegmental Phonology allows for an unbounded number of transitions between nasal and oral within a segment, it cannot express a contrast involving a sequence of two oral or nasal features due to the Obligatory Contour Principle (Leben 1973; Goldsmith 1976; Odden 1986).

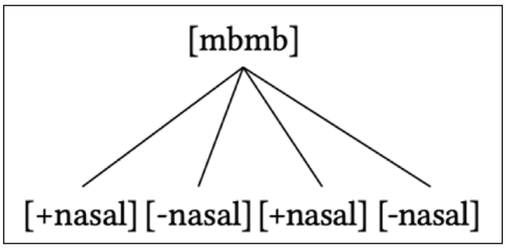

Figure 5: Autosegmental representation of the unattested complex segment [mbmb].

Several Feature Geometric approaches have been proposed over the years to represent the different featural tiers of Autosegmental Phonology. Within these models, nasal segments are usually specified for the Soft Palate node. However, authors have proposed several ways of accounting for the distinct phonological behaviour of various types of complex nasal segments. Given how many such proposals exist, it is not possible to review all of them here. I discuss Durvasula's (2009) proposal, which differs only minimally from Piggott's (1992) earlier account. Both of these representational frameworks are successful in accounting for the distinction between [NT]s that arise from post-oralization, and those that occur from an enhancement of voicing. However, neither model is able to account for the distinction between pre-nasalization and post-oralization in Panãra.

Durvasula (2009) proposes distinct Feature Geometric representations for two types of partially nasal stops: nasal-based partially nasal stops (N-PNS) and voiced-based partially nasal stops (V-PNS). According to his analysis, N-PNS are derived from simple underlying nasal consonants /N/ in languages with a two-way /T, N/ contrast, with no laryngeal contrast in oral stops. The phonological behaviour of N-PNS straightforwardly mirrors the typology of shielding, where they surface with pre- or post-oralization when adjacent to a phonemically oral vowel. V-PNS, as their name suggests, are contrastively voiced stops /D/ that surface with pre-nasalization in languages with a three-way /T, D, N/ contrast in stops. In such languages, nasalization is an enhancement mechanism of the [+voice] feature of voiced stops. The phonological representations of N-PNS and V-PNS are shown in **Figure 6**, where N-PNS are specified for the Soft Palate node, and V-PNS are specified for Glottal Tension under the Larynx node.

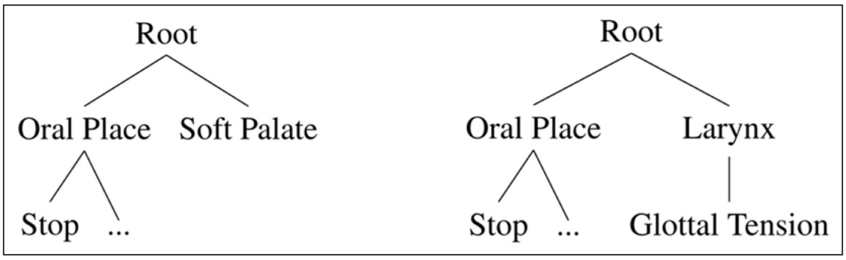

Figure 6: Phonological representation of N-PNS (left) and V-PNS (right).

The post-oralized nasals observed in Panãra can be straightforwardly captured by the phonological representation of N-PNS. In fact, Durvasula describes the partially-nasalized stops of Mebêngôkre, Apinayé, and Kaingang, three Jê languages closely related to Panãra, as example cases of N-PNS. While most languages with N-PNS, including all other Jê languages, have a voiced oral portion in the partially nasal consonant, N-PNS need not necessarily have voicing during their oral portion, as is the cases in Jambi Malay and Panãra. The pattern of Panãra pre-nasalization, however, does not fit within Durvasula's feature geometric framework. Panãra pre-nasalized stops cannot be modeled as V-PNS, as they are inherently voiceless, and the language does not, in fact, exhibit any laryngeal contrast for oral stops (see **Table 1**). Pre-nasalized stops in Panãra result from co-articulatory nasalization from a contrastively nasal vowel preceding an oral obstruent, rather than from enhancement of a voicing feature. As such, while Durvasula's model is intended to account for two distinct types of partially-nasal stops, it cannot account for the distinction between pre-nasalization and post-oralization in Panãra.

