Towards a Theory of Subsegmental and Subfeatural Representations: The Phonology and Typology of Nasality

by

Myriam Lapierre

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Committee in charge:

Professor Sharon Inkelas, Co-Chair
Professor Lev Michael, Co-Chair
Professor Larry Hyman
Associate Professor Darya Kavitskaya
Assistant Professor Susan Lin

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Abstract

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This study addresses one of the most fundamental questions in formal phonology, namely *What are the units of phonological representation that grammars manipulate?* Linguists have long assumed that segments and binary features are the basic atoms of phonological representations. The present study challenges this assumption by proposing that subsegmental units can be defined with respect to two distinct dimensions of representation: (i) the temporal dimension; and (ii) the spatial dimension, roughly equivalent to the physical magnitude of an articulatory gesture. I draw on two case studies providing instrumental data on two endangered Amazonian languages of Brazil, Panãra [kre] and Kawaiwete [kyz]. Using oral and nasal airflow data, I show that, on the one hand, Panãra exhibits a surface contrast between prenasalized oral stops [^{n}t] and postoralized nasal stops [n^{t}], which crucially differ in the extent of the duration of nasal airflow. On the other hand, Kawaiwete exhibits a distinction between fully oral, partially nasal, and fully nasal vowels, which crucially differ with respect to their degree of opening of the velo-pharyngeal port.

The proposed representational model integrates the basic architecture of Q Theory (Inkelas & Shih 2016; 2017; Shih & Inkelas 2014; 2019) and subfeatural representations (Lionnet 2017) into a single unified framework. On the basis of the Panãra data, I argue for Q theoretic subsegmental representations, which divide the segment into three quantized and linearly ordered subsegments, (q^1 q^2 q^3). This architecture provides the level of granularity necessary to distinguish between post-oralized nasals and pre-nasalized obstruents, where the former is represented with two nasal subsegments followed by one oral subsegment, and the latter is represented with a single nasal subsegment followed by two oral subsegments. Building on these Q theoretic representations, I argue on the basis of Kawaiwete for a scalar decomposition of phonological features, where continuous values can be grouped into one of three possible subfeatural categories: [+F], [xF], and [−F]. In the case of the feature [nasal], I argue for three perceptibly distinct degrees of nasalization: fully nasal [+nasal], partially nasal [$x$nasal], and fully oral [−nasal]. I show that a model of phonological representations which makes use of both subsegments and subfeatures is not only able to account for the data from both Panãra and Kawaiwete, but can also be extended to account for the full typology of phonological processes involving local nasalization or oralization.

Para todos os Panãra e os Kawaiwete.

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Chapter 1

Introduction

1.1 Overview

This study addresses one of the most fundamental questions in formal phonology, namely *What are the units of phonological representation that grammars manipulate?* Linguists have long assumed that segments and binary features are the basic atoms of phonological representations. However, over the last few decades, a large body of literature has shown converging evidence that segmental and featural representations are insufficient to capture the range of phonological patterns observed across the world's languages. For example, internally-dynamic segments, such as prenasalized stops (e.g. [mb]) and affricates (e.g. [ts]) pose a clear problem to the notion of featurally-uniform segments (e.g. Anderson 1976; Sagey 1986; Steriade 1993, 1994). In response to these important findings, phonologists have begun to develop phonological representations including a much more fine-grained level of detail.

I build on this body of work by discussing various ways in which segments may be partially nasal. Nasality is particularly relevant to the study of phonological representations, as it is traditionally represented with the use of the binary feature [+/−nasal]. However, several studies have shown that, in some languages, nasality requires a more fine-grained distinction than can be represented in a segmental model with binary phonological features. For example, consonants may be partially nasalized, such as prenasalized (e.g. [mb]), postnasalized (e.g. [bm]) and medionasalized [bmb]) stops, which are attested in the two Brazilian languages Kaingang (Wiesemann 1972) and Karitiana (Storto 1999). Desmeules-Trudel & Zamuner (2019, 2021) show that phonemically nasal vowels are perceived differently from coarticulatorily nasalized vowels in Canadian French, and that the difference lies in the temporal extension of the velum lowering gesture during the vowel. Furthermore, Durie (1985) analyzed Acehnese [ace] phonology as exhibiting weak and strong nasalization, and Merrifield (1963) similarly describes three distinctive levels of vocalic nasality in Palantla Chinantec [cpa]: oral, lightly nasal, and heavily nasal.

The present study deepens our understanding of phonological representations by presenting a typology of local nasal and oral assimilation processes, as well as detailed case studies providing instrumental data on each of the three major types of processes uncovered within this typological survey. The first case study comes from Panãra (ISO code: kre), a Jê language of Central Brazil, which exhibits a distinction between two types of [NT]s (i.e. complex segments consisting of a nasal consonant followed by a homorganic oral obstruent) arising from distinct phonological processes: (i) post-oralization of nasal consonants, and (ii) pre-nasalization of oral obstruents. These two processes illustrate cases of local assimilation, triggered by vowels and undergone by consonants. Post-oralization is a process of partial local oral assimilation, and pre-nasalization is a process of partial local nasal assimilation. The second case study comes from Kawaiwete (ISO code: kyz), a Tupí-Guaraní language also spoken in Central Brazil, which exhibits a distinction between fully oral, partially nasal, and fully nasal vowels. The partially nasal vowels arise from a process of local nasal assimilation, triggered by nasal consonants.

This novel data from two understudied Amazonian languages provide crucial evidence that the phonological grammar can and does make very fine-grained distinctions at both the subsegmental and subfeatural levels of representation. I show that a representational grammar which combines both subsegments (i.e., units smaller than a segment) and subfeatures (i.e., units smaller than a feature) can account for all patterns of local nasal and oral assimilation documented in my typological survey, as well as the two case studies presented in Chapters 3 and 4.

The proposed representational model integrates the basic architecture of Q Theory (Inkelas & Shih 2016; 2017; Shih & Inkelas 2014; 2019) and Subfeatural representations (Lionnet 2017) into a single unified framework. On the basis of the Panãra data, I argue for Q-theoretic subsegmental representations, which divide the segment into three quantized subsegments on the temporal dimension. This architecture provides the level of granularity necessary to distinguish between post-oralized nasals and pre-nasalized obstruents, where the former is represented with two nasal subsegments followed by one oral subsegment, and the latter is represented with a single nasal subsegment followed by two oral subsegments.

Building on these Q-theoretic representations, I argue on the basis of Kawaiwete for Subfeatural representations, which divide the features into three quantized subfeatures on the physical dimension, roughly equivalent to the physical magnitude of an articulatory gesture. A representational model with three quantized values of the feature [nasal], namely [+nasal], [$x$nasal], and [−nasal] is able to derive the patterns of nasal-oral and oral-nasal interpolation observed in Kawaiwete's partially nasal vowels, which are crucially distinct from both fully oral and fully nasal vowels.

I follow current work in phonology by analyzing assimilation phenomena from the Panãra and Kawaiwete case studies within the framework of Agreement-by-Correspondence (Walker 2000, Hansson 2001, 2010, Rose & Walker 2001, 2004). I expand the scope of phenomena that may be modeled using Agreement-by-Correspondence, showing how all patterns of local nasal and oral assimilation may be modeled as agreement between corresponding subsegments, formalized as OUTPUT-OUTPUT IDENTITY constraints. Agreement-by-Correspondence is particularly well suited to modeling patterns of local nasal and oral assimilation, as it accounts for both full and partial segmental assimilation, as well as the basic observation that (sub)segments that are similar to one another (i.e. which share a number of phonological features) and/or local to one another are more likely to interact with each other. By combining the proposed subsegmental and subfeatural representations with the machinery afforded by Agreement-by-Correspondence, I allow for modeling phonological phenomena at a much finer scale.

This study is outlined as follows: Chapter 1 presents an overview of the proposed representational model and grammar. Chapter 2 presents a typology of local nasal and oral assimilation processes. Chapter 3 discusses patterns of V → C local assimilation in Panãra, including both nasal and oral assimilation processes. Chapter 4 discusses patterns of C → V nasal assimilation in Kawaiwete. Taken together, the case studies from these two languages cover the vast majority of the attested patterns of local nasal and oral assimilation. Chapter 5 provides a summary of the proposed representational model and grammar, and discusses some avenues for future research.

1.2 Empirical basis

A large set of literature has discussed where to draw the line between phonetics and phonology, and which sets of phenomena fall within the realm of each of these components of the grammar. This study takes a bottom-up approach, cataloguing all empirical phenomena which can be broadly described as patterns of local nasal or oral assimilation, without any *a priori* categorization of these types of phenomena. In this way, I present a single unified treatment of two sets of phenomena which have traditionally been treated separately: patterns of local phonological assimilation, and patterns of phonetic coarticulation. As such, I use the terms local assimilation and coarticulation interchangeably throughout. A major hypothesis of the work presented here, then, is that a single phonological principle underlies all patterns of local nasal and oral assimilation. This view presents a rather radical shift in the treatment of the phonetics-phonology interface and significantly increases the empirical scope of the typology of nasality presented in Chapter 2, and of the model of phonological representation and grammatical derivation presented in Chapters 3 and 4.

In Chapter 2, I describe all patterns of local nasal and oral assimilation which are (un)attested in the world's languages, as well as which restrictions hold on particular types of systems. As will be shown, particular assimilation patterns are only observed in languages which exhibit specific properties relating to their phonemic inventories of nasal and oral segments. Processes of local nasal and oral assimilation may be partial, in that they affect only a portion of the segment undergoing assimilation, or complete, in that they affect the segment's entire duration. Patterns of partial local nasal and oral assimilation are more common than patterns of complete assimilation. Indeed, very often, it is the case that the onset and offset of velic movement do not neatly align with a segment boundary, where a segment boundary may be defined by an articulatory or corresponding acoustic landmark of a gesture involving the lips or tongue. This temporal misalignment is at the core of patterns of *partial* local nasal and oral assimilation.

While phonological analyses of nasality have often labeled certain segments as [+nasal] and others as [−nasal], this characterization is, for the most part, an oversimplification. For instance, for any input /NV/, /N/ may assimilate to the orality of /V/ by becoming (partially) [−nasal], or /V/ may assimilate the nasality of /N/ by becoming (partially) [+nasal]. This scenario is schematized in (1a) and (1b), respectively. Likewise, for any input /DṼ/, /D/ may assimilate to the nasality of /Ṽ/ by becoming (partially) [+nasal], or /Ṽ/ may assimilate the orality of /D/ by becoming (partially) [−nasal]. This scenario is schematized in (2a) and (2b), respectively.

(1) a. /NV/ ⟶ [$\text{N}^{\tilde{\text{V}}}$V]
b. /NV/ ⟶ [N^{D}V]

(2) a. /DṼ/ ⟶ [D^{N}Ṽ]
b. /DṼ/ ⟶ [D^{V}Ṽ]

The typology reveals that edges of adjacent segments overwhelmingly tend to share the same value for the feature [+/−nasal], which may be attributed to some mechanical properties of the velum. When only the edges of segments agree for the feature [+/−nasal], this results in complex nasal segments. I argue that the specific assimilation strategy employed by a given language to resolve this type of nasal-oral mismatch at a segment boundary is predictable from the language's system of contrasts. First, complete segment assimilation for the feature [+/−nasal] is only observed when the segment type resulting from the assimilation process is not itself observed in a given language's phonemic inventory. For instance, English does not exhibit a contrast in vowel nasality, but various studies have noted that vowels often undergo coarticulatory nasalization throughout their entire duration when adjacent to a nasal consonant (e.g. Cohn 1990). In comparison, in languages that do exhibit a contrast in vowel nasality, vowels sometimes undergo ç nasalization when adjacent to a nasal consonant; however, this seems to involve only *partial* nasal assimilation, affecting only a portion of the vowel's duration, as in (1a). Building on Stanton's (2017, 2018) work, I claim that languages make use of patterns of local nasal and oral assimilation which minimize the neutralization of phonological contrasts. In this sense, complete segment assimilation necessarily results in greater loss of information as to the identity of the underlying consonant, as none of its underlying value for the feature [+/−nasal] is observed on the surface. Partial segment assimilation, on the other hand, preserves the underlying feature [+/−nasal] on a portion of the segment undergoing assimilation, resulting in a smaller magnitude of contrast neutralization.

Perceptual salience of the cues to a particular phonological contrast also plays an important role in determining which of the two adjacent segments assimilates to the [+/−nasal] value of the other. For instance, vowel nasality is less perceptually salient than consonant nasality. For this reason, it is common for languages with a contrast in vowel nasality to exhibit patterns of local nasal or oral assimilation that enhance the cues to the contrast in vowel nasality (Stanton 2017, 2018). For instance, it is common for Amazonian languages which exhibit a contrast in vowel nasality to also exhibit a pattern of local oral assimilation where nasal consonants are partially oralized when adjacent to a phonemically oral vowel. Additionally, complex consonants of the type [CN], where the initial portion is oral and the final portion is nasal, are typologically rare. In comparison, complex consonants of the type [NC], where the initial portion is nasal and the final portion is oral, are much more widely attested. This is because [NC] segments combine the most perceptually salient portions of both an oral and a nasal stop, while [CN] segments combine the least perceptually salient portions of both oral and nasal stops. This asymmetry provides a functional explanation for the greater cross-linguistic frequency of [NC] compared to [CN], as well as of processes which give rise to [NC] segments compared to those that give rise to [CN] segments.

1.3 The representational model

This section provides an overview of the proposed representational model, which integrates the basic architecture of Q Theory (Inkelas & Shih 2016; 2017; Shih & Inkelas 2014; 2019) and Subfeatural representations (Lionnet 2017) into a single unified framework. I argue that phonological representations must be decomposed into tripartite units on two planes of representation, as segments may be partially nasal on either (i) the temporal domain, where a segment is nasalized during a portion of its duration; or (ii) the spatial domain, where a segment is realized with only partial opening of the velo-pharyngeal port. Figure 1a presents a tripartite division of the segment on the temporal scale, represented by the x axis, where the schematic duration of a traditional segment is divides into three quantized and linearly ordered subsegments, q^1, q^2 and q^3. Figure 1b presents a tripartite division of the feature scale on the spatial scale, represented by the y axis, where the schematic magnitude of the velo-pharyngeal port opening for the traditional [+/−nasal] feature values is divides into three quantized subfeatures [+nasal], [x nasal] and [−nasal] representing oral, partially nasal, and fully nasal sounds respectively.

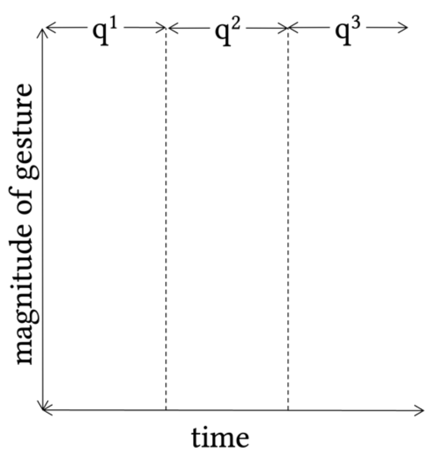

Figure 1a: Temporally defined subsegments

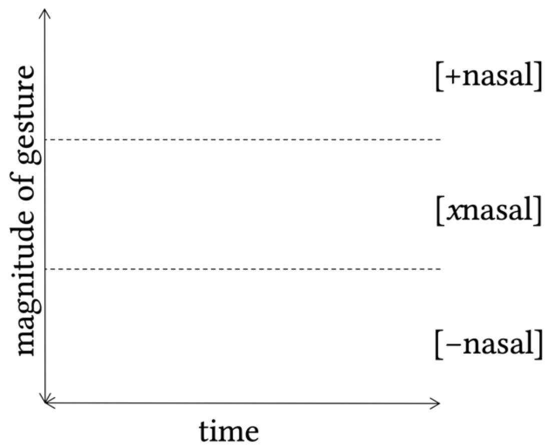

Figure 1b: Spatially defined subfeatures

Section 1.3.1 fleshes out the representation of temporally defined subsegments within the framework of Q Theory; and Section 1.3.2 fleshes out the representation of spatially defined Subfeatures within the framework of Subfeatures.

1.3.1 Q Theory

The representational model proposed here assumes that the segment [Q] may be decomposed into a series of three quantized, temporally ordered subsegments (q^1 q^2 q^3). Q Theory builds on Aperture Theory (Steriade 1993, 1994) by proposing that the three subsegments of a canonical short segment roughly corresponding to the onset, c-center, 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 SPE, namely the quantization of the temporal dimension into phonological units made up of feature bundles which 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, whether [+F], [–F], or [∅F]. 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 Classic SPE, Autosegmental Phonology, and Aperture Theory.

For example, given a phonotactic sequence of type /CVN/, the model assumes the Q-theoretic subsegmental representation in (3), where each segment is composed of three quantized subsegments, indexed from 1 to 3. Note that here, and throughout, capital letters are used as cover symbols to refer to natural classes of segments, such as consonants /C/, oral vowels /V/, and nasal consonants /N/. Corresponding small caps letters are used to represent to Q-theoretic subsegments corresponding to the same natural classes.

(3) /CVN/
(C^1 C^2 C^3) (V^1 V^2 V^3) (N^1 N^2 N^3)

The two case studies from Panãra and Kawaiwete presented in Chapters 3 and 4 of this study, respectively, provide crucial evidence in favour of a Q-theoretic analysis. In addition, previous data has been discussed by Shih & Inkelas (2019) supporting the clear need for a tripartite division of the segment: e.g., segments consisting of triple tone contours (4a), triphthongs (4b), and pre-nasalized affricates (4c).

(4)	Segment	Subsegment	Example
	a. ã̂	(L^1 H^2 L^3)	Mende contour mbã̂, 'companion' (Leben 1978:186)
	b. e̯ai̯	(e^1 a^2 i^3)	Romanian triphthong cite̯ai̯, 'read.IND.IMPF.2SG' (Dindelegan 2013:12)
	c. ndz	(n^1 d^2 z^3)	Pre-nasalized affricate (e.g. Steriade 1993)

Some languages also provide evidence from crucial pairs of 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 of post-oralized and pre-nasalized [NT]s in Panãra laid out in Chapter 3. 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 (5), where the early falling tone is represented by a single high tone subsegment, followed by two low tone subsegments, and the late falling tone is represented with two high tone subsegments, followed by a single low tone subsegment. Similarly, the authors provide the Q-theoretic representations for Hungarian affricates in (6), where the first is represented with a stop subsegment, followed by two fricative subsegments, and the second is represented with two stop subsegments, followed by a single fricative subsegment.

(5) a. Early falling (H^1 L^2 L^3) b. Late falling (H^1 H^2 L^3)

(6) a. /ts/ (t^1 s^2 s^3) b. /tʃ/ (t^1 t^2 $ʃ^3$)

In addition, the typology of local nasal and oral assimilation laid out in Chapter 2 points to a clear need for subsegmental representations within the phonological grammar. As will be shown, many languages exhibit partially nasal segments, but the typology reveals two clear examples supporting the need for Q-theoretic representations. The case of nasal consonant circum-oralization observed in Karitiana and Kaingang provides a straightforward and elegant use of tripartite subsegmental representations (Garvin, Lapierre & Inkelas 2018), where b^1 and b^3 have feature bundles corresponding to oral [b], and m^2 has the feature bundle corresponding to nasal [m], as in (8).

(8) [bmb]
(b^1 m^2 b^3)

Desmeules-Trudel & Brunelle (2018) provide instrumental data for Canadian French vowels which further support the need for tripartite subsegmental representations. As will be discussed in Chapter 2, the authors document a three-way distinction in vowel nasality, where vowels may be fully oral, nasalized, or fully nasal. Partially and fully nasal vowels crucially differ with respect to the temporal extension of the velum lowering gesture during the vowel. Velum lowering begins early in the production of the vowel for fully nasal vowels, whereas it begins significantly later for nasalized vowels. This data suggests that partially and fully nasal vowels crucially differ in terms of the temporal alignment of the velum lowering gesture within the time course of the vowel. Assuming tripartite subsegmental representations, the distinction between fully oral, partially nasal, and fully nasal vowels in Canadian French can be represented with distinct numbers of subsegments that are specified as [+nasal]. Oral vowels can be represented with three oral vowel subsegments (9a); nasalized vowels can be represented with two oral subsegments followed by one nasal subsegment (9b); and fully nasal vowels (after an oral obstruent[1]) can be represented with one oral subsegment followed by two nasal subsegments (9c).

(9)	a. (V^1 V^2 V^3)	Fully oral vowel
	b. (V^1 V^2 Ṽ^3)	Partially nasal vowel
	c. (V^1 Ṽ^2 Ṽ^3)	Fully nasal vowel

1.3.2 Subfeatural representations

Since the early days of formal phonology (Jakobson, Fant & Halle 1952; Jakobson & Halle 1956; Chomsky & Halle 1968), models of representational phonology have assumed that distinctive features may be specified with binary values [+F], and [−F]. Subsequent innovations argued in favour of feature unspecification [∅F] (e.g. Archangeli 1988a, 1988b; Mester & Itô 1989, Steriade 1993, 1994). More recently, the basic notion of binary distinctive features has been challenged. For instance, Smolensky & Goldrick (2016) propose that feature strength can be represented gradiently. Following Lionnet (2017), the subfeatural model proposed here assumes that all (sub)segments may be specified as [+nasal], [−nasal], or [*x*nasal], where [*x*nasal] represents a degree of nasalization intermediate to, and perceptibly distinct from [+nasal] and [−nasal].

Subfeatural representations build on the standard notion of contrastive features by exploding them into scalar subfeatures, which capture a category of distinctive, but non-contrastive intermediate values deriving from effects of coarticulation. The subfeatural level of representation allows for gradience in the degree of a distinctive feature, making it particularly well suited to a model of phonological representations aiming to capture the phonologization of local assimilation phenomena. While partial degrees of vowel nasality, such as nasal vowel coarticulation in English, have traditionally been relegated to phonetic implementation (e.g. Cohn 1990), I argue here that all local nasal and oral assimilation phenomena derive from

[1] See Section 2.7 for a discussion of partial oralization of the nasal vowel following an oral obstruent, providing a potential explanation for why (V^1) is represented without a tilde in example (9c).

phonological pressures and should therefore be modeled within the phonological grammar. To this end, I model the case study from Kawaiwete in Chapter 4 using both subsegments and subfeatures.

Subfeatures are represented with a value that can be any number drawn from a continuous scale whose endpoints are 0 and 1, corresponding to [–F] and [+F], respectively. Using this quantification method, subfeatures are able to capture the magnitude of a phonological feature, such as nasality. This continuous scale is functionally subdivided into three categories, namely [–F], [xF], and [+F]. Crucially, these subfeatural specifications represent the only three relevant values of the feature [F], namely oral, partially nasalized, and nasal in the case of the feature [nasal]. In this way, while subfeatures technically allow for modeling continuous values of a feature, the phonological grammar is only sensitive to three ranges of values on the subfeatural scale. Any segment whose value is [xF] is sufficiently coarticulated such that the resulting segment is perceptually distinct from both [+F] and [–F].

I build on Lionnet's (2017) work by showing how subsegmental and subfeatural representation can be used to model patterns of interpolation. I propose that Window Theory (Keating 1990) be augmented, such that windows span the duration of a subsegment, rather than a segment, and subfeatural values provide window width specifications. This architecture provides a more detailed representational architecture, which better informs the path of the interpolation curve between different targets.

Evidence that subfeatures are not simply the result of phonetic implementation and should be represented within the phonology comes from partial rounding effects in Laal (Chad, Isolate). Lionnet (2017) argues that the Laal data provides evidence that the phonological grammar is able to access the output of coarticulation. On the basis of acoustic evidence, the author shows that labial consonants incur an intermediate level of assimilatory rounding on a target vowel, where the resulting vowel is represented as [$x$round] in the output. For example, the coarticulatory effect of labial consonants on [ɨ, ə] in Laal is such that partially round [ɨ$^{\text{B}}$, ə$^{\text{B}}$] constitute a perceptually distinct category from both [–round] [ɨ, ə] and [+round] [u, o], where the superscript [$^{\text{B}}$] indicates a segment realized with a value of [$x$round]. Examples of words realized with a value of partial rounding equal to [$x$round] are presented in (10).

(10) a. /kə̀ə̀m-ə́/ ⟶ [kə̀ə̀$^{\text{B}}$mə́] ‘trees (sp)’
b. /sə̀g-ó/ ⟶ [sə̀$^{\text{B}}$gó] ‘bags’

Complete rounding assimilation in Laal requires two segmental triggers, a [+round] vowel and a labial consonant. The labial consonant triggers partial rounding assimilation on a [–round] vowel, such as /ì, ə̀/, deriving [$x$round] [ì$^{\text{B}}$, ə̀$^{\text{B}}$] in (10a) and (10b), respectively. Complete rounding assimilation, then, is triggered by [+round] vowels and target s[$x$round] vowels. This stepwise derivation is exemplified in (11).

(11) a. /ɓìr-ú/ ⟶ [ɓì$^{\text{B}}$rú] ⟶ [ɓùrú] ‘hooks’
b. /tə̀b-ó/ ⟶ [tə̀$^{\text{B}}$bó] ⟶ [tòbó] ‘fish sp.’

The typology of local nasal and oral assimilation presented in Chapter 2 presents cases that parallel the pattern in Laal and provide further evidence in favour of subfeatural representations. The case of Kaiowá nasal consonant oralization provides a straightforward example that may be accounted for by making use of a subfeatural analysis. As discussed in

Section 2.2.3, Kaiowá exhibits both partial and complete consonant oralization (Cardoso 2009). A single oral vowel immediately following a phonemically nasal consonant causes post-oralization of the relevant consonant, such that input /m, n, ŋ, ŋʷ/ are realized as [mb, nd, ŋg, ŋgʷ], as in (12). Post-oralized [mb, nd, ŋg, ŋgʷ] constitute a perceptually distinct category from nasal consonants [m, n, ŋ, ŋʷ], as in (13).

(12)	a. /tukũmo/ ⟶ [tukũmbɔ]	'rope'
	b. /mãniɲu/ ⟶ [mãndɨdʒu]	'cotton'
	c. /tũŋusu/ ⟶ [tũŋgusu]	'flea'
	d. /itĩŋʷaɾa/ ⟶ [ĩtĩŋgʷaɾa]	'nostril'

(13)	a. /mĩʃĩ/ ⟶ [mĩʃĩ]	'small'
	b. /ʃiɾĩnõ/ ⟶ [ʃĩɾĩnɔ̃]	'hummingbird'
	c. /kũɲã/ ⟶ [kũɲã]	'female'
	d. /ŋʷãhe/ ⟶ [ŋʷãhe]	'to arrive'

Kaiowá oral vowels and voiced oral stops are both specified as [–nasal], while nasal vowels and nasal stops are specified as [+nasal]. Using subfeatural values, post-oralized nasal consonants are [$x$nasal]. Drawing a parallel to the Laal case discussed above, complete consonant oralization is triggered by a preceding [–nasal] vowel and targets all [$x$nasal] consonants, namely [mb, nd, ŋg, ŋgʷ], as in (14).

(14)	a. /suɾumi/ ⟶ [suɾubi]	'catfish'
	b. /seɾanupe/ ⟶ [seɾadupe]	'in the savanna'
	c. /oŋa/ ⟶ [ɔga]	'house'
	d. /haŋʷe/ ⟶ [hagʷe]	'hair'

Similarly, coarticulatory vowel nasalization in English provides an additional pattern that may be analyzed using subfeatural representations. As will be discussed in Section 2,4, vowels in English are realized as fully nasal when flanked by two nasal consonants (e.g., /mæn/ ⟶ [mæ̃n]), and as only partially nasal when adjacent to only one nasal consonant (e.g., /mæt/ ⟶ m$^{\tilde{æ}}$æt]). Between an oral consonant and a nasal consonant, vowels are realized with a cline-like gradient increase in nasality over the course of their duration. Vowels between a nasal and an oral consonant are realized with a similar cline-like gradient decrease in nasality over the course of their duration. Assuming tripartite subfeatural representations, the distinction between fully oral, partially nasal, and fully nasal vowels in English can be represented with distinct values of subfeatures for the feature [nasal]. Oral vowels can be represented as [–nasal]; nasalized vowels can be represented as [$x$nasal]; and the fully nasal vowels can be represented as [+nasal].

1.3.3 Combining the pieces

A representational grammar incorporating elements of both subsegments and subfeatures can account for all patterns of local nasal and oral assimilation documented in the typological survey in Chapter 2, as well as the details of the two case studies presented in Chapters 3 and 4. Within the proposed representational framework then, a segment may be divided into three quantized subsegments on the temporal dimension, and into three quantized subfeatures on the physical dimension, roughly equivalent to the physical magnitude of an articulatory gesture or its perceptual strength. This division of the segment on the temporal scale and of the feature on the spatial scale is presented schematically in Figure 2 below.

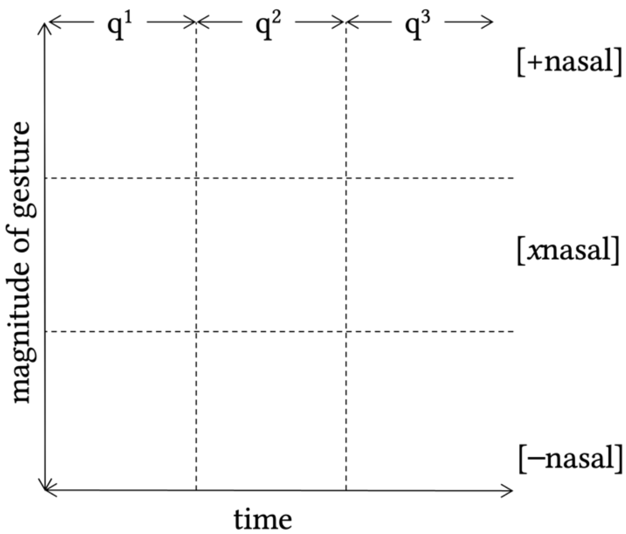

Figure 2: Temporally-defined subsegments and spatially-defined subfeatures

1.4 The grammar

I follow current work in phonology by modeling assimilatory phenomena from the two case studies presented in this study within the framework of Agreement-by-Correspondence (ABC). While the framework was originally designed to account for patterns of long-distance consonant harmony (Walker 2000; Hansson 2001, 2010; Rose & Walker 2004), recent work within ABC has extended the mechanism of feature agreement to account for vowel harmony (e.g., Sasa 2009, Walker 2009, 2014, Rhodes 2012), dissimilation (Bennett 2013, 2015a, 2015b), and processes of local assimilation (e.g., Wayment 2009; Inkelas & Shih 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. In addition, the innovation of ABC+Q (Agreement-by-Correspondence + Q Theory; Shih & Inkelas 2019), allows for feature agreement between *sub*segmental units.

In this study, I expand the scope of phenomena that may be modeled using ABC+Q. Specifically, while patterns of coarticulation have often been relegated to phonetic implementation, I argue that all patterns of local nasal and oral assimilation derive from agreement between corresponding subsegments. By combining the proposed subsegmental and subfeatural representations with the machinery afforded by Agreement-by-Correspondence, I allow for modeling phonological phenomena at a much finer scale.

Correspondence relationships between (sub)segments results from (i) a scale of similarity, according to which two (sub)segments are in a correspondence relationship if they share a given (set of) phonological feature(s); and (ii) a scale of distance, according to which two (sub)segments are in a correspondence relationship if they are local to one another on a given phonological tier. ABC+Q is particularly well suited to modeling patterns of local nasal and oral assimilation, as it accounts not only for full segmental assimilation, but for partial segmental assimilation as well. Full segmental assimilation is elegantly captured by the basic generalization that phonological units that are similar to one another, i.e. which share a number of phonological features, are likely to interact with one another, while partial segmental assimilation is captured by the generalization that linearly adjacent edges of segments often share the same value for the feature [nasal].

Correspondence relationships between (sub)segments is governed via a family of CORRESPONDENCE constraints, which require correspondence between pairs of (sub)segments that meet a given similarity or distance criterion. Agreement between corresponding (sub)segments is governed via a family of OUTPUT-OUTPUT IDENTITY constraints, which require corresponding (sub)segments to have identical values of a given feature [F] in the output. Recent work within Agreement-by-Correspondence has shown that formally separating CORRESPONDENCE and OUTPUT-OUTPUT IDENTITY constraints has little utility, and suggest combining them into a single conflated constraint (Hansson 2014, Walker 2015, Shih & Inkelas 2019). Following these conventions, I conflate pairs of CORRESPONDENCE and OUTPUT-OUTPUT IDENTITY constraints in the analyses presented in Chapter 3 and 4, referring to them jointly 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.

1.4.1 A grammar of subsegments

Chapter 3 introduces data from a previously undocumented phonological distinction in Panãra (ISO code: kre), a Jê language of Central Brazil, and shows that Q Theory's subsegmental representations are necessary to model its grammatical status and behaviour. Panãra exhibits a previously distinction between two types of [NT]s arising from distinct phonological processes: post-oralization of nasal consonants (15a), and pre-nasalization of oral obstruents (15b). These 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.'

(15) 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 __

The Panãra data provides clear evidence in favour of a tripartite model of subsegmental representations, such as Q Theory (Inkelas & Shih 2016; 2017; Shih & Inkelas 2014; 2019). Q Theory's architecture provides the level of granularity necessary to distinguish between post-oralization (15a) and pre-nasalization (15b), where the former is represented with two nasal subsegments followed by one oral subsegment (16a), and the latter is represented with a single nasal subsegment followed by two oral subsegments (16b).

(16) a. Post-oralized nasals
[m^{p}]
↓
(m^{1} m^{2} p^{3})

b. Pre-nasalized stops
[^{m}p]
↓
(m^{1} p^{2} p^{3})

The results of two phonetic experiments support the proposed Q-theoretic representations. The first is a production experiment designed to show that Panãra speakers systematically produce the two types of [NT]s differently (Lin & Lapierre 2019). The second is a perception experiment designed to show that native Panãra listeners can reliably identify a given [NT] token 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.

I model the distribution between [N, T, N^T, $^N T$] in Panãra within a MaxEnt Harmonic Grammar, showing that any Optimality Theoretic grammar must crucially include constraints that reference subsegmental units to correctly derive the pattern. Specifically, three distinct constraint families are needed. The first necessary set of constraints, CORRESPONDENCE constraints, are those that establish crucial correspondence relationships between adjacent subsegments and require them to agree in their value for a given feature. In order to derive the correct patterns of local nasal and oral assimilation observed in consonants, the model requires two types of crucial CORRESPONDENCE relationships. The first establishes a correspondence relationship between any two adjacent q subsegments contained within the same Q segment; and the second is a correspondence relationship between any two adjacent q subsegments separated by a Q segment boundary. An additional constraint, IDENT-IO-q[nasal], requires subsegments in the output have matching values for the feature [+/–nasal] as their corresponding subsegment in the input. Finally, *TN, a markedness constraint penalizing output [TN] sequences, but not [NT] sequences, is also needed. This last constraint accounts for the observation that post-nasalized consonants are very rare crosslinguistically.

I conclude this chapter by showing that previous models of phonological representations are unable to account for the distinction between post-oralization and pre-nasalization in Panãra. I argue that classic models of segmental representation, bipartite subsegmental models, as well as non-linear phonological models are unable to model the crucial distinction in Panãra. And finally, I show that, while gestural models can indeed model the distinction between post-oralized nasals and pre-nasalized stops, such models overpredict distinctions that are not attested within the typology of local nasal and oral assimilation.

1.4.2 A grammar of subfeatures

Chapter 4 of this study introduces previously undocumented phonetic data from Kawaiwete (ISO code: kyz), a Tupí-Guaraní language also spoken in the Brazilian Amazon, and argues that subfeatural representations, in combination with Q Theory's subsegmental representations, are necessary to model the grammatical status and behaviour of fully oral, partially nasal, and fully nasal vowels. This representational machinery derives the patterns of nasal-oral and oral-nasal interpolation observed in Kawaiwete partially nasal vowels. Taken together, the data from Kawaiwete provide crucial evidence that the information relevant to encoding the distinction between fully oral, partially nasal, and fully nasal vowels is dynamic over the timecourse of the vowel, and relative to their immediate segmental context.

Building on the representational framework laid out in Chapter 3, I argue on the basis of Kawaiwete for a tripartite representation of not only the segment, but also the feature. Following Lionnet (2017)'s subfeatural representations, I postulate three quantized values of the feature [nasal], namely [+nasal], [$x$nasal], and [−nasal]. This representational machinery derives the patterns of interpolation observed in Kawaiwete vowels, where oral vowels between two oral consonants are realized with three [−nasal] subsegments (17a); oral vowels between a nasal and an oral consonant are realized with one [+nasal] subsegment, one [$x$nasal] subsegment, and one [−nasal] subsegment (17b); oral vowels between an oral and a nasal consonant are realized with one [−nasal] subsegment, one [$x$nasal] subsegment, and one [+nasal] subsegment (17c); nasal vowels after an oral consonant are likewise realized with one [−nasal] subsegment, one [$x$nasal] subsegment, and one [+nasal] subsegment (17c); and nasal vowels after a nasal consonant are realized with three [+nasal] subsegments (17d).

(17) a. $(\mathrm{v}^1\ \mathrm{v}^2\ \mathrm{v}^3)$
b. $(\tilde{\mathrm{v}}^1\ \overset{x}{\mathrm{v}}^2\ \mathrm{v}^3)$
c. $(\mathrm{v}^1\ \overset{x}{\mathrm{v}}^2\ \tilde{\mathrm{v}}^3)$
d. $(\tilde{\mathrm{v}}^1\ \tilde{\mathrm{v}}^2\ \tilde{\mathrm{v}}^3)$

The results of a nasal airflow experiment support the proposed subsegmental and subfeatural analysis, showing that oral vowels between two oral consonants are realized as fully oral, while nasal vowels after nasal consonants are realized as fully nasal. Oral vowels between an oral and a nasal consonant, as well as nasal vowels after oral consonants, are both realized as partially nasal, with a cline in nasal airflow extending for the entire vowel's duration. Taken together, the results of this experiment shows that native speakers of Kawaiwete systematically produce oral and nasal vowels distinctly, and that their particular realization is dependent on the immediate segmental context in which they appear.

Building on the family of Correspondence & Agreement constraints laid out in Chapter 3, I model the distribution of Kawaiwete's different types of vowels within a Harmonic Grammar and show that it must make reference to both subsegments and subfeatures to correctly derive the observed patterns. I conclude that an analysis integrating elements of Q Theory, Subfeatural representations, and the ABC framework can derive patterns of nasal-oral and oral-nasal interpolation. Specifically, this model requires the addition of GRADIENT-CORRESPONDENCE constraints, a subfamily of CORRESPONDENCE constraints, which requires that (sub)segments not differ by a value exceeding a certain threshold x for a given phonological feature, rather than requiring strict, categorical identity in feature values.

Finally, in Chapter 5, I show how the proposed representational model is not only able to account for patterns of interpolation in Kawaiwete vowels, but it does so by proposing a particular grammatical mechanism by which surface interpolation functions are derived. While previous work on nasal interpolation (e.g. Cohn 1990, Keating 1990) provided crucial and lasting insights into the articulatory mechanisms that govern local assimilation, the predictions of these earlier models are difficult to evaluate and implement without an accompanying mathematical or computational tool to derive the concrete output of an interpolation function. Here, I show how an analysis integrating elements of Q Theory, Subfeatural Theory, and the ABC framework can derive such patterns of nasal-oral interpolation.

Chapter 2

The typology of local nasal and oral assimilation

2.1 Overview

A study which proposes a model of phonological representations requires a strong typological foundation, including an overview of both attested and unattested phonological alternations, as well as their distributional asymmetries. To this end, the goals of this chapter are to determine which types of nasal and oral assimilation systems are attested and unattested in the world's languages, as well as which restrictions hold on particular types of systems. I expand on previous typological work on nasal and oral segments by consolidating and analyzing all logically possible patterns of local nasal and oral assimilation, including patterns of partial and complete assimilation.

As will be shown, particular assimilation patterns are only observed in languages which exhibit specific properties relating to their phonemic inventories of nasal and oral segments. I use a bottom-up empirical approach to this typological survey which does not crucially differentiate between phonetic and phonological processes. While certain types of processes, such as nasal assimilation, are often attributed to phonetic implementation, and other patterns, such as nasal consonant post-oralization, are often attributed to the phonology, I treat all of these empirical patterns of local nasal and oral assimilation as equivalent to one another. Crucially, I show that all of these patterns can be accounted for in the phonology by the same mechanism, namely local assimilation, and as such, I use the terms coarticulation and local assimilation interchangeably.

The rest of this chapter is organized as follows: Section 2.2 provides phonetic and phonological background on processes of local nasal and oral assimilation; Section 2.3 discusses the methodology employed to conduct the typological survey; Sections 2.4-2.7 present each of the local nasal and oral assimilation processes, as well as the relevant properties of the segmental inventories of the languages where they are observed; and finally, Section 2.8 presents a summary of the (un)attested patterns of nasal and oral assimilation.

2.2 Background

Nasal consonants are characterized by the presence of nasal airflow and the absence of oral airflow, which is achieved by lowering the velum while simultaneously producing an obstruction in the oral cavity at any given place of articulation. The acoustic signature of nasal consonants consists in the presence of nasal murmur, characterized by nasal formants and oral antiformants (Fujimura 1962, Fant 1970, Kurowski & Blumstein 1993). Nasal formants are observed at approximately 250, 2500 and 3250 Hz for a relatively long vocal tract; and the frequencies of oral antiformants vary depending on the place of articulation of the obstruction in the oral cavity (Johnson 2012, Ladefoged & Johnson 2015). Meanwhile, nasal vowels are characterized by the presence of both oral and nasal airflow, which is achieved by simultaneously lowering both the jaw and the velum, in addition to any lip or tongue articulation depending on the place of articulation of the vowel. The acoustic signature of nasal vowels consists in the presence of oral formants, as well as nasal formants and antiformants (Fujimura 1962, Johnson 2012). The spectrogram of a nasal vowel is characterized by "blurring" of the region below approximately 1200 Hz, appearing as a relatively flat spectrum with no clear dominant spectral prominences in this range of frequencies (Stevens 1998, Shosted 2006). This is the result of relative weakening of F1 and widening of its bandwidth from the introduction of an oral formant, nasal formant, and nasal anti-formant occurring in this region (Johnson 2012, Shosted 2006).

Because movement of the velum is distinct from the movements of other articulators in the speech apparatus, the typology of nasal and oral assimilation differs in crucial ways from the typology of assimilation of other familiar phonological features. Indeed, patterns of nasal assimilation are largely determined by a basic mechanical property of velic articulation, namely the fact that the velum moves relatively slowly compared to other oral articulators (Moll & Daniloff 1971, Bell-Berti 1993, Krakow 1993), such as the tongue, lips, larynx and vocal folds. In addition, movement of the velum is largely independent from the movement of all other oral and glottal articulators[1]. While the onset and offset of vocal fold vibration for the production of voiced sounds often aligns relatively well with the beginning and the end of particular segments, which may be operationalized by particular gestural landmarks (e.g. the achievement of lip closure for a bilabial stop), the onset and offset of nasality often does not coincide with these same landmarks of the gestures of oral articulators. As a result, nasal assimilation is often characterized by a temporal misalignment of articulatory gestures between the velum and the oral articulators. These patterns of temporal misalignment between oral and nasal articulators are rampant, justifying the need for detailed typological work on patterns of nasal and oral segmental alternations.

While phonological analyses of nasality often label certain segments as [+nasal] and others as [−nasal] (or as [nasal] and [∅nasal]), this characterization is, for the most part, an oversimplification which fails to capture some crucial facts about the phonetic realization of nasality. Onset of velum lowering rarely aligns with the beginning or the end of any particular segment. For instance, for any input /NV/ consisting of a sequence of a [+nasal] consonant and a [−nasal] vowel, /N/ may assimilate to the feature value of /V/ by becoming (partially) [−nasal], or /V/ may assimilate the feature value of /N/ by becoming (partially) [+nasal]. These scenarios are illustrated schematically in (1a) and (1b), respectively. Likewise, for any input /ṼD/ consisting of a sequence of a [+nasal] vowel and a [−nasal] consonant, /D/ may assimilate to the feature value of /Ṽ/ by becoming (partially) [+nasal], or /Ṽ/ may assimilate the feature value of /D/ by becoming (partially) [−nasal]. These scenarios are exemplified schematically in (2a) and (2b), respectively.

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[1] Note, however, that contraction of the palatoglossus muscle, which originates at the palatine raphe (the midline of the palate) and inserts in the posterolateral tongue, plays a role in raising and retracting the tongue dorsum (Kent 1997), which also has the effect of creating a slight opening of the velo-pharyngeal port in the case of low vowels (e.g., Dixit, Bell-Berti & Haris 1987).

(1) a. /NV/ → $[N^{\tilde{V}}V]$
b. /NV/ → $[N^{D}V]$

(2) a. /ṼD/ → $[\tilde{V}^{N}D]$
b. /ṼD/ → $[\tilde{V}^{V}D]$

Following this line of reasoning, all of the logically possible types of local nasal and oral assimilation processes are summarized in Table 1, where columns indicate whether the spreading feature is [−nasal] in the case of oral assimilation, or [+nasal] in the case of nasal assimilation, and whether the assimilation pattern is triggered by vowels and affects consonants (left), or whether it is triggered by consonants and affects vowels (right). The row in the table also indicate whether the process is partial, affecting only a part of a segment, or complete, affecting the segment's entire duration.

Table 1: Cross-linguistically attested patterns of local nasal and oral assimilation

	Oral		**Nasal**	
	V → C	**C → V**	**V → C**	**C → V**
Partial	Yes	?	Yes	Yes
Complete	Yes	No	Yes	Yes

An important generalization relates to the fact that, on the one hand, nasal assimilation may be triggered by both vowels and consonants, and may likewise target both vowels and consonants, and in both cases, assimilation may be partial or complete. On the other hand, local oral assimilation processes appear to be somewhat more restricted. Such assimilation patterns are much more saliently represented within the literature as processes triggered by phonemically oral vowels, and targeting phonemically nasal consonants, where assimilation may be partial or complete. While there may be some evidence for potential processes causing nasal vowels to become partially oralized in the context of oral consonants, the picture is less clear for this part of the typology, as will be discussed in Section 2.5. In addition, cases of nasal vowels becoming fully oralized by an adjacent oral consonant are unattested.

As will be shown in the following subsections, it is possible for a given language to exhibit more than one assimilation pattern in different phonotactic contexts. For instance, French exhibits C → V partial nasal assimilation the case of an /NV/ input sequence, as well as V → C partial nasal assimilation in the case of an input /ṼD/ sequence (Cohn 1990). As will be discussed in Section 2.6, there is also some evidence that French may exhibit C → V oral assimilation in the case of an input /DṼ/ sequence, suggesting that French assimilation may be determined by rightward spreading of a [+/−nasal] feature, regardless of whether the trigger is a vowel or a consonant, and specified as oral or nasal in the input.

The results of the typological survey also reveal that edges of adjacent segments overwhelmingly tend to share the same value for the feature [+/−nasal], often giving rise to complex nasal segments, i.e. in vowels or consonants containing both a nasal and an oral portion. Which of the two adjacent segments assimilates to the [+/−nasal] value of the other seems to be largely predictable on the basis of the system of phonological contrasts that are relevant to a particular language, and the perceptual salience of each of these contrasts. In particular, nasal vowels as well as complex [CN] are perceptually dispreferred. Assimilation of an entire segment for the feature [+/−nasal] is only attested when that segment does not exhibit a contrast in nasality.

2.3 Methodology

The typological survey on patterns of local nasal and oral assimilation presented in this chapter is the results of over 7 years of research on nasality and South American languages, including data gathered from a wide variety of sources during this period of time. This typological survey is not intended to be an exhaustive review of the literature on nasality in South American languages, but it is rigorous and extensive. I have carried out a thorough review of the literature discussing various aspects of the grammar of languages of the Jê family, including an exhaustive literature review discussing the phonetics and the phonology of Jê languages. Table 2 summarizes the literature reviewed on Jê languages. This typological survey is partially motivated and supplemented by my own fieldwork on several languages of the Jê family, totalling over 10 months of *in-situ* fieldwork working with speakers of Panãra, Mẽbêngôkre, Kajkwakhrattxi, and Xavante since 2014.

Table 2: Primary sources reviewed in the typological survey on languages of the Jê family

Language	Sources
Panãra (Krenakarore)	Dourado 1990, 1993, 2001; Salanova 2011; Bardagil Mas 2018; Vasconcelos 2013; Lapierre 2016, accepted a, accepted b, in press; Nikulin 2016, 2017, 2020; Lapierre & Lin 2018, 2019; Lin & Lapierre 2019
Timbira	Popjes & Popjes 1986; Alves 2004, 2007, 2010; Amado 2004; Miranda 2010; Silva 2011; Souza 2011; Nikulin 2016, 2017, 2020
Kĩsêdjê (Suyá)	Santos 1997; Nonato 2014; Nikulin 2016, 2017, 2020; Rodrigues & Ferreira-Silva 2011; Huff & Lapierre 2021
Tapayuna/Kajkwakhrattxi (Suyá)	Camargo 2010, 2015; Rodrigues & Ferreira-Silva 2011; Nikulin 2016, 2017, 2020; Beauchamp 2019; Huff & Lapierre 2021
Mẽbêngôkre	Salanova 2001, 2007, 2011; Salanova & Silva 2011; Lapierre 2016; Nikulin 2016, 2017, 2020
Apinayé	Anderson 1976; Davis 1996; Salanova 2001; Oliveira 2005; Nikulin 2016, 2017, 2020
Xavante (A'uwẽ)	McLeod 1974; Oliveira 2007; Pickering 2010; Estevam 2011; Quintino 2000, 2012, 2018; Nikulin 2017, 2020; Huff 2021; Carrick 2021
Xerente (Laklanõ)	Mattos 1973; Souza 2008; Nikulin 2017, 2020
Kaingang	Wiesemann 1972; Nikulin 2020
Xokleng	Urban 1985; Nikulin 2020

In collaborative work with Lev Michael beginning in 2016, I have exhaustively surveyed all of the literature discussing the phonetics and phonology of languages of the Tupí-Guaraní family, and the Tupían stock more broadly, with a particular focus on the nasality systems of these languages. Table 3 summarizes the literature reviewed on Tupían languages. The findings of this in-depth typological survey on nasality in Tupí-Guaraní and Tupían have been recorded in a database which is intended to be made available through the South American Phonological Inventory Database (Michael et al. 2021), and will serve as the basis for the elaboration of a series of papers, currently in preparation, on the typology of nasality across various Amazonian language families. Starting in the Fall of 2020, this work benefitted from funding from the National Science Foundation (Award #1918064, Co-PIs Lev Michael & Susan Lin) and the help of four excellent undergraduate research assistants: Sebastian Clendenning-Jimenez, Teela Huff, Jasper Talwani, and Nicholas Carrick. Partial results of this typological survey on the nasality systems of Tupí-Guaraní languages have been presented at the 8th Conference on Indigenous Languages of Latin America (Lapierre & Michael 2017), at the University of Texas at Austin; and at 3rd conference on Sound Systems of Latin America (Lapierre & Michael 2018), at the University of Massachusetts, Amherst. This work is supplemented by my own fieldwork with speakers of two languages of the Tupí-Guaraní family: Kawaiwete and Paraguayan Guaraní. My work with the Kawaiwete community began in 2018, and my work on Paraguayan Guaraní was carried out in the context of a Field Methods class taken at the University of Ottawa in the Winter semester of 2016.

Table 3: Primary sources reviewed in the typological survey on languages of the Tupí family

Language	Sources
Mbyá	Guedes 1983; Dooley 1984, 2006, 2008; Martins 2003; Thomas 2014
Kaiowá	Bridgeman 1961, 1966; Harrison & Taylor 1971; Cardoso 2008, 2009; Taylor & Taylor 2010
Pai Tavytera	Escobar Imlach 2017
Teko (Émérillon)	Rose 2000, 2002, 2003, 2008
Asuriní do Tocantins	Harrison 1971, 1975; Nicholson 1975/2009, 1978; Soares 1979; Cabral 2012
Guajajára	Bendor-Samuel 1963, 1966; Soares 1979; Castro 2007; Silva 2010; Harrison & Harrison 2013; Barboza 2015
Nhandeva	Costa 2003a, 2003b, 2007; Seara, Quadros & Martins 2021
Tembé	Rice 1934; Boudin 1978; Eiró 2001; Duarte 2003, 2007; Orjuela & Meira (ms.)
Tapirapé	Leite 1977, 2003; Almeida 1983; Costa 2007; Praça 2007
Parakanã	Gomes 1991; Silva 1999; Silva 2003
Suruí do Tocantins	Neves 2004/2005; Lopes 2014; Miranda 2018
Achê	Sammons 1977; Rößler 2008
Tapiete	González 2005, 2008
Chiriguano	Dietrich 1986; Daviet 2016
Avá-Canoeiro (Avá-Canoeiro Tocantins)	Borges 2006; Silva 2015
Avá-Canoeiro (Avá-Canoeiro Goiás)	Borges 2006
Xetá	Rodrigues 1978; Vasconcelos 2008
Araweté	Castro 1986; Vieira & Leite 1998; Alves 2008; Solano 2009; Silva, Picanço & Rodrigues 2010; Alves 2018

Asuriní do Xingu	Nicholson 1982; Pereira 2009, 2011; Alves 2008
Jorá	Danielsen & Gasparini 2015
Anambé do Cairari	Julião 1993, 2005; Baraúna 2016; Miranda 2018
Guarayu	Armoye 2009
Nheengatú (upper Rio Negro)	Taylor 1985; Borges 1991; Moore, Facundes & Pires 1994; Cruz 2011
Nheengatú (médio Rio Amazônas)	Schwade 2014
Kayabí (Kawaiwete)	Dobson 1988, 1997; Souza 2004; Weiss 2005
Yuqui	Villafañe 2004, 2014; Gallinate 2021
Kokama-Kokamilla	Faust & Pike 1959; Soares 1979; Cabral 1997; Vallejos 2010; Viegas 2010
Omagua (San Joaquín de Omaguas)	Sandy & O'Hagan 2020
Omagua (Kambeba)	Santos 2015
Apiaká	Ehrenreich 1895; Padua 2007
Siriono	Priest 1980; Gasparini 2012
Parintintin/Tenharim	Pease & Betts 1971; Sampaio 1997; Betts 1981, 2012; Marçoli 2018
Tupinambá	Barbosa 1956; Rodrigues 1957
Júma	Abrahamson & Abrahamson 1980, 1984
Uru-Eu-Wau-Wau	Netto & Moraes 1993; Sampaio 1997, 2001; dos Santos et al. (ms.); dos Santos (2020)
Karipuna	Abrahamson & Abrahamson 1980; dos Santos (2020)
Kamayurá	Salzer 1976; Silva 1981; Seki 2000
Guajá (Guajá do Caru)	Nascimento 2008
Guajá (Guajá do Alto Turiaçu)	Cunha 1987
Urubu Ka'apor	Kakumasu 1964, 1968; Caldas 2009; Lopes 2009; Santos 2018
Zo'e	Cabral 1995, 1998; Castro & Carvalho 1998; Cabral, Rodrigues & Carvalho 2010
Wayampi	Grenand 1980; Jensen 1984; Santos 2002; Copin 2012
Içuã (Júma)	Abrahamson 1968
Awetí	Monserrat 1977; Drude 2008, 2009, 2021; Sabino 2016
Sateré-Mawé	Graham & Graham 1978; Drude 2008; Silva 2010
Paraguayan Guaraní	Gregores & Suárez 1967; Goldsmith 1976; Rivas 1974, 1975; Piggott 1992; Walker 1998,1999; Estigarribia 2020, 2021
Suruí de Rondônia	Bontkes 1974/2009, 1978, 1978; van der Meer 1982; Guerra 2004
Gavião do Jiparaná	Stute 1985; Moore 1984, 2017; Gavião 2019
Cinta Larga	Sandberg 1976; Sandberg 1977, 1988; Sandberg & Sandberg 1978; Neto 1991
Akuntsú	Aragon & Cabral 2005; Aragon 2008, 2013, 2014
Karo	Gabas 1989, 1999

Wayoró	Moore & Galucio 1994; Nogueira 2011, 2019
Kuruaya	Costa 1998, 2002; Picanço 2005, 2010; Silva 2009
Sakirabiá	Moore & Galucio 1994; Galucio 1994, 2001
Mundurukú (Mundurukú do Cururu)	Braun & Crofts 1965; Crofts 1985
Mundurukú (Mundurukú do Pará)	Picanço 2005, 2010, 2012
Mundurukú (Mundurukú de Madeira)	Santos 2013
Tuparí	Rodrigues & Caspar 1957; Moore & Galucio 1994; Seki 2001; Alves 2004; Singerman 2016, 2018
Makuráp	Braga 1992, 1996, 2005; Moore & Galucio 1994
Xipaya	Fargetti & Rodrigues 2008, 2021
Juruna	Fargetti 1992, 2001
Puruborá	Galucio 2005
Karitiana	Landin & Landin 1973; Landin 1976/2008, 1983/2005; Kindell 1981; Storto 1999; Everett 2007
Warázu	Ramirez, Vegini & de França 2017

Beyond this focus on Eastern Amazonian languages, I have reviewed the literature discussing the phonetics and phonology of other Amazonian languages, with a particular focus on their nasality systems. This work was supplemented by personal communications, involving in-depth discussions on this topic with many language experts conducting fieldwork on Amazonian languages over the years. A substantial number of such conversations took place in December 2019, when I co-organized with Lev Michael and Susan Lin the first workshop for the NSF-funded South American Nasality Project held at the University of California, Berkeley. This week-long workshop brought together all of the collaborating researchers for the project: Marina Magalhães, Nelsy Lorena Orjuela Salinas, Kelsey Neely, Wesley Nascimento dos Santos, Wilson de Lima Silva, Jorge Emilio Rosés Labrada, Adam Singerman, Thiago Chacon, as well as Lev Michael, Susan Lin, Ronald Sprouse, and myself. During this workshop, each of the collaborating researchers provided a detailed overview of the basic phonology and nasality systems of the following languages: Kubeo, Desano and Máíhɨki (Tukano), Yaminahua (Pano), Yuhup (Nadahup), Mako and Piaroa (Sáliba), Panãra (Jê), Guajá, Kawahiva and Kawaiwete (Tupí-Guaraní), and Tuparí (Tupí).

In addition to my survey on languages of Amazonia, I have carried out an extensive review of the literature discussing various aspects of the phonetics, phonology, and morphology of nasal sounds. Much of the literature providing instrumental data on nasal sounds focuses on widely spoken languages, such as English, French, Portuguese, and Spanish. Whenever available, however, this data was supplemented with experimental reports on the nasality systems of languages spoken in other parts of the world, and non-Indo-European languages in particular.

To supplement all of this data, I have, on various occasions, carried out qualitative surveys of the typology of nasality by examining various phonological inventory databases, namely the South American Phonological Inventory Database (Michael et al. 2021), PHOIBLE (Moran & McCloy 2019), and the UCLA Phonological Segment Inventory Database (Maddieson 1984). When available, I have reviewed work specific to the typology of nasality in other parts of the world (e.g. Rolle 2013). I have also consulted various fieldworkers and language experts working in various parts of the world on phonetic and phonological patterns of oralization and nasalization.

Finally, it is worth noting that I am a native speaker of both French and English, a fluent speaker of Portuguese and Spanish, and a functional speaker of several of the languages on which I have carried out fieldwork, especially Panãra. My evaluation of all of the analyses and data discussing the nasality systems of these languages, then, is supplemented by my own experience with, and (second-language) intuitions about these languages.

2.4 C → V nasal assimilation

This section presents attested types of local nasal and oral assimilation processes which are triggered by nasal consonants and undergone by an oral vowel. This particular pattern is perhaps the most widely studied and best understood pattern of nasal/oral assimilation. C → V nasal assimilation may affect any vowel adjacent to a nasal consonant, regardless of whether feature assimilation spreads leftward or rightward, reflecting patterns of anticipatory (1a) and progressive (1b) nasal assimilation respectively. While patterns of C → V nasal assimilation may affect the entire duration of the vowel, as in (3), nasalization of the underlyingly oral vowel may be only partial, as in (4).

(3)	a. /VN/ → [ṼN]	(4)	a. /VN/ → [V$^{\tilde{V}}$N]
	b. /NV/ → [NṼ]		b. /NV/ → [N$^{\tilde{V}}$V]

The functional motivation for the patterns in (3) and (4) comes from some basic facts about the articulation of nasal consonants. A nasal consonant is articulated by producing a complete closure in the oral cavity and simultaneously lowering the velum. The velum's slow patterns of lowering and raising often cause segments that are adjacent to the nasal consonant to be partially nasalized. More specifically, the assimilatory patterns in (3) are observed when the phonologically nasal consonant requires the velum to be fully lowered during the entire duration of the consonant, i.e. during the entire closure in the oral cavity. In the case of anticipatory nasal assimilation in (3a), the velum begins to lower during the production of the vowel preceding the nasal consonant, and the velum lowering gesture is achieved at the onset of the consonant, i.e. when the closure in the oral cavity is achieved. In the case of progressive nasal assimilation in (3b), the velum begins to raise during the production of the vowel following the nasal consonant, that is, only after the closure in the oral cavity has been released. The velum raising gesture is then achieved during the production of the vowel.

These articulatory patterns are schematized in the gestural scores below. Figure (1a) represents anticipatory nasal assimilation, and Figure (1b) represents progressive nasal assimilation. The direction of nasal spreading is indicated by the arrows above the transcribed phonotactic sequence. The symbol /N/ stands for any nasal consonant, which may be produced with an oral closure at any point of articulation, e.g. bilabial, alveolar, velar, etc. The symbol /Ṽ/ represents a nasal vowel with any point of articulation in the oral cavity, e.g. high, mid, low; and front, central or back.

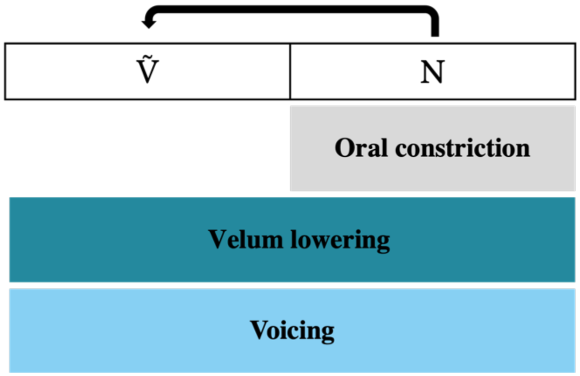

Figure 1a: Gestural score representing anticipatory vowel nasalization, triggered by a phonemically nasal consonant

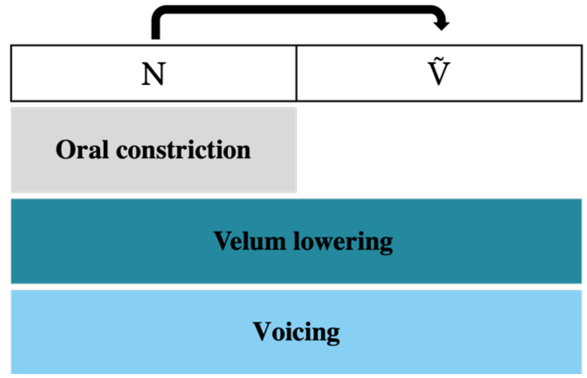

Figure 1b: Gestural score representing progressive vowel nasalization, triggered by a phonemically nasal consonant

The gestural scores above assume that the velum begins to lower at vowel onset in the case of Figure (1a), and that the velum achieves its full closure at vowel offset in the case of Figure (1b). However, as noted above, nasal assimilation may affect a smaller proportion of the vowel, and languages vary with respect to the timepoint during the vowel at which velum lowering begins and velum raising is achieved. For instance, velum lowering may begin once the gestural target of the vowel in the oral cavity is achieved, or at the c-center of the vowel's gestural plateau. The same is true for the timepoint at which velum raising is achieved in a vowel following a nasal consonant. In such cases, only a portion of the vowel is nasalized.

Patterns of C → V nasal assimilation, such as those in (3) and (4), are attested in languages with two different types of phonological inventories: (i) languages with nasal consonants, but no contrastive nasal vowels; and (ii) languages with both contrastive nasal vowels and contrastive nasal consonants. The results of my survey reveal that all languages which have a contrast in nasality for consonants but not for vowels exhibit this pattern of partial nasal assimilation. However, only a subset of languages with both contrastive nasal consonants and vowel exhibit this pattern, and languages of this type are more likely to have only a portion of the vowel affected by the nasal gesture of the nasal consonant. This seems like a natural consequence of these types of systems of contrast. In a language that does not exhibit a contrast in nasality for vowels, nasalization of the vowel does not result in the neutralization of a contrast between oral and nasal vowels.

Meanwhile, since coarticulatory vowel nasalization provides redundant perceptual cues relating to the identity of the nasal consonant, C → V nasal assimilation only provides additional information to a speaker when the nasalization does not incur any loss of information relating to the identity of the vowel, i.e. when the language does not have a contrast in vowel nasality. However, when the language does have a contrast in vowel nasality, nasalizing oral vowels that are adjacent to nasal consonants results in at least partial loss of information about the underlying oral or nasal quality of the vowel that is affected by assimilation. For this reason, C → V nasal assimilation affects only a subset of languages with a contrast in nasality for both vowels and consonants, and is less likely to affect the entire duration of the vowel, so that the underlying status of the vowel may be inferable from the timepoint in the vowel where velum lowering gesture begins or is completed. In such systems, it is frequent for a velum lowering gesture to begin right at the onset of the phonemically nasal vowel, but at a later timepoint in the production of a vowel in the case of a phonemically oral vowel produced with anticipatory nasal coarticulation from an immediately following nasal consonant.

English is by far the most widely studied language with contrastive nasal consonants but no contrastive nasal vowels. The results of my typological survey suggest that it is indeed a good representative of this type of system. In seminal work on the topic, Cohn (1990) and Keating (1990), show that in English, vowels are unspecified for the feature nasal, and their phonetic realization as oral or nasal can be obtained by interpolation between adjacent consonants. Between two oral consonants, vowels are realized as fully oral. Between two nasal consonants, vowels are realized as fully nasal, as in Figure (2a). Between an oral consonant and a nasal consonant, vowels are realized with a cline-like gradient increase in nasal airflow over the course of their duration, as in Figure (2b). Vowels between a nasal and an oral consonant are realized with a similar cline-like gradient decrease in nasal airflow over the course of their duration, as in Figure (2c).

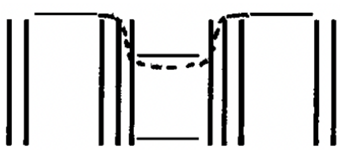

Figure 2a: Interpolation of vowel nasality between two nasal consonants in English, from Cohn (1990:148)

Figure 2b: Interpolation of vowel nasality between an oral consonant and a nasal consonant in English, from Cohn (1990:148)

Figure 2c: Interpolation of vowel nasality between a nasal consonant and an oral consonant in English, from Cohn (1990:148)

Figure 3, taken from Cohn (1990:145-147), presents nasal airflow traces from the production of English words by a male speaker of American English in different phonotactic contexts. Figure (3a) illustrates a nasal flow trace for the word /mɛn/ ‘men’; Figure (3b) illustrates a sample nasal airflow trace for the word /bin/ ‘bean’; and Figure (3c) illustrates a nasal flow trace for the word /nid/ ‘need’. As can be seen, vowels are affected by coarticulatory nasality during the entirety of their duration, which Cohn explains by proposing that values of vowel nasality in English are unspecified in their underlying representation and determined by interpolation between the [+/−nasal] values of adjacent consonants.

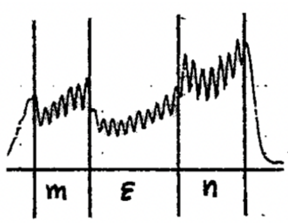

Figure 3a: Nasal flow trace for the word /mɛn/ ‘men’ by a male speaker of American English, from Cohn (1990:147)

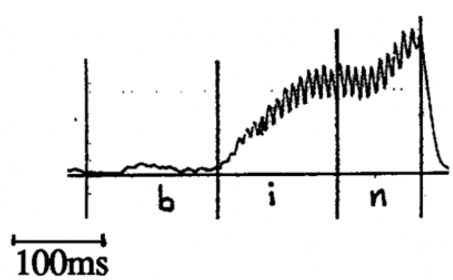

Figure 3b: Nasal flow trace for the word /bin/ ‘bean’ by a male speaker of American English, from Cohn (1990:145)

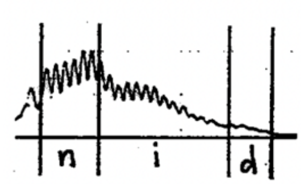

Figure 3c: Nasal flow trace for the word /nid/ ‘need’ by a male speaker of American English, from Cohn (1990:145)

The general pattern of vowel nasalization observed in English seems to be common in other languages that lack contrastive nasal vowels, such as Korean (Jang, Kim & Cho 2018), and Spanish (Solé 1992, Planas 2020, Bongiovanni 2021).

French is the second most widely studied language in terms of the properties of its nasal system. Canadian French has 12 phonemic oral vowels and 4 phonemic nasal vowels, /ẽ, ɑ̃, ɔ̃, œ̃/ which contrast with oral vowel counterparts. Desmeules-Trudel & Brunelle (2018) show that in underlying oral vowel-nasal consonant sequences /VN/, the onset of nasal airflow begins during the production of the vowel. Figure 4 shows that the onset of nasal airflow begins at approximately 25% of the vowel duration for phonologically nasal vowels /Ṽ/, at approximately 50% of vowel duration for an underlyingly oral vowel in a syllable closed by a nasal consonant /VN$/ (left), and at about 75% of vowel duration for an underlyingly oral vowel in an open syllable followed by a heterosyllabic nasal consonant /V$N/ (right). In this case, coarticulatory nasalization affects only a portion of vowel duration, rather than its entire duration, as in the case of English.

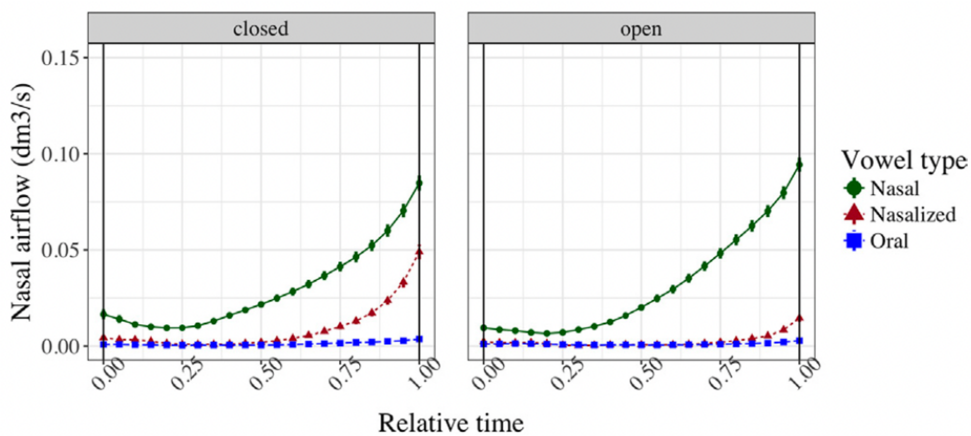

Figure 4: Mean nasal airflow, per syllable type in Canadian French vowels in a closed syllable /VN$/ (left) and in an open syllable /V$N/ (right), from Desmeules-Trudel & Brunelle (2018)

Desmeules-Trudel & Brunelle (2018) also observe that the extent of coarticulatory nasalization is greater in closed /VN$/ sequences than in open /V$N/ syllables, as they note that the former context does not contrast with hypothetical */ṼN$/, but the latter structure does contrast with underlying /Ṽ$N/ sequences. This work, then, provides evidence that contrast plays an important role in determining patterns of nasal coarticulation, not only as a general property of a language's phonology, but also as a more specific determinant of phonetic realizations in particular phonotactic environments.

Patterns of C → V nasal assimilation are also observed among understudied languages, such as Lakota (Siouan). With 5 oral vowels and 3 nasal vowels in its phonemic inventory, Lakota exhibits clear patterns of both anticipatory and progressive nasalization of oral vowels when adjacent to nasal consonants, with a greater degree of progressive nasalization (Scarborough et al. 2015). The authors show that in phonemically oral vowels in a /VN/ context, vowels start off as oral and become increasingly more nasal across their duration, while in the parallel /NV/ context, vowels start off as nasal and maintain a relatively flat nasality profile. Scarborough et al.'s (2015) results also show that phonemically nasal vowels exhibit an overall greater degree of acoustic nasalization (i.e. a lower A1-P0 value) compared to phonemically oral vowels affected by coarticulatory nasalization.

The results of my typological survey suggest an interesting correlation between the relative number of nasal vowels in a language's phonemic inventory and its patterns of local nasal and oral assimilation. Languages with C → V nasal assimilation generally have fewer nasal vowels than oral vowels, such as French and Lakota, while languages with V → C oral assimilation (see Section 2.4) generally have the same number of oral and nasal vowels. This suggests that vowel nasality may have a lower functional load in the phonological system of a language with a smaller proportion of phonemic nasal vowels, which in turn may play a role in determining which pattern of local nasal or oral assimilation the language employs. Indeed, Wedel et al. (2013) show that the front rounded nasal vowel /œ̃/ in French exhibits a low functional load in the lexicon, and link this finding to the merging of /ɛ̃/ and /œ̃/ in many dialects of French. In addition, Scarborough et al. (2015) show that /NV/ and /NṼ/ sequences have also merged in some dialects of Lakota.

Furthermore, instrumental articulatory data shows that the configuration of the oral articulators in the production of "homorganic" oral and nasal vowel pairs in French and Hindi actually differs significantly (Shosted et al. 2012, Carignan 2014, Carignan et al. 2015). These findings suggest that vowel nasality in these languages may be cued by more than just the presence of nasal airflow, such as with distinct formant values. Indeed, Beddor et al. (1986) provide perceptual data suggesting that vowel nasalization may affect perceived vowel height, pointing to a potential precursor to diachronic changes in nasal vowel height. If the phonemic distinction between oral and nasal vowels is not solely dependent on the presence of nasal airflow, then the effect of coarticulatory vowel nasalization on phonemically oral vowels when adjacent to nasal consonants may not result in the neutralization of the contrast between oral and nasal vowels.

In comparison, it appears that the oral articulation of oral and nasal vowel pairs in languages with V → C oral assimilation is much more similar. Articulatory data on vowel production is unfortunately not available for languages of this type, as the majority of them are spoken by small indigenous groups in South America. However, qualitative evaluation of F1-F2 charts available for some of these languages (e.g. Guerra 2004, Picanço 2005, Lapierre 2016, Santos 2018) shows that the formant values of oral and nasal vowel pairs are much more similar. One possible interpretation of this data is that oral and nasal vowel pairs do not significantly differ in their tongue position for these languages. If the phonemic distinction between oral and nasal vowels is primarily cued by the presence of acoustic nasality, the effect of coarticulatory vowel nasalization on phonemically oral vowels when adjacent to nasal consonants would result in the neutralization of the contrast between oral and nasal vowels. Given this logic, this could explain why such languages generally tend to employ the mirror pattern of V → C oral assimilation, effectively avoiding contrast neutralization.

2.5 V → C nasal assimilation

Local nasal assimilation triggered by a phonemically nasal vowel and undergone by an oral consonant is also commonly observed. This process is attested as both rightward spreading nasalization, reflecting a pattern of progressive nasal assimilation (5a), and as leftward spreading nasalization, reflecting a pattern of anticipatory nasal assimilation (5b). Patterns of V → C nasal assimilation are often restricted to only a part of the consonant, giving rise to partially nasal consonants, namely pre-nasalized ^{N}C and post-nasalized C^{N}. That said, nasalization of the entire consonant, as in (6), is also attested in some languages. In such cases of complete nasal assimilation, the consonant itself is usually either sonorant or voiced.

(5) a. $/\tilde{V}C/ \rightarrow [\tilde{V}^{N}C]$
b. $/C\tilde{V}/ \rightarrow [C^{N}\tilde{V}]$

(6) a. $/\tilde{V}C/ \rightarrow [\tilde{V}N]$
b. $/C\tilde{V}/ \rightarrow [N\tilde{V}]$

A nasal vowel is produced by simultaneously lowering both the jaw and the velum, in addition to any lip or tongue articulation, depending on the place of articulation of the vowel. As previously noted, the velum's relatively slow movement can cause adjacent segments to be partially or fully nasalized. The pattern of progressive nasal assimilation in (5a) involves achieving full lowering of the velum during the production of the vowel, and only completing the closure of the velo-pharyngeal port during the production of the immediately following consonant. The pattern of anticipatory nasal assimilation in (5b), on the other hand, involves beginning to lower the velum during the production of the consonant immediately preceding the nasal vowel, such that the velo-pharyngeal port has achieved (close to) maximal opening at the onset of the vowel.

These articulatory patterns are represented schematically in the gestural scores below. Figure (5a) represents anticipatory nasal assimilation, and Figure (5b) represents progressive nasal assimilation. The direction of nasal spreading is indicated by the arrows above the transcribed phonotactic sequence. The symbol /N/ stand is for any nasal consonant, which may be produced with an oral closure at any point of articulation, e.g. bilabial, alveolar, velar, etc. The symbol $/\tilde{V}/$ represents a nasal vowel, with any point of articulation in the oral cavity, e.g. high, mid, low; and front, central or back.

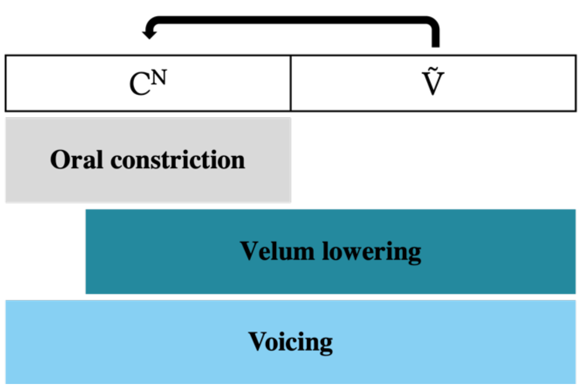

Figure 5a: Gestural score representing anticipatory consonant nasalization, triggered by a phonemically nasal vowel

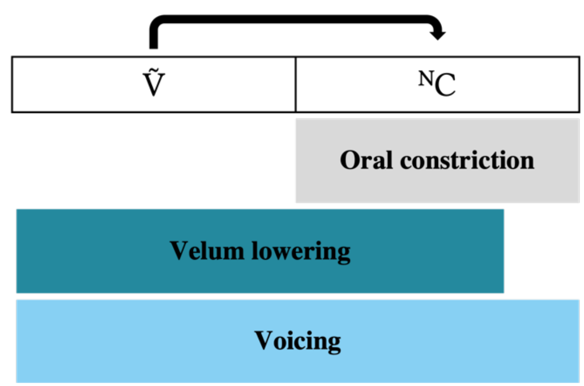

Figure 5b: Gestural score representing progressive consonant nasalization, triggered by a phonemically nasal vowel

In the gestural scores above, the velum begins to lower after the closure in the oral cavity has been achieved in the case of Figure (5a), and the velum achieves a full closure before the release of the constriction in the oral cavity in Figure (5b). However, nasal assimilation may affect the entire duration of the consonant, and languages vary with respect to the timepoint during the consonant at which velum lowering begins and velum raising is achieved.

Patterns of V → C nasal assimilation are only attested in languages with contrastive nasal vowels in their phonological inventory. That said, languages of this type may or may not contain contrastive nasal consonants in their segmental inventories, and there appears to be a clear correlation between the presence or absence of underlying nasal consonants in the language's phonemic inventory and the extent of the consonant that is affected by coarticulatory nasalization. In languages with both contrastive nasal vowels and contrastive nasal consonants, the process tends to only affect a portion of the consonant; while in languages with only contrastive nasal vowels, the process tends to affect the entire consonant's duration. As noted in previous subsection, these patterns follow from the perspective of contrast neutralization: In a language that does not exhibit a contrast in nasality within its consonant inventory, full consonant nasalization does not result in the merging of any phonemic contrasts. Meanwhile, in a language that does exhibit a contrast in nasality within its consonant inventory, partial nasalization of an underlyingly oral consonant allows for additional perceptual as to the nasal identity of an adjacent phonemic nasal vowel, while avoiding a complete loss of contrast in consonant nasality.

The pattern in (5a), where a nasal vowel causes a part of a following oral consonant to be nasalized (/ṼC/ → [Ṽ^{N}C]), is observed in French. Cohn (1990:120) shows that following a nasal vowel, voiceless /t/ often has a very brief initial portion containing nasal airflow, and that voiced /d/ shows a very similar pattern, albeit with a great proportion of its duration being affect by progressive coarticulatory nasalization. These patterns are illustrated in Figure (6a) and (6b) respectively, taken from Cohn (1990:121).

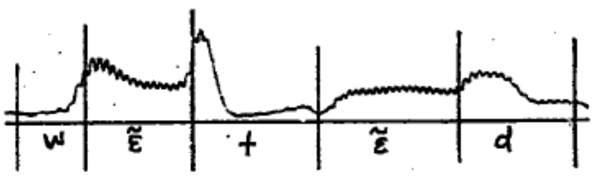

Figure 6a: Nasal flow trace for the word /lwɛ̃tɛ̃/ 'lointain' by a female speaker of European French, from Cohn (1990:121)

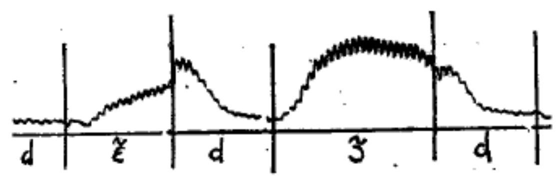

Figure 6b: Nasal flow trace for the word /dɛ̃dɔ̃/ 'dindon' by a female speaker of European French, from Cohn (1990:121)

Tapiete, a Tupí-Guaraní language spoken in Argentina, Bolivia, and Paraguay, provides an additional example of progressive V → C nasal assimilation resulting in pre-nasalized consonants. González (2005) notes that "the sequence of a vowel plus a nasal consonant before a voiceless stop constitutes an allophonic variation of a nasal vowel," such that an input sequence of the type /ṼT/ surfaces with consonant pre-nasalization, giving rise to surface [NT] sequences. The author notes that the articulation of a nasal vowel with or without a nasal consonant following it is common in casual speech (7a), while the nasal consonant is clearly perceptible in careful speech, but the nasal vowel may surface as oral (7b).

(7)	a. /pẽte/ → [pẽnte ~ pẽte]	'one'
	b. /pẽte/ → [pente]	'one'

Other languages exhibiting similar patterns include Kaingang (Jê, Wiesemann 1972), Máíhĩki (Lev Michael, personal communication), Waorani (Fawcett, in press), as well as Panãra (see Chapter 3), among several others. Patterns of consonant pre-nasalization seem much more typologically common in the Amazon than the available descriptive literature leads one to believe. It appears that this phenomenon is commonly underrepresented in phonological descriptions, perhaps due to the fact that it may not always be very perceptually salient, and is therefore often assumed to be a "phonetic" rather than "phonological" process.

The occurrence of consonant pre-nasalization (5a) is significantly more common than the occurrence of consonant post-nasalization (5b). According to the sample of 2,186 languages contained in PHOIBLE (Moran & McCloy 2019), [mb] is attested in 292 languages, while [bm] is attested in only one (Eastern Arrernte, Breen & Dobson 2005). Similarly, [mp] is attested in 37 languages, while [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 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, 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 consonant nasality is more perceptually salient in post-vocalic than pre-vocalic position. Taken together, this evidence suggests that the complex segment [mp] combines the most perceptually salient portions of both an oral and a nasal stop, providing a functional explanation for its greater cross-linguistic frequency compare to [pm]. In comparison, [pm] combines the least perceptually salient portions of both an oral and a nasal stop, making it an unlikely segment type to grammaticalize cross-linguistically.