6.3 Two subsegments are not enough

Aperture Theory (Steriade 1993; 1994) provided the first formal proposal for the representation of temporally ordered subsegments. This framework posits that segments can be subdivided into bipartite subsegmental representations, where stops and affricates have two distinct phonological phases, stop closure (A_0), and stop release (A_{max}); whereas vowels, approximants, and fricatives have a single position in their segmental representation. This model of the subsegment is particularly well suited to representing pre-nasalized and post-nasalized stops (28).

(28)	a. Pre-nasalized	b. Post-nasalized	c. Nasal stop	d. Oral stop
	[nas]	[nas]	[nas]	A_0A_{max}
	|	|	/\	
	A_0A_{max}	A_0A_{max}	A_0A_{max}	

In (28a), the closure phase is linked to a privative nasal feature, resulting in a pre-nasalized stop, e.g. [mb]; in (28b), only the release phase is linked to a nasal feature, resulting in a post-nasalized stop, e.g. [bm]; in (28c), both the closure and release phases are linked to a nasal feature, resulting in a fully nasalized stop, e.g. [m]; and in (28d) neither the closure nor the release phase is linked to a nasal feature, and the stop is fully oral, e.g. [b]. Aperture Theory, then, overcomes one of the major shortcomings of Autosegmental Phonology, namely its inability for linear sequencing of features on a single segment.

However, Aperture Theory's inherently bipartite nature does not provide the level of granularity needed to account for the distinction between post-oralization and pre-nasalization in Panãra. While Aperture Theory is well suited to represent a segment such as [mb] and [bm], it predicts that a contrast between post-oralized nasals and pre-nasalized stops should not be possible, as both types of [NT]s have the same structure, i.e. a linear sequence of the features [+nasal][–nasal] on the two subsegmental phases. This particular prediction of the phonological neutralization between post-oralization and pre-nasalization within Aperture Theory was noted by Maddieson & Ladefoged (1993) who, at the time, lacked evidence that such a distinction is in fact attested. Inkelas & Shih (2017) similarly observe Aperture Theory's a under-generation problem for contour tones.

While Aperture Theory constitutes fundamental pioneering work and provides crucial machinery for representing bipartite segments, there now exists a large body of converging evidence indicating that two subsegments are in fact not sufficient to capture the level of granularity permitted by human languages (e.g., Akinlabi & Liberman 2001; Hyman 2007; Pycha 2009; 2010; Remijsen 2013; Remijsen & Ayoker 2014; Shih & Inkelas 2014; 2019; Inkelas & Shih 2016; 2017).

As will be discussed in §7.1, two Brazilian languages, Karitiana and Kaingang, exhibit a type of complex nasal consonant of the type [^{b}m^{b}] with both pre-oralization and post-oralization. The data from these two languages clearly shows that a bipartite representation of the segment does not provide the level of granularity necessary to capture the subsegmental complexity of phonological patterns across the world's languages. In her presentation of the Karitiana pattern, Storto (1999) correctly observes that tripartite circum-oralized nasal consonants, such as [^{b}m^{b}], are not readily amenable to a bipartite representation of the segment. In an attempt to capture the facts of circum-oralization while maintaining the strictly bipartite model of the segment proposed by Aperture Theory, Storto notes that one must necessarily resort to associating one of the two phases of a stop with two distinct values of the nasal feature. Storto chooses to represent these temporally sequenced features on the stop closure (A_0) (29).

(29)
```
[–nasal][+nasal][–nasal]
         \/              |
         A0              Amax
```

As noted in Garvin et al. (2018), the same issues arise in this approach as in Autosegmental approaches that rely on multiply linked timing nodes. In other words, this reintroduces the problems that characterized Autosegmental Phonology: lack of linear ordering within a single timing slot, and the many-to-one association between features and timing slots.

6.4 Gestures carry too much information

Articulatory Phonology (Browman & Goldstein 1989; 1992) assumes that the phonological grammar manipulates articulatory gestures. Gestures are the smallest phonological unit, and lexical items may contrast gesturally. For instance, the English words 'mad' and 'bad' minimally differ in the presence vs. absence of a velum lowering gesture, and the words 'ban' and 'band' minimally differ in the timing of the velum lowering gesture. As characterizations of physical events, gestures occur in space and over time. The temporal dimension of gestures is continuous, though the gestures themselves are discrete grammatical units. Gestures are not concrete articulations, but abstract articulatory targets. Gestural phasing results in a structure called a gestural score, a representation that displays the duration of the individual gestures as well as the overlap among them.