While post-nasalized consonants are indeed typologically uncommon, anticipatory V → C partial nasal assimilation resulting in post-nasalized consonants of the type [TN] is observed in the Mumuye dialect of Adamawa (Shimizu 1983, Maddieson & Ladefoged 1993), a language of Northeastern Nigeria. The Zing dialect of Mumuye exhibits a total of fifteen surface post-nasalized consonants, namely [pm, bm, vm, tn, dn, sn, zn, rŋ, ʃɲ, ʒɲ, kn, kŋ, gŋ, kpmŋ, gbmŋ, wŋ]. These consonants are allophones of plain oral consonants before one of the phonemically nasal vowels /ĩ, ẽ, ã, õ, ũ/, as in the example in (8).

(8) /dũ/ → [dnũ] 'follow'

In languages with contrastive nasal vowels but which lack a series of contrastive nasal consonants, the process of local nasal assimilation generally affects the entire consonant rather than only a portion of its duration. This is exemplified for Xavante (McLeod 1974; Oliveira 2007; Pickering 2010; Quintino 2012, 2018; Carrick 2021), where the underlyingly oral consonants /b, d, z, ɾ, h, w, j/ surface as fully nasal [m, n, w̃, j̃, ɾ̃, h̃] when they immediately precede a phonologically nasal vowel, as in (9). It is worth noting, however, that alternative descriptions of Xavante analyze the nasal consonants /m, n, ɲ/ as underlying, and derive the homorganic surface voiced obstruents [b, d, z] from local oral assimilation with an adjacent phonemically oral vowel (Huff 2021).

(9) a. /ʔĩbɾõtõ/ → [ʔĩmɾõtõ] 'without a pair'
b. /dãbrĩ/→ [nãmɾĩ] 'to braid'

Akan, a Kwa language spoken in Ghana, has a phonemic inventory containing both oral and nasal vowels, but only oral consonants (Schachter & Fromkin 1968). The language exhibits surface nasal consonants, a subset of which are derived from a pattern of local nasalization from an adjacent nasal vowel, exemplifying the pattern in (6a). The Akan data in (10) shows that underlyingly oral voiced stops and approximants are nasalized when they precede phonemically nasal vowels.

(10) a. /bã/ → [mã] ‘to give’
b. /dã/ → [nã] ‘and’
c. /jã/ → [ɲã ~ j̃ã] ‘receive’
d. /w̃ãdĩ/ → [ŋwãnĩ ~ w̃ãnĩ] ‘scrape’
e. /h̃ũ/ → [ɦ̃ũ] ‘fear’

Patterns of complete nasalization of voiced oral consonants triggered by a phonemically nasal vowel are observed in several African languages, such as Ebrié (Sande 2019, Russell 2021), a Kwa language of Ghana; and Emai (Schaefer & Egbokhare 2017), an Edoid language of Nigeria. Similar analyses have also been proposed for American indigenous languages such as Bolivian Guaraní (Daviet 2016) and Teko (Rose 2002, 2003, 2008), two languages of the Tupí-Guaraní family, as well as Bribri (Chevrier 2017), a Chibchan language of Costa Rica.

2.6 V → C oral assimilation

Patterns of V → C oral assimilation, termed *environmental shielding* by Herbert (1986), are widespread among languages of the Amazon. The assimilation process causes a nasal consonant to undergo coarticulatory oralization, triggered by an immediately adjacent contrastively oral vowel. As with other assimilation patterns, patterns of V → C oral assimilation are observed as both leftward assimilation (11a) and rightward assimilation (11b). Unlike the other cases discussed above, however, shielding involves the spreading of *orality*, rather than of nasality. This pattern is often restricted to only a part of the consonant, giving rise to partially nasal surface consonants, namely pre-oralized ^{C}N and post-oralized N^{C} nasal consonants, reflecting patterns of progressive and anticipatory oral assimilation, respectively.

(11) a. /NV/ → [$N^{C}V$]
b. /VN/ → [$V^{C}N$]

An oral vowel is produced with a raised velum and a nasal consonant is realized with a lowered velum. Given that the velum moves relatively slowly, an input sequence consisting of a nasal consonant followed by an oral vowel may either be realized with nasalization of the vowel, or with oralization of the consonant. Shielding occurs when the velum, which is lowered for the production of the nasal consonant, is fully raised before the oral constriction (e.g. lip closure) of the underlying nasal consonant is released, as in (11a). Alternatively, the velum may begin to lower after the oral constriction of the underlying nasal consonant has been achieved, leaving the initial portion of the consonant without nasality, as in (11b).

These articulatory patterns are represented schematically in the gestural scores in the Figures below. Figure (7a) represents anticipatory oralization of a nasal consonant, and Figure (7b) represents progressive oralization of a nasal consonant. The direction of nasal spreading is indicated by the arrows above the transcribed phonotactic sequence. The symbol /N/ stand is for any nasal consonant, which may be produced with an oral closure at any point of articulation, e.g. bilabial, alveolar, velar, etc. The superscript symbol /^{C}/ stands for the oralized portion of a nasal consonant, which is generally voiced. The symbols /V/ represents an oral, with any point of articulation in the oral cavity, e.g. high, mid, low; and front, central or back.

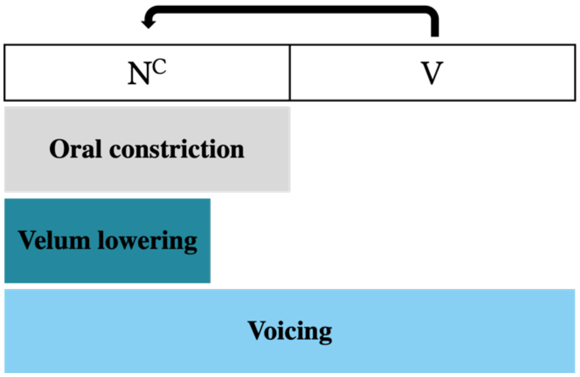

Figure 7a: Gestural score representing anticipatory oralization of a nasal consonant, triggered by a phonemically oral vowel

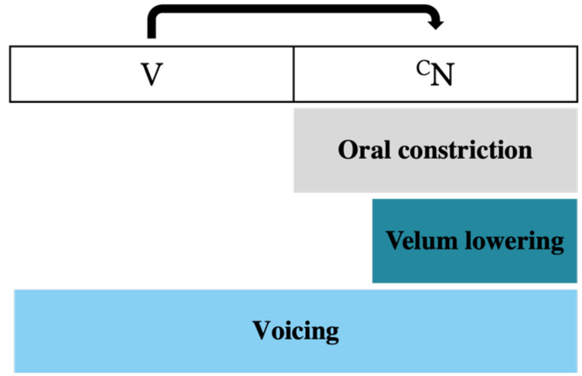

Figure 7b: Gestural score representing progressive oralization of a nasal consonant, triggered by a phonemically oral vowel

In the gestural scores above, it is assumed that the velum begins to lower at consonant onset in the case of Figure (7a), and that the velum is then fully raised before the constriction in the oral cavity is released. In the case of Figure (7b), the velum begins to lower after the constriction in the oral cavity is achieved for the production of the consonant. The results of my survey reveal that the only reported case of shielding involving complete, rather than partial, oralization of a nasal consonant comes from Stanton's (2017, 2018) analysis of Landaburu's (2000) data from Andoque, a language isolate spoken in Colombia. Following Landaburu's analysis, Andoque exhibits contrastive nasality in its vowel inventory, but not its consonant inventory, and the nasal consonants [m, n] are allophones of /b, d/ before phonemically nasal vowels, as in (12a). Following Stanton's reanalysis of phonological grammar of the language, Andoque exhibits contrastive nasality in both its consonant and vowel inventories, and the voiced oral stops [b, d] are allophones of /m, n/ before phonemically oral vowels, as in (12b).

(12) a. /DṼ/ → [NṼ]
b. /NV/ → [DV]

The Andoque data, then, may be analyzed as a case of anticipatory oralization of a nasal consonant, triggered by a phonemically oral vowel. I do not know of any language in which a phonemically nasal consonant is fully oralized following a phonemically oral vowel, as in (13).

(13) /VN/ → [VC] (unattested)

It is worth noting that cases of complete oralization of an underlying nasal consonant are also attested in other languages that exhibit shielding, when the relevant consonant is crucially contained between two adjacent oral vowels, as in (14). Two languages that exhibit this pattern are Kaiowá (Cardoso 2009) and Zo'é (Cabral 1998).

(14) /VNV/ → [VCV]

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). This basic claim is strongly supported by Stanton's (2018) typological survey of languages with environmental shielding, which shows that all languages with patterns of V → C oral assimilation exhibit a contrast between oral and nasal vowels, as well as between oral and nasal consonants. Furthermore, shielding is not attested in languages which lack a three way contrast in stops /p, b, m/ (Wetzels & Nevins 2018). In other words, languages which exhibit local V → C oral assimilation exhibit a contrast in nasality for both vowels and consonants.

The most famous and complex cases of shielding are from two Brazilian Amazonian languages, Karitiana (Tupí, Storto 1999) and Kaingang (Jê, Wiesemann 1972). 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 (15). Phonemically nasal consonants are realized as fully nasal [m] only when they occur adjacent to nasal vowels and/or word boundaries (15a). They are realized as post-oralized [mb] when they occur before an oral vowel (15b); they are realized as pre-oralized [bm] when they occur after an oral vowel (15c); and they are realized as circum-oralized [bmb] when they occur between two oral vowels (15d).

		Karitiana		Kaingang	
(15)	a. /m/ → [m] / {Ṽ, #}__{Ṽ, #}	ã**m**ãŋ˺	'to plant'	**m**õmæ̃ŋ	'fear'
	b. /m/ → [mb] / {Ṽ, #}__V	ã**mb**o	'to climb'	ɸũ**mb**u	'tobacco'
	c. /m/ → [bm] / V__{Ṽ, #}	hi**bm**ĩnã	'roasted'	ha**bm**æ̃	'to listen'
	d. /m/ → [bmb] / V__V	api**bmb**ik˺	'to pierce'	ke**bmb**a	'to try out'

Instrumental and quantitative data on patterns of shielding is scarce, but some brief descriptive accounts are available. Figure (8), taken from Demolin, Storto & Haude (2006:6), provides a spectrogram and audio waveform for the word [kidnda] 'thing' in Karitiana containing a pre- and post-oralized nasal consonant. Figure (9), taken from Pessoa (2012:96), provides a spectrogram for the word [mbakɨdn] 'little bird' in Krenak (Macro-Jê), containing both a postoralized and a preoralized consonant. In both figures, the shielded consonants appear inside of a blue box. In both cases, it's possible to see that the oral portion(s) of the complex nasal consonant are quite brief compared to the nasal portion. This is consistent with several descriptive statements about the realization of oralized consonants among Amazonian languages as well as the typological observation that the nasal portion of an [ND] consonant with a voiced release is significantly longer than the oral portion (Maddieson & Ladefoged 1993, Riehl 2008, Cohn & Riehl 2012, Stanton 2017).

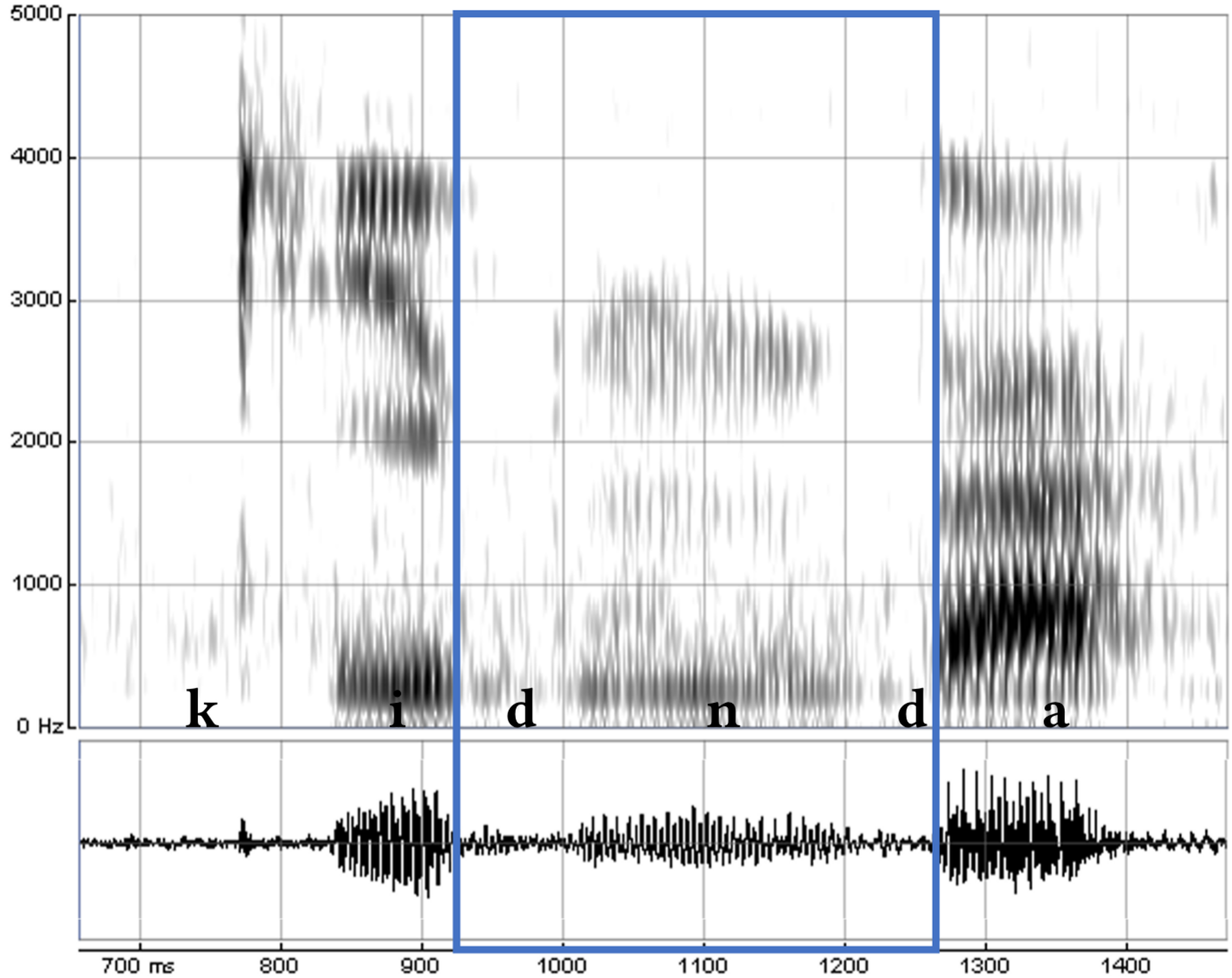

Figure 8: Spectrogram and audio waveform for the word [kidnda] 'thing' in Karitiana, modified from Demolin, Haude & Storto (2006:6). The pre- and post-oralized nasal consonant appears inside the blue box

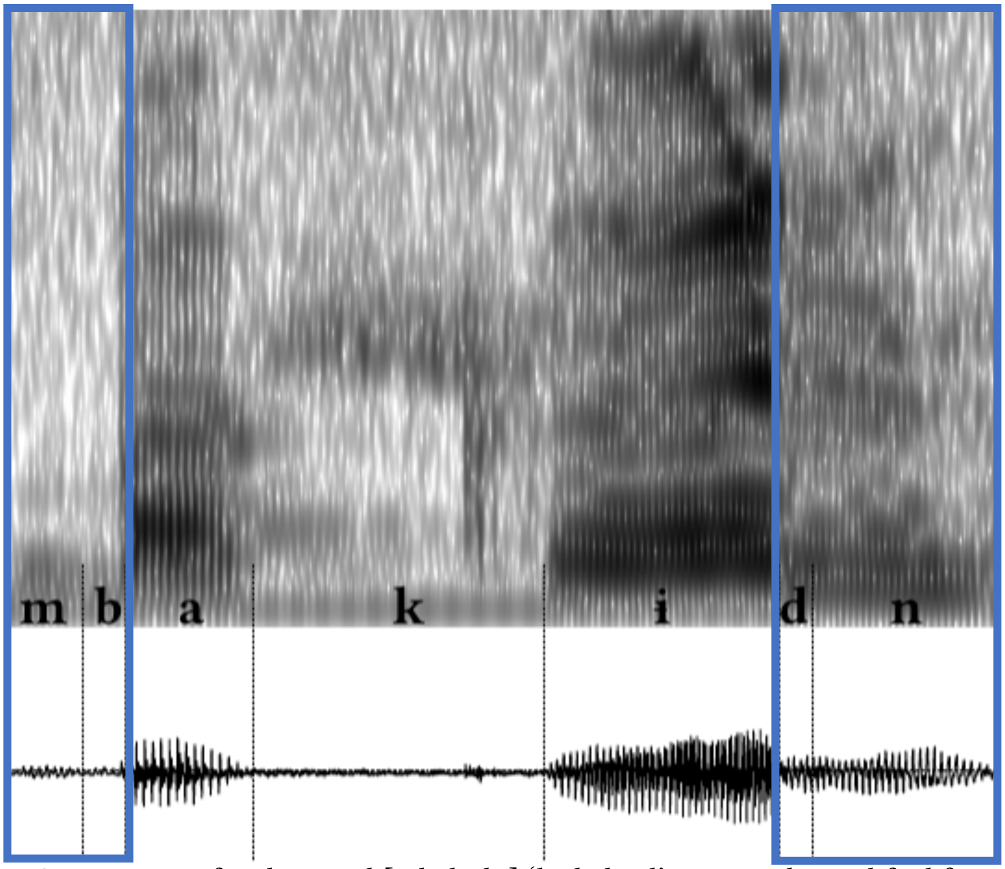

Figure 9: Spectrogram for the word [mbakɨdn] 'little bird' in Krenak, modified from Pessoa (2012:96). The pre- and post-oralized nasal consonants appear inside the blue boxes

2.7 C → V oral assimilation

The only potentially unattested pattern of nasal/oral assimilation is oral assimilation triggered by an oral consonant and undergone by a nasal vowel. Indeed, the results of my survey reveal that an analysis involving oralization of a phonemically nasal vowel by an adjacent oral consonant has not been proposed for any language. As will be argued below, however, an analysis of partial progressive oral assimilation of a phonemically nasal vowel, triggered by an oral consonant (16a) is compatible with some instrumental data from Canadian French. I have not found any potential case of anticipatory oral assimilation, as in (16b). Furthermore, my typological survey suggests that patterns of local C → V oral assimilation are always restricted to a part of the nasal vowel, and never affect the vowel's entire duration, as in (17).

(16)	a. /CṼ/ → [C$^{\mathrm{V}}$Ṽ]	(17)	a. /CṼ/ → [CV]
	b. /ṼC/ → [Ṽ$^{\mathrm{V}}$C]		b. /ṼC/ → [VC]

A nasal vowel is produced with a lowered velum, and an oral consonant is produced with a raised velum. Local oral assimilation, triggered by an oral consonant and affecting a phonemically nasal vowel, would involve that the velum remain raised during the entire duration of the oral consonant, and into the consonant release, in the case of (16a). Specifically, the velum lowering gesture for the nasal vowel would not begin right at vowel onset, but at some point into the vowel. In the case of (16b), the velum would be lowered for the production of the nasal vowel, and it would achieve a full closure at some point into the vowel's duration, crucially before the offset of the vowel and the closure for the following oral consonant.

These articulatory patterns are represented schematically in the gestural scores below. Figure (10a) schematizes anticipatory vowel oralization, and Figure (10b) schematizes progressive vowel oralization. The direction of nasal spreading is indicated by the arrows above the transcribed phonotactic sequence. The symbol /C/ stands for any oral consonant, which may be produced with an oral closure at any point of articulation, e.g. bilabial, alveolar, velar, etc. The symbol /Ṽ/ represents a nasal vowel with any point of articulation in the oral cavity, e.g. high, mid, low; and front, central or back. The superscript symbol /^{V}/ stands for the oralized portion of a nasal vowel.

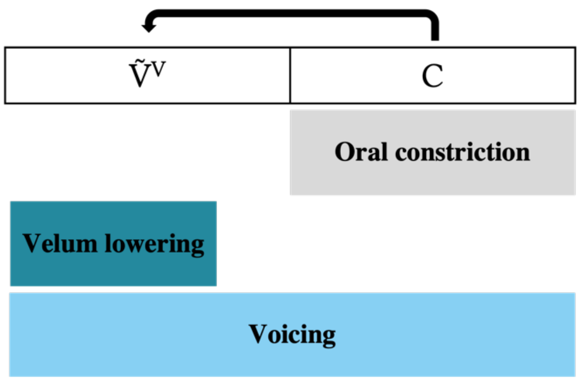

Figure 10a: Gestural score representing anticipatory vowel oralization, triggered by a phonemically oral consonant

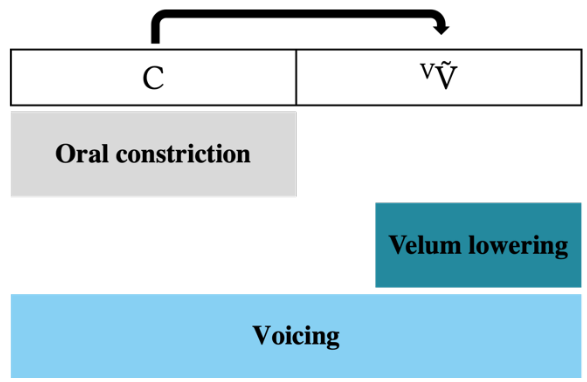

Figure 10b: Gestural score representing progressive vowel oralization, triggered by a phonemically oral consonant

In the gestural scores above, the velum achieves a full closure before vowel offset in the case of Figure (10a), and it begins to lower after vowel onset in the case of Figure (10b). As noted above, nasal vowel oralization could theoretically affect the vowel's entire duration; however, such patterns of oralization are unattested. This hypothetical scenario would involve the erasure of the nasal gesture, i.e. of the [+nasal] feature.

While my typological survey reveals that nasal vowel oralization is not explicitly discussed as a pattern of local oral assimilation for any language anywhere in the literature, some of the French data presented in Section 2.4 is compatible with an interpretation according to which nasal vowels are partially oralized when adjacent to an oral consonant. According to Desmeules-Trudel & Brunelle's (2018) nasal airflow data on Canadian French nasal vowels (Figure 4), notable nasal airflow only begins at approximately 25% of vowel duration, in the case of phonemically nasal vowels appearing in both open and closed syllables. In the data reported by the authors, nasal vowels always appeared after an oral obstruent[2], suggesting that the late onset of velum lowering for the nasal vowel may be attributed to local oral assimilation triggered by the preceding oral consonant. In order to test for the specific effect of the oral consonant, it would be necessary to compare the realization of nasal vowels in different phonological

[2] Nasal vowels in French are not restricted to appearing after an oral obstruent; rather, the target words used in this study were explicitly chosen by the authors to target this particular phonotactic environment.

environments, such as word-initial, after a nasal consonant, and after an oral consonant. I leave this endeavour to future work.

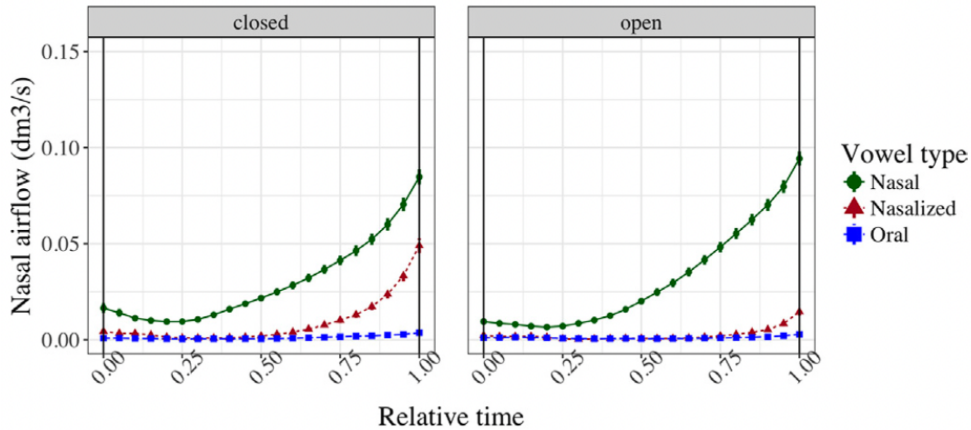

Figure 11: Mean nasal airflow, per syllable type in Canadian French vowels in a closed syllable /VN$/ (left) and in an open syllable /V$N/ (right), from Desmeules-Trudel & Brunelle (2018)

Cohn's (1990) European French data shows a very similar pattern of late onset of nasal airflow in phonemically nasal vowels that follow oral consonants, as in Figure (12a, Cohn 1990:97). In comparison, Cohn's data shows that nasal vowels that immediately follow nasal consonants show consistent nasal airflow throughout their duration, and immediately at vowel onset, as in Figure (12b, Cohn 1990:108). This pattern is to be expected, as the nasality from the nasal consonant and the immediately following nasal vowel can be interpreted as resulting from a single velum lowering gesture extending throughout the duration of both segments. Functionally, the late onset of velum lowering in the production of a nasal vowel may serve to avoid the post-nasalization of the preceding oral consonant, which would result in a complex [CN] segment. As discussed in Section 2.3, post-nasalized [CN] segments are very rare cross-linguistically, which may be attributed to the fact that they combine the least perceptually salient portions of both oral stops and nasal stops.

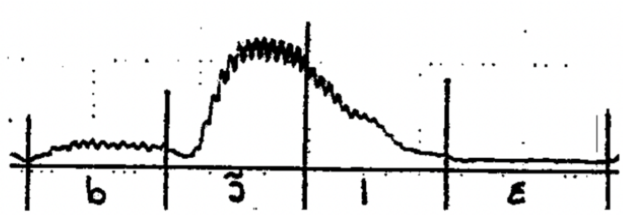

Figure 12a: Nasal flow trace for the word /bɔ̃-lɛ/ 'good milk' by a female speaker of European French, from Cohn (1990:97)

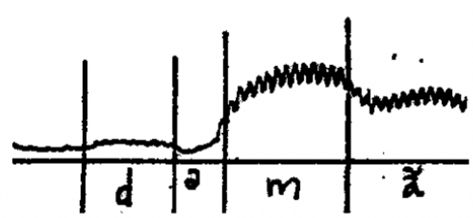

Figure 12b: Nasal flow trace for the word /(lɛ)dəmɑ̃/ 'in an ugly way' by a female speaker of European French, from Cohn (1990:108)

If the attested pattern of partial oralization of nasal vowels *after* oral consonants can be attributed to the avoidance of surface [CN] segments, the absence of the mirror pattern, whereby a nasal vowel is partially oralized *before* an oral vowel, can also likely be attributed to the fact that surface [NC] segments are considered phonetically and phonologically well-formed. Indeed, it was noted that a complex nasal segment in which the initial portion is nasal and the final portion is oral combines the most perceptually salient portions of both a nasal stop and an oral stop.

It seems plausible that many more languages could exhibit patterns of partial oralization of phonemically nasal vowels, and that such cases are simply underreported. One possible explanation for the underreporting of this pattern may be that vowel nasality is notorious for its low perceptual salience (e.g. Bowern 2008). As such, linguists reporting on phonological patterns may simply not be able to identify, without the help of instrumental data, the timepoint in a vowel where nasal airflow begins. In addition, the presence of some nasal airflow is possible without being perceptible at all if the velopharyngeal port opening is sufficiently small (Warren et al. 1993). As such, it seems very likely that linguists documenting nasal vowels may not be able to say anything particularly meaningful about whether nasal airflow begins right at vowel onset or at a slightly later timepoint in the vowel. In addition, when such patterns are indeed documented instrumentally, as in the case of French discussed by Desmeules-Trudel & Brunelle (2018) and Cohn (1990), the late onset of nasal airflow is not a characteristic of the realization of the vowel that is given a detailed discussion.

Three additional case studies presented in this section are also logically compatible with an analysis according to which phonemically nasal vowels are fully oralized when they are adjacent to a voiced oral consonant, namely Andoque, Xavante, and Akan. However, the simple fact that no phonological description of any of these languages has in fact proposed a vowel denasalization analysis to account for the empirical facts relating to phonotactic distributions is, in itself, informative to the current typology of local nasal/oral assimilation. The basic pattern relating to the distribution of oral and nasal segments in these three languages is summarized in (18).

(18)	a. [NṼ]	c. [TṼ]	e. *[DṼ]
	b. [DV]	d. [TV]	f. *[NV]

In Andoque, Xavante, and Akan, nasal consonants are only observed when adjacent to a nasal vowel, as in (18a), and voiced oral obstruents are only attested when adjacent to an oral vowel, as in (18b). However, both nasal and oral vowels may appear when adjacent to a voiceless oral obstruent, as in (18c) and (18d), respectively. For all of these languages, the default analytical assumption has been that a voiced consonant assimilates to the [+/−nasal] feature of the vowel. Schachter & Fromkin (1968), Landaburu (2000), McLeod (1974), Oliveira (2007), Pickering (2010), Quintino (2012, 2018), and Carrick (2021) all take the analytical position that the complementary distribution of nasal and oral segments in (2) is derived via the nasalization of underlyingly voiced oral consonants when immediately adjacent to a phonemically nasal vowel, as in (19a). As noted in Section 2.4, Stanton (2017, 2018) analyzes the Andoque data via oralization of underlyingly nasal consonants when adjacent to phonemically oral vowels, as in (19b).

(19) a. /DṼ/ → [NṼ]
b. /NV/ → [DV]

None of the existing analyses for these languages has posited that vowels assimilate to the [+/−nasal] feature of a consonant, despite the fact that such an analysis is logically possible. This is likely due to the fact that many authors of phonological grammars take the presence of [TṼ] surface sequences, and specifically the presence of minimal pairs of the shape [TṼ] and

[TV], as evidence that nasality is a contrastive feature of vowels in a given language's phonemic inventory. Given the analytical decision that contrastive nasality is needed for vowels, it is possible to derive the surface [+/−nasal] value of consonants via assimilation to an adjacent vowel, and it is not necessary to posit a contrast in nasality for voiced consonants. This, then, provides the most economic phonemic inventory: /V, Ṽ, D, T/. While the most economic analysis may not necessarily be the best one in all cases, principles of economy often guide analytical decisions made by linguists in establishing phonemic inventories.

An alternative analysis of the above data, according to which nasal vowels are oralized next to voiced oral obstruents, as is (20), is logically tenable, but suboptimal. This is because such an analysis would require one to posit a larger phonemic inventory, with a contrast in nasality for both vowels and consonants, namely /V, Ṽ, D, N, T/. In addition, vowel nasality is assumed to be an inherently marked phonological characteristic. Without overt evidence for the presence of a nasal vowel in a given phonotactic sequence (e.g. in a derived environment), authors of phonological grammars generally do not assume the presence of a phonemically nasal vowel, as in (20a).

(20) a. /DṼ/ → [DV]
b. /NV/ → [NṼ]

The empirical generalization that nasal vowels do not oralize when adjacent to oral consonants, then, may not reflect a fundamental truth about local nasal/oral assimilation, but may rather reflect our assumptions as language descriptivists. This pattern follows from the fact that the set of contrasts in a language's phonological system have direct consequences on its specific patterns of local nasal/oral assimilation. As has been noted in the previous sections, patterns of local nasal/oral assimilation that affect the entirety of a segment's duration are only attested when the sound in question is crucially not contrastive in the language's phonemic inventory. For instance, allophonic vowel nasalization in English, which seems to affect the entire vowel's duration, is observed because vowel nasality is crucially not contrastive in English. Likewise, complete nasalization of an underlying oral consonant is only attested in languages which do not possess nasal consonants in their phonemic inventory. Thus, the observation that the feature [−nasal] does not spread from an oral consonant to a phonemically nasal vowel may be a consequence of the fact that all languages have phonemic oral vowels.

That full consonant oralization is attested, but not full vowel oralization, can be attributed to a fundamental difference in the way the feature [+nasal] affects consonants vs. vowels. The consonant inventory of any given language generally exhibits several natural classes that differ by manner of articulation. It is generally the case that allophony in consonant nasality/orality affects only a subset of the consonants in a language's inventory, usually a class of voiced or sonorant consonants. Meanwhile, vowels are generally always voiced and sonorous, and do no exhibit distinct natural classes for manner of articulation in the same way as consonants. Notably, the results of my typological survey reveal that phonemic voiceless nasal vowels are unattested. While complete oralization of nasal consonants results in the neutralization of a contrast in a subset of the inventory of consonants, complete oralization of nasal vowels would result in the neutralization of this contrast across the entire vowel inventory. Taken together, then, these considerations provide additional explanation for the lack of an attested pattern whereby nasal vowels are fully oralized by an adjacent oral consonant.

Finally, it is worth reiterating that vowel nasality is notorious for its low perceptual salience. For this reason, there is a typological trend toward the enhancement of the contrast between oral and nasal vowels, when such a contrast is attested. This was noted by Herbert (1986), and supported by Stanton's (2017) extensive survey of languages with shielding. As noted in Section 2.5, it is common for languages with a contrast between oral and nasal vowels to enhance this contrast. This can be achieved via distinct vowel qualities (e.g. French) for pairs of oral and nasal vowels, or by partially oralizing nasal consonants that are adjacent to phonemically oral vowels. This latter solution represents a pattern of V → C oral assimilation. An inverse pattern of C → V assimilation, whether the oralization of a nasal vowel by an adjacent oral consonant, or the nasalization of an oral vowel by an adjacent nasal consonant, would render the contrast in vowel nasality with already low perceptual salience even less perceptible. As such, the typological trend seems to be to enhance, rather than neutralize, a contrast in vowel nasality when it is present. Indeed, oralization of nasal vowels by an oral consonant would be an important step in the diachronic loss of vowel nasality. In such a system, it is likely that the remaining surface vowels may be analyzed as the result of coarticulatory nasalization by an adjacent nasal consonant.

Perhaps as the result of the fact that the velum moves relatively slowly and that nasality is not very perceptually salient, a cross-linguistic trend toward the extension of the duration of a nasal gesture can be observed. This can be achieved in one of two ways: (i) by extending the duration of time during which the velum is at its articulatory target (i.e. the gestural plateau), or (ii) by slowing down and extending the velum lowering portion of the velic gesture. The reduction of the temporal extension of a nasal gesture is also attested, e.g. in the case of shielding, but the complete erasure of a velum lowering gesture (i.e. of a [+nasal] feature) from an input sequence is very rare. The diachronic loss of nasality has been noted in the rare case of Athabascan nasal consonant oralization. However, my survey results reveal that there exists no parallel attested case of nasal vowel oralization, which can likely be attributed to the reasons mentioned above. Indeed, the lack of spreading of the feature [−nasal] has been discussed in the literature on nasality, and has motivated the proposal that the feature [nasal] is in fact privative, without a possible [−nasal] value (e.g. Steriade 1993). It has since been shown that several languages do require a binary distinction in the feature [+/−nasal] (e.g. Trigo 1993). That said, the generalizations that the feature [−nasal] does not spread over a long-distance domain, and that there are many more restrictions on the local spreading of [−nasal] compare to [+nasal], stills hold.

2.8 Summary of (un)attested patterns

This Chapter provided a summary of all attested and unattested patterns of local nasal and oral assimilation, summarized in Table 1 and repeated below in Table 8.

Table 8: Cross-linguistically attested patterns of local nasal and oral assimilation

	Oral		**Nasal**	
	V → C	**C → V**	**V → C**	**C → V**
Partial	Yes	?	Yes	Yes
Complete	Yes	No	Yes	Yes

In Section 2.3, it was shown that patterns of local C → V nasal assimilation are well documented. Full vowel nasalization is attested in languages which do not have a contrast in nasality for vowels, like English; and partial vowel nasalization is also attested in languages which do have a contrast in nasality for vowels, like French and Lakota. In Section 2.4, it was shown that local V → C nasal assimilation is also attested. Full consonant nasalization is attested in languages that exhibit a contrast in nasality for vowels but not for consonants, like Xavante, Bolivian Guaraní and Akan; and partial consonant nasalization is also attested in languages which exhibit a contrast in nasality for both vowels and consonants, like French, Tapiete and Mumuye. It was also shown that partial consonant nasalization resulting in pre-nasalized [NC] segments is significantly more common than in post-nasalized [CN] segments. In Section 2.5, it was shown that local V → C oral assimilation is attested, but only in languages with have a contrast in nasality for vowels. Full consonant oralization is rare, and only plausible for languages which do not contrast voiced oral consonants /D/ and nasal consonants /N/, such as Andoque; and partial consonant nasalization is attested in languages which contrast nasality in both vowels and consonants, such as Karitiana, Kaingang and Krenak. In Section 2.6, it was shown that some patterns of local C → V oral assimilation are attested. Specifically, partial nasal vowel oralization after an oral consonant is attested in French, which exhibits a contrast in nasality for both vowels and consonants. Both partial nasal vowel oralization *before* an oral consonant, and full nasal vowel oralization, are unattested. All logically possible patterns of partial nasal/oral assimilation are attested, compared to only a subset of logically possible patterns of full nasal/oral assimilation.

In addition to the specific cases of attested and unattested patterns of local nasal/oral assimilation detailed in each of the subsections, some general patterns emerge from this typological overview. First, the typology reveals that edges of adjacent segments overwhelmingly tend to share the same value for the feature [+/−nasal], which may be attributed to some mechanical properties of the velum. It was noted that the velum moves relatively slow in comparison to oral articulators, such as the tongue, lips, and vocal folds. When only the edges of segments agree for the feature [+/−nasal], this results in complex nasal segments, i.e. in vowels or consonants containing both a nasal and an oral portion.

Which of the two adjacent segments assimilates to the [+/−nasal] value of the other seems to be largely predictable on the basis of the system of phonological contrasts that are relevant to a particular language, and the perceptual salience of each of these contrasts. Assimilation of an entire segment for the feature [+/−nasal] is only attested when that segment does not exhibit a contrast in nasality. This is because full assimilation of a given segment class for the feature [+/−nasal] would result in the loss of a contrast in nasality for a particular class of segments. For instance, full vowel nasalization is attested in English, likely due to the fact that English does not exhibit a contrast in nasality for vowels. Likewise, full consonant nasalization is attested in Akan because the language does not exhibit a contrast in nasality for consonants. Partial segment assimilation seems to be more common than full segment assimilation, and is possible even when a given language exhibits a contrast in nasality for both vowels and consonants. It was shown that this is likely possible due to the fact that phonologically nasal segments may be distinguished from phonologically oral segments with partial coarticulatory nasalization, based on the portion of the duration of the segment that is realized with nasality. For instance, French distinguishes phonemically nasal vowels from phonemically oral vowels with coarticulatory nasalization from an adjacent phonemic nasal consonant, where the former is realized with nasal airflow during a greater proportion of the vowel's duration than the latter.

Perceptual salience of the cues to a particular phonological contrast, as well as the markedness of particular segment types, also play a role in determining which of two adjacent segments assimilates to the [+/−nasal] value of the other. It was shown that post-nasalized consonants of the type [CN] are very rare crosslinguistically, while pre-nasalized consonants of the type [NC] are much more widely attested. In addition, patterns of local nasal/oral assimilation resulting in [CN] segments are underattested, while mirror patterns of assimilation resulting in [NC] segments are widespread. It was argued, on the basis of phonetic evidence, that complex segments of the type [NC] combine the most perceptually salient portions of both an oral and a nasal stop, while segments of the type [CN] combine the least perceptually salient portions of both oral and nasal stops, providing a functional explanation for the greater cross-linguistic frequency of [NC].

It was also shown that vowel nasality is less perceptually salient than consonant nasality. As such, it is common for languages with a contrast in vowel nasality to exhibit patterns of local nasal/oral assimilation that enhance the cues to the contrast in vowel nasality. For instance, shielding is commonly observed in Amazonian languages which exhibit a contrast in nasality for vowels, where nasal consonants are partially oralized when adjacent to a phonemically oral vowel.

Finally, patterns of local nasal assimilation are more prevalent than patterns of local oral assimilation, and assimilatory patterns that result in the erasure of a [+nasal] feature (or the deletion of a velum lowering gesture) are very rare. While consonant denasalization is attested but very rare, full vowel denasalization is unattested, according to the present typological survey.

In order to successfully account for the generalizations documented in this typological survey of local nasal/oral assimilation patterns, any model of phonological representations must allow for (i) partially nasal segments, where a portion of the segment is nasal and another portion of the segment is oral; (ii) nasal oral assimilation, where segments, or edges of segments, assimilate the [+/−nasal] value of an adjacent segment; and (iii) interpolation, or cline-like gradient increases and decreases in nasality over the course of segment's duration. Segments may be partially nasal with respect to two distinct dimensions of representation: (i) temporally, where a segment is nasalized during only a portion of its duration; and (ii) spatially, where the degree of velopharyngeal port opening varies over the time course of a segment. While partial opening of the velopharyngeal port is possible as a transition between a fully raised and a fully lowered velum in a velum lowering or raising gesture, partial velic opening does not seem to be possible as an articulatory target on its own. Therefore, a successful model of phonological representations will allow for partial degrees of nasalization only as part of an interpolation function between a [+nasal] segment and a [−nasal] segment. In the following chapters, I lay out the key components of the representational model needed to successfully account for the results of the typology of local nasal and oral assimilation.

Chapter 3

Evidence for subsegments: A case study from Panãra

3.1 Overview

This chapter introduces novel data from Panãra (ISO code: kre), a Jê language spoken in Brazil, which supports the need for finer-grained phonological representations. I argue on the basis of Kawaiwete for a quantized decomposition of the segment on a horizontal dimension of representation, where each segment is comprised of three temporally ordered subsegments (q^1 q^2 q^3), (Inkelas & Shih 2016; 2017; Shih & Inkelas 2014; 2019). The goal of this chapter is to propose a grammar of subsegmental representations which provides enough granularity to account for the full range of typological phenomena involving patterns of local nasalization and oralization, while at the same time not providing more detail than is strictly necessary.

Panãra exhibits nasal stop-obstruent sequences which are the result of two distinct phonological processes: (1a) post-oralization and devoicing of nasal stops before oral vowels and approximants, and (1b) pre-nasalization of oral obstruents after phonemically nasal vowels. 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.'

(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 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).

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 mapped to 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 Maximum Entropy Harmonic Grammar, the grammar must crucially include constraints that reference q subsegments.

(2) a. Post-oralized nasals

$$[m^p] \downarrow (m^1\ m^2\ p^3)$$

b. Pre-nasalized stops

$$[^m p] \downarrow (m^1\ p^2\ p^3)$$

The results of two phonetic experiments support the proposed Q-theoretic representations. The first is a production experiment designed to show that Panãra speakers systematically produce the two types of [NT]s differently (Lin & Lapierre 2019). The second is a perception experiment designed to show 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 chapter is structured as follows: Section 3.2 provides background on Panãra and the phonological patterns that give rise to the two types of [NT]s; Section 3.3 summarizes the results of the production and perception experiments; Section 3.4 presents the proposed Q-theoretic analysis; Section 3.5 models the data within MaxEnt HG, showing that the grammar must crucially make reference to subsegments; Section 3.6 discusses how alternative models of phonological representations cannot capture the relevant pattern; and Section 3.7 concludes.

3.2 Background on Panãra

Panãra is a language belonging to the Northern branch of the Jê family, and it is spoken today by a community of approximately 630 people who live in the demarcated Panará Indigenous Land in the Eastern Amazon. The Panãra's territory consists of 495,000 hectares on the border between the states of Pará and Mato Grosso in Central Brazil, and it falls within the municipality of Guarantã do Norte. Until 1973, the Panãra inhabited a large area in northern Mato Grosso that stretched from the Cachimbo mountain range to the plains where the city of Colíder is located today. At the time, the population numbered up to 600 individuals who were divided among nine villages distributed over the entire territory (Schwartzman 1995). In 1973, the Panãra were contacted by Brazilian national society, which resulted in a dramatic population loss caused by the spread of measles and malaria. By 1976, the 68 Panãra survivors had been removed from their native land and resettled in the neighbouring Xingu Indigenous Land (Schwartzman 1984: 232-233). The ancestral land of the Panãra was made available by the Brazilian government for mining, farming, and settling. In the late 1980s, the Panãra began the process of reclaiming a part of their original land that was still intact. With the support of several Brazilian and international non-governmental organizations such as the Instituto Socioambiental, their current Indigenous Land was identified in 1994 and officially demarcated in 1998. In 1995, the Panãra built a new village, Nãnsêpotiti, on the banks of the Iriri River, and in 2012, the population began to spread to four new villages: Sõnkwê, Sõkârãsã, Kôtikô, and Canaã. As of September 1st, 2018, the number of inhabitants in each one of the villages was the following: Nãnsêpotiti (*n*=281), Sõnkwê (*n*=84), Sõkârãsã (*n*=131), Kôtikô (*n*=110), and Canaã (*n*=24) (SESAI 2018).

The dramatic population loss that resulted from contact was followed by significant efforts to repopulate. Today, approximately 70% of the population is below the age of 20. Despite the low demography, Panãra is a vital language spoken by all native members of the community. Most Panãra are monolingual in their language, with the exception of the young men, who have varying degrees of proficiency in Brazilian Portuguese as a second language. Children's knowledge of Portuguese is generally limited to basic vocabulary, and elementary school classes are conducted in Panãra by Panãra school teachers.

The data presented here was collected during my own fieldwork with the Panãra community between the years of 2015 and 2019, totalling seven months of fieldwork spent in the villages of Nãnsêpôtiti, pictured in Figure 1 below, and Sõkârãsã. All data presented here is original and was collected through a combination of participant observation, spoken narratives, and controlled elicitation. The airflow and perception data presented here was collected in Nãnsêpôtiti in 2018. During all of my time in the village, I speak Panãra almost exclusively in my daily interactions with members of the community. As a result, I am a functional speaker of Panãra and have attained a level of conversational fluency in the language. This practical linguistic knowledge has allowed me to understand the grammar of the language as it is used in informal interactions, and to gather substantive linguistic data beyond the context of structured elicitation.

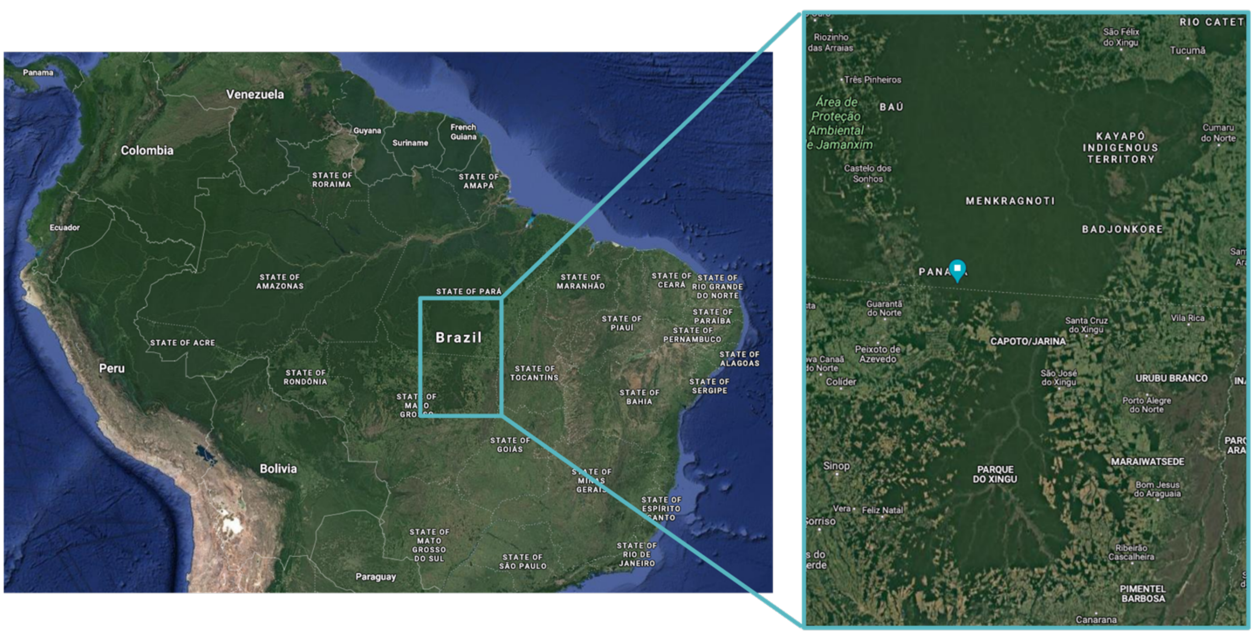

Figure 1: Location of the Panãra village of Nãnsêpôtiti. Image taken from Google Maps [Accessed February 2020]

3.2.1 Phonemic inventory

As shown in Tables 1 & 2, Panãra has an extensive segmental inventory with 45 phonemes, including 17 consonants and 28 vowels. The consonant inventory includes four distinctive series of stops: singleton obstruent, geminate obstruent, singleton nasal, and geminate nasal. The first three series contrast four places of articulation, namely bilabial, alveolar, palatal, and velar; while the last series contrasts only two places of articulation, namely bilabial, and alveolar. Panãra also has three approximants, with bilabial, alveolar, and palatal points of articulation. Note that the obstruents [s, sː] are phonetically realized with an alveolar place of articulation; however, these two consonants clearly form a natural class with the palatal nasal /ɲ/ and the palatal approximant /j/, as evidenced by phonological processes in the language (Lapierre accepted *a*). Panãra's vowel inventory is especially large, with a total of 28 contrastive vowels, which can be either oral or nasal, and short or long[1]. Oral vowels contrast three backness values and three height values. Nasal vowels also contrast three backness values, but only two height values.

Panãra's consonant inventory is provided in Table 1, and its vowel inventory in Table 2. Note that several of the example words exhibit a process of word-initial [i] epenthesis, not discussed in this dissertation. For a detailed description of the phonological grammar of the language, see Lapierre (accepted *a*, accepted *b*).

Table 1: Consonant phonemes

	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 2: Vowel phonemes

Short oral		
i	ɯ	u
e	ɤ	o
ɛ	a	ɔ

Short nasal		
ĩ	ɯ̃	ũ
ẽ	ɤ̃	õ

Long oral		
iː	ɯː	uː
eː	ɤː	oː
ɛː	aː	ɔː

Long nasal		
ĩː		
ẽː	ɤ̃ː	õː

[1] Note that the vowel [ɯ̃] has a very low functional load, as it has only been observed in two words, namely /mɯ̃n/ → [mɯ̃ŋ] 'directional' and /pɯ̃n-a/ → [ˈpɯ̃ː.ɾɤ̃] 'one/PROPER.NAME'. The vowel [ũ] is also infrequent in the lexicon, though not nearly as much as [ɯ̃].

Tables 3-5 provide minimal and near-minimal pairs supporting the phonemic status of each consonant. The minimal pairs in Table 3 illustrate a four-way contrast in place of articulation for both singleton and geminate obstruents /p, t, s, k, pː, tː, sː, kː/, as well as for singleton nasals /m, n, ɲ, ŋ/; a two-way contrast for geminate nasals /mː, nː/; and a three-way contrast for approximants /w, ɾ, j.

Table 3: Consonant place of articulation contrasts

Consonant	Minimal and near-minimal pairs	
p : t	/pɯ/ [pɯ] 'achiote'	/tɯ/ [tɯ] 'to die'
t : s	/tɯ/ [tɯ] 'to die'	/sɯ/ [sɯ] 'seed'
s : k	/sɤ/ [sɤ] 'pain, spicy, hawk'	/kɤ/ [kɤ] 'skin, bark'
pː : tː	/pːu/ [ipːu] 'full'	/tːu/ [itːu] 'potato'
tː : sː	/tːu/ [itːu] 'potato'	/sːɯ/ [isːɯ] 'fire'
sː : kː	/ɲĩsːɤ/ [ɲĩsːɤ] 'again'	/kːɤ/ [ikːɤ] 'embira'
m : n	/mĩ/ [mĩ] 'caiman'	/nĩ/ [nĩ] 'locative postposition'
n : ɲ	/nĩ/ [nĩ] 'locative postposition'	/ɲĩ/ [ɲĩ] 'meat'
ɲ : ŋ	/ɲɤ̃/ [ɲɤ̃] 'grey four-eyed opossum'	/ŋɤ̃ː/ [ŋɤ̃ː] 'yes'
mː : nː	/mːɤ̃ː/ [ĩmːɤ̃ː] 'rhea'	/nːɤ̃/ [ĩnːɤ̃] 'big'
w : ɾ	/kwɤn/ [kwɤŋ] 'to dig'	/kɾɤn/ [kɾɤŋ] 'to pull'
ɾ : j	/kɾan/ [kɾaɲ] 'inside'	/kjan/ [kjaɲ] 'short'
w : j	/ŋwa/ [ĩŋkwa] 'home'	/ŋja/ [ĩŋkja] 'paca'

Table 4 presents minimal pairs supporting a three-way contrast in manner of articulation between obstruents, nasals, and approximants.

Table 4: Consonant manner of articulation contrasts

Consonant	Minimal and near-minimal pairs	
p : m	/pĩ/ [pĩ] 'fire wood'	/mĩ/ [mĩ] 'caiman'
pː : mː	/pːu/ [ipːu] 'full' /pːẽ/ [ipːẽ] 'foreigner'	/mːũn/ [ĩmːũŋ] 'up there' /mːẽn/ [ĩmːẽɲ] 'to throw away'
p : w	/pɯ/ [pɯ] 'achiote'	/wɯ/ [wɯ] 'wide, big'
t : n	/tɤmjɤ/ [tɤmpjɤ] 'grandchild[2]'	/nɤ̃pjɤ/ [nɤ̃pjɤ ~ nɤ̃ᵐpjɤ] 'mother[3]'
tː : nː	/ja—tːɤ̃/ [jatːɤ̃] 'in that direction'	/ja—nːɤ̃/ [janːɤ̃] 'that one is fat'
n : ɾ	/kɾɛnõ/ [kɾɛnõ] 'shallow water'	/kɾɛɾõ/ [kɾɛɾõ] 'without a hole'
t : s	/tõ/ [tõ] 'sibling, other'	/sõ/ [sõ] 'food'
ɲ : s	/ɲi/ [ĩnsi] 'big'	/si/ [si] 'bone'
ɲ : j	/ɲɤ̃/ [ɲɤ̃] 'grey four-eyed opossum'	/ja/ [ja] 'proximal demonstrative'
k : ŋ	/kɤ/ [kɤ] 'skin'	/ŋɤ/ [ĩŋkɤ] 'parliament'

And finally, Table 5 presents minimal pairs supporting a length contrast for all obstruents /p, t, s, k, pː, tː, sː, kː/, and the bilabial and alveolar nasals /mː, nː/.

[2] For female ego, refers to SD, SS, DS, DD, ZSD ZSS, ZDS, ZDD, BD, and BS. For male ego, refers to SD, SS, DS, DD, BSD BSS, BDS, BDD, ZD, and ZS.
[3] Refers to M and MZ, for both male and female egos.

Table 5: Consonant length contrasts

Consonant	Minimal and near-minimal pairs	
p : pː	/pɯt/ [pɯːti] ‘one’ /kjepɯt/ [kjepɯːti] ‘Kjêypyti (PROPER.NAME)’	/pːɯt/ [ipːɯːti] ‘howler monkey’
m : mː	/mɤ̃/ [mɤ̃] ‘dative clitic’ [kjepɯːtimɤ̃] ‘for Kjêpyti’	/mːɤ̃ː/ [ĩmːɤ̃ː] ‘rhea’
t : tː	/tu/ [tu ~ itu] ‘stomach’	/tːu/ [itːu] ‘potato’
n : nː	/nĩ/ [nĩ] ‘locative postposition’ [kukrɛnĩ] ‘at the house’	/nːĩ/ [ĩnːĩ] ‘dry’
s : sː	/sɯ/ [sɯ ~ isɯ] ‘seed’	/sːɯ/ [isːɯ] ‘fire’
k : kː	/kon/ [koŋ] ‘knee’ [kjepɯtikoŋ] ‘Kjêpyti’s knee’	/kːon/ [ikːoŋ] ‘capuchin monkey’

Tables 6-9 provide minimal and near-minimal pairs supporting the phonemic status of each vowel. The minimal pairs in Table 6 illustrate a three-way height contrast for front vowels /i, e, ɛ/, central vowel /ɯ, ɤ, a/, and back vowels /u, o, ɔ/.

Table 6: Vowel height contrasts

Vowel quality	Minimal and near-minimal pairs	
i : e	/sːi/ [isːi] ‘name’	/sːe/ [isːe] ‘bow, to run’
e : ɛ	/kje/ [kje] ‘earth oven, wild garlic’ /tep/ [teːpi] ‘close’	/krɛ/ [krɛ] ‘hole’ /tɛp/ [tɛːpi] ‘fish’
ɯ : ɤ	/sɯ/ [sɯ] ‘seed’	/sɤ/ [sɤ] ‘pain, spicy, hawk’
ɤ : a	/kɤ/ [kɤ] ‘skin’	/ka/ [ka] ‘cough, 2.SG.ABS’
u : o	/puː/ [puː] ‘field’	/poː/ [poː] ‘to arrive’
o : ɔ	/po/ [po] ‘white, to burn’	/pɔ/ [pɔ] ‘flute’

The minimal pairs in Table 7 illustrate a three way backness contrast for high vowels /i , ɯ, u/, mid vowels /e, ɤ, a/, and low vowels /ɛ, a, ɔ/.

Table 7: Vowel backness contrasts

Vowel quality	Minimal and near-minimal pairs	
i : ɯ	/sːi/ [isːi] ‘name’	/sːɯ/ [isːɯ] ‘fire’
ɯ : u	/tɯ/ [tɯ] ‘leaf’	/tu/ [tu] ‘stomach’
e : ɤ	/se/ [se] ‘fast, vagina’	/sɤ/ [sɤ] ‘pain, spicy, hawk’
ɤ : o	/kɤ/ [kɤ] ‘skin’	/ko/ [ko] ‘stick’
ɛ : a	/simɛ/ [simpɛ] ‘true, really’	/ma/ [ĩmpa] ‘liver’
a : ɔ	/pa/ [pa] ‘arm’	/pɔ/ [pɔ] ‘flute’

The minimal pairs in Table 8 provide evidence of contrastive vowel nasality for 10 vowel qualities, namely six short vowels /ĩ, ẽ, ɯ̃, ɤ̃, ũ, õ/ and four long vowels /ĩː, ẽː, ɤ̃ː, õː/. Unlike oral vowels which contrast three height values, nasal vowels only contrast two height values.

Table 8: Vowel nasality contrasts

Vowel quality	Minimal and near-minimal pairs	
i : ĩ	/si/ [si] 'bone'	/sĩ/ [sĩ] 'meat'
iː : ĩː	/pɾiː/ [pɾiː] 'small pacu'	/sĩː/ [sĩː] 'to sit, feces'
e : ẽ	/kje/ [kje] 'earth oven, wild garlic'	/kjẽn/ [kjẽɲ] 'stone', /ŋjẽ/ [ĩŋkjẽ] '1.sg.abs'
eː : ẽː	/apɾeː/ [apɾeː] 'dirt'	/pɾẽː/ [pɾẽː] 'who'
ɯ : ɯ̃	/j–amɯ/ [jampɯ] 'tail.cont' /nɯn/ [ĩntɯŋ] 'capybara'	/ja–mɯ̃n/ [jamɯ̃ɲ] 'bring that' /mɯ̃n/ [mɯ̃ŋ] 'adlative directional'
a : ɤ̃	/pa/ [pa] 'arm'	/pɤ̃/ [pɤ̃] 'owl'
aː : ɤ̃ː	/paː/ [paː] 'foot'	/pɤ̃ː/ [pɤ̃ː] 'child, small'
u : ũ	/tu/ [tu] 'belly'	/tũn/ [tũm] 'old'
o : õ	/to/ [to] 'exclamation'	/tõ/ [tõ] 'sibling, other'
oː : õː	/joː/ [joː] 'termite'	/j–õːsɤ/ [jõːsɤ] 'longing.cont'

Finally, Table 9 provides evidence of contrastive vowel length, for both oral /iː, eː, ɛː, ɯː, ɤː, aː, uː, oː, ɔː/ and nasal vowels /ĩː, ẽː, ɤ̃ː, õː/. Note that the long nasal vowels [ɯ̃ː, ũː] are only attested as a result of penultimate vowel lengthening (Lapierre accepted *a*), but are not attested contrastively, likely as the result of an accidental lexical gap.

Table 9: Vowel length contrasts

Vowel quality	Minimal and near-minimal pairs	
i : iː	/kɾi/ [kɾi] 'village'	/kɾiː/ [kɾiː] 'lie'
e : eː	/se/ [se] 'fast, vagina' /sõse/ [sõse] 'breast'	/seː/ [seː] 'vein' /sõseː/ [sõseː] 'fishing line'
ɛ : ɛː	/ŋɾɛ/ [ĩŋkɾɛ] 'egg'	/ŋɾɛː/ [ĩŋkɾɛː] 'to dance'
ɯ : ɯː	/tɯ/ [tɯ] 'dead'	/tɯː/ [tɯː] 'banana leaf'
ɤ : ɤː	/kɤ/ [kɤ] 'skin'	/kɤː/ [kɤː] 'axe, to scream'
a : aː	/pa/ [pa] 'arm'	/paː/ [paː] 'foot, yes'
u : uː	/pːu/ [ipːu] 'full'	/puː/ [puː] 'field, far'
o : oː	/po/ [po] 'white, to burn'	/poː/ [poː] 'to arrive'
ɔ : ɔː	/tɔ/ [tɔ] 'to knock'	/tɔː/ [tɔː] 'to sing, fly, leave'
ĩ : ĩː	/sĩ/ [sĩ] 'meat'	/sĩː/ [sĩː] 'to sit, feces'
ẽ : ẽː	/pːẽ/ [ipːẽ] 'foreigner /ŋokɾẽ/ [ŋ͡kokɾẽ] 'heart'	/pẽː/ [pẽː] 'language, to speak' /kukɾẽː/ [kukɾẽː] 'to eat'
ɤ̃ : ɤ̃ː	/pɤ̃/ [pɤ̃] 'owl'	/pɤ̃ː/ [pɤ̃ː] 'child, small'
õ : õː	/sõsɤ/ [sõsɤ] 'greedy'	/sõːsɤ/ [sõːsɤ] 'longing/yearning'

3.2.2 Relevant phonological processes

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 contrastively approximants[4] 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/ → [mᵖ, nᵗ, nˢ, ŋᵏ] / $_\sigma$[__{V, w, ɾ, j}
b. → [m, n, ɲ, ŋ] / $_\sigma$[__Ṽ

(3)	a. /mɯ/ → [ĩmᵖɯ]	'man/penis'
	b. /na/ → [ĩnᵗa]	'rain'
	c. /nɤ̃ɲo/ → [nɤ̃nˢo]	'mouse'
	d. /ŋɤ/ → [ĩŋᵏɤ]	'parliament'
	e. /ŋjẽ/ → [ĩŋᵏjẽ]	'1.SG.ABS'
	f. /swɤmɾõ/ → [swɤmᵖɾõ]	'tapioca bread'

(4)	a. /mɤ̃-mɯ̃n/ → [mɤ̃mɯ̃ŋ]	'come.IMP'
	b. /nõpjõ/ → [nõpjõ ~ nõᵐpjõ]	'few'
	c. /ɲɤ̃sɯ/ → [ɲɤ̃sɯ ~ ɲɤ̃ⁿsɯ]	'deer'
	d. /ŋɤ̃ː/ → [ŋɤ̃ː]	'yes'

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 (Hyman 1975; Herbert 1986; Stanton 2017, 2018; Wetzels & Nevins 2018) 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 (274 ms) than that of a simple [N] (141 ms) or [T] (212 ms), but shorter than the combined duration of [N] and [T] (353 ms). 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

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

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, $^{\text{ŋ}}$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][5] ‘play’
d. /kjɤ̃-kĩn/ → [kjɤ̃kĩɲ ~ kjɤ̃$^{\text{ŋ}}$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 (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). 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, such as 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 and output mappings as well as relevant examples. Note that all nasalization and oralization processes in Panãra are strictly local, and long-distance nasal harmony is not attested.

[5] 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 word-final [i] epenthesis, accompanied by penultimate vowel lengthening (Lapierre accepted *b*).

Table 3: Phonotactic sequencing of nasal and oral segments

Phonotactic sequence		Example		Gloss
Input	Output	Input	Output	
a. /ṼNV/	[ṼN^{T}V]	/nɣ̃ɲo/	[nɣ̃n^{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’

Post-oralization and pre-nasalization are not simply the result of phonetic implementation: They must 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. 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 accepted *b*). 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-pɣ̃ː/ ⟶ [ĩn^{t}ɔpɣ̃ː ~ n^{t}ɔpɣ̃ː ~ tɔpɣ̃ː] ‘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 minimal and near-minimal pairs in (11-15). Figure 1 below 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’

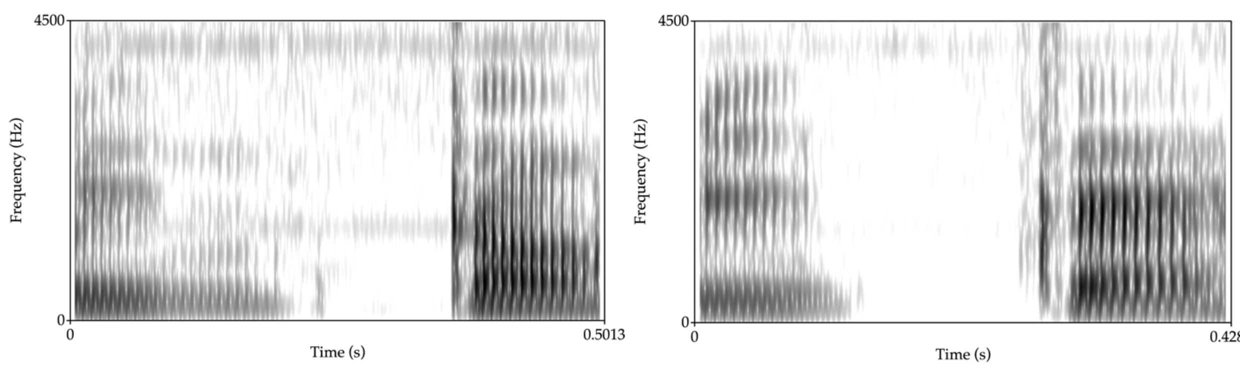

Figure 1: Spectrograms from the production of the [ṼNTV] sequences in the words /mĩnɔ/ [mĩn^{t}ɔ] ‘caiman eye’ (post-oralization, left), and /mĩtɛ/ [mĩ^{n}tɛ] ‘caiman leg’ (pre-nasalization, right)

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. Adequate characterization of the differences between languages requires that these points be noted, 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 shown 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 Aperture Theory (Steriade 1993; 1994), and Autosegmental Phonology (Clements 1976; Goldsmith 1976). 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 that [+/–nasal] is a binary feature), 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-oralization of nasal stops and pre-nasalization of oral obstruents in Panãra.

3.3 Experimental evidence

3.3.1 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: oral lag, velum raising, and voicing lag.

These three 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[6]: (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). All of these articulatory landmarks are indicated for one token of a post-oralized nasal stop (left) and a pre-nasalized stop (right) in Figure 2. As described in Lin & Lapierre (2019), offset of vocal fold

[6] 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].

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.

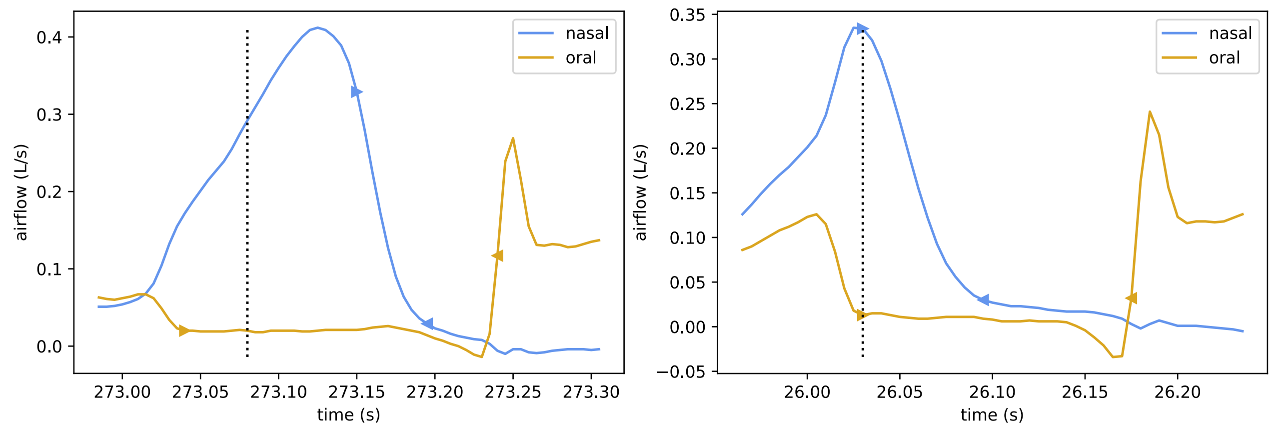

Figure 2: Oral (orange) and nasal (blue) airflow channel during the production of the [ṼNTV] sequences in the word /mĩnɔ/ [mĩn^{t}ɔ] 'caiman eye' (post-oralization, left), and /mĩtɛ/ [mĩ^{n}tɛ] 'caiman leg' (pre-nasalization, right)[7]

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. The model's estimated duration of oral lag is 100 ms for post-oralized nasals, and 27 ms for pre-nasalized stops. Its estimated duration of voicing lag is 78 ms for post-oralized nasals, and 43 ms for pre-nasalized stops. And finally, its estimated duration of velum raising is 83 ms for post-oralization, and 51 ms for pre-nasalization. In other words, 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 these latter [NT]s, the oral closure is always achieved

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

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 mapped to gestural scores to 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, from onset to offset release.

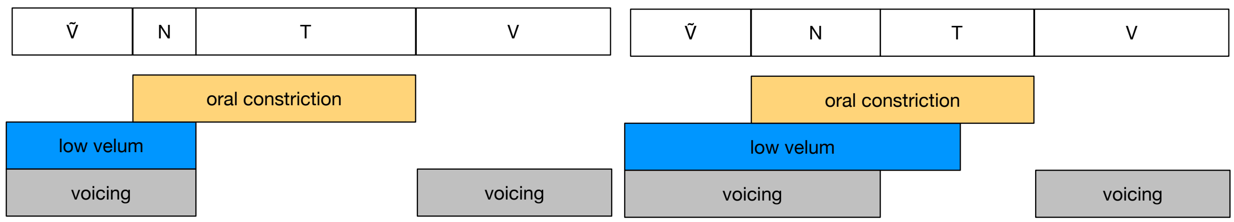

Figure 3: Gestural scores for a pre-nasalized stop (left) and post-oralized nasal (right)[8]

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.

3.3.2 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.

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

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

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).

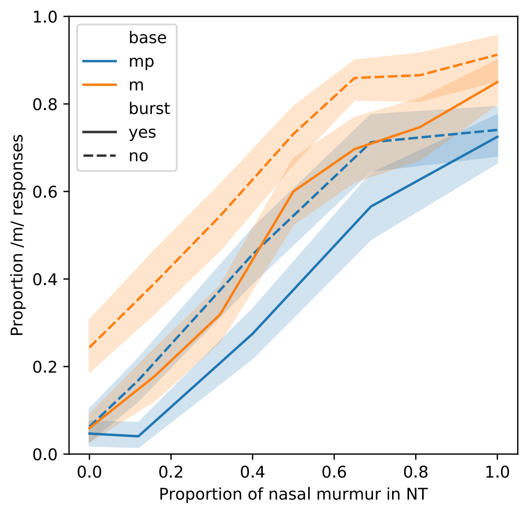

Figure 4: Proportion of /m/ responses by relative duration of nasal murmur to oral stop closure, and by quality of nasal murmur and presence of stop burst[9]

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 be mapped to different representational structures in Panãra's phonological grammar.

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

3.4 A Q-theoretic subsegmental analysis

3.4.1 Background

Q Theory is a model of representational phonology which decomposes the segment [Q] into a series of quantized, temporally ordered subsegments (q) (Inkelas & Shih 2016; 2017; Shih & Inkelas 2014; 2019). Q Theory builds on Aperture Theory (Steriade 1993, 1994) by proposing that the canonical short segment is represented with three[10] subsegments (q^1 q^2 q^3) roughly corresponding to the onset, c-center, and release of a gesture. Q Theory assumes much of the same machinery as SPE, namely the quantization of the temporal dimension into phonological units made up of feature bundles which 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, including possible underspecification. As such, 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 Classic SPE, Autosegmental Phonology, and Aperture Theory.

3.4.2 Proposal

The combined results of the production and perception experiments presented in §3.3 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 (e.g., Shih & Inkelas 2019). The 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 [–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 Section 3.6, previous models of phonological representations are not sufficient to capture the distinction between post-oralized nasals and pre-nasalized stops in Panãra.

[10] Segments may deviate from this canon by possessing more or fewer subsegments (Inkelas & Shih 2017; Garvin et al. 2018, 2020; Schwarz et al. 2019).

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

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

3.4.3 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 (21).

(21) a. ($\mathrm{m}^1\ \mathrm{p}^2\ \mathrm{p}^3$) c. ($\mathrm{p}^1\ \mathrm{m}^2\ \mathrm{p}^3$) e. ($\mathrm{p}^1\ \mathrm{p}^2\ \mathrm{m}^3$)
b. ($\mathrm{m}^1\ \mathrm{m}^2\ \mathrm{p}^3$) d. ($\mathrm{m}^1\ \mathrm{p}^2\ \mathrm{m}^3$) f. ($\mathrm{p}^1\ \mathrm{m}^2\ \mathrm{m}^3$)

The question that naturally arises in considering these predictions is the following: Are all of the segment types in (21) attested? While 4/6 of these hypothesized segments are indeed attested, the simple answer is *no*. Like its predecessor models such as segmental and Autosegmental Phonology (see Section 3.6), 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 (21d) and (21e) 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 §3.3, the distinction between pre-nasalized ($\mathrm{m}^1\ \mathrm{p}^2\ \mathrm{p}^3$) (21a) and post-oralized nasals ($\mathrm{m}^1\ \mathrm{m}^2\ \mathrm{p}^3$) (21b) is robust in Panãra. Similarly, segments of the type [$^{\mathrm{b}}$m] are widely attested in many Amazonian languages that exhibit environmental shielding (see Stanton 2017 for an extensive typological survey), and [$^{\mathrm{p}}$m] is attested contrastively in Alyawarra (Australia; Yalopp 1977). Given available descriptions of these languages, it appears that both the South American and Alyawarra patterns are best mapped to ($\mathrm{p}^1\ \mathrm{m}^2\ \mathrm{m}^3$), the structure in (21f). Pessoa (2012:96) provides spectrograms of the Krenak (Macro-Jê, ISO code: kqq) words /ŋɾaŋ/ [ŋ$^{\mathrm{g}}$ɾa$^{\mathrm{g}}$**ŋ**] 'rattlesnake' and /makɨn/ [m$^{\mathrm{b}}$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 [$^{\mathrm{b}}$m] segments are pre-oralized allophones of underlying nasal stops. Similarly, Yalopp (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 (21e) and (21f) 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 (21e) and (21f) is improbable (but not impossible), and can be ruled out by appealing to 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 (21e) 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 (22a) 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 (22b) states that the grammar is more faithful to q subsegments of nasal stops occurring before than after a vowel.

(22) a. MAX(p^3)/_V >> MAX(m^3)/_V
b. MAX(m)/_V >> MAX(m)/V_

The segment type in (21c) is attested in two Brazilian Amazonian languages, Karitiana (Tupí, Storto 1999) and Kaingang (Jê, 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 (23). Phonemically nasal consonants are realized as fully nasal [m] only when they occur adjacent to nasal vowels and/or word boundaries (23a). They are realized as post-oralized [mb] when they occur before an oral vowel (23b); they are realized as pre-oralized [bm] when they occur after an oral vowel (23c); and, key for this analysis, they are realized as circum-oralized [bmb] when they occur between two oral vowels (23d). As such, Karitiana and Kaingang not only exhibit the segment type in (21c) by the rule in (23d), but they also exhibit the segment types in (21b) and (21f) by the rules in (23b) and (23c), respectively.

		Karitiana		Kaingang	
(23)	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 (21d) 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] in 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 (21d), then, can be ruled out by the P-map constraints in (22).

Finally, that all six of the segment types in (21) 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 (22). Rather, languages may make use of a combination of these structures (e.g. Panãra has structures (21a) and (21b); Karitiana and Kaingang have structures (21b), (21c), and (21f)), but will also create lexical oppositions via additional phonological features.

3.4.4 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 (21) 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^si] '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.

The goal of this chapter is to propose a grammar of subsegmental representations which provides enough granularity to account for the full range of typological phenomena involving patterns 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.

3.5 A grammar of subsegments

3.5.1 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. To model the observed distribution between [N, T, N^T, ^NT] and derive the correct patterns of local nasal and oral assimilation observed in consonants within an Optimality Theoretic grammar, a total of five constraints that crucially make reference to q subsegments are needed. These five constraints belong to three distinct constraint families.

The first set of constraints needed are those that establish crucial correspondence relationships between adjacent subsegments across a segment boundary. This set of constraint accounts for the overwhelming cross-linguistic tendency for edges of segments to agree in nasality or orality. As noted in Chapter 1, I follow recent practice in Agreement-by-Correspondence which collapses Correspondence and Identity constraints (Hansson 2014, Walker 2015, Shih & Inkelas 2019) given the low utility in separating them out. Defined in Q-theoretic terms (Shih & Inkelas 2019), the first correspondence constraint establishes correspondence and drives agreement between any two adjacent q subsegments separated by a Q segment boundary and requires that they agree in the feature [+/–nasal], as in (26).

(26) **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 (26), the derivational grammar of Panãra requires a more specific constraint establishing cross-segment subsegmental correspondence, which crucially specifies that the first subsegment be a consonant and the second subsegment be a vowel. This additional correspondence 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%. 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], as in (27).

(27) **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].

As a result of the fact that Panãra has both of the constraints in (26) and (27) active within its grammar, input sequences of the /NV/ that surface without post-oralization are penalized by both of these constraints, while input sequences of the type /ṼT/ that surface without pre-nasalization are only penalized by the general constraint in (26). Taken together, then, the constraints in (26) and (27) capture the fact that /NV/ input sequences are repaired more frequently than /ṼT/ input 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 consonants, 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 original proposal formalizes this using a MINIMUM DISTANCE constraint (Flemmin 2002, 2008), which is evaluated by looking at the proportion of a vowel's raw duration that is oral or nasal. This is implemented here as 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], as in (25).

(25) **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].

Taken together, the two constraints in (25) and (26) effectively prioritize vowel faithfulness over consonant faithfulness. While (26) 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. The addition of (25) in the grammar of Panãra effectively forces any modification in nasality or orality between the input and the output to be realized on consonants, rather than vowels. In other words, this pair of constraints enforces the preservation of vowel faithfulness for the feature [+/–nasal], at the expense of consonant faithfulness for the same feature.

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 and output mappings of subsegments for the feature [+/–nasal], as in (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, as in (28).

(28) *TN: Assign one violation for every consecutive pair of subsegments (q_i, q_j) if qi is a voiceless oral obstruent and qj 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), (T N T). This pattern observed in Panãra follows from the general markedness of [TN] segments cross-linguistically, as discussed in Chapter 2, justifying its formulation as a markedness constraint. As previously argued, 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. This perception-based explanation provides a functional explanation 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.

3.5.2 A MaxEnt Harmonic Grammar of subsegments

I model the grammar of Panãra [NT]s within a Maximum Entropy Harmonic Grammar (MaxEnt HG; e.g. Goldwater & Johnson 2003, Wilson 2006, Hayes & Wilson 2008). MaxEnt HG is a probabilistic variant of Harmonic Grammar 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 harmony scores closer to zero are observed more frequently.

The MaxEnt Grammar Tool (George et al. 2006) was used to learn constraint weights and compute the probability of all candidates. Tables 4-7 below exhaustively present the input data provided to the learning algorithm. All four constraints were given default initial weights of μ=0, and a prior of σ^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 4 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 occurs 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 4: Tableau for /ṼNV/ input sequence

/ṼNV/ (Ṽ¹ Ṽ² Ṽ³)(N¹ N² N³)(V¹ V² V³)	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$^{\underline{Ṽ}}$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 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.

Table 5: Tableau for /ṼTV/ input sequence

/ṼTV/ (Ṽ¹ Ṽ² Ṽ³)(T¹ T² T³)(V¹ V² V³)	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$^{\underline{\text{N}}}$TV] (Ṽ Ṽ Ṽ)($\underline{\text{N}}$ 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$^{\underline{\text{V}}}$TV] (Ṽ Ṽ Ṽ)(T T T)(V V V)	1			1		22.98	0	0
d. [$\underline{\text{V}}$TV] ($\underline{\text{V V V}}$)(T T T)(V V V)				3		23.58	0	0

Table 6 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.

Table 6: Tableau for /VNṼ/ input sequence

/VNṼ/ (V^1 V^2 V^3)(N^1 N^2 N^3)(Ṽ^1 Ṽ^2 Ṽ^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$^{\underline{\text{T}}}$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$^{\underline{\tilde{\text{V}}}}$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

Finally, Table 7 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].

Table 7: Tableau for /VTṼ/ 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$^{\underline{N}}$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$^{\underline{V}}$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

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.

3.6 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. Section 3.6.1 first considers classic models of segmental representation; Section 3.6.2 considers non-linear accounts of Autosegmental Phonology and Feature Geometry; Section 3.6.3 discusses Aperture Theory; and finally, Section 3.6.4 considers gestural frameworks, including Articulatory Phonology and Gestural Coordination Theory, and how they can be easily be integrated within Q Theory.

3.6.1 Segments are not enough

Many of the basic tenets of the Sound Pattern of English (SPE, Chomsky & Halle 1968) are still widely used in modern phonology, in particular the idea of a transformational grammar in which input structures undergo a series of phonological transformations and are mapped to output structures. SPE assumes 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 (28).

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

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 Section 2.6). As Anderson argues, 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 face the obvious challenge of needing to account for the existence of segments of the type [bm]. 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.

3.6.2 Non-linear approaches are not enough

Autosegmental Phonology (Clements 1976; Goldsmith 1976) was developed, in part, to account for the behaviour of long-distance nasal harmony 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 the 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 map to the same structure, neutralizing the distinction between these two types of complex segments (29a). 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 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 (29b).

(29)	a. [mb]		b. [bm]	
	/\		/\	
	[+nasal][–nasal]		[+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 changes 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).

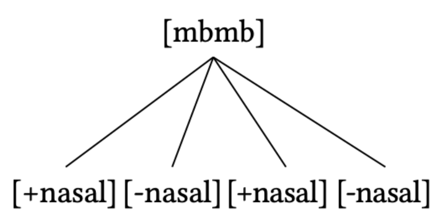

Figure 5: Autosegmental representation of the unattested complex segment [mbmb]

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 many 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. 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.

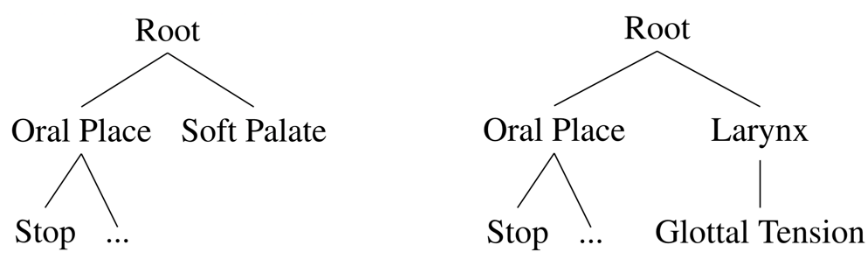

Figure 6: Phonological representation of N-PNS (left) and V-PNS (right)

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 so neatly 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.