Articulatory Phonology can easily account for temporal misalignment between oral and nasal gestures, as velic gestures can be modeled as partially (or fully) overlapping the duration of an oral gesture. As a result, complex 'segments'[10] such as [mb] are straightforwardly accounted

[10] I use the term 'segment' here for convenience to refer to complex phones such as [mb] and [bmb], but the notion of a segment does not in fact exist in Articulatory Phonology.

for within this framework, crucially accounting for the functional motivation of processes such as pre-nasalization and post-oralization. That said, given the representation of the temporal dimension as a continuous variable, Articulatory Phonology vastly overpredicts that temporal alignment between oral and nasal gestures could happen at *any* timepoint in the duration of *any* of the gestures involved. This is an unwanted prediction, as the full range of patterns that may be derived from these mechanics is unattested.

Gafos' (2002) theory of Gestural Coordination builds on this weak point of Articulatory Phonology by phonologizing the notion of articulatory landmarks, thereby accounting for the crucial ways in which gestures are organized with respect to one another. Landmarks constitute the internal temporal structure of gestures, effectively decomposing gestures into several subcomponents. The full set of articulatory landmarks is the following: (i) ONSET, the onset of movement toward the target of the gesture; (ii) TARGET, the timepoint at which the gesture achieves its target; (iii) C-CENTER, the mid-point of the gestural plateau; (iv) RELEASE, the onset of movement away from the target; and (v) RELEASE OFFSET, the timepoint at which active control of the gesture ends. These landmarks are schematized in **Figure 7**.

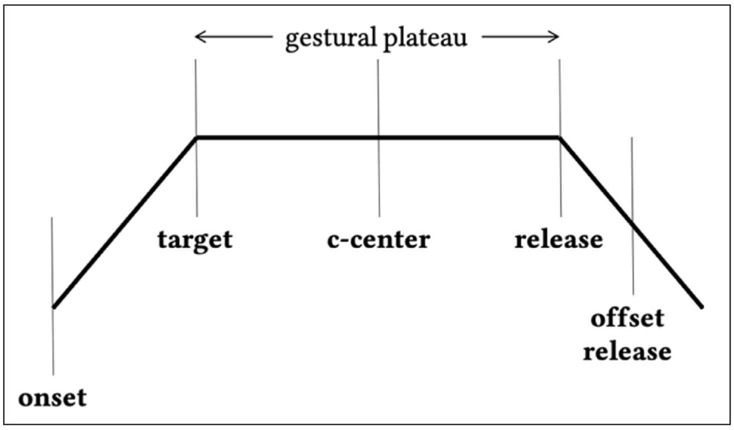

Figure 7: Gestural Landmarks of Gestural Coordination Theory.

Within this framework, temporal organization is expressed through coordination relations between gestures. A coordination relation specifies that a landmark within the temporal structure of one gesture is synchronous with a landmark within the temporal structure of another gesture. Coordination relations are expressed through coordination constraints, instantiated using the notion of Alignment, as developed by McCarthy and Prince (1993) within Optimality Theory (Prince & Smolensky 1993). The formulation of this alignment constraint is presented in (30). Coordination relation constraints interact with each other, as well as with other constraints in the grammar, thus giving rise to a grammar of gestural coordination.

(30) ALIGN(G1, landmark1, G2, landmark2): Align landmark1 of G1 to landmark2 of G2, where Landmark$_i$ takes values from the set {ONSET, TARGET, C-CENTER, RELEASE, OFFSET RELEASE}

The distinction between pre-nasalization and post-oralization in Panãra is straightforwardly captured within Gestural Coordination Theory. Specifically, a bilabial post-oralized nasal stop [m^p] would be modeled by aligning the RELEASE of the velum lowering gesture to the TARGET of the lip closing gesture. Since pre-nasalization involves a shorter temporal extent of the velum lowering gesture into the stop closure than post-oralization, a bilabial pre-nasalized stop [^{m}p] would simply be modeled by aligning the RELEASE of the velum lowering gesture earlier into the lip closing gesture, namely to the ONSET of the lip closing gesture. These coordination relations are formalized in (31) and (32), respectively.

(31) Coordination relation between nasal and oral gestures in post-oralized [m^p]: ALIGN(Nasal gesture, RELEASE, Oral gesture, TARGET): Align RELEASE of the velum lowering gesture to TARGET of the lip closing gesture

(32) Coordination relation between nasal and oral gestures in pre-nasalized [^{m}p]: ALIGN(Nasal gesture, RELEASE, Oral gesture, ONSET): Align RELEASE of the velum lowering gesture to ONSET of the lip closing gesture

While the distinction between pre-nasalization and post-oralization can be captured rather elegantly within the framework of Gestural Coordination, the Theory's predictions are too powerful. Gestural Coordination Theory does remedy one of the weaknesses of Articulatory Phonology by constraining the possible ways in which gestures can be anchored to one another, but the number of possible phonological distinctions predicted by Gestural Coordination Theory still over-generates too many distinct phonological categories. Assuming the alignment of two gestures, a velum lowering gesture and a lip closing gesture, the ONSET of the velum lowering gesture could be aligned to the ONSET, TARGET, C-CENTER, RELEASE, or the OFFSET RELEASE of the lip closing gesture. This scenario generates a total of 9 possible coordination relations. Furthermore, each one of these five landmarks of the lip closing gesture could itself be aligned to any of these same landmarks for the velum lowering gesture, yielding a total of 25 logically possible ways of aligning these two gestures to one another. While several of the predicted patterns are indeed attested (see §7.1), many of the predicted coordination relations entail much too small articulatory differences to form distinct phonological categories within the grammar of any given language.

For these reasons, Gestural Coordination Theory fares better as a descriptive tool than as a Theory intended to predict the range of possible phonological distinctions and contrasts in human languages. Without further constraining mechanisms (e.g. the P-Map, Steriade 2009; see §7.1), the predictions of this Theory still face an over-generation problem.

7 Discussion

7.1 Testing the predictions of Q Theory

Q Theory is not only able to account for the distinction between post-oralization and pre-nasalization in Panãra, but given its tripartite architecture, it in fact correctly predicts that such a distinction should exist. Within this framework, phonological distinctions are made at the subsegmental level, as a result of each subsegment's feature matrix. Q Theory, then, predicts six different types of partially nasal consonants; that is, six different logically possible permutations of oral and nasal subsegments for a given tripartite segment (33).

(33)	a.	(m^1 p^2 p^3)	d.	(m^1 p^2 m^3)
	b.	(m^1 m^2 p^3)	e.	(p^1 p^2 m^3)
	c.	(p^1 m^2 p^3)	f.	(p^1 m^2 m^3)

The question that naturally arises in considering these predictions is the following: Are all of the segment types in (33) attested? While 4/6 of these hypothesized segments are indeed attested (33a, b, c, f), the simple answer is *no*. Like its predecessor models such as segmental and Autosegmental Phonology (see §6), Q Theory has the capacity to represent segments that are (thus far) unattested in human languages. Given that Q Theory is also constrainable by the same mechanisms that constrain other models of segments, such as articulatory and perceptual constraints (Steriade 2009), the unattested segment types in (33d) and (33e) can be ruled out by appealing to other functional pressures that are assumed to always be at play, regardless of the representational model that one adopts.

As clearly demonstrated by the production and perception data in §3, the distinction between pre-nasalized (m^1 p^2 p^3) (33a) and post-oralized nasals (m^1 m^2 p^3) (33b) is robust in Panãra. Similarly, segments of the type [^{b}m] are widely attested in many Amazonian languages that exhibit environmental shielding (see Stanton 2017 for an extensive typological survey), and [^{p}m] is attested in Alyawarra (Australia; Yallop 1977), contrasting with both with both obstruent /p/ and nasal /m/. Given available descriptions of these languages, it appears that both the South American and Alyawarra patterns are best represented as (p^1 m^2 m^3) (33f). Pessoa (2012: 96) provides spectrograms of the Krenak (Macro-Jê, ISO code: kqq) words /ŋɾaŋ/ [ŋ^{g}ɾa$^{\mathbf{g}}$**ŋ**] 'rattlesnake' and /makɨn/ [m^{b}akɨ$^{\mathbf{d}}$**n**] 'little bird,' showing that the nasal portions of the pre-oralized nasal stops are significantly longer than the oral portions. The author further provides phonological evidence that these [^{b}m] segments are pre-oralized allophones of underlying nasal stops. Similarly, Yallop (1977) states that "[t]he plosive element [of Alyawarra] is of shorter duration than the nasal element and the nasally released plosives are in a number of ways related to nasals rather than to plosives."