3.6.3 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 (30).

(30)

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 (30a), the closure phase is linked to a privative nasal feature, resulting in a pre-nasalized stop, e.g. [mb]; in (30b), only the release phase is linked to a nasal feature, resulting in a post-nasalized stop, e.g. [bm]; in (30c), both the closure and release phases are linked to a nasal feature, resulting in a fully nasalized stop, e.g. [m]; and in (30d) 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 are mapped to 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 2009; Pycha 2009, 2010; Remijsen 2013; Remijsen & Ayoker 2014; Shih & Inkelas 2014, 2019; Inkelas & Shih 2016, 2017).

The data from Karitiana and Kaingang presented in (23) clearly show 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), as in (31).

(31) [−nasal][+nasal][−nasal]
\/ |
A_0 A_{max}

As noted by Garvin et al. (2019), while necessary within the strictures of Aperture Theory, this proposal requires one to revert to Autosegmental representations. 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.

3.6.4 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’[11] such as [mb] are straightforwardly accounted 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 a pathological prediction, as the full range of patterns that may be derived from these mechanics is unattested.

Gafos’ 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.

[11] 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.

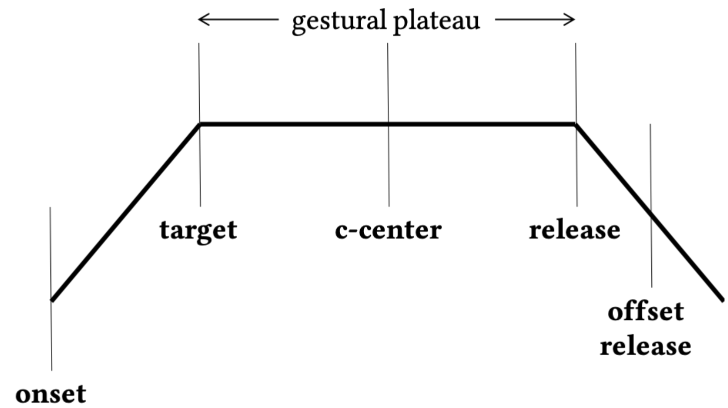

Figure 7: Gestural Landmarks of Gestural Coordination Theory

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 (32). Coordination relation constraints interact with each other, as well as with other constraints in the morpho-phonological grammar, thus giving rise to a grammar of gestural coordination.

(32) 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 (33) and (34), respectively.

(33) 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

(34) 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 5 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, as discussed in §3.4.3, 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, the predictions of this Theory still face an over-generation problem. As discussed in the following subsection, can Q Theory provide the necessary constraint to Gestural Coordination Theory.

3.6.4.1 Integrating Gestural Coordination with Q Theory

The machinery afforded by Gestural Coordination Theory is compatible with, and can be easily integrated within Q Theory. Doing so simultaneously provides the tools necessary to overcome Gestural Coordination Theory's over-generation problem, and offers welcome phonetic grounding to the rather abstract subsegmental units of Q Theory. The representational model presented in this section does not make distinct phonological predictions as the ones laid out in §3.4.3, but simply fleshes out the phonological content of q subsegments, and how they may be articulatory grounded using familiar notions from gestural frameworks. This combines the strengths of both frameworks, namely the descriptive utility of Gestural Coordination Theory and the predictive power of Q Theory.

The tripartite nature of Q Theory is partly informed by findings from Articulatory Phonology, which show that segments are produced with three distinct articulatory phases. Previous accounts of Q Theory have noted that q subsegments can be phonetically grounded in what roughly correspond to the onset, c-center, and release of a gesture (Shih & Inkelas 2019). While this basic proposal generally holds for segments such as plain oral stops, the relationship between landmarks and q anchoring is more complex. Here, I build on Q Theory's original proposal by showing how subsegments, like segments, can be understood to represent a time interval whose left and right boundaries are defined with gestural landmarks as their temporal anchors.

The mapping between subsegments and gestural landmarks is rather straightforward when the production of the relevant phone involves a single articulatory gesture, such as in the realization of the plain voiceless bilabial stop [p], represented within Q Theory as (p^1 p^2 p^3). If subsegments are temporal windows anchored between gestural landmarks, then the production of a bilabial stop can be schematized as in Figure 8. Here, q^1 represents the time window between the ONSET and TARGET of the lip closing gesture; q^2 represents the time window between the TARGET and RELEASE of this gesture; and q^3 represents the time window between the RELEASE and the OFFSET RELEASE. All of the subsegments that contain an interval of a gesture receive the phonological features associated with that gesture. In the case of the plain voiceless bilabial stop (p^1 p^2 p^3), all three of its subsegments contain an interval of the lip closing gesture, and will thus be phonologically specified as [+labial, –continuant]. Note that q subsegments represent abstract, non-uniform time intervals, which follows from the fact that the silent period of a stop is generally longer than that of its closure and release phases.

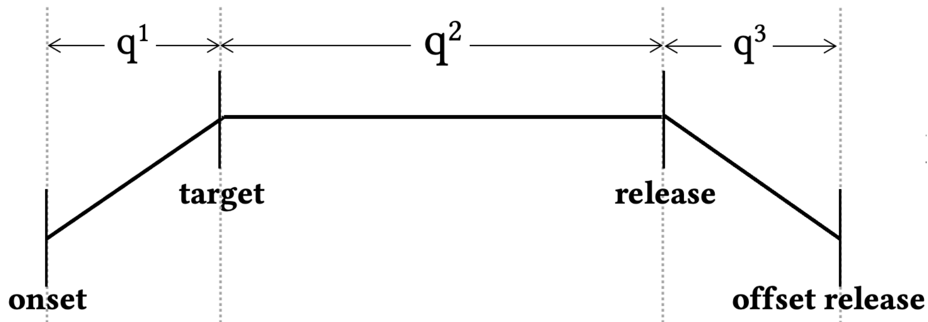

Figure 8: Mapping of subsegments to articulatory landmarks of a lip closing gesture in a voiceless bilabial stop [p] (p^1 p^2 p^3)

Some segments involve multiple simultaneous articulatory gestures, adding a layer of complexity to the mapping between subsegments and gestural landmarks. The production of partially nasal consonants minimally involves a gesture for the constriction in the oral cavity, as well as a velum lowering gesture, and requires coordination between articulatory landmarks of these two gestures. In this scenario, the left and right edges of q subsegments may simultaneously be aligned with articulatory landmarks from more than one gesture. During the production of [NT]s in Panãra, the alignment of the articulatory landmarks for the velum lowering gesture will crucially differ in its alignment to the edges of q subsegments during the production of a post-oralized nasal stop (m^1 m^2 p^3) and a pre-nasalized oral stop (m^1 p^2 p^3). The Q-theoretic mappings presented here assume that the crucial segments are preceded by a nasal vowel and followed by an oral vowel, as in the phonotactic sequence [ṼNTV], the only phonological environment in which post-oralization and pre-nasalization contrast.

During the production of a bilabial post-oralized nasal stop [m^p] (m^1 m^2 p^3), q^1 represents the time window between the Onset and Target of the lip closing gesture, as well as between the C-center and Release of the velum lowering gesture; q^2 represents the time window between the Target and Release of the lip closing gesture, as well as between the Release and the Offset release of the velum lowering gesture; and q^3 represents the time window between the Release and the Offset release of the lip closing gesture. This mapping between gestural landmarks and q subsegments is schematized in Figure 9, and assumes the phonotactic sequence in (35).

(35) (Ṽ^1 Ṽ^2 Ṽ^3)(m^1 m^2 p^3)(V^1 V^2 V^3)

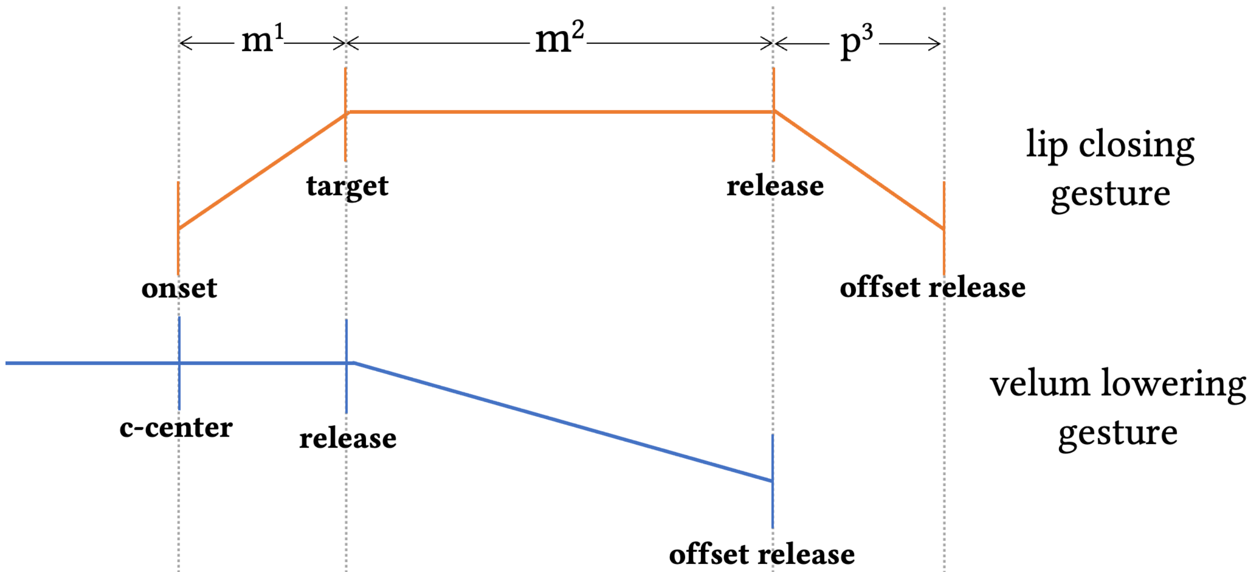

Figure 9: Mapping of subsegments to articulatory landmarks in a bilabial post-oralized nasal stop [m^p] (m^1 m^2 p^3)

During the production of a bilabial pre-nasalized stop [^mp] (m^1 p^2 p^3), the velum lowering gesture persists during a smaller proportion of the total duration of the stop closure. For the lip closing gesture, the alignment of the articulatory landmarks of the lip closing gesture align to q subsegment edges is the same as was described for the production of the bilabial post-oralized nasal consonant [m^p] (m^1 m^2 p^3). However, the alignment of the landmarks of the velum lowering gesture crucially differs. Specifically, q^1 represents the time window between the ONSET and TARGET of the lip closing gesture, as well as between the RELEASE and the OFFSET RELEASE of the velum lowering gesture; q^2 represents the time window between the TARGET and RELEASE of the lip closing gesture; and q^3 represents the time window between the RELEASE and the OFFSET RELEASE of this same gesture. As such, in this mapping between gestural landmarks and q subsegments, the velum lowering gesture is only associated to q^1, but not to q^2 or q^3. This is presented schematically in Figure 10, which assumes the phonotactic sequence in (36).

(36) ($\tilde{V}^1$ $\tilde{V}^2$ $\tilde{V}^3$)(m^1 p^2 p^3)(V^1 V^2 V^3)

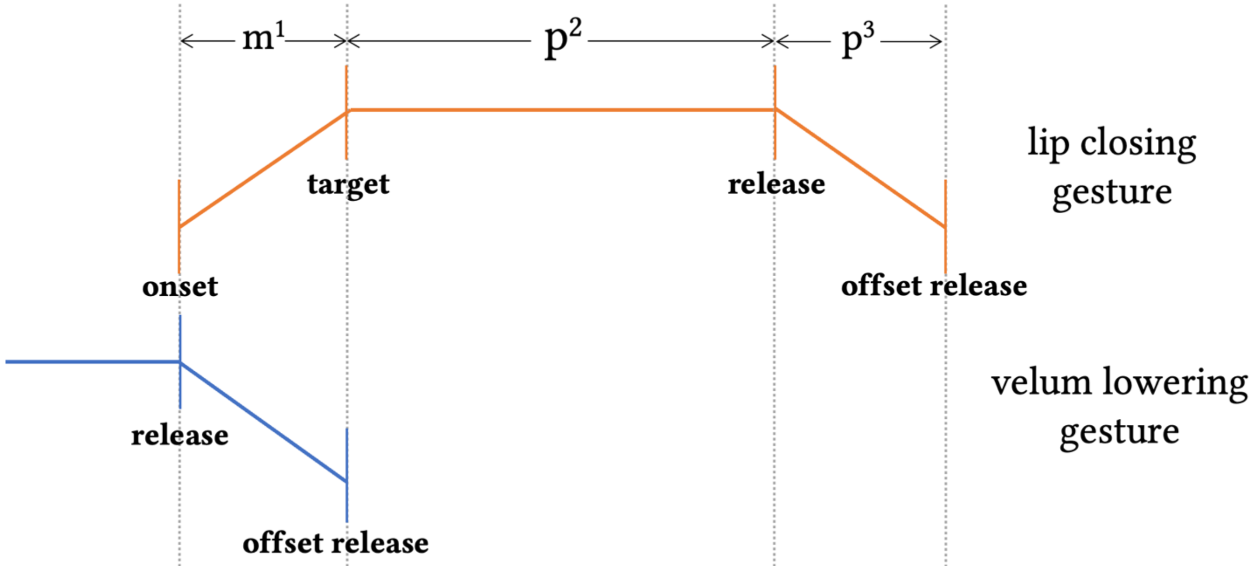

Figure 10: Mapping of subsegments to articulatory landmarks in a bilabial pre-nasalized stop [ᵐp] (m^1 p^2 p^3)

Q Theory constrains Gestural Coordination Theory's machinery because phonological distinctions are made at the subsegmental level, resulting from the feature matrices that emerge from the mapping of gestural landmarks to q subsegment edges. Q Theory does not predict that all possible permutations of anchorings of articulatory landmarks to q subsegment edges will result in distinctive or contrastive segments. Only insofar as these different anchorings of gestural landmarks to q subsegment edges give rise to different subsegmental feature matrices are phonological distinctions predicted to occur, as discussed in §3.4.3.

For instance, the distinction between post-oralized (m^1 m^2 p^3) and pre-nasalized (m^1 p^2 p^3) arises from the fact that q^2 of the former contains a portion of the velum lowering gesture, while q^2 of the latter does not contain a portion of this gesture. This gives rise to two different sets of feature matrices, [+nasal][+nasal][–nasal] and [+nasal][–nasal][–nasal], respectively. In comparison, Q Theory does not predict a contrast between hypothetical (m^1 m^2 p^3)$_i$ and (m^1 m^2 p^3)$_j$, where (m^1 m^2 p^3)$_i$ is gesturally defined as in Figure 9, and (m^1 m^2 p^3)$_j$ is identical, with the exception that q^1 has as its left anchor the TARGET of the velum lowering gesture and as its right anchor the RELEASE of this gesture (i.e. q^1 corresponds to the entire gestural plateau of the velum lowering gesture), as in Figure 11. Since both mappings of gestural landmarks to q subsegment edges give rise to the same featural matrix, namely [+nasal][+nasal][–nasal], Q Theory predicts that (m^1 m^2 p^3)$_i$ and (m^1 m^2 p^3)$_j$ should crucially not be distinct from one another. This prediction is borne out in the Panãra data, where the (m^1 m^2 p^3)$_i$ allophone surfaces when the relevant segment immediately follows a nasal vowel (35), and (m^1 m^2 p^3)$_j$ allophone surfaces when it follows an oral vowel (37).

(37) (V^1 V^2 V^3)(m^1 m^2 p^3)(V^1 V^2 V^3)

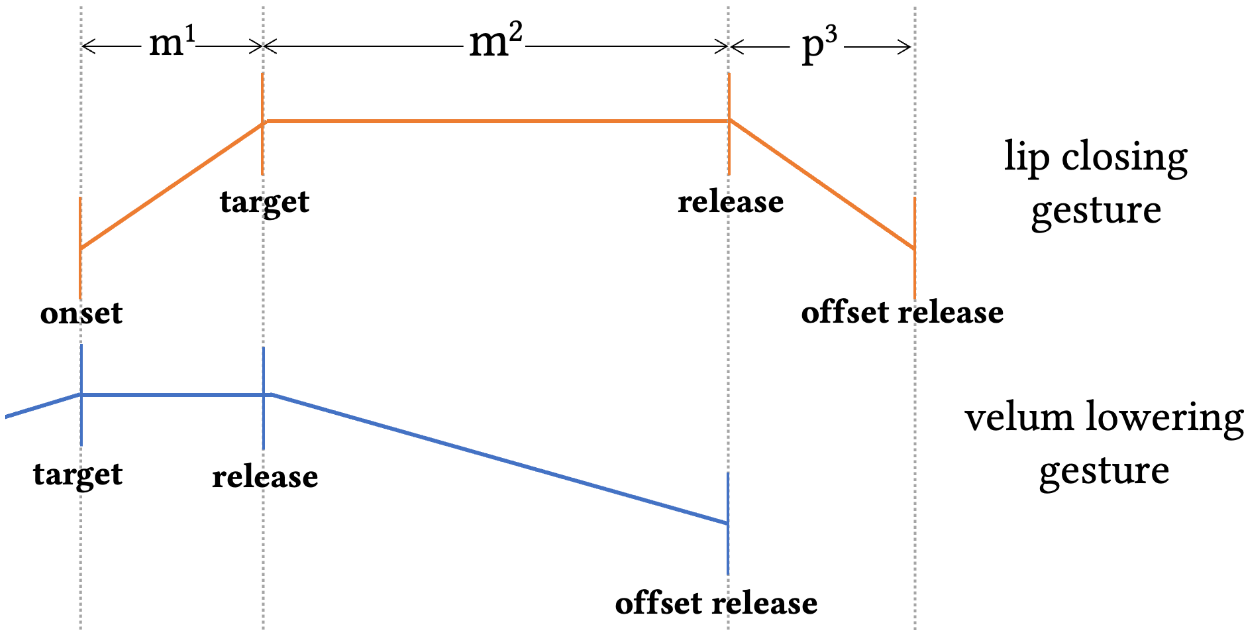

Figure 11: Mapping of subsegments to articulatory landmarks in a bilabial post-oralized nasal stop [m^p] (m^1 m^2 p^3) following an oral vowel

3.7 Conclusion

This chapter 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/ ⟶ [$^m p$, $^n t$, $^n s$, $^ŋ k$]). 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). It was shown that q subsegments represent abstract, non-uniform time intervals, which may be anchored between any two relevant gestural landmarks. In this way, Q Theory may be articulatory grounded within a gestural framework, such as Gestural Coordination Theory (Gafos 2002). Subsegments receive their featural makeup as direct mapping of the gestures with which they overlap.

Chapter 4

Evidence for subfeatures: A case study from Kawaiwete

4.1 Overview

This chapter introduces novel data from Kawaiwete (ISO code: kyz), a Tupí-Guaraní language spoken in Brazil, which supports the need for finer-grained phonological representations. I argue on the basis of Kawaiwete for a scalar decomposition of phonological features on a vertical dimension of representation, where the continuous values can be grouped into one of three possible subfeatural categories: [+F], [xF], and [−F] (Lionnet 2017). In the case of the feature [nasal], I argue for three perceptibly distinct degrees of nasalization: [+nasal], for fully nasal units; [$x$nasal], for partially nasal units; and [−nasal], for fully oral units. This representational framework is independent from, but compatible with, the decomposition of the segment into subsegmental units on the horizontal dimension of representation, as was laid out in Chapter 3.

The empirical support for these phonological representations comes from a distinction between fully oral, partially nasal, and fully nasal vowels in Kawaiwete. These different categories of vowels arise from a phonemic contrast in vowel nasality, as well as patterns of C → V local nasal assimilation. I provide airflow data supporting the claim that the three categories of vowels exhibit differences in degrees of nasalization.

The findings of the airflow experiment show that partially nasal vowels are realized by phonetic interpolation as a continuous, cline-like gradient increase or decrease in nasal airflow over the time course of the vowel. Oral vowels between two oral consonants are realized as fully oral, while nasal vowels after nasal consonants are realized as fully nasal. Oral vowels between an oral and a nasal consonant, as well as nasal vowels after oral consonants, are both realized as partially nasal, with a cline in nasal airflow extending for the entire vowel's duration. This novel data from Kawaiwete supports the proposed subsegmental and subfeatural analysis, and provides evidence that the information relevant to encoding the contrast between oral and nasal vowels in this language is dynamic over the time course of the vowel, and dependent on the vowel's immediate segmental context.

Previous work has demonstrated the continuous, rather than discrete, function of nasality (e.g. Cohn 1990, Keating 1990). While patterns of dynamic interpolation are recognized as a linguistic phenomenon (Pierrehumbert 1980; Keating 1990; Pierrehumbert & Beckman 1988; Cohn 1990; McPherson 2011), their effects have been relegated to issues of phonetic implementation and have not been included under the scope of phonological theory. Drawing on the instrumental data from Kawaiwete, I expand the scope of phonological theory and account for patterns of dynamic interpolation within the phonological grammar. I show how a formal representational model integrating both subsegments and subfeatures, when implemented within a model of Agreement-by-Correspondence, allows for the derivation of patterns of nasal-oral interpolation observed in Kawaiwete vowels.

This chapter is structured as follows: Section 4.2 provides background on Kawaiwete and the phonological patterns that give rise to the different types of vowels; Section 4.3 summarizes the findings of the airflow experiment; Section 4.4 presents the proposed representational model; Section 4.5 models the data from Kawaiwete within Harmonic Grammar, showing that the grammar must crucially make reference to both subsegments and subfeatures; Section 4.6 discusses how alternative models of phonological representations cannot capture the relevant pattern, and offers a formal model which captures the insights of Window Theory (Keating 1990); and finally, Section 4.7 concludes.

4.2 Background on Kawaiwete

Kawaiwete (ISO code: kyz; also known as Kayabi) is a Tupí-Guaraní language spoken by approximately 2200 people who live in four different indigenous territories distributed in the Brazilian states of Mato Grosso and Pará: the Xingu, Apiaká-Kayabi, Cayabi, and Cayabi Gleba Sul Indigenous Lands. According to some reports, the language is still spoken by some of the elders in the Caiabi and Apiaká-Kayabi Indigenous Lands. However, the majority of the Kawaiwete, and in particular the members of the younger generations, who inhabit those areas are now monolingual in Portuguese. The Kawaiwete language is still in daily use by those who inhabit the Xingu (approximately 70% of the entire population), though the majority of them also have knowledge of Portuguese (Lima et al., 2009).

Based on reports by speakers of Kawaiwete, there are two main dialects of Kawaiwete spoken in the Xingu, which I will refer to as the Kapiwat and Jawarum dialects. The Kapiwat dialect is spoken by the community of approximately 200 people who live in the village of Kapiwat. This community mostly consists of one extended family, who migrated from the Apiaká-Kayabi Indigenous Land. Kawaiwete is reportedly no longer transmitted to children in the Apiaká-Kayabi Indigenous Land, such that the language is now only spoken by those of the older generation in that area. This represents a situation of recent and rapid language shift from Kawaiwete to Portuguese, considered alarming to the Kawaiwete from the Xingu. As such, the Kapiwat dialect of Kawaiwete remains vital because it continues to be transmitted as a native language in this one particular village of the Xingu.

The dominant dialect of Kawaiwete spoken in all other villages of the Xingu is the Jawarum dialect, which I name after the Diauarum Indigenous Post, the main administrative and political center of the Kawaiwete community in the Xingu. This particular dialect is considered more prestigious, and it is the dialect being taught to children in schools, even in Kapiwat. The Kapiwat and Jawarum dialects crucially differ with respect to the presence of long-distance nasal assimilation in the Kapiwat dialect, but not in the Jawarum dialect. Most speakers of the Kapiwat dialect are bidialectal, meaning that they are able to switch, often unconsciously, to the Jawarum dialect when in the presence of speakers of this dialect. Because of the intense contact situation between the two dialects in the Xingu and the social stigma associated with the use of long-distance nasal assimilation, speakers of Kapiwat are rapidly shifting to the Jawarum dialect.

The data presented here was collected in the Xingu Indigenous Land over the summer of 2019. During this first field trip to a Kawaiwete-speaking community, I spent two weeks in Jawarum, and two weeks in Kapiwat. The two villages, located just 10 minutes downriver from one another, are pictured in Figure 1 below.

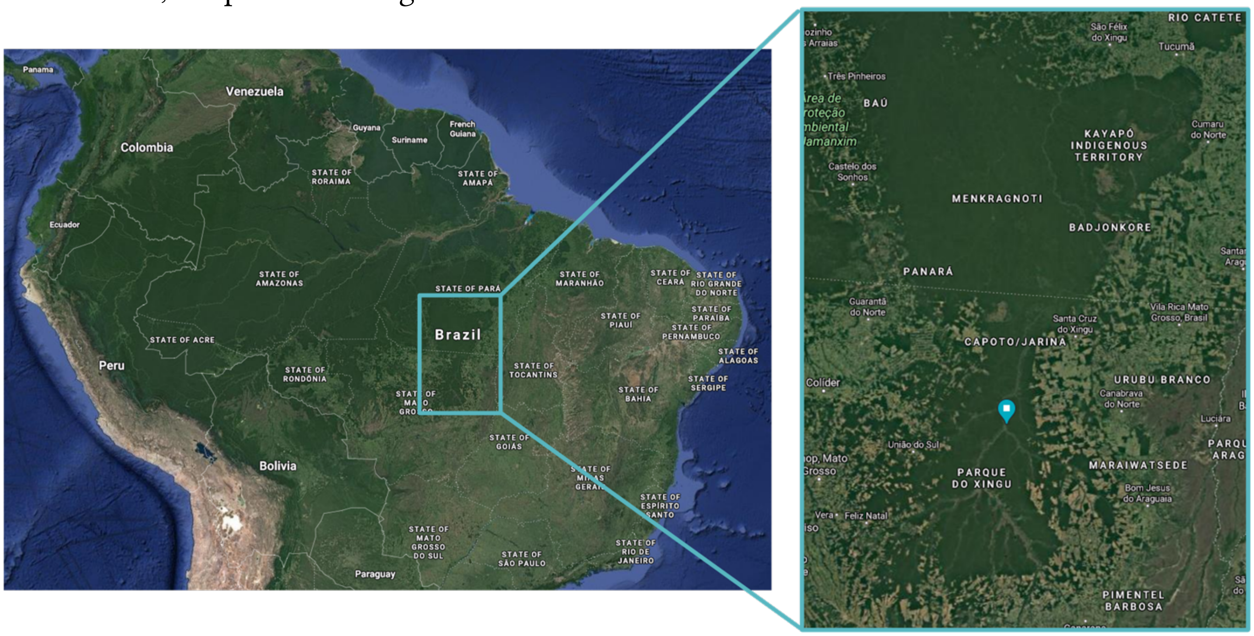

Figure 1: Location of the Kawaiwete village of Kapiwat. Image taken from Google Maps [Accessed February 2020]

4.2.1 Phonemic inventory

This section presents my phonemic analysis of Kawaiwete. For an alternative analysis, see Souza (2004). Kawaiwete's segmental inventory is typically Tupí-Guaraní, with a total of 14 consonants, and 11 vowels, as shown in Tables 1 & 2. Consonants contrast three manners of articulation: obstruent, sonorant, and nasal. Obstruents contrast seven places of articulation: bilabial, labio-dental, alveolar, palatal, velar, labio-velar, and glottal; while sonorants contrast only three places of articulation, and nasals contrast four. Specifically, sonorants contrast labio-dental, alveolar, and palatal points of articulation, while nasals contrast bilabial, alveolar, palatal and velar points of articulation. Nasalized sonorants are also observed as the result of phonological processes but are not phonemic. Vowels in Kawaiwete may be oral or nasal, but this contrast appears to be restricted to the root-final syllable, which coincides with the location of primary lexical stress. Vowels are analyzed as contrasting two heights: high and low; and three values of backness: front, central, and back.

Kawaiwete's consonant inventory is provided in Table 1, and its vowel inventory in Table 2.

Table 1: Consonant phonemes. Phones in parentheses result from surface allophony

	bilabial	labio-dental	alveolar	palatal	velar	labio-velar	glottal
obstruent	p	f	t	s	k	kʷ	ʔ
sonorant		ʋ	ɾ	ɟ			
nasal	m		n	ɲ	ŋ		

Table 2: Vowel phonemes

Oral		
i	ɨ	u
ɛ	a	ɔ

Nasal		
ĩ	ɨ̃	ũ
ɛ̃	ã	

Tables 3-4 provide near-minimal pairs supporting the phonemic status of each consonant. Table 3 presents near-minimal pairs supporting a three-way contrast in manner of articulation between obstruents, sonorants, and nasals.

Table 3: Consonant manner of articulation contrasts

Consonant	Minimal and near-minimal pairs	
f : ʋ	[pɔfat̚] ‘PROPER.NAME’	[kapiʋat̚] ‘capybara’
p : ʋ	[piɾa] ‘fish’	[ʋɨɾa] ‘animal’
ʋ : m	[uruʋu] ‘vulture’	[aʋ̃ãmũ] ‘now’
p : m	[miaɾa] ‘jaguar’	[piɾa] ‘fish’
t : ɾ	[meɾu] ‘fly’	[mɨtũ] ‘curassow’
ɾ : n	[jaɾɛ] ‘PL.INCL.POSS’	[janɛ] ‘1.PL.INCL.NOM’
t : n	[imatãũ] ‘to pull’	[imanau] ‘to give’
ɾ : s	[kuɾuɾu] ‘frog’	[kasuɾu] ‘dog’
s : ɟ	[ʔɨsãŋ] ‘cold’	[aɟãn] ‘spirit’
t : ɟ	[tɛ] ‘2.SG.NOM, let’s go’	[ɟe] ‘1.SG.NOM’
ɟ : ɲ	[jaɨ] ‘month, moon’	[ɲãʔĩ] ‘brother/cousin.VOC.DIM’
k : ŋ	[ŋã] ‘3.PL.MASC.♂’[1]	[kaŋ] ‘head’

The near-minimal pairs in Table 4 illustrate a seven-way contrast in place of articulation for obstruents /f, p, t, s, k, kʷ, ʔ/, a three-way contrast for sonorants /ʋ, ɾ, ɟ/, as well as a four-way contrast for nasals /m, n, ɲ, ŋ/.

[1] Third plural pronoun denoting a groups of males, uttered by a male speaker.

Table 4: Consonant place of articulation contrasts

Consonant	Minimal and near-minimal pairs	
f : p	[pɔfat̚] 'PROPER.NAME'	[vɨɾapat̚] 'bow'
p : t	[pɛ] 'path, piece, LOC'	[tɛ] '2.SG, let's go'
t : s	[tũŋ] 'flea'	[sĩŋ] 'white'
t : k	[kutap̚] 'type of frog'	[ɟekap̚] 'my fat'
k : kʷ	[kaʔɾa] 'yam'	[kʷataʔi] 'dog'
k : ʔ	[ɟekap̚] 'my fat'	[ɟeʔap̚] 'my hair'
v : ɾ	[vɨ] 'blood'	[ɾɨɟat̚] 'PROPER.NAME'
ɾ : ɟ	[anɨɾa] 'bat'	[aŋuɟa] 'mouse'
m : n	[kaɾamũ] 'again'	[kʷanũ] 'hawk'
n : ɲ	[kɨnã] '3.SG.FEM.♂'[2]	[kuɲã] 'woman'
ɲ : ŋ	[ɲãʔĩ] 'brother/cousin.VOC.DIM'	[ŋã] 3.PL.MASC.♂'[1]

Tables 5-7 provide near-minimal pairs supporting the phonemic status of each vowel. The minimal pairs in Table 5 illustrate a two-way height contrast for front vowels /i, ɛ/, central vowel /ɨ, a/, and back vowels /u, ɔ/.

Table 5: Vowel height contrasts

Consonant	Minimal and near-minimal pairs	
i : ɛ	[miaɾa] 'jaguar'	[mɛɾu] 'fly'
ɨ : a	[kɨp̚] 'louse'	[ɟekap̚] 'my fat'
u : ɔ	[ʔɔʔɔ] 'meat (of something)'	[ʔuʔa] 'to fall' / [ʔaʔu] 'to eat'

The near minimal pairs in Table 6 illustrate a three way backness contrast for high vowels /i, ɨ, u/ and low vowels /ɛ, a, ɔ/.

Table 6: Vowel backness contrasts

Consonant	Minimal and near-minimal pairs	
i : ɨ	[kaʔi] 'monkey'	[aʔɨ] 'sloth'
ɨ : u	[aʔɨ] 'sloth'	[ɟau] 'left'
ɛ : a	[tɛ] '2.sg'	[tata] 'fire'
a : ɔ	[ʔɔʔɔ] 'meat'	[ʔuʔa] 'to fall'
i : u	[uɾuβi] 'catfish'	[uɾuβu] 'vulture'

Finally, the near minimal pairs in Table 7 provide evidence of contrastive vowel nasality for 5 vowel qualities /ĩ, ɨ̃, ũ, ɛ̃, ã/. Note that phonemically nasal vowels only ever occur in root-final position.

[2] Third singular pronoun denoting a female, uttered by a male speaker.

Table 7: Vowel nasality contrasts

Consonant	Minimal and near-minimal pairs	
i : ĩ	[kaʔi] 'monkey'	[ɲãʔĩ] 'brother/cousin.VOC.DIM'
ɛ : ɛ̃	[ɛ̃ʔɛ̃] 'sweet'	[ɛnɛ] '2.SG'
ɨ : ɨ̃	[kɨnã] '3.SG.FEM.♀'	[mɨ̃ɲã] 'who?'
a : ã	[tupa] 'shelf'	[tupã] 'thunder'
u : ũ	[iaku] 'guan'	[ikũ] 'tongue'

Vowel-vowel sequences, such as [ɨi, ui, ɛi, ai, ɔi, ɛu, au, ɨ̃ĩ, ũĩ, ãĩ, ãũ], are frequent in Kawaiwete. I leave to future work the question of whether such vowel sequences should be considered single complex units (i.e. diphthongs) or sequences of vowels which occupy the nucleus of distinct syllables. For now, I note that root-final vowel-vowel sequences seem to function as a single complex vowel, while root-initial and root-internal vowel-vowel sequences seem to function as sequences of vowels, based on patterns of syllabification.

4.2.2 Relevant phonological processes

Moving beyond the basic segmental inventory of Kawaiwete, in which the Jawarum and Kapiwat dialects are similar; I now discuss the grammar of nasality, in which the two dialects differ. Both dialects exhibit a pattern of local nasal assimilation from a nasal vowel onto an adjacent vowel. In addition, the Kapiwat dialect, but not the Jawarum dialect, exhibits long-distance anticipatory nasal assimilation, in which sonorants assimilate in nasality to a following phonemically nasal vowel. The local and long-distance patterns are grammatically conditioned, and modeling them requires augmenting phonological representations with both subsegmental and subfeatural units, as will be argued in Sections 4.4 and 4.5.

Both the Jawarum and Kapiwat dialects exhibit local nasal assimilation triggered by nasal consonants and affecting vowels. Vowels are nasalized when they are immediately adjacent to a phonemically nasal consonant. Local nasal assimilation in Kawaiwete is bidirectional and is insensitive to morpheme boundaries. This process is schematized as a phonological rule in (1) for ease of exposition. Words exemplifying the relevant process are provided in (2). Allophonically nasalized vowels vary with respect to their degree of nasalization, but are generally realized as less perceptibly nasal than phonemically nasal vowels. Note that I transcribe allophonically nasalized vowels with a tilde below the vowel to distinguish them from phonemically nasal vowels, which are transcribed with the standard tilde diacritic above the corresponding vowel symbol.

(1) V → V̰ / {N_, _N}

(2) a. /faɨɾum/ → [faɨɾṵm] ‘ring’ (Jawarum & Kapiwat)
b. /kaʔaɾan/ → [kaʔaɾa̰n] ‘leaf/book’
c. /anɨɾa/ → [a̰nɨ̰ɾa] ‘bat’
d. /miat/ → [mḭat̚] ‘jaguar’
e. /kaninɛ/ → [ka̰nḭnɛ̰] ‘macaw’
f. /ʝakɨɾan/ → [ʝakɨɾa̰n] ‘cicada’
g. /ipɨtaŋ/ → [ipɨta̰ŋ] ‘yellow’

One of the main differences between the phonology of the Kapiwat and Jawarum dialects has to do with the phenomenon of long-distance nasal assimilation, which is observed in the Kapiwat, but not the Jawarum, dialect of Kawaiwete. I use the term *long-distance* here to indicate a process whose trigger can affect the realization of segments that are not immediately linearly adjacent to it. This class of phenomena is often termed *harmony* in the literature, and similar phenomena in related Tupí-Guaraní languages are traditionally referred to as *nasal harmony* (e.g. Gregores & Suárez 1967; Goldsmith 1976; Guedes 1983; Piggott 1992; Walker 1998, 1999; Thomas 2014; Estigarribia 2020). Given that long-distance nasal assimilation in Kawaiwete appears to be somewhat restricted in its domain and realization compared to other languages with nasal harmony, I choose the more neutral term *long-distance nasal assimilation* to refer to the relevant phonological process.

In the Kapiwat dialect, phonemically nasal vowels trigger an anticipatory process of long-distance nasal assimilation, which affects all segmental material up to one syllable to the left of the trigger, as is schematized in (3) and exemplified in (4). Phonemically nasal vowels are the only triggers of long-distance nasal assimilation, and they only occur in root-final position. Nasal consonants never trigger long-distance nasal assimilation, even when they occur in root-final position. All voiced segments, i.e. all vowels /i, ɛ, ɨ, a, u, ɔ/and sonorants /ⱱ, ɾ, ʝ/ undergo assimilation, surfacing as a nasalized. All obstruents /f, p, t, s, k, kʷ, ʔ/ are transparent[3] non-undergoers of long-distance nasal assimilation.

(3) /V, R/ → [V̰, R̰] / $_(V)$(C)Ṽ

(4) a. /tukumã/→ [tukṵmã] ‘type of palm’ (Kapiwat)
b. /ⱱaimĩ/ → [ⱱ̰a̰ḭmĩ] ‘old woman’
c. /aⱱamũ/ → [aⱱ̰a̰mũ] ‘now’
d. /piɾãĩ/ → [pḭɾ̰ãĩ] ‘fish’
e. /aɾusĩ/ → [aɾ̰ṵsĩ] ‘rice’

Long-distance nasal assimilation is not observed in the Jawarum dialect, as evidenced by the forms in (5).

[3] Preliminary findings of airflow data analysis in word with long-distance nasal assimilation suggests that obstruents may actually undergo long-distance nasal assimilation and become realized with nasalization, rather than being transparent non-undergoers of assimilation. The data suggests that a complete closure of the velum is not achieved during the production of oral obstruents, as nasal airflow is observed during their production. For the purposes of this analysis, I assume that they are transparent, and I leave the question of nasality in obstruents in Kawaiwete (and other languages) to future work.

(5) a. /tukumã/→ [tukṵmã] ‘type of palm’ (Jawarum)
b. /aⱱamũ/ → [aⱱa̰mũ] ‘now’
d. /piɾãĩ/ → [piɾãĩ] ‘fish’
e. /aɾusĩ/ → [aɾusĩ] ‘rice’

The vast majority of roots in the Kawaiwete lexicon are di- or trisyllabic, and long-distance nasal assimilation does not affect any segmental material beyond the syllable immediately to the left of the trigger. As such, I have not observed the effects of long-distance nasal assimilation across morpheme boundaries to the left of the trigger. It is possible that prefixes to the left of a monosyllabic root containing a phonemically nasal vowel can be affected by long-distance nasal assimilation, but given that such roots are so vanishingly rare in my data, it is not possible to provide a definitive answer to this question at this time.

Prefixes, as well as compound material, are not affected by long-distance nasal assimilation coming from a following morpheme with two or more syllables ending in a contrastive nasal vowel. This is exemplified in (6). Example (6a) consists of a root-root nominal compound composed of the morphemes /aⱱasi/ ‘corn’ and /kamĩ/ ‘mingau’[4], where nasality of the final vowel of the morpheme on the right does not spread across the root-root boundary and affect any of the segments in the morpheme on the left. In (6d) the /u/ of /kaɾu/ is sometimes realized with nasalization as [ṵ], likely as a result of local nasal assimilation from immediately adjacent [ⱱ̰].

(6) a. /aⱱasi-kamĩ/ → [aⱱasi-ka̰mĩ] ‘corn mingau’ (Kapiwat)
b. /ⱱɨɾa-sɔkɛ̃/ → [ⱱɨɾa-sɔ̰kɛ̃] ‘chicken’
c. /ʝe-ɾenupɨʔã/ → [ʝe-ɾenṵpɨ̰ʔã] ‘my knee’
d. /kaɾu-ⱱamũ/ → [kaɾu-ⱱ̰a̰mũ] ‘afternoon’

In compounds that include two roots, both of which contain a final phonemic nasal vowel, long-distance nasal assimilation spreads independently in both compounds, with the two root final nasal vowels more strongly nasalized than the other vowels in the roots. This gives rise to intervals of light-heavy-light-heavy nasalization, as in the example in (7).

(7) a. /aɾusĩ-kamĩ/ → [aɾ̰ṵsĩ-ka̰mĩ] ‘rice mingau’ (Kapiwat)

In the case of suffixes attaching to the right of a root-final nasal vowel or nasal consonant, nasality from the root segment spreads rightward to all vowels at the left edge of the suffix, as in (8a-b). Nasality spreading is blocked by any oral obstruents within the suffix, as seen in (8c-d). In comparison, these same suffixes are fully oral when they attach to an oral root (i.e. a root ending in a phonemically oral vowel), as in (9).