Whether any given language distinguishes between the structures in (p^1 p^2 m^3) (33e) and (p^1 m^2 m^3) (33f) remains an open question. To the best of my knowledge, the distinction is not attested, but this gap is likely due to the inherent markedness of this particular type of complex nasal segments. Nasally-released plosives, or pre-oralized nasal stops, are very rare crosslinguistically, even more so than pre-nasalized stops or post-oralized nasals. According to the sample of 2,186 languages contained in PHOIBLE (Moran & McCloy 2019), the segment [mb] is attested in 292 languages, while the segment [bm] is attested in only one (Eastern Arrernte, Breen & Dobson 2005). Similarly, the segment [mp] is attested in 37 languages, while the segment [pm] is attested in only two.

That segments of the type [–nasal][+nasal] are less frequent than those of the type [+nasal][–nasal] is likely due to the fact that the release burst of oral stops is more perceptually salient than that of nasal stops in a CV sequence (Blumstein & Stevens 1980; Wright 2004). Furthermore, it was found that the nasal murmur in VN syllables carried more perceptual information on the consonant's place of articulation than did nasal murmur in NV syllables (Malécot 1956; Nord 1976), suggesting that nasals are more perceptually salient in post-vocalic than pre-vocalic position. This may be due to the fact that a common perceptual cue to a nasal consonant is coarticulatory nasalization on an adjacent vowel, and that coarticulation of nasality is more pronounced on a vowel preceding, rather than following, a nasal consonant (Beddor & Onsuwan 2003).

Given these observations, the absence of a language-internal distinction between the structures in (33e) and (33f) is improbable (but not impossible), as predicted by the P-Map (or 'Perceptibility-map,' Steriade 2009) constraints, which inform the relative degree of perceptibility of different contrasts in various phonological environments. P-map constraints prevent segment inventories from containing two segments that are, from a perceptual standpoint, not sufficiently distinct from one another (see also Garvin et al. 2018). The particular constraints needed to rule out the segment type in (33e) should state that (i) oral stop bursts are more perceptually salient than nasal stop bursts, and (ii) nasal consonants are more perceptually salient in post-vocalic than pre-vocalic position[3]. For instance, the constraint ranking in (34a) states that the grammar is more faithful to q subsegments of oral stops occurring before a vowel, than to q subsegments of nasal stops in the same environment. The ranking in (34b) states that the grammar is more faithful to q subsegments of nasal stops occurring before than after a vowel.

(34) a. IDENT(p^3)/_V ≫ IDENT(m^3)/_V
b. IDENT(m)/_V ≫ IDENT(m)/V_

The segment type in (33c) is attested in two Brazilian Amazonian languages, Karitiana (Tupí, ISO code: ktn; Storto 1999) and Kaingang (Jê, ISO code: kgp; Wiesemann 1972), and results from a complex pattern of environmental shielding. Both Karitiana and Kaingang possess a contrast in oral and nasal vowels, as well as a series of phonemically nasal consonants /m, n, ɲ, ŋ/. These nasal consonants undergo partial oralization when they occur immediately before or after a phonemically oral vowel (35). Phonemically nasal consonants are realized as fully nasal [m] only when they occur adjacent to nasal vowels and/or word boundaries (35a). They are realized as post-oralized [mb] when they occur before an oral vowel (35b); they are realized as pre-oralized [bm] when they occur after an oral vowel (35c); and, key for this analysis, they are realized as circum-oralized [bmb] when they occur between two oral vowels (35d). As such, Karitiana and Kaingang not only exhibit the segment type in (33c) by the rule in (35d), but they also exhibit the segment types in (33b) and (33f) by the rules in (35b) and (35c), respectively.

(35)		Karitiana		Kaingang	
a.	/m/ → [m] / {Ṽ, #}_{Ṽ, #}	ã**m**ãŋ˺	'to plant'	**m**õmæ̃ŋ	'fear'
b.	/m/ → [m^{b}] / {Ṽ, #}_V	ã**m**^{b}o	'to climb'	ɸũ**m**^{b}u	'tobacco'
c.	/m/ → [^{b}m] / V_{Ṽ, #}	hi^{b}**m**ĩnã	'roasted'	ha^{b}**m**æ̃	'to listen'
d.	/m/ → [^{b}m^{b}] / V_V	api^{b}**m**^{b}ik˺	'to pierce	ke^{b}**m**^{b}a	'to try out'

The structure in (33d) is, to the best of my knowledge, unattested. While this segment type is definitely possible to articulate, the oral closure of a circum-nasalized oral stop [^{m}b^{m}] would likely not be perceptually salient enough to become phonologized in any given language. As noted above, this is because the release burst of oral stops is a more robust perceptual cue than that of nasal consonants, such that a CV and VC transitions are more perceptually salient than NV and VN transitions (Wright 2004). In addition, the steady-state portion of oral stops consists of only silence, making it a very weak perceptual cue unless followed by an oral stop burst. The silence characterizing the realization of an oral stop closure also does not contain any information regarding place of articulation. In contrast, however, the steady state portion of nasal stops is characterized by nasal murmur, containing both formants and antiformants, which serve to identify both manner and place of articulation (Malécot 1956; Nord 1976; Kurowski & Blumstein 1993). The steady state portion of a nasal, then, contains more information than does the steady state portion of an oral stop. As such, the complex segment [^{m}p^{m}] combines the least perceptually salient portions of both an oral and a nasal stop, making it an unlikely segment type to grammaticalize in any language. Circum-nasalized oral stops such as those in (33d), then, can be dispreferred by appealing to the P-map constraints in (34).

Finally, that all six of the segment types in (33) are not attested in a single language is not at all surprising. Phonological distinctions resting on very small auditory differences are always rare, and it is well known that languages make use of many different phonological features involving different place and manner features to create distinct lexical contrasts. As such, it is highly improbable that any given language would make use of the full range of phonological structures in (34). Rather, languages may make use of a combination of these structures (e.g. Panãra has structures (33a) and (33b); Karitiana and Kaingang have structures (33b), (33c), and (33f)), but will also create lexical oppositions via additional phonological features.

7.2 Contrastive vs. distinctive phonological structures

The typological pattern described here for Panãra raises an important question regarding the scope of a theory of phonological representations, and the range of typological phenomena that it should be able to capture. Notably, the distinction between post-oralized nasals stops and pre-nasalized oral stops in Panãra is one that arises through phonological derivation: That is, the two types of [NT]s are not distinct phonemes which are present in the input; rather, they are the result of the application of phonological processes targeting two different classes of phonemes, /N/ and /T/. Indeed, Maddieson & Ladefoged's (1993) claim that post-oralized nasals and pre-nasalized stops do not require distinct phonological representations is based on their observation that "[there is] no language in which these two classes of sounds contrast with each other". This claim follows from the fact that, traditionally, the role of representational phonology has been to capture *contrastive* differences; that is, differences that are present in the input (e.g. Saussure 1916; Kiparsky 1985; Steriade 1987; Archangeli 1988; Avery & Rice 1989). Likewise, many of the complex nasal segment types in (33) are also attested as the result of phonological derivation.

Recent work, however, has shown that the phonological grammar encodes much more detailed information than was previously thought (e.g. Kingston & Diehl 1994; Johnson 1997; Pierrehumbert 2001). A good theory of phonological representations should account for more than contrastive units: It should also be able to account for distinctive structures. I assume Kiparsky's (2018) definition of the concept of distinctiveness, according to which segments may be non-contrastive (that is, distributionally predictable) but still perceptually salient to speakers. Distinctive structures are derived, as opposed to contrastive structures, which are present in the input. Given that the typology of nasality involves many coarticulatory phenomena, it is important to extend the scope of representational phonology to include those derived structures that may be perceptually salient to speakers of a given language if such distinctive structures enhance the underlying contrasts and aid in lexical retrieval (e.g., Flemming 2002; 2004; Steriade 2009; Lionnet 2017; Kiparsky 2018).

Following this terminology, /N/ and /T/ are contrastive in Panãra because the opposition between oral and nasal segments is present in the input. The phonological structures that result from post-oralization and pre-nasalization are distinctive, as they arise from the application of a phonological transformation. Unlike /N/ and /T/, (m^1 m^2 p^3) and (m^1 p^2 p^3) are not structures that exist in the input. The two types of [NT]s, however, can and do can occur in the same phonotactic environment, [ṼNTV], as in the minimal pair /kjã-ɲi/ → [kjãn^{s}i] 'big head' vs. /kjã-si/ → [kjã^{n}si] 'skull.' The distinction between post-oralized nasals and pre-nasalized stops, then, is one that aids Panãra speakers in lexical retrieval, and thus falls squarely within the realm of phonology.