(8) a. /kunumĩ-uu/ → [kṵnṵmĩ-ṵṵ] ‘young man’ (Kapiwat)
b. /kaʔaɾan-uu/ → [kaʔaɾa̰n-ṵṵ] ‘money’
c. /ⱱaimĩ-ɛtɛ/ → [ⱱ̰a̰ḭmĩ-ɛ̰tɛ] ‘very old woman’
d. /kaʔaɾan-ɛtɛ/ → [kaʔaɾa̰n-ɛ̰tɛ] ‘notebook’

4

(9) a. /kaʔi-uu/ → [kaʔi-uu] ‘big monkey’ (Kapiwat)
b. /kaʔi-ɛtɛ/ → [kaʔi-ɛtɛ] ‘capuchin monkey’

As has been observed for Kawaiwete thus far, the undergoers of nasalization appear to exhibit a lower degree of nasality than the triggers of nasalization. This is supported by metalinguistic comments by native speakers of the Kapiwat dialect, suggesting that a binary distinction between nasal and oral vowels is insufficient to capture their intuitions about the realization of vowels. For instance, the word /aⱱasi/ [aⱱasi] ‘corn’ contains three oral vowels, and speakers unanimously agree that the correct spelling should be <awasi>. In comparison, the word /aɾusĩ/ [aɾṵsĩ] ‘rice’, realized with long-distance nasal assimilation in the Kapiwat dialect, must be written with a tilde on the final vowel (*<arusi>), but speakers note that the second vowel of the word is not strong enough to be written with a tilde (?<arũsĩ>), but it is also distinct from a true oral vowel (<arusĩ>).

In the following section, I discuss phonetic data from an airflow experiment which supports the impressionistic claims about the patterns of nasalization in Kawaiwete laid out here. The goal of the experiment was to measure the differences in the magnitude of nasal airflow in oral, partially nasal, and phonemically nasal vowels in Kawaiwete. The results show that native speakers of Kawaiwete systematically produce the different types of vowels distinctly. These findings, then, support the need for distinct phonological structures to account for the three different types of vowels in Kawaiwete. In addition, the phonetic analysis reveals that the realization of nasality is dynamic, suggestive of the kind of interpolation effects observed in other languages. Similar dynamic interpolation patterns have often been consigned to the extra-theoretical domain of phonetic implementation. However, as seen above, at least one (if not both) of the patterns is clearly grammatical, dialect-specific, and subject to morphological conditioning, and will thus be included in the phonological grammar of Kawaiwete.

4.3 Instrumental evidence

The phonetic experiment presented in this section was designed to test whether speakers of Kawaiwete produce partially nasal vowels distinctly from both oral vowels and nasal vowels. To this end, oral and nasal airflow data was collected from 4 native speakers (2 female, 2 male) of the Kapiwat dialect of Kawaiwete and 1 female native speaker of the Jawarum dialect.

The stimuli items for the experiment were crucially selected to create the relevant phonotactic environment for the realization of fully oral, partially nasal, and fully nasal vowels. Fully oral vowels are observed in words that do not exhibit phonemic nasal vowels or phonemic nasal consonants. As was detailed in Section 4.2.2, partially nasal vowels arise from two distinct phonological processes: (i) local nasal assimilation from an adjacent phonemic nasal vowel, and (ii) long-distance nasal assimilation. As such, the experiment included stimuli items in which these particular phonological environments were met, namely (i) words with phonemic nasal consonants, but no phonemic nasal vowels; and (ii) words with phonemically nasal vowels. Finally, fully nasal vowels are observed in words that exhibit both phonemic nasal vowels and phonemic nasal consonants.

The results of the experiment show that Kawaiwete speakers do indeed produce oral vowels, partially nasal vowels, and fully nasal vowels distinctly from one another, but that the realization of all vowels is dynamic and crucially dependent on the immediately preceding and following segmental context.

4.3.1 Methodology

In the summer of 2019, I collected oral and nasal airflow data in the Kawaiwete village of Kapiwat, located in the Xingu Indigenous Land. The plan to conduct a phonetics experiment was presented to community leaders, and the community council designated one of the school teachers, Mu'ni Kayabi, to work with me in collecting the data. Mu'ni took me to each one of main households in the village, and we were greeted by the residents who invited us in to drink some mingau or coffee. During this informal conversation, I explained the goals and procedure of the experiment in Portuguese, and Mu'ni followed up with a more detailed explanation in Kawaiwete about how to use the equipment used to carry out the recordings of airflow data. We then asked those around whether they were interested in participating, and proceeded to record those who volunteered and consented.

Using an EGG-D800 produced by Laryngograph, which contains two separate pressure transducers, we captured nasal and oral airflow data. The EGG-D800 device was paired with the use of a handheld Oro-Nasal Rothenberg mask, which contains two isolated chambers, thus allowing for oral and nasal airflow to be captured in isolation from one another. The EGG-D800 also contains an auxiliary input into which an ECM-500L/SK microphone was connected. The microphone was clipped onto the Oro-Nasal mask, which allowed us to simultaneously collect acoustic recordings of the data. This is the same physical setup as the one described in Section 3.3.1 for the collection of oral and nasal airflow data and acoustic recordings for Panãra.

We collected airflow data from a total of 20 native speakers of Kawaiwete between the ages of 8 and 46 (mean = 21.6 years old), including 12 female speakers. While children were not actively recruited as participants for the experiment, we collected data from two children aged 8 and 9 years old, as the children requested to take part in the experiment after seeing their parents participate. Their parents consented and were present during data collection. The data analyzed and discussed here is from 5 speakers, including 3 female speakers. The remaining 15 speakers' data was discarded due to an improper seal of the Oro-Nasal mask around the speaker's nose and jaw (n=11), or to a malfunctioning of the EGG-D800 (n=4), which sometimes generated a very high amplitude noise at 3450 Hz and 57.75 dB SPL, masking the waveform at an average of approximately 62 dB SPL and making it impossible to reliably parse the data.

We recorded participants during the production of trisyllabic words falling into one of four categories: (i) words containing only oral vowels and oral consonants; (ii) words containing only oral vowels and one or more nasal consonants; (iii) words containing one phonemically nasal vowel and only oral consonants; and (iv) words containing one phonemically nasal vowel and one or more nasal consonants.

Participants were instructed to hold the mask tightly over their nose and mouth, and the researchers provided feedback on the position of the mask so as to minimize leakage of airflow. I guided the participants through the task by producing each target word, and participants were asked to simply repeat what had been said. This particular method allowed participants to feel more at ease, as they are not familiar with experimental designs, and to make it clear to them that the task did not involve any evaluation of their reading abilities. Each of the 24 target words was presented verbally, in isolation, and participants produced a total of four repetitions of each target word, organized into four semi-randomized blocks. The experiment took 13 minutes to complete, on average.

I quantified the proportion of nasal airflow to total airflow (i.e. nasal airflow/nasal airflow+oral airflow) during the production of vowels in all trisyllabic words. First, with the help of a Python script written by Susan Lin, I calibrated all of the airflow data, for both the oral and nasal airflow channels, to ensure that the zero value was meaningful, and to convert abstract pressure units into liters per second (L/s) values. I then segmented the acoustic data by hand, locating the onset and offset of every vowel token. With a Praat script written with the help of Ronald Sprouse, I then extracted the average value of both nasal and oral airflow, in liters per second, for the initial, middle, and final portion of each vowel in the corpus. This method served to visualize dynamic changes in nasal airflow over the time course of the vowel, and specifically allowed for comparison in nasal airflow across the hypothesized first, second, and third Q-theoretic subsegments of each vowel. Each vowel was also coded for whether it occurred in the initial, medial, or final syllable of the word.

Figure 2 below illustrates how the data was parsed, coded, and extracted, for one token of the word /kumana/ ‘bean’ uttered by a male speaker. The first channel in the Figure represents nasal airflow, in L/s; the second channel represents oral airflow, in L/s; and the third channel is the spectrogram. The textgrid at the bottom shows how each vowel was parsed, indicating the interval of time for which the average values or oral and nasal airflow were calculated for each of the durations of V1, V2, and V3. Importantly, for each vowel in each word, the Praat script divided the total duration of that vowel into three equal sized chunks, and produced average oral and nasal airflow values for each of the three chunks.

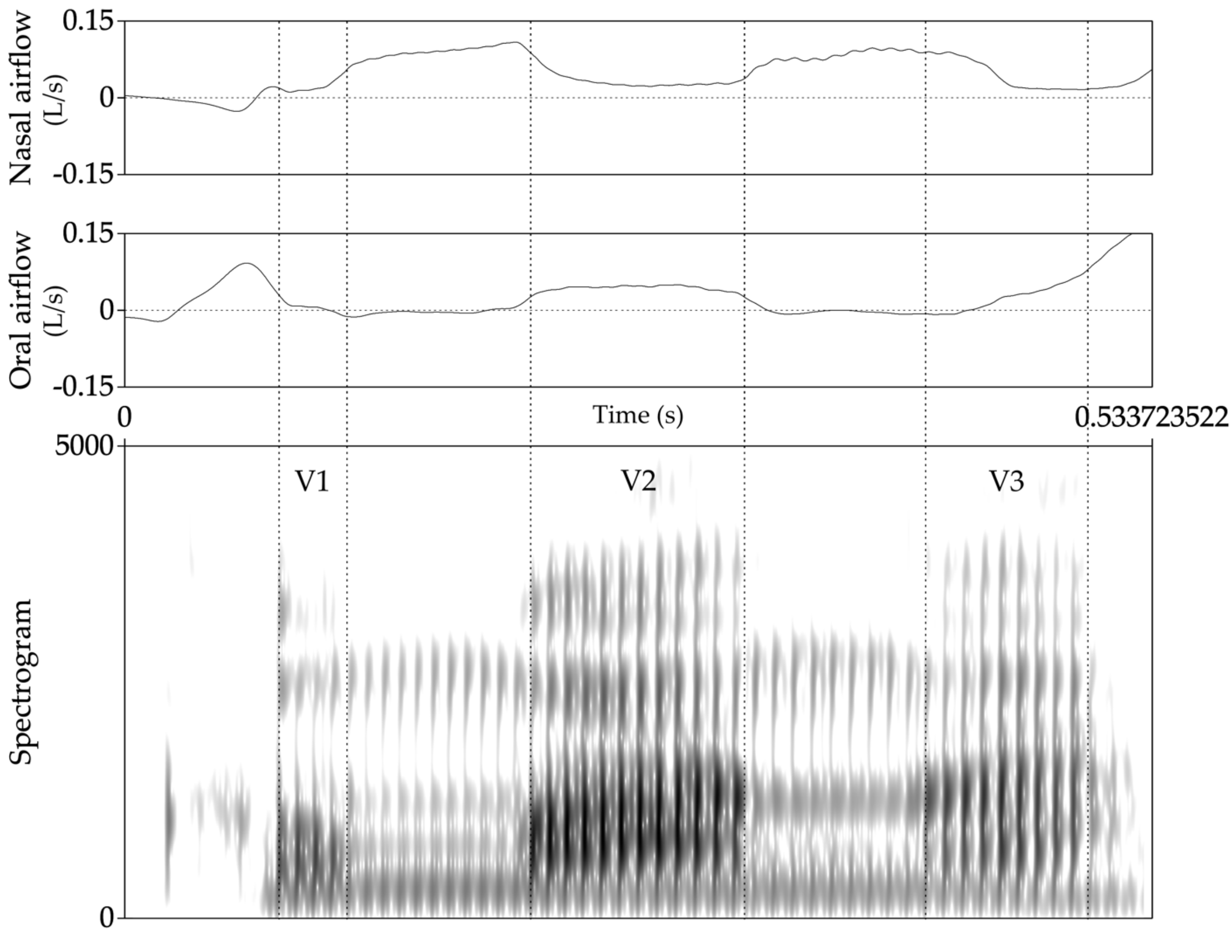

Figure 2: Nasal airflow, oral airflow, spectrogram, and textgrid (from top to bottom) for the production of the word /kumana/ [ku̯ma̯na̯] 'bean'

The percentage of nasal airflow was calculated for each portion of each vowel in the target words, using the formula in (10). Percentage nasal airflow then, is the quantity of nasal airflow divided by the total of nasal airflow, i.e. the sum of nasal airflow and oral airflow.

(10) $$\% \text{ Nasal airflow} = \frac{\text{Nasal airflow}}{(\text{Nasal airflow} + \text{oral airflow})}$$

In the discussion of the results below, a value of approximately 0% nasal airflow indicates the presence of oral airflow, and the absence of nasal airflow; a value between 0% and 50% indicates the presence of both oral and nasal airflow but a greater proportion of oral airflow; a value of approximately 50% nasal airflow indicates that roughly the same amount of oral and nasal airflow was recorded; and a value between 50% and 100% indicates the presence of both oral and nasal airflow, but a greater proportion of nasal airflow.

Note that negative values are also observed in some cases, and that these should be interpreted as equivalent to values at 0%, i.e. in the presence of oral airflow and the absence of nasal airflow. Negative values result from the calibration of the raw airflow, needed to ensure meaningful zero values. In practice, airflow measurements of a true zero are never observed. For this reason, a zero value was operationalized as the range of values between 0.001 and -0.001.

Any nasal airflow value below zero, when input into the mathematical equation in (10), results in negative percentage values, which may simply be interpreted as the absence of nasal airflow.

4.3.2 Results

This Section presents the results of the airflow experiment for each word category among the stimuli, allowing for the isolation of each type of vowel, i.e. fully oral, partially nasal, and fully nasal, in the crucial phonotactic environments where they occur. As will be shown, the predictions are borne out: Fully nasal vowels exhibit an overall higher percentage of nasal airflow that partially nasal vowels, which in turn exhibit an overall higher percentage of nasal airflow than fully oral vowels. Section 4.3.2.1 discusses words containing only oral vowels and oral consonants; Section 4.3.2.2 discusses words containing only oral vowels and one or more nasal consonants; Section 4.3.2.3 discusses words containing one phonemically nasal vowel and only oral consonants; Section 4.3.2.4 discusses words containing one phonemically nasal vowel and one or more nasal consonants; and finally, Section 4.3.2.5 summarizes the findings. Where differences between the speakers of Kapiwat and the speaker of Jawarum are observed, these are explicitly discussed in the relevant sections. The data from all speakers has been pooled when no differences are observed.

4.3.2.1 Words with oral consonants and oral vowels

Trisyllabic words with no phonemic nasal vowels and no phonemic nasal consonants provide the crucial phonotactic environment for fully oral vowels. In these words, the percentage of nasal airflow on all of the vowels is roughly 0, as expected for fully oral vowels. This can be seen in Figure 3 below, which presents the percentage of nasal airflow in the initial, middle, and final portions (labeled q^1, q^2, and q^3 respectively) of the first, second, and third vowels in words of the shape /(C)VCVCV(C)/. Figure 2 presents pooled data for all five speakers for the words /avasi/ ‘corn’, /akɨkɨ/ ‘brown howler monkey’, /piɾapep/ ‘stingray’, /kuɾuɾu/ ‘frog’, /ɨkɨʔɟu/ ‘cricket’, and /tapiʔit/ ‘tapir’, exemplifying the complete absence of nasality in oral vowels between two oral consonants.

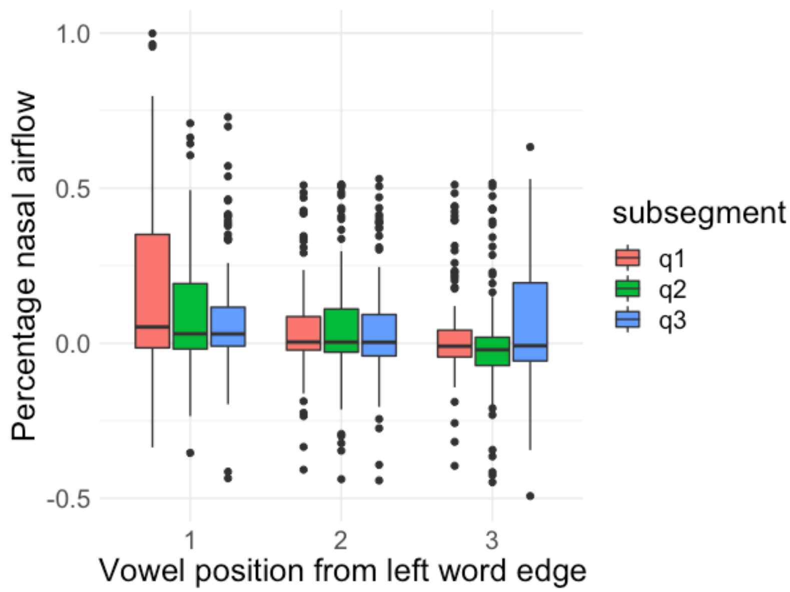

Figure 3: Percentage nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /(C)VCVCV(C)/

The percentage nasal airflow during the first, second and third subsegments of the second vowel in trisyllabic words with no nasal consonants or nasal vowels provides a clear example of a fully oral vowel. Oral vowels between two oral consonants, such as V2 in Figure 3, are realized as fully oral, with a low flat plateau of nasal airflow averaging 0% nasal airflow throughout the vowel's entire duration.

It is worth noting that the first third of the first vowel, and the last third of the last vowel in the words do seem to have higher nasal airflow than the other portions of those same vowels, or any portion of the second vowel. This pattern resembles a phenomenon observed in many other Amazonian languages (e.g. Tembé (Orjuela & Meira, ms.), Akuntsú (Aragon 2008), Xetá (Rodrigues 1978, Vasconcelos 2008), Parakanã (Gomes 1991), and Xavante (Davis 1966)), which I term *boundary nasalization*. Boundary nasalization is characterized by the presence of some nasal airflow at the beginning and/or at the end of a phonological word or phrase, i.e. before or after a pause or a period of silence. Nasalization of this type is often imperceptible, but may at times be sufficient to cause sound changes (e.g., Rodrigues 1981, 1986, 2003), and the phonologization of nasal consonants in word-initial position. Boundary nasalization can likely be attributed, in word onset position, to a raising of the velum in the change from a neutral rest position, during which the velum is lowered to allow for breathing, to a speech at rest position, during which the velum is raised as a speaker is getting ready to speak. In word offset position, early velum lowering may be attributed to a change in the position of the velum from a speech ready position to a neutral at rest position, during which the velum is lowered to allow for breathing. Given the natural articulatory basis for boundary nasalization, this phenomenon is likely to be cross-linguistically common, and not specific to Amazonian languages.

Initial boundary nasalization was observed for only 4 of the 5 speakers, including the Jawawrum speaker as well as both male speakers, indicating that the effects of boundary nasalization are not dialect or gender-specific. A more detailed look at the percentage of nasal airflow in all /VC/ initial words for those four speakers who exhibit patterns of initial boundary nasalization suggests that the velum is indeed closing over the course of the initial vowel. This can be observed in Figure 4, which presents the percentage nasal airflow in the first, second, and third subsegments of words beginning with an oral vowel immediately followed by an oral consonant, namely /aⱱasi/ ‘corn’, /akɨkɨ/ ‘brown howler monkey’, /ɨkɨʔɟu/ ‘cricket’, /aɾusĩ/ ‘rice’, /aⱱamũ/ ‘now’, and /ɨkɨʔɨ̃ɨ̃/ ‘pepper’. Average nasal airflow is at roughly 30% in the first portion of the vowel, 20% in the second portion, and 15% in the last third, suggesting a slow closure of the velum which is interpolated over the time course of the word-initial vowel.

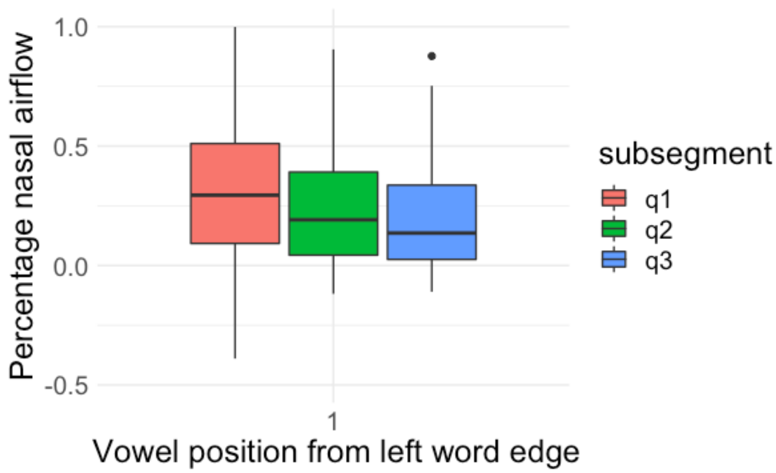

Figure 4: Percentage nasal airflow in the first, second, and third subsegments of the first vowel in /VC/ initial words

It is possible, and plausible, that boundary nasalization is also observed in initial consonants, but a full analysis of this phenomenon falls beyond the scope of this study. I leave this question, as well as a more detailed discussion of boundary nasalization and a formal account of its effects, to future work. The discussion of the results in the following subsections instead focuses on effects of nasalization that are attributable to segmental triggers, namely (i) local nasal assimilation triggered by a phonemically nasal consonant, or (ii) long-distance nasal assimilation triggered by a phonemically nasal vowel.

4.3.2.2 Words with nasal consonants and oral vowels

Trisyllabic words with a phonemic nasal consonant but no phonemically nasal vowels provide the crucial phonotactic environment for partially nasal vowels in Kawaiwete. The percentage of nasal airflow presents a cline-like gradient increase over the time course of the vowel between an oral and a nasal consonant, and a cline-like gradient decrease over the time course of the vowel between a nasal consonant and an oral consonant. Figure 5 presents the percentage of nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /CVCVCVN/, with a single nasal consonant in word-final position. Figure 5 presents pooled data for all five speakers for the words /faɨɾum/ ‘ring’, /kaʔaɾan/ ‘notebook’, /ɟakɨɾan/ ‘cicada’, and /kaɾupam/ ‘deer’, exemplifying the effects of anticipatory local nasal assimilation from a final nasal consonant onto a preceding vowel.

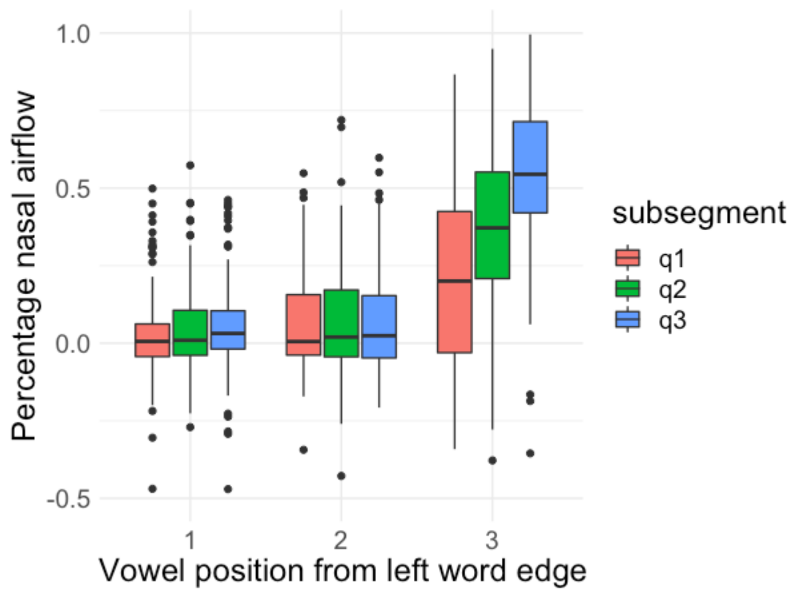

Figure 5: Percentage nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /CVCVCVN/

The percentage of nasal airflow on all three portions of the first and second vowels of words containing a final nasal consonant pattern in the same way as fully oral vowels, as described in Section 4.3.2.1 above. Specifically, these vowels are realized with a low flat plateau of nasal airflow, as they both occur between two oral consonants. Note that all four words of the type /CVCVCVN/ begin with an initial oral consonant. As such, the effects of boundary nasalization are not observed in V1, as it does not occur in phonological word or phrase-initial position.

The percentage of nasal airflow on each of the three portions of the third vowel of a /CVCVCVN/ word, however, is crucially different from that of the three portions of the third vowel in a /(C)VCVCV(C)/ word, as it exhibits the effects of anticipatory local nasal assimilation. The percentage of nasal airflow gradually increases in the first, second, and third portions of this third vowel, which immediately precedes the final nasal consonant. Average nasal airflow is at roughly 20% in the first portion of the third vowel, 35% in its second portion, and 55% in its last portion.

This effect can be attributed to local nasal assimilation from the final nasal consonant onto the immediately preceding vowel. This nasalization effect is realized as a positive slope in the nasal airflow of this vowel over the course of its duration: the closer the relevant portion of the vowel to the nasal coarticulation triggering nasal consonant, the higher the percentage of nasal airflow on that portion of the vowel. As can be seen in Figure 5 above, the increase in nasal airflow begins during the first portion of the last vowel, and does not seem to affect any portion of the second vowel, where percentage nasal airflow averages at zero. The domain of nasal assimilation triggered by the nasal consonant, then, can be defined as the immediately preceding vowel: the velum begins to lower at the beginning of the vowel, and reaches maximal opening at the end of the vowel.

Figure 6 presents the percentage of nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /CVNVCV(C)/, with a single nasal consonant in word-medial position. Figure 6 presents pooled data for all five speakers for the words /ɟanɨpap/ ‘American genipa’, /anɨɾa/ ‘bat’, and /kuimaʔɛ/ ‘man’, exemplifying the effect of progressive local nasal assimilation from a nasal consonant onto a following vowel.

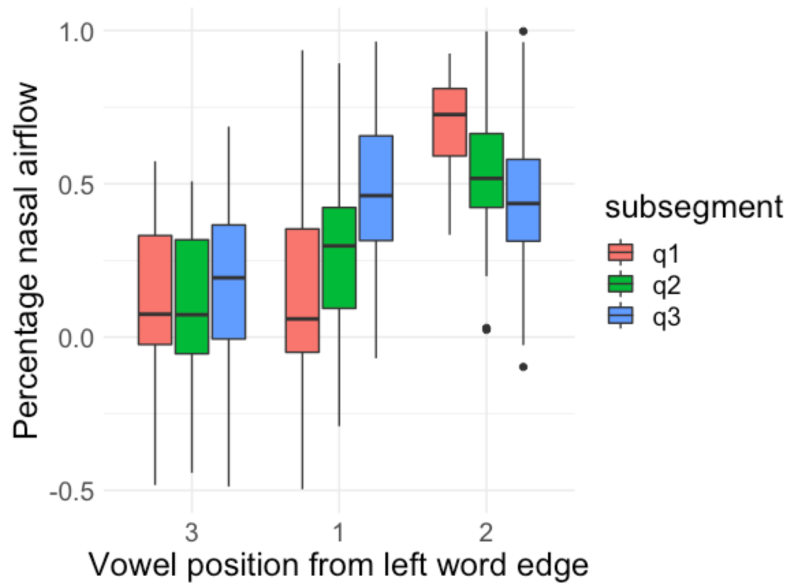

Figure 6: Percentage nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /(C)VNVCV(C)/

The percentage of nasal airflow in the third vowel of /CVNVCV(C)/ words parallels the pattern observed on the third vowel of a /(C)VCVCV(C)/ word: each of the three portions of the vowel is roughly at zero, but the last portion shows a slight increase which can likely be attributed to boundary nasalization.

The first and second vowels of a /CVNVCV(C)/ show a slightly different pattern from those observed so far, but are fully compatible with the phenomena here discussed. The pattern observed in the first vowel of a /CVNVCV(C)/ seems to show the additive effects of anticipatory local nasal assimilation triggered by a nasal consonant, as well as the effect of initial boundary nasalization. The observed pattern resembles that of a plateau across the three subsegments of the first vowel, at roughly 28% nasal airflow. A slight increase in nasal airflow is observed over the course of the vowel, but the difference in percentage nasal airflow in the first, second, and third portions of the first vowel is very minimal, and unlikely to be perceptible.

In the second vowel of a /CVNVCV(C)/, we observe a pattern of progressive local nasal assimilation, triggered by a nasal consonant and onto an immediately following vowel. This is the inverse pattern seen in the last vowel of /CVCVCVN/ words: Whereas in vowels immediately preceding a nasal consonant, nasal airflow increases over the course of the vowel; in vowels immediately following a nasal consonant, nasal airflow decreases over the course of the vowel. Average nasal airflow is at roughly 80% in the first portion of the third vowel, 57% in the second portion, and 45% in the last third. While the overall slope of post-nasal vowels mirror the pattern observed in pre-nasal vowels, the actual percentages of nasal airflow is overall higher in the post-nasal vowel than in the pre-nasal vowel.

Finally, trisyllabic words with multiple nasal consonants and no phonemically nasal vowels provide the crucial environment for fully nasal vowels. In these types of words, the percentage nasal airflow presents a high flat plateau in vowels between two nasal consonants.

Figure 7 presents the percentage of nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /CVNVNV/ and /NVNVNV/, with two word-medial nasal consonants. Figure 7 presents pooled data for all five speakers for the words /kumana/ ‘bean’, /kaninɛ/ ‘macaw’, and /mainumɨ/ ‘hummingbird’, exemplifying the combined effects of both anticipatory and progressive local nasal assimilation.

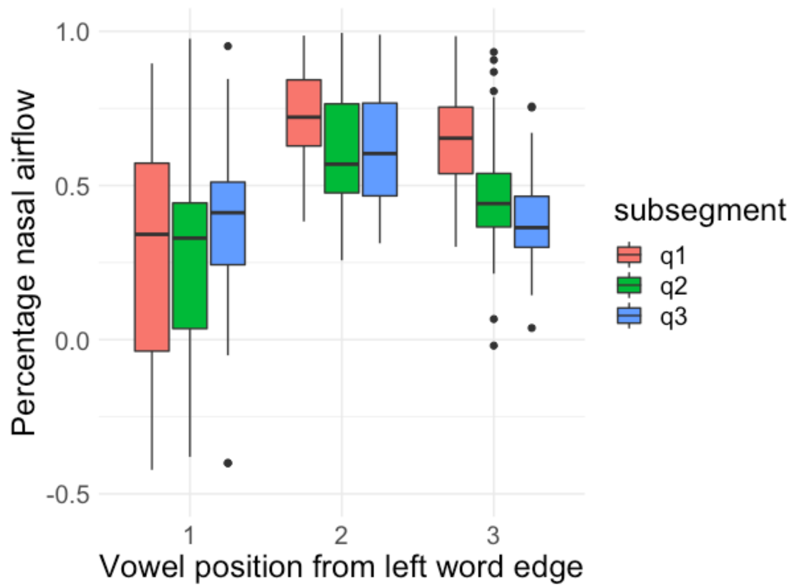

Figure 7: Percentage nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /CVNVNV/ and /NVNVNV/

V2 in Figure 7 presents an example of a fully nasal vowel: The percentage nasal airflow of V2 in /CVNVNV/ and /NVNVNV/ words shows an additive effect of the assimilatory nasalization triggered by both the immediately preceding and immediately following nasal consonants. Whereas a vowel preceding a nasal consonant shows an increase in nasal airflow over the course of its duration, and a vowel following a nasal consonant shows a decrease in nasal airflow over the course of its duration, a vowel between two nasal consonants seems to show a steady plateau of relatively high nasal airflow, comparable to the pattern observed for phonemically nasal vowels immediately following a nasal consonant (see Section 4.3.2.4). Average nasal airflow is at roughly 72% in the first portion of the third vowel, and 55% in its second and third portions. This suggests that, rather than lowering the velum for the production of the phonemically oral vowel between two nasal consonants, the velum remains lowered throughout the course of the vowel’s duration. The difference in percentage of nasal airflow in the first and second portions of V2 can likely be attributed to the release of the oral constriction at the onset of the vowel, or to the fact that the jaw opens gradually over the course of the vowel. The relative increase in jaw opening likely increases the overall volume of oral airflow, thus decreasing the percentage nasal airflow, which is calculated as a proportion of the total airflow during that particular time interval.

4.3.2.3 Words with oral consonants and a nasal vowel

Trisyllabic words with a single phonemically nasal vowel in word-final position and no nasal consonants provide the crucial phonological environment in which fully nasal vowels and the effects of anticipatory long-distance nasal assimilation can be observed. In these types of words, the percentage of nasal airflow present a cline-like gradient increase from the beginning of V2 to the end of V3 for speakers of the Kapiwat dialect. Figure 8 below presents the percentage of nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /(C)VCVCṼ/, with a single phonemically nasal vowel in word-final position. Figure 8 presents pooled data for all four speakers of the Kapiwat dialect for the words /ɨkɨʔĩɨ̃/ ‘pepper’, /ɟasiʔũ/ ‘mosquito’, /aɾusĩ/ ‘rice’, and /ɟɨapĩɨ̃/ ‘axe’.

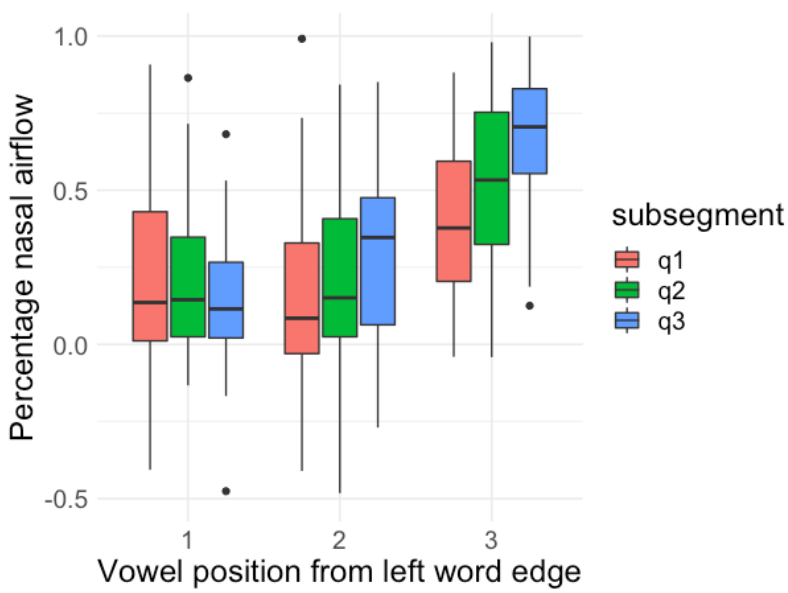

Figure 8: Percentage nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /(C)VCVCṼ/ uttered by speakers of the Kapiwat dialect

In trisyllabic /CVCVCṼ/ words with a final phonemically nasal vowel and no nasal consonants, the pattern of nasal airflow in V1 parallels that observed for V1 in /CVCVCVN/ and /(C)VCVCV(C)/ words: While all three portions of the initial vowel have roughly zero percent nasal airflow, the first and second portions of this vowel seems to have a very slightly higher percentage of nasal airflow than the last third of this same vowel, likely as a result of boundary nasalization.

The pattern observed in V2 and V3 of /CVCVCṼ/ words is particularly interesting: The percentage nasal airflow gradually and steadily increases from the first portion of V2 to the third portion of V3. This pattern supports the existence of a phenomenon of anticipatory long-distance nasal assimilation in Kawaiwete, which is triggered by a phonemically nasal vowel and affects the sonorants up to one syllable preceding the syllable with a nasal vowel. This pattern is non-iterative, as the domain of long-distance nasal assimilation does not extend beyond the vowel immediately preceding the long-distance nasal assimilation trigger. In this sense, the velum begins to lower at the beginning of the second vowel, and continues to lower gradually until it reaches maximal opening during the last portion of the phonemically nasal vowel, i.e. the word-final vowel. In this sense, the domain of nasalization of a phonemically nasal vowel spans two syllables.

Figure 9 below presents the percentage of nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /(C)VCVCṼ/ uttered by the speaker of the Jawarum dialect. When compared to Figure 8 above, Figure 9 illustrates how V2 does not exhibit any nasalization effect in words with a final phonemically nasal vowel. Indeed, the percentage of nasal airflow shows a low flat plateau, typical of oral vowels that occur between two oral consonants. This data, then, supports the hypothesis that the phenomenon of long-distance nasal assimilation is only observed for speakers of the Kapiwat dialect of Kawaiwete.

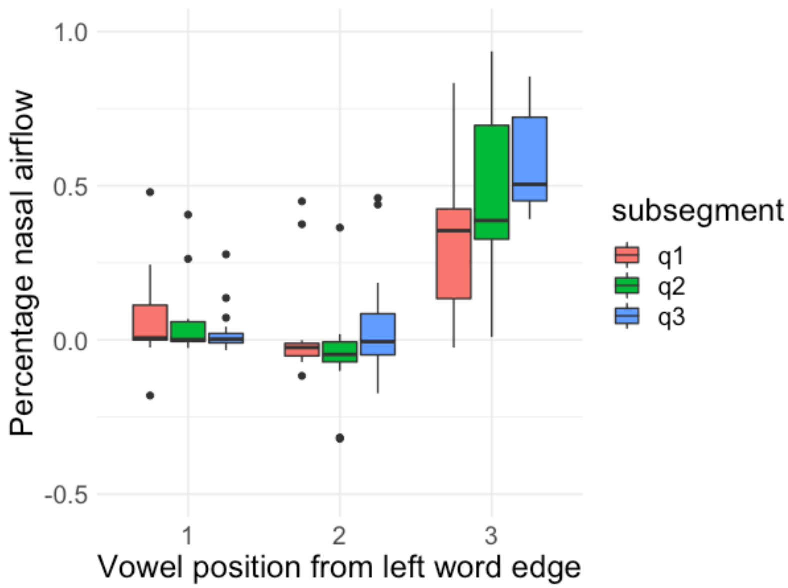

Figure 9: Percentage nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /(C)VCVCṼ/ uttered by a speaker of the Jawarum dialect

4.3.2.4 Words with nasal consonants and a nasal vowel

Trisyllabic words with a single phonemically nasal immediately preceded by a nasal consonant provide a crucial phonological environment in which fully nasal vowels are observed. In these types of words, the percentage of nasal airflow presents a high flat plateau throughout the duration of the word-final fully nasal vowel. Figure 10 below presents the percentage of nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /CVNVNṼ/, with a phonemically nasal vowel in word-final position, and two word-medial nasal consonants. Figure 10 presents pooled data for all five speakers for the word /kunumĩ/ 'boy'.

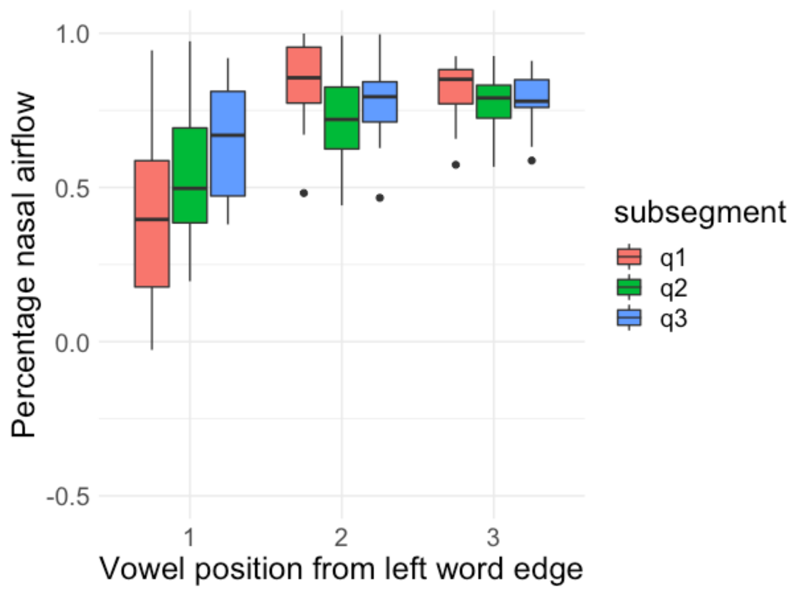

Figure 10: Percentage nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /CVNVNṼ/

In trisyllabic /CVNVNṼ/ with a phonemic nasal vowel, an initial oral consonant, and two medial nasal consonants, V1 follows the expected pattern of a vowel preceding a nasal consonant, with a gradual increase in the percentage of nasal airflow over the duration of the vowel. In addition, V2 follows the pattern of a vowel that occurs between two nasal consonants, with a high flat plateau across the three portions of the vowel.

The crucial difference between /CVNVNṼ/ and /CVNVNV/ words lies in the realization of V3: Whereas in /CVNVNV/, the percentage of nasal airflow in V3 starts high and decreases gradually over the course of the vowel, V3 in /CVNVNṼ/ exhibits a high flat plateau of nasal airflow. This difference can be attributed to the phonemic status of the nasal vowel in /CVNVNṼ/ words but not in /CVNVNV/ words. As such, a vowel whose nasal airflow decreases over its duration is interpreted as phonemically oral. Given that a immediately following a nasal consonant already exhibits the maximal possible amount of nasal airflow, nasal airflow cannot increase further over the course of the vowel's duration. A vowel with a high plateau of nasal airflow in word-final position, then, is interpreted as a phonemically nasal vowel, when it immediately follows a phonemically nasal consonant. This pattern can be explained as a combination of the effects of progressive local nasal assimilation from the immediately preceding nasal consonant, and the inherent nasality of the phonemically nasal vowel itself.

Finally, Figure 11 below presents the percentage of nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /CVCVNṼ/, with a phonemically nasal vowel in word-final position, and a single word-medial nasal consonant which immediately precedes the nasal vowel. Figure 11 presents pooled data for all five speakers for the word /tukumã/ 'tucum'.

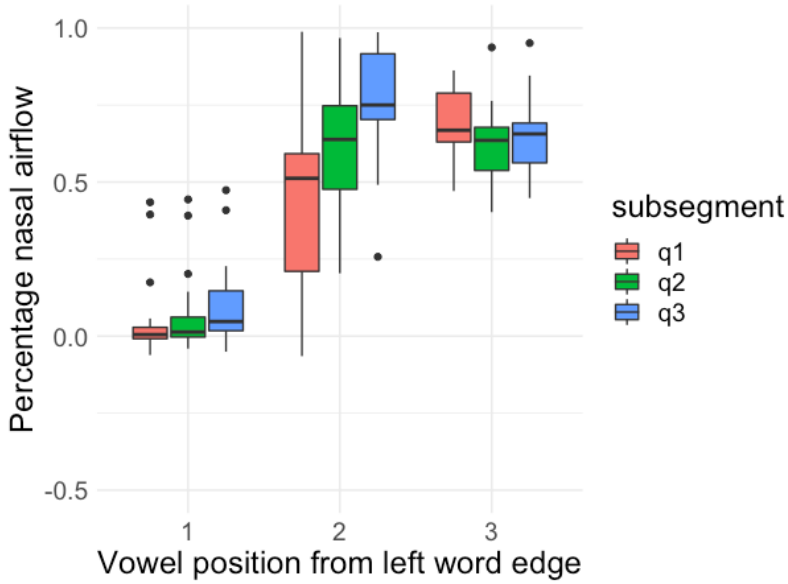

Figure 11: Percentage nasal airflow in the first, second, and third subsegments of the first, second, and third vowels in words of the shape /CVCVNṼ/

In trisyllabic /CVCVNṼ/ with a phonemic nasal vowel, each one of the vowels follows the expected pattern, given its adjacency to nasal and oral consonants, as well as the vowel's phonemically oral or nasal status. Percentage of nasal airflow in V1 is at about zero for each one of the three portions of the vowel, as is expected of an oral vowel between two oral consonants. Note that the absence of an effect of initial boundary nasalization is likely due to the fact that V1 is preceded by an oral obstruent, and is not in fact in word-initial position. V2 in a /CVCVNṼ/ exhibits the pattern expected of an oral vowel before an oral and a nasal consonant, with a steep increase in percentage of nasal airflow over the course of its duration. Finally, V3 in /CVCVNṼ/ patterns identically to V3 in /CVNVNṼ/, with a high plateau of percentage of nasal airflow, which combines the effects of the coarticulatory nasalization from the immediately preceding nasal consonant, and the inherent nasality of the phonemic nasal vowel itself.

4.3.2.5 Summary of findings

Figure 12 summarizes the major findings of the oral and nasal airflow experiment for Kawaiwete vowels, showing their realization in particular phonotactic environments. The graphs presents pooled data for all five speakers. Figure 12A summarizes the realization of phonemically nasal vowels occurring after an oral consonant, showing a dynamic increase in percentage nasal airflow over the vowel's duration. Figure 12B summarizes the realization of phonemically nasal vowels occurring after a nasal consonant, showing a high flat plateau of percentage nasal airflow over the vowel's duration. Figure 12C summarizes the realization of phonemically oral vowels between two nasal consonants, showing a high flat plateau of percentage nasal airflow over the vowel's duration. Figure 12D summarizes the realization of phonemically oral vowels between an oral and a nasal consonant, showing a dynamic increase in percentage nasal airflow over the vowel's duration. Figure 12E summarizes the realization of phonemically oral vowels between a nasal and an oral consonant, showing a dynamic decrease in percentage nasal airflow over the vowel's duration. And finally, Figure 12F summarizes the realization of phonemically oral vowels between two oral consonants, showing a low flat plateau of percentage nasal airflow over the vowel's duration.

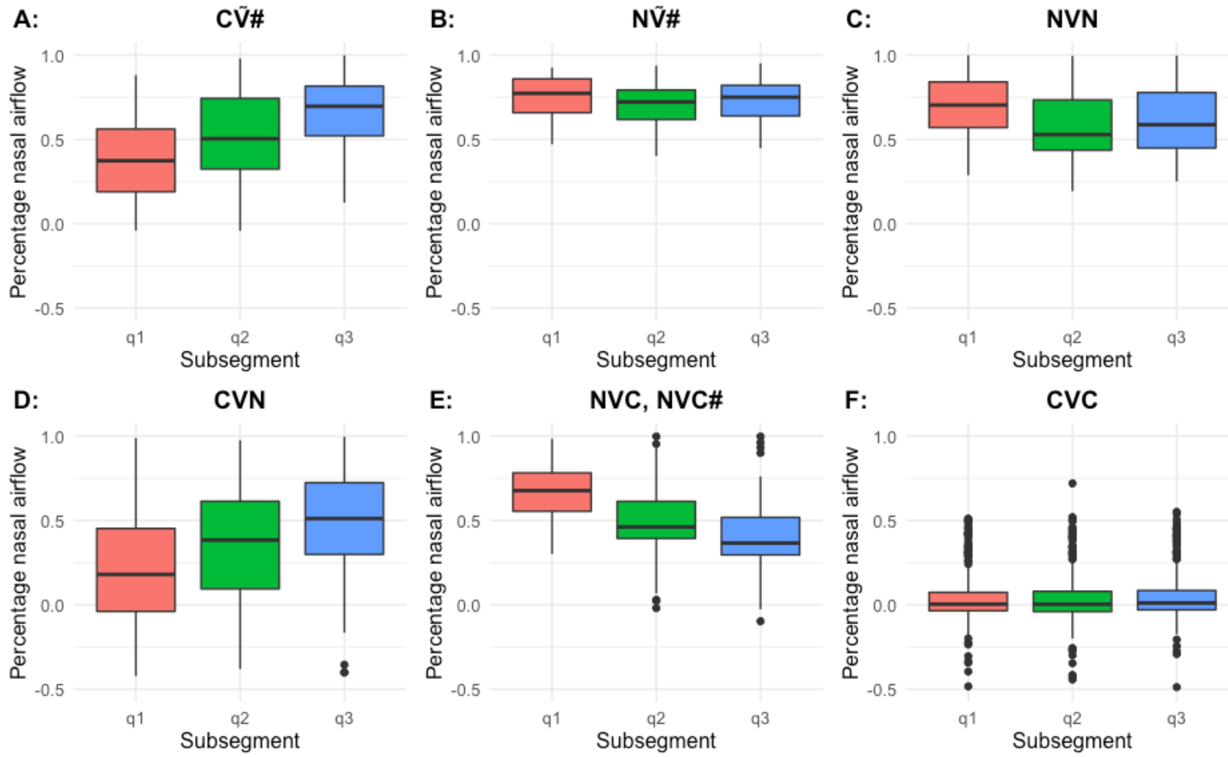

Figure 12: Percentage nasal airflow for vowels in specific phonotactic environments, namely (A) /CṼ#/; (B) /NṼ#/; (C) /NVN/; (D) /CVN/; (E) /NVC, NV#/; and (F) /CVC/

One of the major findings of the experiment, then, is that there is no single pattern for the realization of an oral or a nasal vowel, and that the information relevant to encoding the contrast between oral and nasal vowels in Kawaiwete is crucially dynamic over the duration of the vowel, and relative to the immediately preceding and following segmental context. Fully oral vowels are realized with a low flat plateau of nasal airflow, as in 12F; partially nasal vowels are realized with a cline in nasal airflow over the course of their duration, as in 12A, 12D, and 12E; and fully nasal vowels are realized with a high flat plateau in nasal airflow, as in 12B and 12C.

The patterns observed in the realization of vowels in Kawaiwete resembles that observed for other languages with similar typological characteristics. The patterns of positive and negative interpolation observed for partially nasal vowels, which arise from a process of local nasal assimilation triggered by an immediately adjacent nasal consonant, mirrors the patterns observed for the realization of vowels in English, as documented by Cohn (1990). In addition, the realization of phonemically nasal vowels after nasal consonants with a high flat plateau of nasal airflow mirrors the realization of nasal vowels after nasal consonants in French, also documented by Cohn (1990). The realization of phonemically nasal vowels after oral obstruents in Kawaiwete patterns similarly to the realization of nasal vowels after oral obstruents in French. However, the positive slope interpolation occurs over the vowel's entire duration in Kawaiwete, whereas it occurs in the first half of the duration of the vowel in French, with the second half realized as a high flat plateau of nasal airflow (Cohn 1990, Desmeules-Trudel & Brunelle 2018).

In order to successfully account for the data from Kawaiwete, any model of phonological representations must be able to capture the dynamic nature of airflow contours over the duration of a vowel, whether this be by a positive slope, a negative slope, or a flat plateau. In the following subsection, I propose an ABC+Q analysis, which incorporates the use of both subsegments and subfeatures, as well as feature agreement between subsegments in a correspondence relationship. Specifically, the proposed analysis offers a formal implementation of the observation that some types of vowels seem to interpolate values between different endpoints (Pierrehumbert 1980; Keating 1990; Pierrehumbert & Beckman 1988; Cohn 1990; McPherson 2011).

4.4 A subsegmental and subfeatural analysis

4.4.1 Background

The results of the oral and nasal airflow experiment discussed in Section 4.3 show that the pattern of bidirectional local nasal assimilation and the pattern of anticipatory long-distance nasal assimilation are realized very similarly, with a dynamic interpolation over a range of values whose endpoints are representative of fully oral and fully nasal vowels. The domain of interpolation differs for the two processes, spanning the duration of one vowel in the case of local nasal assimilation, and of two syllables, in the case of long-distance nasal assimilation. Taken together, the data from Kawaiwete suggests that both processes of nasal assimilation are grammatical, and not simply the result of mechanical pressures from velic articulation. For this reason, I argue that both processes result from phonological pressures and should therefore be modeled within the phonological grammar.

Modeling patterns of oral-nasal interpolation requires that phonological representations allow for intermediate values of nasality which change over the time course of a vowel. To this end, I propose that the Q-theoretic model of subsegmental representations presented in Chapter 3 be augmented with subfeatures. I follow Lionnet's (2017) model of subfeatural representations, and I assume that all (sub)segments may be specified as [+nasal], [–nasal], or [$x$nasal], where [$x$nasal] represents a degree of nasalization intermediate to, and perceptibly distinct from both [+nasal] and [–nasal].

Subfeatural representations build on the standard notion of contrastive features by exploding them into scalar subfeatures, which capture a category of distinctive, but non-contrastive intermediate values. The subfeatural level of representation allows for gradience in the degree of a distinctive feature, making it particularly well suited to a model of phonological representations aiming to capture the phonologization of assimilation phenomena.

Subfeatures are represented with a value that can be any number drawn from a continuous scale whose endpoints are 0 and 1, corresponding to [–F] and [+F], respectively. Using this quantification method, subfeatures are able to capture the magnitude of a phonological feature, such as nasality. This continuous scale is functionally subdivided into three categories, namely [–F], [xF], and [+F]. Crucially, these subfeatural specifications represent the only three relevant values of the feature [F], namely fully oral, partially nasal, and fully nasal in the case of the feature [nasal]. In this way, while subfeatures technically allow for modeling continuous values of a feature, the phonological grammar is only sensitive to three ranges of values on the subfeatural scale. Any segment whose value is [xF] is sufficiently coarticulated such that the resulting segment is perceptually distinct from both [+F] and [–F].

I build on Lionnet's (2017) work by showing how subsegmental and subfeatural representation can be used to model patterns of interpolation. I propose that Window Theory (Keating 1990) be augmented, such that windows span the duration of a subsegment, rather than a segment, and subfeatural values provide window width specifications. This architecture provides a more detailed representational architecture, which better informs the path of the interpolation curve between different targets.

4.4.2 Proposal

The results of the airflow experiment presented in §3.3 suggest that oral vowels, partially nasal vowels, and fully nasal vowels are produced differently by native speakers of Kawaiwete, and that the differences in their realization is crucially sensitive to the immediate phonotactic environment in which the relevant vowel appears. These findings support the need for distinct phonological representations for the three categories of vowels.

Building on the representational framework developed in Chapter 3, I assume that segments may be divided on the horizontal, temporal plane into three quantized subsegments (q^1 q^2 q^3) and that the phonological grammar is able to manipulate these subsegmental units. I argue on the basis of Kawaiwete for a model of phonological representations in which features are likewise divisible on the vertical, spatial scale intro three quantized values, [+nasal], [*x*nasal], and [−nasal] (Lionnet 2017), representative of distinct positions of the velum. This division of the segment on both the temporal and spatial scales is presented schematically in Figure 13 below.

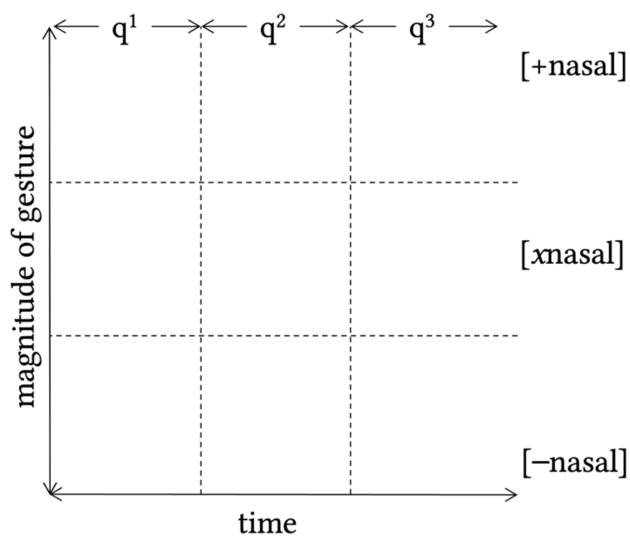

Figure 13: Temporally and spatially-defined subsegments

The architecture of the proposed subsegmental and subfeatural model provides the level of granularity necessary to distinguish between fully oral vowels, partially nasal vowels, and fully nasal vowels in Kawaiwete. This representational machinery derives the patterns of nasal-oral interpolation observed in Kawaiwete, where oral vowels between two oral consonants are realized with three [−nasal] subsegments (11a); oral vowels between a nasal and an oral consonant are realized with one [+nasal] subsegment, one [$x$nasal] subsegment, and one [–nasal] subsegment (11b); oral vowels between an oral and a nasal consonant are realized with one [–nasal] subsegment, one [$x$nasal] subsegment, and one [+nasal] subsegment (11c); nasal vowels after an oral consonant are also realized with one [–nasal] subsegment, one [$x$nasal] subsegment, and one [+nasal] subsegment (11d); and nasal vowels after a nasal consonant are realized with three [+nasal] subsegments (11e).

(11) a. $(C_1\ C_2\ C_3)\ (V_1\ V_2\ V_3)\ (C_1\ C_2\ C_3)$
b. $(N_1\ N_2\ N_3)\ (\tilde{V}_1\ \overset{\times}{V}_2\ V_3)\ (C_1\ C_2\ C_3)$
c. $(C_1\ C_2\ C_3)\ (V_1\ \overset{\times}{V}_2\ \tilde{V}_3)\ (N_1\ N_2\ N_3)$
d. $(C_1\ C_2\ C_3)\ (V_1\ \overset{\times}{V}_2\ \tilde{V}_3)$
e. $(N_1\ N_2\ N_3)\ (\tilde{V}_1\ \tilde{V}_2\ \tilde{V}_3)$

A subsegment with the subfeatural specification [$x$nasal] represents partial nasality, which is only possible between a subsegment specified as [–nasal] and a subsegment specified as [+nasal], as in (12a); or between a subsegment specified as [+nasal] and a subsegment specified as [–nasal], as in (12b). This restriction on the distribution of the subfeatural value [$x$nasal] is supported by the empirical generalization that partially nasal values are only attested in the dynamic motion of the velum between a raised and lowered state, as in (12a), or between a lowered and a raised state, as in (12b).

(12) a. **Positive slope interpolation**

$$\begin{array}{ccc} & [\overset{\times}{V}] & \\ & \downarrow & \\ (V^1 & \overset{\times}{V}^2 & \tilde{V}^3) \\ \begin{bmatrix} -\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} & \begin{bmatrix} x\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} & \begin{bmatrix} +\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} \end{array}$$

b. **Negative slope interpolation**

$$\begin{array}{ccc} & [\overset{\times}{V}] & \\ & \downarrow & \\ (\tilde{V}^1 & \overset{\times}{V}^2 & V^3) \\ \begin{bmatrix} +\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} & \begin{bmatrix} x\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} & \begin{bmatrix} -\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} \end{array}$$

Possible gestural targets for the velum include lowered and raised; and crucially, a partially open velo-pharyngeal port does not constitute a possible gestural target for the velum. This follows from basic properties of muscle mechanics: When a muscle contracts, it contracts completely (Silverthorn 2010:426). Individual muscle fibers do not partially contract, and cannot vary the intensity of their contraction. Rather, to vary the strength of a muscular contraction requires soliciting a greater number of motor units, where a motor unit is a single neuron and the muscle fibers it innervates.

The realization of [$x$nasal], then, is inherently dynamic: It represents a partially open state of the velo-pharyngeal port, *en route* between a raised velum and a lowered velum. For this reason, [$x$nasal] values are not contrastive in the input. However, [$x$nasal] values may be distinctive, as in the case of Kawaiwete, representing a range of quantifiable values that can be categorized as perceptually distinct from both [+nasal] and [–nasal]. That the subfeatural value [$x$nasal] is phonologically meaningful allows for a straightforward implementation of a grammar of phonological interpolation. In the next subsection, I solve for the range of values of the subfeature [$x$nasal] in Kawaiwete vowels.

4.4.2.1 Solving for the value of x

This subsection provides a method for quantifying the subfeatural value of [$x$nasal] using instrumental airflow data from Kawaiwete oral, partially nasal, and fully nasal vowels. Given that subfeatures refer to perceptual categories, rather than purely articulatory or acoustic categories, the methodology presented here should be considered subject to further refinements from data gathered in a perceptual experiment. I take Lionnet's (2017) formula for calculating the value of [xF] as a starting point, presented in (13). The equation calculates the proportion of increase from [–F] to [xF] as the ratio between the difference of ([xF] – [–F]) and ([+F] – [–F]).

(13) $$x\text{F} = \frac{[x\text{F}] - [-\text{F}]}{[+\text{F}] - [-\text{F}]}$$

The numbers used to solve the equation in (14) were obtained from the nasal airflow measurements reported in Section 4.3. The percentage nasal airflow values obtained are 0.02 for a [–nasal] vowel, 0.70 for a [+nasal] vowel, and 0.36 for a [$x$nasal]. The value for a [–nasal] vowel was obtained by calculating the average value of the percentage of nasal airflow in the second subsegment of the second vowel in the words /akɨkɨ/ 'brown howler monkey', /avˀasi/ 'corn', /piɾapep/ 'stingray', /ɨkɨʔɟju/ 'cricket', /tapiʔit/ 'tapir', and /kuɾuɾu/ 'frog', for all five speakers (mean=0.0242, First quartile=−0.0339, Third quartile=0.1064). The value for a [+nasal] vowel was obtained by calculating the average value of the percentage of nasal airflow in the second subsegment of the third vowel in the words /tukumã/ 'tucum', /aɾusĩ/ 'rice', /ɟɨapĩĩ/ 'axe', /ɟasiʔũ/ 'mosquito', /avˀamũ/ 'now', /ɨkɨʔĩĩ/ 'pepper', and /kunumĩ/ 'boy', for all five speakers (mean=0.7002, First quartile=0.5718, Third quartile=0.8225). The value for a [$x$nasal] vowel was obtained by calculating the average value of the percentage of nasal airflow in the second subsegment of the third vowel in the words /kaɾupam/ 'deer', /kaʔaɾan/ 'notebook', /faɨɾum/ 'ring', and /ɟakɨɾan/ 'cicada', for all five speakers (mean=0.3577, First quartile=0.2071, Third quartile=0.5469).

(14) $$\begin{aligned} x &= \frac{\%\text{NasFlo}[\check{\tilde{\text{V}}}] - \%\text{NasFlo}[\text{V}]}{\%\text{NasFlo}[\tilde{\text{V}}] - \%\text{NasFlo}[\text{V}]} \\ &= \frac{0.36 - 0.02}{0.70 - 0.02} \\ &= \frac{0.34}{0.68} \\ &= 0.5 \end{aligned}$$

The value of 0.5 obtained from solving the equation in (14) indicates that the difference in percentage of nasal airflow between a partially nasal vowel [$\check{\tilde{\text{V}}}$] and an oral vowel [V] is (roughly) 50% of the difference between a fully nasal [Ṽ] and a fully oral vowel [V]. This is exactly as expected. As was noted in the previous subsection, [xF] indicates a range of values, rather than a single value. To operationalize the range of values equal to [xF], I calculate the interquartile range of the nasal airflow measurements for partially nasal vowels. First, (15) solves for the first quartile of percentage nasal airflow measurements for partially nasal vowels, i.e. the lower limit of the range of values which I classify as [$x$nasal].

(15) **First quartile of [V̽]**

$$x = \frac{\%\text{NasFlo}[\overset{\times}{\text{V}}] - \%\text{NasFlo}[\text{V}]}{\%\text{NasFlo}[\tilde{\text{V}}] - \%\text{NasFlo}[\text{V}]} = \frac{0.21 - 0.02}{0.70 - 0.02} = \frac{0.19}{0.68} = 0.28$$

(16) solves for the third quartile of percentage nasal airflow measurements for partially nasal vowels, i.e. the upper limit of the range of values which I classify as [$x$nasal].

(16) **Third quartile of [V̽]**

$$x = \frac{\%\text{NasFlo}[\overset{\times}{\text{V}}] - \%\text{NasFlo}[\text{V}]}{\%\text{NasFlo}[\tilde{\text{V}}] - \%\text{NasFlo}[\text{V}]} = \frac{0.21 - 0.02}{0.70 - 0.02} = \frac{0.55}{0.68} = 0.81$$

Following the values obtained in (15) and (16), which are on a scale of 0 to 1, the interquartile range of values of [$x$nasal] is from 0.28 to 0.81, with a mean of 0.5. The range of values of [−nasal] is from 0.0 to 0.279, and the range of values of [+nasal] is from 0.811 to 1. The values obtained here were calculated from the pooled set of airflow data for all five speakers of Kawaiwete. However, I follow Lionnet (2017) in assuming that the range of values that may be categorized as [+nasal], [−nasal], and [$x$nasal] varies by speaker and can be calculated for each individual to account for inter-speaker variation.

4.4.3 Testing the predictions of subfeatures

The representational model presented here allows for a tripartite division of both the segment and the feature. If segments can be decomposed into three subsegments, and features can be divided into three subfeatural values, this allows for 27 distinct segment types. The architecture laid out here is therefore very powerful, predicting more distinct segment types than previous models of representational phonology. In this subsection, I lay out all of the logically possible segment types predicted by the proposed representational machinery, and I discuss those that are attested and those that are not.

The first four segment types are those in (17a-d), which are attested in the Kawaiwete data discussed in Section 4.3 above. As was argued in Section 4.4.2, the segment type in (17a), with three [−nasal] subsegments, represents the realization of oral vowels between two oral consonants in Kawaiwete. The segment type in (17b), with three [+nasal] subsegments, represents the realization of an oral vowel between two nasal consonants, or of a phonemically nasal vowel after a nasal consonant. The segment type in (17c), with one [−nasal], one [$x$nasal], and one [+nasal] subsegments represents an oral vowel between an oral and a nasal consonant;

and the segment type in (17d), with one [+nasal], one [*x*nasal], and one [–nasal] subsegments, represents an oral vowel between a nasal and an oral consonant, respectively.

(17) a. (ᴠ^1 ᴠ^2 ᴠ^3) c. (ᴠ^1 ᴠ̃ͯ^{2} ᴠ̃^{3})
b. (ᴠ̃^{1} ᴠ̃^{2} ᴠ̃^{3}) d. (Ṽ^1 ᴠ̃ͯ^{2} ᴠ^3)

The four segment types in (18a-c) are potentially attested in French (see Figure 11, Section 2.7), where the segment structure in (18a), with one [*x*nasal] and two [–nasal] subsegments, represents an oral vowel after a nasal consonant; the segment in (18b), with two [–nasal] and one [*x*nasal] subsegments, represents an oral vowel before a nasal consonant; the segment in (18c), with one [*x*nasal] and two [+nasal] subsegments, represents a nasal vowel after an oral consonant. The segment in (18d), with two [+nasal] and one [*x*nasal] subsegments, represents a nasal vowel before an oral consonant. To the best of my knowledge, this segment type is unattested, but it may be found in a language which exhibits C → V oral assimilation, such as Karitiana and Kaingang (see Section 2.7).

(18) a. (ᴠ̃ͯ^{1} ᴠ^2 ᴠ^3) c. (ᴠ̃ͯ^{1} ᴠ̃^{2} ᴠ̃^{3})
b. (ᴠ^1 ᴠ^2 ᴠ̃ͯ^{3}) d. (ᴠ̃^{1} ᴠ̃^{2} ᴠ̃ͯ^{3})

The two segment types in (19a) and (19b) are those that are attested in non-iterative long-distance nasal assimilation in Kawaiwete. The segment in (19a), with one [–nasal] and two [*x*nasal] subsegments, represents the vowel in the syllable immediately preceding the triggering vowel; and (19b), with two [*x*nasal] and one [+nasal] subsegments, represents the nasal vowel triggering the pattern of long-distance nasal assimilation itself. Crucially, the sequence of (19a) and (19b) represents a pattern of oral-nasal interpolation spanning the duration of two segments in a system with leftward long-distance nasal assimilation.

(19) a. (ᴠ^1 ᴠ̃ͯ^{2} ᴠ̃ͯ^{3})
b. (ᴠ̃ͯ^{1} ᴠ̃ͯ^{2} ᴠ̃^{3})

The segment types in (20a) and (20b) represent the mirror pattern of nasal-oral interpolation spanning two segments, in a hypothetical system with rightward long-distance nasal assimilation. The segment in (20a), with one [+nasal] and two [*x*nasal] subsegments, represents the vowel in the syllable immediately preceding the triggering vowel; and (20b), with two [*x*nasal] and one [–nasal] subsegments, represents the nasal vowel triggering the pattern of long-distance nasal assimilation itself. To the best of my knowledge, a language exhibiting non-iterative progressive long-distance nasal assimilation affecting only the syllable immediately following the trigger has not been documented, but this type of system seems like a perfectly plausible hypothetical human language. I leave the testing of this prediction to future work.

(20) a. (ᴠ̃^{1} ᴠ̃ͯ^{2} ᴠ̃ͯ^{3})
b. (ᴠ̃ͯ^{1} ᴠ̃ͯ^{2} ᴠ^3)

The segment type in (21) with three [*x*nasal] subsegments represents a segment with partial nasalization throughout its entire duration. Though unattested as of yet, I suspect that such vowels may exist in languages with long-distance nasal assimilation realized as an interpolation over multiple syllables. Specifically, I suspect that the system of long-distance nasal assimilation attested in Paraguayan Guaraní, another language of the Tupí-Guaraní family, may very well be of this type.

(21) (V̽^{1} V̽^{2} V̽^{3})

Although articulatory data on the realization of nasal harmony in Paraguayan Guaraní is not available, several pieces of evidence suggest that nasal harmony is indeed realized with the same pattern of slow, gradual lowering of the velum. Gregores & Suárez (1967:66), for instance, provide the following impressionistic description of nasal harmony:

> “The nasalization of the particular phonemes is more or less strong according to their position in the nasal span. […] [N]asalization occurs covering a span of variable length, in which the velum appears to be lowered increasingly from medium to strong, so that the nasal timbre is strongest toward the end of the nasal span.”

Furthermore, the six segment types in (22a-f) are the only segment types which, in addition to those in (17a) and (17b), do not include any [*x*nasal] subsegments. While the segment structures in (22) are unattested in vowels, they are indeed attested in stop consonants, as was discussed in Section 3.4.3. I refer the reader to this section for a more detailed discussion.

(22) a. (V^1 V^2 Ṽ^3) c. (Ṽ^1 Ṽ^2 V^3) e. (Ṽ^1 V^2 Ṽ^3)
b. (V^1 Ṽ^2 Ṽ^3) d. (Ṽ^1 V^2 V^3) f. (V^1 Ṽ^2 V^3)

The use of the subfeatural value [*x*nasal] appears to be of relevant for the phonological representation of vowels, but not necessarily for consonants. This is likely due to the fact that the amount of velo-pharyngeal port opening needed for nasal airflow to be perceptually salient is likely much smaller in consonants than in vowels, because nasal consonants are realized with all of the airflow escaping through the nasal cavity, while nasal vowels are realized with airflow escaping from both the oral and nasal cavities. Theoretically speaking, then, the amount of nasal airflow present during the production of a nasal vowel is only half of that present during the production of a nasal consonant. The amount of velo-pharyngeal port opening needed for the production of a partially nasal vowel with the subfeatural value [*x*nasal] is likely sufficient to produce the percept of a [+nasal] vowel when the oral cavity is closed, such as in the production of a nasal consonant. If this hypothesis is indeed correct, I predict that the featural value [*x*nasal] is not, in fact, relevant to the representation of nasal consonants. I leave the testing of this prediction to future work.

The two segment types in (23a-b) are unattested. I argue that this is because the [*x*nasal] subsegment appears between two [–nasal] subsegments, as in (23a), or between two [+nasal] subsegments, as in (23b). As was noted in the previous subsection, [*x*nasal] subsegments may only appear between a [–nasal] and a [+nasal] subsegment, or vice versa, as partial opening of the velo-pharyngeal port is only possible as a dynamic transition between a fully raised and a fully lowered velum, or between a fully lowered and a fully raised velum.

(23) a. (V^1 V̽^{2} V^3)
b. (Ṽ^1 V̽^{2} Ṽ^3)

Finally, the last six segment types in (24a-f) are likewise unattested. Each of these six segment types include one [–nasal], one [*x*nasal], and one [+nasal] subsegment, with the [*x*nasal] subsegment appearing at either the right or the left segment boundary. As a result, these six segment types involve more than one change in the state of the velum, with a rapid shift from a [–nasal] subsegment to an immediately following [+nasal] subsegment, or from a [+nasal] subsegment to an immediately following [–nasal] subsegment. As was noted in Chapter 1, the velum lowers and raises relatively slowly, and small differences in vowel nasality are not perceptually salient. For these reasons, I predict that such segment types should be ruled out by the derivational grammar, as they are unattested and are predicted to be impossible.

(24) a. (V̽^{1} V^2 Ṽ^3) c. (V^1 Ṽ^2 V̽^{3}) e. (V̽^{1} V^2 Ṽ^3)
b. (Ṽ^1 V^2 V̽^{3}) d. (V̽^{1} Ṽ^2 V^3) f. (Ṽ^1 V^2 V̽^{3})

4.4.4 Contrastive vs. distinctive phonological structures

As was noted for the distinction between pre-nasalization and post-oralization in Panãra, the distinction between oral vowels, nasalized vowel, and fully nasal vowels in Kawaiwete is one that arises through phonological derivation. This is due to the fact that, in its phonemic inventory, Kawaiwete only contrasts a series of [–nasal] vowels with a series of [+nasal] vowels. The phonologically derived [*x*nasal] vowels are the result of coarticulatory nasalization, consistent with Lionnet's (2017) claim that subfeatural values of [*x*F] are not present in the input, but may be present in the output. Specifically, [*x*nasal] vowels in Kawaiwete arise via interpolation between a [–nasal] vowel subsegment, and a [+nasal] vowel subsegment.

As was noted in Section 3.4.4, a body of work has shown that the phonological grammar encodes very detailed phonetic information (e.g. Kingston & Diehl 1994; Johnson 1997; Pierrehumbert 2001). As has been shown by detailed perception experiments, speakers of languages with a contrast in vowel nasality, such as Canadian French, can distinguish very fine-grained differences in nasality during the production of vowels (Desmeules-Trudel & Zamuner 2019, 2021), and that partially nasal vowels are crucially perceived as distinct from both oral and nasal vowels. A three-way distinction in magnitude of nasal airflow is further supported by various studies examining patients with nasal cavity deformities, such as cleft palate. Warren et al. (1993) note that sounds produced with a velo-pharyngeal port opening of less than 0.1 cm^2 do not appear to cause a salient percept of nasality, and that the velo-pharyngeal port opening must be larger than 0.2 cm^2 for the production of nasal consonants to be perceived as normal in adults. When the velo-pharyngeal port opening is larger than 0.1 cm^2, and smaller than 0.2 cm^2, listeners can identify the presence of nasality in "non-nasal" sounds. Taken together, these results suggests a three-way distinction in perceptibility of nasality, as predicted by subfeatural representations: Non-nasal sounds are produced with a velo-pharyngeal opening of less than 0.10 cm^2; lightly nasalized sounds[5] are produced with a velopharyngeal opening value of *x*, where

[5] Maeda (1993) shows that perceived degree of nasalization is also dependent on vowel quality, where the three vowels [i, a, u] are perceived as having different degrees of nasalization even when degree of velopharyngeal opening is held constant.

$0.10\ cm^2 < x > 0.20\ cm^2$; and fully nasal sounds are produced with a velo-pharyngeal opening of more than $0.20\ cm^2$.

A goal of this work is to extend the scope of phonological representations to include those derived structures that are perceptually salient to speakers of a given language. In the case of Kawaiwete, several arguments can be made in favour of perceptually salient distinction between fully oral, partially nasal, and fully nasal vowels. First, Kawaiwete speakers of the Jawarum dialect are keenly aware of the presence of nasalized sounds in the speech of the Kapiwat speakers for those words that exhibit long-distance nasal assimilation. Jawarum speakers will often make very direct metalinguistic comments of the type "Kapiwat speakers speak in a way that is very nasal." This type of comment likely describes the presence of detectable nasality on the vowel immediately preceding the long-distance nasal assimilation trigger in the speech of Kapiwat speakers, which is crucially distinct from the production of Jawarum speakers for those same words (which are realized without long-distance nasal assimilation).

Despite the observation that partially nasal vowels are perceptually salient in the speech of Kapiwat speakers of Kawaiwete, discussions with native speakers of the language about the orthographic representation of nasality in vowels further suggest that partially nasal vowels are distinct from both oral and nasal vowels. As previously noted, speakers' metalinguistic comments reveal that a binary distinction between nasal and oral vowels is insufficient to capture their native intuitions about the realization of vowels. The word /aʋasi/ [aʋasi] 'corn' contains three oral vowels, and speakers unanimously agree that the correct spelling should be <awasi>. In comparison, the word /aɾusĩ/ [aɾṵsĩ] 'rice', realized with long-distance nasal assimilation in the Kapiwat dialect, must be written with a tilde on the final vowel (*<arusi>), but speakers note that the second vowel of the word is not strong enough to be written with a tilde (?<arũsĩ>), but it is also distinct from a true oral vowel (<arusĩ>). These metalinguistic comments are supported by the results of the production experiment presented in Section 4.3, which shows that the degree of nasal airflow in the second vowel of a trisyllabic word with long-distance nasal assimilation is different from the degree of nasal airflow in both the first and the third vowel.

Ideally, the perceptual accounted presented here should be supported by data from a perception experiment targeting the perception of the three distinct types of Kawaiwete vowels. I leave this open line of research to future work. For now, it suffices to say that the available data shows converging evidence that partially nasal vowels are indeed distinct from both fully oral and fully nasal vowels in Kawaiwete, and that representational phonology should be able to capture those distinctions. The goal of this chapter is to propose a grammar of subfeatural representations which provides enough granularity to account for the full range of typological phenomena involving patterns of local nasalization and oralization, as outlined in Chapter 2. The division of both the segment and the feature into tripartite subsegments and subfeatural values achieves this goal, but also provides a powerful theoretical apparatus which predicts a total of 27 distinct segment types, some of which are not attested. In the following section, I show that implementing the subsegmental and subfeatural model proposed here restricts the restricts the predictions of the model to reflect only those types of segments that are indeed attested in the typological of local nasal and oral assimilation presented in Chapter 2.

4.5 A grammar of subsegments and subfeatures

4.5.1 Constraints

The distinction between fully oral, partially nasal, and fully nasal vowels in Kawaiwete provides additional evidence that phonological grammars can and do manipulate subfeatures. To model the patterns of interpolation sketched above and the distribution between fully oral, partially nasal, and fully nasal vowels within an Optimality Theoretic grammar, a total of five constraints that crucially make reference to q subsegments and *x* subfeatures are needed. These five constraints belong to three distinct constraint families, two of which have already been introduced in Chapter 3.

Any constraint manipulating (sub)featural values are in tension with the most basic constraint, which requires subsegments in the output have matching feature values as their corresponding subsegment in the input. As in the Panãra case study, this faithfulness constraint penalizes changes in the input and output mappings of subsegments for the feature [+/–nasal], as in (25).

(25) **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].

The second constraint family needed to analyze the patterns of local nasal assimilation in Kawaiwete establishes crucial correspondence relationships between subsegments and requires them to agree in the value of a given feature. As noted in Chapter 1, I follow recent practice in Agreement-by-Correspondence which collapses Correspondence and Identity constraints (Hansson 2014, Walker 2015, Shih & Inkelas 2019) given the low utility in separating them out. Constraints (26) and (27) require consecutive subsegments to have the same value of nasality. Constraint (26) requires that pairs of corresponding q subsegments contained within the same Q segment have identical values for the feature [+/–nasal]. Constraint (27) requires that pairs of corresponding q subsegments separated by a Q segment boundary have identical values for the feature [+/–nasal]. The need for these constraints has been discussed in Chapter 3.

(21) (V̽^{1} V̽^{2} V̽^{3})

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

(27) **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].

For the sake of clarity, let us illustrate the Correspondence relationships established by constraints (26) and (27) for example (28).

(28) $(\text{C}^1\ \text{C}^2\ \text{C}^3)\ (\text{V}^1\ \text{V}^2\ \text{V}^3)\ (\text{N}^1\ \text{N}^2\ \text{N}^3)$

CORR-(qq) establishes a correspondence relationship between C^1 and C^2, C^2 and C^3, V^1 and V^2, V^2 and V^3, N^1 and N^2, and N^2 and N^3, since each of these pairs of subsegments are immediately adjacent to each other and contained within the same Q segment, as in (29).

(29) $(\text{C}^1{}_\text{i}\ \text{C}^2{}_\text{i,j}\ \text{C}^3{}_\text{j})\ (\text{V}^1{}_\text{k}\ \text{V}^2{}_\text{k,l}\ \text{V}^3{}_\text{l})\ (\text{N}^1{}_\text{m}\ \text{N}^2{}_\text{m,n}\ \text{N}^3{}_\text{n})$

CORR-q:Q:q establishes a correspondence relationship between C^3 and V^1, and between V^3 and C^1, since each of these pairs of subsegments are immediately adjacent to each other and separated by exactly one Q segment boundary, as in (30).

(30) $(\text{C}^1\ \text{C}^2\ \text{C}^3{}_\text{i})\ (\text{V}^1{}_\text{i}\ \text{V}^2\ \text{V}^3{}_\text{j})\ (\text{N}^1{}_\text{j}\ \text{N}^2\ \text{N}^3)$

In addition to the above two constraints requiring categorical identity in feature values for subsegments, the analysis of fully oral, partially nasal, and fully nasal vowels in Kawaiwete also requires the use of a subfamily of CORRESPONDENCE constraints. This subfamily of constraints, rather than requiring strict, categorical identity in feature values between pairs of corresponding subsegments, requires that they not differ by an amount exceeding a certain threshold for a given feature. I will call this family of constraints GRADIENT-CORRESPONDENCE-qq. The first constraint of this subfamily, GRAD-CORR-(qq), requires that pairs of corresponding q subsegments contained within the same Q segment not differ by an amount exceeding *x* for the feature [nasal], as in (31). The second constraint, GRAD-CORR-q:Q:q, requires that pairs of corresponding q subsegments separated by a Q segment boundary not differ by an amount exceeding *x* for the feature [nasal], as in (32). This last subfamily of constraints accounts for the observation that the velum moves relatively slowly, and that a movement of the velum resulting in a change from an open to a closed velo-pharyngeal port, or from a closed to an open velo-pharyngeal port, often spans more than two subsegments.

(31) **GRAD-CORR-(qq)**: 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; *and*
iv. q_i and q_j differ by an amount exceeding *x* for the feature [nasal].

(32) **GRAD-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 differ by an amount exceeding *x* for the feature [nasal].

4.5.2 A Harmonic Grammar of subsegments and subfeatures

I model the grammar of Kawaiwete vowels within a Harmonic Grammar (HG; Legendre, Miyata & Smolensky 1990). HG is a variant of Optimality Theory in which constraints are assigned weights, and each constraint violation incurs a penalty score equal to the constraint weight. For each candidate, a $\mathscr{H}$armony score is calculated by adding up the penalty score for each of the constraint violations. The winning candidate is the one with the lowest harmony score. OT Help (Staubs et al. 2010) was used to learn constraint weights.

Tables 1-6 below exhaustively present the input data provided to the learning algorithm. For ease of exposition, the numbering on each of the q subsegments has been left out in the representation of the candidates, but the following subsegmental representation can be assumed for every segment in the output: (q^1 q^2 q^3). In Tables 1-4, the vowel in the underlying representation is assumed to be [–nasal], i.e. unspecified for nasality; and in Tables 5-6, the vowel in the underlying representation is assumed to be [+nasal].

Table 8 presents the Tableau for an input /CVN/ sequence. In all of the candidates for this Tableau, C^3 is in correspondence with V^1, V^1 is in correspondence with V^2, V^2 is in correspondence with V^3, and V^3 is in correspondence with N^1. In Candidate (a), all of the vowel subsegments surface as [–nasal]. In Candidate (b), the first two vowel subsegments surface as [–nasal], and the last vowel subsegment surfaces as [+nasal]. In Candidate (c), the first vowel subsegment surfaces as [–nasal], and the last two vowel subsegments surface as [+nasal]. In Candidate (d), all of the vowel subsegments surface as [+nasal]. In Candidate (e), the first vowel subsegment surfaces as [–nasal], the second vowel subsegment surfaces as [*x*nasal], and the last vowel subsegment surfaces as [+nasal]. In Candidate (f), the first and last vowel subsegments surface as [+nasal], and the second vowel subsegment surfaces as [*x*nasal]. In Candidate (g), the first and last vowel subsegments surface as [–nasal], and the second vowel subsegment surfaces as [*x*nasal]. And finally, in Candidate (h), the first two vowel subsegments surface as [–nasal], and the last vowel subsegment surfaces as [*x*nasal].