The simple fact that the phonological grammar is able to manipulate subsegmental units in an input-output mapping further suggests that subsegments are indeed a crucial component of the phonological grammar. Note that an alternative analysis, whereby /N^T/ → [N] / _Ṽ and /^{N}T/ → [T] / V_, is also possible, but was not adopted for reasons of analytical parsimony. In addition, the data in (11–15), which show that the phonological grammar of Panãra is sensitive to the presence of derived [NT]s for the application of other phonological processes, such as word-initial [i] epenthesis and denasalization. These observations clearly show that post-oralization and pre-nasalization are not simply the result of phonetic implementation, and that they must be accounted for within the phonological grammar.

8 Conclusion

This article provided evidence for a phonological distinction between pre-nasalized oral stops and post-oralized nasal stops in Panãra, a Jê language of Central Brazil. These two types of surface [NT]s result from two distinct phonological processes: post-oralization of underlying nasal consonants (/m, n, ɲ, ŋ/ → [m^p, n^t, n^s, ŋ^k]), and pre-nasalization of underlying oral obstruents (/p, t, s, k/ → [^mp, ^nt, ^ns, $^{\text{ŋ}}k$]). The distinction between these two types of structures is robust, and is supported by both articulatory and perception experimental data.

Oral and nasal airflow data, as well as acoustic recordings collected during a production experiment (Lin & Lapierre 2019) show that the onset of velum raising happens significantly later after the achievement of oral closure in post-oralized nasals vs. pre-nasalized stops. Likewise, the onset of the velum raising gesture happens significantly later after the offset of vocal fold vibration in post-oralized nasals; and the velum raising gesture is realized significantly more slowly. Furthermore, the results of Lapierre & Lin's (2019) perception experiment suggest that native Panãra listeners can systematically differentiate between surface [NT]s arising from post-oralization and pre-nasalization, and that they make use of a number of acoustic cues in identifying a given [NT] token.

Taken together, the experimental data clearly supports the need for a tripartite representation of the segment, as proposed by Q Theory (e.g. Shih & Inkelas 2019). This framework of subsegmental representations decomposes the segment [Q] into a series of three quantized, temporally ordered subsegments (q^1 q^2 q^3). Unlike previous models of representational phonology, the tripartite architecture of Q Theory provides the level of granularity necessary to distinguish between post-oralized nasals and pre-nasalized stops, where the former is represented with two nasal subsegments followed by one oral subsegment (m^1 m^2 p^3), and the latter is represented with a single nasal subsegment followed by two oral subsegments (m^1 p^2 p^3).

The patterns of local nasal and oral assimilation and the observed distribution between [N, T, N^T, ^NT] in Panãra are analyzed within an ABC+Q framework, embedded within MaxEnt HG. ABC+Q is particularly well suited to modeling patterns of local nasal and oral assimilation, as it partial segmental assimilation is elegantly captured by the simple generalization that linearly adjacent edges of segments often share the same value for the feature [nasal]. MaxEnt HG, a probabilistic variant of HG, crucially allows for modeling the non-categorical behaviour of Panãra process of oral obstruent pre-nasalization.

Abbreviations

Ṽ = nasal vowel segment, V = oral vowel segment, N = nasal consonant segment, T = short oral obstruent segment, R = approximant segment, ᴠ̃ = nasal vowel subsegment, ᴠ = oral vowel subsegment, ɴ = nasal consonant subsegment, ᴛ = short oral obstruent subsegment.

Acknowledgements

My heartfelt thanks go out to the Panãra community for allowing me to study their language and become a part of their community, especially to my adoptive mother Sookre and my adoptive father Kôkâ. All the people who participated in my understanding of the data presented here are too many to name, but I wish to specifically acknowledge the participants of the experiments discussed here. Many people provided comments and feedback at numerous stages of this work, including Sharon Inkelas, Lev Michael, Larry Hyman, Darya Kavitskaya, Susan Lin, and Karee Garvin, as well as three anonymous reviewers. All remaining errors are my own. This research was supported by the Social Sciences and Humanities Research Council of Canada (Award number 752-2016-1985), as well as two Robert Oswalt Endangered Language Grants.

Competing interests

The author has no competing interests to declare.

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