Candidates (a) and (g) are ruled out because they both incur violations of CORR-q:Q:q and GRAD-CORR-q:Q:q, since V^3 is [–nasal] and N^1 is [+nasal], and Candidate (g) additionally incurs a violation of IDENT-IO-q. Candidates (b) and (c) are ruled out, as they both incur a violation of GRAD-CORR-(qq) because one of the pairs of corresponding vowel subsegments differ by an amount exceeding x for the feature [nasal]. Candidate (b) also incurs one violation of IDENT-IO-q, while Candidate (c) incurs two violations of this constraint. Candidates (d) and (f) are ruled out because they both incur three violations of IDENT-IO-q, as well as violations of CORR-q:Q:q and GRAD-CORR-q:Q:q, since C^3 is [–nasal] and V^1 is [+nasal]. Candidate (h) is ruled out because it incurs a violation of IDENT-IO-q; a violation of CORR-q:Q:q, since V^3 is [*x*nasal] and N^1 is [+nasal]; as well as a violation of CORR-(qq), because V^2 is [–nasal] and V^3 is [*x*nasal]. The optimal candidate, Candidate (e), incurs only two violations of CORR-(qq), due to the fact that none of the pairs of corresponding vowel subsegments have identical values of for the feature [+/–nasal], as well as two violations of IDENT-IO-q.

Table 8: Tableau for /CVN/ input sequence

/CVN/ $(\mathrm{C}^1\ \mathrm{C}^2\ \mathrm{C}^3)(\mathrm{V}^1\ \mathrm{V}^2\ \mathrm{V}^3)(\mathrm{N}^1\ \mathrm{N}^2\ \mathrm{N}^3)$	CORR-q:Q:q	GRAD-CORR-(qq)	IDENT-IO-q	CORR-(qq)	GRAD-CORR-q:Q:q	ℋarmony
	8	5	3	1	1	
a. [CVN] $(\mathrm{C\ C\ C}_i)(\mathrm{V}_{ik}\ \mathrm{V}_{kl}\ \mathrm{V}_{jl})(\mathrm{N}_j\ \mathrm{N\ N})$	1				1	9
b. $[\mathrm{CV}^{\tilde{\mathrm{V}}}\mathrm{N}]$ $(\mathrm{C\ C\ C}_i)(\mathrm{V}_{ik}\ \mathrm{V}_{kl}\ \tilde{\mathrm{V}}_{jl})(\mathrm{N}_j\ \mathrm{N\ N})$		1	1	1		9
c. $[\mathrm{C}^{\mathrm{V}}\tilde{\mathrm{V}}\mathrm{N}]$ $(\mathrm{C\ C\ C}_i)(\mathrm{V}_{ik}\ \tilde{\mathrm{V}}_{kl}\ \tilde{\mathrm{V}}_{jl})(\mathrm{N}_j\ \mathrm{N\ N})$		1	2	1		12
d. $[\mathrm{C}\tilde{\mathrm{V}}\mathrm{N}]$ $(\mathrm{C\ C\ C}_i)(\tilde{\mathrm{V}}_{ik}\ \tilde{\mathrm{V}}_{kl}\ \tilde{\mathrm{V}}_{jl})(\mathrm{N}_j\ \mathrm{N\ N})$	1		3		1	18
☞ e. $[\mathrm{C}\overset{\times}{\mathrm{V}}\mathrm{N}]$ $(\mathrm{C\ C\ C}_i)(\mathrm{V}_{ik}\ \overset{\times}{\tilde{\mathrm{V}}}_{kl}\ \tilde{\mathrm{V}}_{jl})(\mathrm{N}_j\ \mathrm{N\ N})$			2	2		8
f. $[\mathrm{C}^{\tilde{\mathrm{V}}}\overset{\times}{\mathrm{V}}{}^{\tilde{\mathrm{V}}}\mathrm{N}]$ $(\mathrm{C\ C\ C}_i)(\tilde{\mathrm{V}}_{ik}\ \overset{\times}{\tilde{\mathrm{V}}}_{kl}\ \tilde{\mathrm{V}}_{jl})(\mathrm{N}_j\ \mathrm{N\ N})$	1		3	2	1	20
g. $[\mathrm{C}^{\mathrm{V}}\overset{\times}{\mathrm{V}}{}^{\mathrm{V}}\mathrm{N}]$ $(\mathrm{C\ C\ C}_i)(\mathrm{V}_{ik}\ \overset{\times}{\tilde{\mathrm{V}}}_{kl}\ \mathrm{V}_{jl})(\mathrm{N}_j\ \mathrm{N\ N})$	1		1	2	1	14
h. $[\mathrm{CV}^{\overset{\times}{\mathrm{V}}}\mathrm{N}]$ $(\mathrm{C\ C\ C}_i)(\mathrm{V}_{ik}\ \mathrm{V}_{kl}\ \overset{\times}{\tilde{\mathrm{V}}}_{jl})(\mathrm{N}_j\ \mathrm{N\ N})$	1		1	1		12

Table 9 presents the Tableau for an input /NVC/ sequence. In all of the candidates for this Tableau, N^3 is in correspondence with V^1, V^1 is in correspondence with V^2, V^2 is in correspondence with V^3, and V^3 is in correspondence with C^1. In Candidate (a), all of the vowel subsegments surface as [–nasal]. In Candidate (b), the first vowel subsegment surfaces as [+nasal], and the last two vowel subsegments surface as [–nasal]. In Candidate (c), the first two vowel subsegments surface as [+nasal], and the last vowel subsegment surfaces as [–nasal]. In Candidate (d), all of the vowel subsegments surface as [+nasal]. In Candidate (e), the first vowel subsegment surfaces as [+nasal], the second vowel subsegment surfaces as [*x*nasal], and the last vowel subsegment surfaces as [–nasal]. In Candidate (f), the first and last vowel subsegments surface as [+nasal], and the second vowel subsegment surfaces as [*x*nasal]. In Candidate (g), the first and last vowel subsegments surface as [–nasal], and the second vowel subsegment surfaces as [*x*nasal]. And finally, in Candidate (h), the first vowel subsegment surfaces as [*x*nasal], and the last two vowel subsegments surface as [–nasal].

Candidates (a) and (g) are ruled out because they both incur violations of CORR-q:Q:q and GRAD-CORR-q:Q:q, since N^3 is [+nasal] and V^1 is [–nasal], as well as a violation of IDENT-IO-q. Candidates (b) and (c) are ruled out because they both incur a violation of GRAD-CORR-(qq), as one of the pairs of corresponding vowel subsegments differ by an amount exceeding *x* for the feature [nasal]. Candidate (b) also incurs one violation of IDENT-IO-q, while Candidate (c) incurs two violations of this constraint. Candidates (d) and (f) are ruled out because they both incur three violations of IDENT-IO-q; as well as one violation of both CORR-q:Q:q and GRAD-CORR-q:Q:q, since V^3 is [+nasal] and V^1 is [–nasal]. Candidate (h) is ruled out because it incurs a violation of IDENT-IO-q; a violation of CORR-q:Q:q, since N^3 is [+nasal] and V^1 is [*x*nasal]; as well as a violation of CORR-(qq), as V^1 is [*x*nasal] and V^2 is [–nasal]. The optimal candidate, Candidate (e), only incurs two violations of CORR-(qq), due to the fact that none of the pairs of corresponding vowel subsegments have identical values of for the feature [+/–nasal], as well as two violations of IDENT-IO-q.

Table 9: Tableau for /NVC/ input sequence

/NVC/ (N^1 N^2 N^3)(V^1 V^2 V^3)(C^1 C^2 C^3)	CORR-q:Q:q	GRAD-CORR-(qq)	IDENT-IO-q	CORR-(qq)	GRAD-CORR-q:Q:q	$\mathscr{H}$armony
	8	5	3	1	1	
a. [NVC] (N N N$_i$)(V$_{ik}$ V$_{kl}$ V$_{jl}$)(C$_j$ C C)	1				1	9
b. [N$^{\tilde{V}}$VC] (N N N$_i$)($\tilde{V}_{ik}$ V$_{kl}$ V$_{jl}$)(C$_j$ C C)		1	1	1		9
c. [N$\tilde{V}^{V}$C] (N N N$_i$)($\tilde{V}_{ik}$ $\tilde{V}_{kl}$ V$_{jl}$)(C$_j$ C C)		1	2	1		12
d. [N$\tilde{V}$C] (N N N$_i$)($\tilde{V}_{ik}$ $\tilde{V}_{kl}$ $\tilde{V}_{jl}$)(C$_j$ C C)	1		3		1	18
☞ e. [N$\overset{\times}{V}$C] (N N N$_i$)($\tilde{V}_{ik}$ $\overset{\times}{V}_{kl}$ V$_{jl}$)(C$_j$ C C)			2	2		8
f. [N$^{\tilde{V}}\overset{\times}{V}^{\tilde{V}}$C] (N N N$_i$)($\tilde{V}_{ik}$ $\overset{\times}{V}_{kl}$ $\tilde{V}_{jl}$)(C$_j$ C C)	1		3	2	1	20
g. [N$^{V}\overset{\times}{V}^{V}$C] (N N N$_i$)(V$_{ik}$ $\overset{\times}{V}_{kl}$ V$_{jl}$)(C$_j$ C C)	1		1	2	1	14
h. [N$^{\overset{\times}{V}}$VC] (N N N$_i$)($\overset{\times}{V}_{ik}$ V$_{kl}$ V$_{jl}$)(C$_j$ C C)	1		1	1		12

Table 10 presents the Tableau for an input /CVC/ sequence. In all of the candidates for this Tableau, C^3 is in correspondence with V^1, V^1 is in correspondence with V^2, V^2 is in correspondence with V^3, and V^3 is in correspondence with C^1. In Candidate (a), all of the vowel subsegments surface as [–nasal]. In Candidate (b), the first vowel subsegment surfaces as [+nasal], and the last two vowel subsegments surface as [–nasal]. In Candidate (c), the first two vowel subsegments surfaces as [+nasal], and the last vowel subsegment surfaces as [–nasal]. In

Candidate (d), all of the vowel subsegments surface as [+nasal]. In Candidate (e), the first vowel subsegment surfaces as [+nasal], the second vowel subsegment surfaces as [*x*nasal], and the last vowel subsegment surfaces as [–nasal]. In Candidate (f), the first and last vowel subsegments surface as [–nasal], and the second vowel subsegment surfaces as [*x*nasal]. And finally, in Candidate (g), And finally, the first vowel subsegment surfaces as [*x*nasal], and the last two vowel subsegments surface as [–nasal].

Candidates (b) and (c) are ruled out because they both incur violations of CORR-q:Q:q and GRAD-CORR-q:Q:q, since C^3 is [–nasal] and V^1 is [+nasal]; as well as violations of both GRAD-CORR-(qq) and CORR-(qq), since as one of the pairs of corresponding vowel subsegments differ by an amount exceeding x for the feature [nasal]. Candidate (b) also incurs one violation of IDENT-IO-q, while Candidate (c) incurs two violations of this constraint. Candidate (d) is ruled out because it incurs two violations of CORR-q:Q:q and two violations of GRAD-CORR-q:Q:q, since C^3 is [–nasal] and V^1 is [+nasal], and V^3 is [+nasal] and C^1 is [–nasal]; as well as three violations of IDENT-IO-q. Candidate (e) is ruled out because it incurs two violations of IDENT-IO-q; violations of both CORR-q:Q:q and GRAD-CORR-q:Q:q, since C^3 is [–nasal] and V^1 is [+nasal]; as well as a violation of CORR-(qq), since both pairs of corresponding vowel subsegments do not have identical values of the feature [+/–nasal]. Candidate (f) is ruled out because it incurs a violation of IDENT-IO-q, as well as two violations of CORR-(qq), as V^1 is [–nasal], V^2 is [*x*nasal], and V^3 is [–nasal]. Candidate (g) is ruled out because it incurs a violation of IDENT-IO-q; a violation of CORR-q:Q:q, since C^3 is [–nasal] and V^1 is [*x*nasal]; as well as a violation of CORR-(qq), as V^1 is [*x*nasal] and V^2 is [–nasal]. The optimal candidate, Candidate (a), does not incur any constraint violation, as there are no pairs of corresponding subsegments that differ in their value for the feature [+/–nasal] in the output, and all of the vowel subsegments surface with the same value for the feature [nasal] in the output as is specified in their input structure.

Table 10: Tableau for /CVC/ input sequence

/CVC/ (C^1 C^2 C^3)(V^1 V^2 V^3)(C^1 C^2 C^3)	CORR-q:Q:q	GRAD-CORR-(qq)	IDENT-IO-q	CORR-(qq)	GRAD-CORR-q:Q:q	ℋarmony
	8	5	3	1	1	
☞ a. [CVC] (C C C_i)(V_{ik} V_{kl} V_{jl})(C_j C C)						0
b. [C$^{\tilde{V}}$VC] (C C C_i)($\tilde{V}_{ik}$ V_{kl} V_{jl})(C_j C C)	1	1	1	1	1	18
c. [C$\tilde{V}^{V}$C] (C C C_i)($\tilde{V}_{ik}$ $\tilde{V}_{kl}$ V_{jl})(C_j C C)	1	1	2	1	1	21
d. [C$\tilde{V}$C] (C C C_i)($\tilde{V}_{ik}$ $\tilde{V}_{kl}$ $\tilde{V}_{jl}$)(C_j C C)	2		3		2	27
e. [C$\overset{\times}{V}$C] (C C C_i)($\tilde{V}_{ik}$ $\overset{\times}{V}_{kl}$ V_{jl})(C_j C C)	1		2	2	1	17
f. [C$^{V}\overset{\times}{V}^{V}$C] (C C C_i)(V_{ik} $\overset{\times}{V}_{kl}$ V_{jl})(C_j C C)			1	2		5
g. [C$^{\overset{\times}{V}}$VC] (C C C_i)($\overset{\times}{V}_{ik}$ V_{kl} V_{jl})(C_j C C)	1		1	1		12

Table 12 presents the Tableau for an input /NVN/ sequence. In all of the candidates for this Tableau, N_3 is in correspondence with V^1, V^1 is in correspondence with V^2, V^2 is in correspondence with V^3, and V^3 is in correspondence with N^1. In Candidate (a), all of the vowel subsegments surface as [–nasal]. In Candidate (b), the first vowel subsegment surfaces as [+nasal], and the last two vowel subsegments surface as [–nasal]. In Candidate (c), the first two vowel subsegments surfaces as [+nasal], and the last vowel subsegment surfaces as [–nasal]. In Candidate (d), all of the vowel subsegments surface as [+nasal]. In Candidate (e), the first vowel subsegment surfaces as [+nasal], the second vowel subsegment surfaces as [*x*nasal], and the last vowel subsegment surfaces as [–nasal]. In Candidate (f), the first and last vowel subsegments surface as [+nasal], and the second vowel subsegment surfaces as [*x*nasal]. In Candidate (g), the first vowel subsegment surfaces as [*x*nasal], and the last two vowel subsegments surface as [+nasal]. In Candidate (h), the first two vowel subsegments surface as [*x*nasal], and the last vowel subsegment surfaces as [+nasal]. And finally, in Candidate (i), all three vowel subsegments surface as [*x*nasal].

Candidate (a) is ruled out because it incurs two violations of CORR-q:Q:q and two violations of GRAD-CORR-q:Q:q, since N_3 is [+nasal] and V_1 is [–nasal], and V_3 is [–nasal] and N_1 is [+nasal]. Candidates (b) and (c) are ruled out because they both incur violations of CORR-q:Q:q and GRAD-CORR-q:Q:q, since V_3 is [–nasal] and N_1 is [+nasal], as well as violations of both GRAD-

Corr-(qq) and Corr-(qq), since as one of the pairs of corresponding vowel subsegments differ by an amount exceeding x for the feature [nasal]. Candidate (b) also incurs one violation of Ident-IO-q, while Candidate (c) incurs two violations of this constraint. Candidate (e) is ruled out because it incurs two violations of Ident-IO-q, violations of both Corr-q:Q:q and Grad-Corr-q:Q:q, since V_3 is [–nasal] and N_1 is [+nasal], as well as two violations of Corr-(qq), since both pairs of corresponding vowel subsegments do not have identical values of the feature [+/–nasal]. Candidate (f) is ruled out because it incurs two violations of Corr-(qq), as well as three violations of Ident-IO-q. Candidates (g) and (h) are ruled out because they both incur three violations of Ident-IO-q, and a violation of Corr-(qq), since one of their pairs of corresponding vowel subsegments do not have identical values of the feature [+/–nasal]. And finally, Candidate (i) is ruled out because it incurs three violations of Ident-IO-q, as well as two violations of Corr-(qq), since both pairs of corresponding vowel subsegments do not have identical values of the feature [+/–nasal]. The optimal candidate, Candidate (d), only incurs three violations of Ident-IO-q, as there are no pairs of corresponding subsegments that differ in their value for the feature [+/−nasal] in the output.

Table 12: Tableau for /NVN/ input sequence

/NVN/ $(N^1\ N^2\ N^3)(V^1\ V^2\ V^3)(N^1\ N^2\ N^3)$	Corr-q:Q:q	Grad-Corr-(qq)	Ident-IO-q	Corr-(qq)	Grad-Corr-q:Q:q	$\mathscr{H}$armony
	8	5	3	1	1	
a. [NVN] $(N\ N\ N_i)(V_{ik}\ V_{kl}\ V_{jl})(N_j\ N\ N)$	2				2	18
b. $[N^{\tilde{V}}VN]$ $(N\ N\ N_i)(\tilde{V}_{ik}\ V_{kl}\ V_{jl})(N_j\ N\ N)$	1	1	1	1	1	18
c. $[N\tilde{V}^{V}N]$ $(N\ N\ N_i)(\tilde{V}_{ik}\ \tilde{V}_{kl}\ V_{jl})(N_j\ N\ N)$	1	1	2	1	1	21
☞ d. $[N\tilde{V}N]$ $(N\ N\ N_i)(\tilde{V}_{ik}\ \tilde{V}_{kl}\ \tilde{V}_{jl})(N_j\ N\ N)$			3			9
e. $[N\overset{\times}{V}N]$ $(N\ N\ N_i)(\tilde{V}_{ik}\ \overset{\times}{V}_{kl}\ V_{jl})(N_j\ N\ N)$	1		2	2	1	17
f. $[N^{\tilde{V}}\overset{\times}{V}^{\tilde{V}}N]$ $(N\ N\ N_i)(\tilde{V}_{ik}\ \overset{\times}{V}_{kl}\ \tilde{V}_{jl})(N_j\ N\ N)$			3	2		11
g. $[N^{\overset{\times}{V}}\tilde{V}N]$ $(N\ N\ N_i)(\overset{\times}{V}_{ik}\ \tilde{V}_{kl}\ \tilde{V}_{jl})(N_j\ N\ N)$	1		3	1		18
h. $[N\overset{\times}{V}^{\tilde{V}}N]$ $(N\ N\ N_i)(\overset{\times}{V}_{ik}\ \overset{\times}{V}_{kl}\ \tilde{V}_{jl})(N_j\ N\ N)$	1		3	1		18
i. $[N\overset{\times}{V}N]$ $(N\ N\ N_i)(\overset{\times}{V}_{ik}\ \overset{\times}{V}_{kl}\ \overset{\times}{V}_{jl})(N_j\ N\ N)$	2		3			25

Table 13 presents the Tableau for an input /C$\tilde{\text{V}}$/ sequence. In all of the candidates for this Tableau, C^3 is in correspondence with $\tilde{\text{V}}^1$, $\tilde{\text{V}}^1$ is in correspondence with $\tilde{\text{V}}^2$, and $\tilde{\text{V}}^2$ is in correspondence with $\tilde{\text{V}}^3$. In Candidate (a), all of the vowel subsegments surface as [+nasal]. In Candidate (b), the first vowel subsegment surfaces as [*x*nasal], and the last two vowel subsegments surface as [+nasal]. In Candidate (c), the first vowel subsegment surfaces as [–nasal], and the last two vowel subsegments surface as [+nasal]. In Candidate (d), all of the vowel subsegments surface as [–nasal]. In Candidate (e), the first vowel subsegment surfaces as [–nasal], the second vowel subsegment surfaces as [*x*nasal], and the last vowel subsegment surfaces as [+nasal]. And finally, in Candidate (f), the first and last vowel subsegments surface as [+nasal], and the second vowel subsegment surfaces as [*x*nasal].

Candidate (a) is ruled out because it incurs a violation of both GRAD-CORR-q:Q:q and CORR-q:Q:q, since C^3 is [–nasal] and $\tilde{\text{V}}^1$ is [+nasal]. Candidate (b) is ruled out because it incurs a violation of IDENT-IO-q; a violation of CORR-q:Q:q, since C^3 is [–nasal] and $\tilde{\text{V}}^1$ is [*x*nasal]; and a violation of CORR-(qq), since V^1 is [*x*nasal], and V^2 is [+nasal]. Candidate (c) is ruled because it incurs a violation of IDENT-IO-q, as well as a violation of both GRAD-CORR-(qq) and CORR-(qq), since one of the pairs of corresponding vowel subsegments differ by an amount exceeding x for the feature [nasal]. Candidate (d) is ruled out because it incurs three violations of IDENT-IO-q. And finally, Candidate (f) is ruled out because it incurs one violation of IDENT-IO-q, as well as two violations of CORR-(qq), since two pairs of corresponding vowel subsegments differ by an amount exceeding x for the feature [nasal]. The optimal candidate, Candidate (e), incurs only two violations of IDENT-IO-q, and two violations of CORR-(qq), $\tilde{\text{V}}^1$ is [–nasal], $\tilde{\text{V}}^2$ is [*x*nasal], and $\tilde{\text{V}}^3$ is [+nasal].

Table 13: Tableau for /CṼ/ input sequence.

/CṼ/ (C^1 C^2 C^3)($\tilde{V}^1$ $\tilde{V}^2$ $\tilde{V}^3$)	CORR-q:Q:q	GRAD-CORR-(qq)	IDENT-IO-q	CORR-(qq)	GRAD-CORR-q:Q:q	ℋarmony
	8	5	3	1	1	
a. [CṼ] (C C C_i)($\tilde{V}_{ik}$ $\tilde{V}_{kl}$ $\tilde{V}_{jl}$)	1				1	9
b. [$C^{\check{V}}\tilde{V}$] (C C C_i)($\check{V}_{ik}$ $\tilde{V}_{kl}$ $\tilde{V}_{jl}$)	1		1	1		12
c. [$C^{V}\tilde{V}$] (C C C_i)(V_{ik} $\tilde{V}_{kl}$ $\tilde{V}_{jl}$)		1	1	1		9
d. [CV] (C C C_i)(V_{ik} V_{kl} V_{jl})			3			9
☞ e. [$C^{V}\check{V}^{\tilde{V}}$] (C C C_i)(V_{ik} $\check{V}_{kl}$ $\tilde{V}_{jl}$)			2	2		8
f. [$C^{\tilde{V}}\check{V}^{\tilde{V}}$] (C C C_i)($\tilde{V}_{ik}$ $\check{V}_{kl}$ $\tilde{V}_{jl}$)	1		1	2	1	14

Table 14 presents the Tableau for an input /NṼ/ sequence. In all of the candidates for this Tableau, N^3 is in correspondence with $\tilde{V}^1$, $\tilde{V}^1$ is in correspondence with $\tilde{V}^2$, and $\tilde{V}^2$ is in correspondence with $\tilde{V}^3$. In Candidate (a), all of the vowel subsegments surface as [+nasal]. In Candidate (b), the first vowel subsegment surfaces as [*x*nasal], and the last two vowel subsegments surface as [+nasal]. In Candidate (c), the first vowel subsegment surfaces as [–nasal], and the last two vowel subsegments surface as [+nasal]. In Candidate (d), all of the vowel subsegments surface as [–nasal]. In Candidate (e), the first vowel subsegment surfaces as [–nasal], the second vowel subsegment surfaces as [*x*nasal], and the last vowel subsegment surfaces as [+nasal]. And finally, in Candidate (f), the first and last vowel subsegments surface as [+nasal], and the second vowel subsegment surfaces as [*x*nasal].

Candidate (b) is ruled out because it incurs a violation of IDENT-IO-q, as well as violations of both GRAD-CORR-q:Q:q and CORR-q:Q:q, since N^3 is [+nasal] and V^1 is [*x*nasal]. Candidate (c) is ruled because it incurs one violation of IDENT-IO-q, as well as violations of both GRAD-CORR-q:Q:q and CORR-q:Q:q, since N_3 is [+nasal] and $\tilde{V}^1$ is [–nasal]. Likewise, Candidate (c) also incurs violations of both GRAD-CORR-(qq) and CORR-(qq), since $\tilde{V}^1$ is [–nasal] and $\tilde{V}^2$ is [+nasal]. Candidate (d) is ruled out because it incurs three violations of IDENT-IO-q, as well as violations of both GRAD-CORR-q:Q:q and CORR-q:Q:q, since N^3 is [+nasal] and $\tilde{V}^1$ is [–nasal]. Candidate (e) is ruled out because it incurs two violations of IDENT-IO-q, as well as violations of both GRAD-CORR-q:Q:q and CORR-q:Q:q, since N^3 is [+nasal] and $\tilde{V}^1$ is [–nasal]. It also incurs two violations of CORR-(qq), since two pairs of corresponding vowel subsegments differ by an amount exceeding *x* for the feature [nasal]. And finally, Candidate (f) is ruled out because it incurs one violation of IDENT-IO-q, as well as two violations of CORR-(qq), since two pairs of corresponding vowel subsegments differ by an amount exceeding *x* for the feature [nasal]. The optimal candidate, Candidate (a), does not incur any constraint violation, as there are no pairs of corresponding subsegments that differ in their value for the feature [+/−nasal] in the output.

Table 14: Tableau for /NṼ/ input sequence.

/NṼ/ $(\mathrm{N}^1\ \mathrm{N}^2\ \mathrm{N}^3)(\tilde{\mathrm{V}}^1\ \tilde{\mathrm{V}}^2\ \tilde{\mathrm{V}}^3)$	CORR-q:Q:q	GRAD-CORR-(qq)	IDENT-IO-q	CORR-(qq)	GRAD-CORR-q:Q:q	ℋarmony
	8	5	3	1	1	
☞ a. [NṼ] $(\mathrm{N\ N\ N_i})(\tilde{\mathrm{V}}_{ik}\ \tilde{\mathrm{V}}_{kl}\ \tilde{\mathrm{V}}_{jl})$						0
b. $[\mathrm{N}^{\overset{\times}{\mathrm{V}}}\tilde{\mathrm{V}}]$ $(\mathrm{N\ N\ N_i})(\overset{\times}{\mathrm{V}}_{ik}\ \tilde{\mathrm{V}}_{kl}\ \tilde{\mathrm{V}}_{jl})$	1		1	1		12
c. $[\mathrm{N}^{\mathrm{V}}\tilde{\mathrm{V}}]$ $(\mathrm{N\ N\ N_i})(\mathrm{V}_{ik}\ \tilde{\mathrm{V}}_{kl}\ \tilde{\mathrm{V}}_{jl})$	1	1	1	1	1	18
d. [NV] $(\mathrm{N\ N\ N_i})(\mathrm{V}_{ik}\ \mathrm{V}_{kl}\ \mathrm{V}_{jl})$	1		3		1	18
e. $[\mathrm{N}^{\mathrm{V}}\overset{\times}{\mathrm{V}}^{\tilde{\mathrm{V}}}]$ $(\mathrm{N\ N\ N_i})(\mathrm{V}_{ik}\ \overset{\times}{\mathrm{V}}_{kl}\ \tilde{\mathrm{V}}_{jl})$	1		2	2	1	17
f. $[^{\tilde{\mathrm{V}}}\overset{\times}{\mathrm{V}}^{\tilde{\mathrm{V}}}]$ $(\mathrm{N\ N\ N_i})(\tilde{\mathrm{V}}_{ik}\ \overset{\times}{\mathrm{V}}_{kl}\ \tilde{\mathrm{V}}_{jl})$			1	2		5

The HG analysis presented in here demonstrates how a grammar that makes use of both q subsegments and *x* subfeatures is able to account for the patterns of local nasal assimilation observed in Kawaiwete. This was implemented by making use of four Correspondence constraints that crucially reference q subsegments and *x* subfeatures: CORR-q:Q:q, CORR-(qq), GRAD-CORR-q:Q:q, and GRAD-CORR-(qq); as well as IDENT-IO-q[F].

4.6 Alternative models of subfeatural representations

In this section, I show that previous models of phonological representations are unable to account for the distinction between fully oral, partially nasalized, and fully nasal vowels in Kawaiwete. Section 4.6.1 first considers classic models of binary feature representation; Section 4.6.2 considers feature underspecification; and finally, Section 4.6.3 discusses how a model of dynamic interpolation (Keating 1990) can be embedded within a subsegmental and subfeatural model of representations.

4.6.1 Binary features are not enough

Classic models of featural representation date back to the time of Structural Phonology (Jakobson et al. 1952, Jakobson & Halle 1956) and of the Sound Pattern of English (SPE, Chomsky & Halle 1968). Many aspects of these early models of representation are still widely used today, including the notion of binary features. According to this concept, each segment is made up of a matrix of binary distinctive features defining its articulatory-acoustic content. In this framework, nasality is generally analyzed as a binary feature with possible positive [+nasal] and negative [–nasal] values.

While in its most classic instantiation, feature matrices apply wholesale to segments, I build off of the analysis presented in Chapter 3 in assuming that segments may be divided into tripartite subsegmental units: (q^1 q^2 q^3). Within the proposed model of subsegmental representations, each subsegment is made up of its own feature matrix. Only subsegments, but not featural values within a given subsegment's feature matrix, may be linearly and temporally ordered with respect to one another. It is also not possible for a given subsegment to simultaneously receive the features [+nasal] and [–nasal], meaning that each subsegment receives at most one featural value, [+/–F] in the case of binary features.

Even with all the richness of Q Theory, binary-valued features still are not sufficient for the task of representing vowels with oral-nasal and oral-nasal interpolation. Q-theoretic representations are particularly helpful in capturing *where* in the course of a segment's production the shift from oral to nasal, or from nasal to oral, takes places, as was observed for Panãra in Chapter 3. However, the pattern in Kawaiwete is one of dynamic interpolation over the time course of an entire vowel, which requires a model of phonological representations able to capture the distinction between fully oral, partially nasal, and fully nasal units. Crucially, no finer-grained division on the horizontal, temporal dimension of representation will serve to model the data from Kawaiwete vowels.

Assuming a model of binary distinctive features augmented with a model of subsegmental representations, a total of eight possible vowel types are possible given the features [+nasal] and [–nasal] (33), only a small subset of which are actually attested. Note that all of these have already been discussed in Section 4.4.3, and I refer the reader there for additional discussion.

(33)	a. ($\tilde{V}^1$ $\tilde{V}^2$ $\tilde{V}^3$)	fully nasal	e. (V^1 V^2 $\tilde{V}^3$)	post-nasalized
	b. (V^1 V^2 V^3)	fully oral	f. (V^1 $\tilde{V}^2$ $\tilde{V}^3$)	pre-oralized
	c. ($\tilde{V}^1$ V^2 $\tilde{V}^3$)	circum-nasalized	g. ($\tilde{V}^1$ $\tilde{V}^2$ V^3)	post-oralized
	d. (V^1 $\tilde{V}^2$ V^3)	circum-oralized	h. ($\tilde{V}^1$ V^2 V^3)	pre-nasalized

The segment types in (33a) and (33b), are the only two vowel types attested in Kawaiwete among the full set of vowels in (33a-h), where the (33a) represents fully nasal vowels appearing immediately after a nasal consonant and oral vowels between two nasal consonants, and (33b) represents fully oral vowels appearing between two oral consonants. Fully nasal vowels (33a) are realized as a high flat plateau of nasal airflow throughout the course of their duration, while fully oral vowels (33b) are realized with a low flat plateau.

This leaves, then, three types of Kawaiwete vowels to be accounted for: oral vowels appearing between a nasal and an oral consonant, oral vowels appearing between an oral and a nasal consonant, and nasal vowels appearing after a nasal consonant. As a reminder, the results of the nasal airflow experiment discussed in Section 4.3 revealed that all of these partially nasal vowels are realized with a cline in nasal airflow extending for the entire vowel's duration in Kawaiwete. None of the vowel types in (33c-h) actually provides a satisfactory solution to the representation of Kawaiwete partially nasalized vowels.

The circum-nasalized vowel in (33c) would be realized with a decrease, followed with an increase in nasal airflow, and the circum-oralized vowel in (33d) would be realized with an increase, followed by a decrease in nasal airflow. The post-nasalized vowel in (33e) predicts that the segment would be realized with a low flat plateau of nasal airflow during the first half of its duration, and with an increase in nasal airflow over the second half of its duration. The pre-oralized vowel in (33f) predicts that the segment would be realized with an increase in nasal airflow over the first half of its duration, and with a high flat plateau of nasal airflow during the second half of its duration. The post-oralized vowel in (33g) predicts that the segment would be realized with a high flat plateau of nasal airflow during the first half of its duration, and with a decrease in nasal airflow over the second half of its duration. And finally, the pre-nasalized vowel in (33h) predicts that the segment would be realized with a decrease in nasal airflow over the first half of its duration, and with a low flat plateau of nasal airflow during the second half of its duration. Indeed, none of these segment types accounts for the pattern of dynamic interpolation observed in Kawaiwete vowels.

4.6.2 Underspecification is not enough

Underspecification theory (Archangeli 1988a, 1988b; Pulleyblank 1988) augmented the representational apparatus originally proposed in Structuralist Phonology and SPE by allowing for segments to have unspecified values for a given phonological feature. This, then, allows for input (sub)segments to have one of three possible values: [+F], [–F], and [∅F]. Though this additional machinery seems promising, Underspecification Theory is likewise unable to capture the representation of Kawaiwete partially nasal vowels. This is because, according to classic Underspecification, (sub)segments that are unspecified for a given feature in their input *must* receive a feature value in the output. This may be achieved by a feature assimilation derivational mechanism, where the value is obtained from an adjacent segment, or via a redundancy rule. Redundancy rules are language and feature specific. This means that each language's grammar has a redundancy rule for each phonological feature stating that unspecified values get mapped to a default value of [+F] or [–F] upon being mapped to output structures.

In the case of Kawaiwete, we could posit the segment types in (34a) and (34b) as the input structures for partially nasal vowels. Specifically, the segment type in (34a) could allow for the representations of oral vowels between a nasal and an oral consonant, and the segment type in (34b) could allow for the representation of oral vowels between an oral and a nasal consonant, or of a nasal vowel after an oral consonant.

(34) a. ([+nasal]^1 [∅nasal]^2 [–nasal]^3) b. ([–nasal]^1 [∅nasal]^2 [+nasal]^3)

However, given that underspecified feature values are not possible in the output within classic Underspecification Theory (Archangeli 1988a, 1988b; Pulleyblank 1988), and that any input segment with the value [∅nasal] would necessarily need to surface as either [+nasal] or [−nasal], this would give rise to the exact same segment structures as in (33e-h). This, then, leaves us with the very same problems discussed in Section 4.6.1 for binary distinctive features. As was noted, none of the segment types in (33e-h) fail to capture the dynamic realization of partially nasal vowels in Kawaiwete, which surface with a cline-like increase or decrease in nasal airflow over the course of their duration.

4.6.2.1 Unary features are not enough

Following the original development of Underspecification Theory (Archangeli 1988a, 1988b; Pulleyblank 1988), it has been broadly acknowledged that, while some phonological features are effectively modeled as binary, with possible positive and negative values ([+F] vs. [−F]); others are better represented as unary, with possible specified and unspecified values ([F] vs. [∅F]). In particular, Steriade (1994, 1995), argued in favour of unary values for the phonological feature [nasal], a proposal which has been widely adopted.

In contrast to what Steriade calls *temporary underspecification*, in which a missing underlying value is filled in with an invariant default value on the surface; unary features provide *permanent underspecification* of the missing value. This means that the phonology is agnostic as to production values, and the phonetic component fills the value in by interpolating across specified values on either side of the segment in question. This approach has some promise for a language like Kawaiwete, which has a need for value interpolation; however, it lacks the ability to specify oral values, crucially needed for the representation of oral consonants and vowels, and is thus not descriptively adequate.

4.6.3 Subfeatures as an implementation of Window Theory

Window Theory (Keating 1990) is a model of phonetic implementation of abstract phonological representations, which interprets phonological features of segments in both time and space. Window Theory, as an instantiation of a target-interpolation model (Pierrehumbert 1980; Keating 1990; Pierrehumbert & Beckman 1988; Cohn 1990; McPherson 2011), assumes an SPE-style phonological module, from which phonological representations are inherited. The output of the model is a fully specified phonetic representation which specifies movements of articulators in space as a function of time.

For a given physical articulatory dimension, such as velum position, each feature value of a segment has associated with it a range of possible spatial values, i.e. a minimum and maximum value that the observed values must fall within. This range of values is a *window*. In Keating's model, the window for a segment and a particular feature value is determined by collecting quantitative values across different contexts. Since an overall range of values is sought, maximum and minimum values are the most important. Cases of apparent underspecification can be seen as cases of very wide windows.

Interpolation between targets results in time-varying context effects. Windows contribute to determining the path through which values are interpolated. Figure 1, taken from

Keating (1990:459), illustrates sequences of windows of various widths. The initial and final segments in Figures (14a) and (14b) are identical, with the middle segment exhibiting different sized windows in the two Figures. Figure (14a) illustrates the effect of a wide window, which allows for feature interpolation between segments. Figure (14b) illustrates the effect of a narrow window, which imposes constraints on interpolation through its own contribution to the curve.

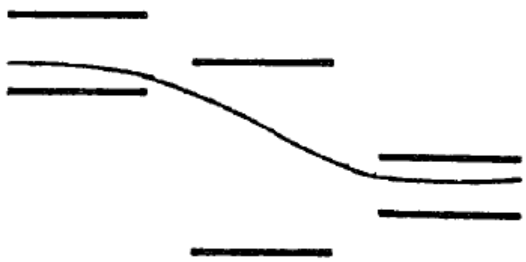

Figure 14a: Illustration of the effect of a wide window, allowing for feature interpolation between segments, from Keating (1990:459)

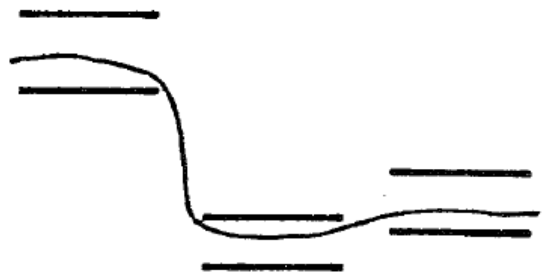

Figure 14b: Illustration of the effect of a narrow window, imposing constraints on interpolation through its own contribution to the curve, from Keating (1990:459)

In its original form, the predictions of Window Theory are difficult to evaluate, as the framework relies on determining from the bottom-up the length and width of each window, by carrying out relevant measures from the dataset. In this sense, Window Theory is able to account for all of the data that it takes as input, but the theory's predictions become circular. In addition, an actual interpolation function has yet to be formally proposed. Window Theory, then, is a conceptual model which intuitively accounts for a class of phenomena which are realized as dynamic interpolation, but it does not include a concrete mathematical or computational tool to derive the particular output values of interpolation.

Here, I show that Window Theory can be embedded within a subsegmental and subfeatural model of phonological representations, allowing for some components of its architecture to be fleshed out. Specifically, Window Theory can be augmented with a subsegmental model, where windows span the duration of a subsegment, rather than a segment; and with a subfeatural model, which provides window width specifications. The proposed model provides a more detailed representational architecture, which better informs the path of the interpolation curve between different targets. Ranges of values can be determined for each subfeatural value, [+nasal], [𝑥nasal], and [−nasal], and these values then provide static window width for each subsegmental window. A preliminary method for measuring window width for each subfeatural category has been laid out in Section 4.2.1.1, where the calculations showed that the subfeatural value [−nasal] ranges between 0 and 0.28; the subfeatural value [𝑥nasal] ranges between 0.281 and 0.81; and the subfeatural value [+nasal] ranges between 0.281 and 1.

Figure 15 illustrates how each subsegment provides its own window, and how featural values delimit the upper and lower bounds of those windows, as indicated by the horizontal solid blue lines. The grammatical component, then, operates from those values, and derives the interpolation function, represented by the diagonal dotted blue line. The function does not necessarily need to be linear, but I represent it as such here for ease of exposition.

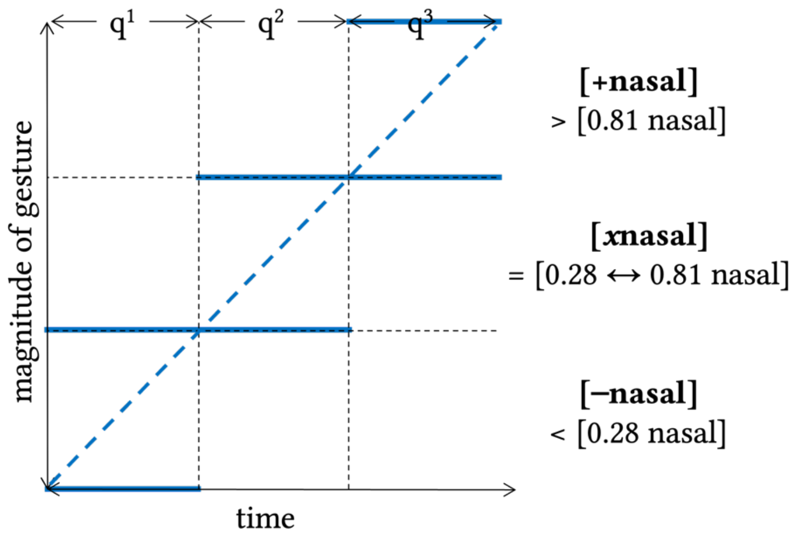

Figure 15: Temporally and spatially-defined subsegments

GRADIENT-CORRESPONDENCE constraints, a subfamily of Agreement-by-Correspondence constraints introduced in Section 4.5.1, provide the derivational mechanism by which interpolation is implemented within a language's grammar. Constraints of this family require that pairs of corresponding q subsegments not differ by an amount exceeding *x* for a given feature, in this case, [nasal]. The representational model presented here, then, builds on the model of target-interpolation presented by Keating's Window Theory.

4.7 Conclusion

This chapter provided evidence for a phonological distinction between fully oral, partially nasal, and fully nasal vowels in Kawaiwete, a Tupí-Guaraní language of Central Brazil. These distinctions in categories of vowels arise from a phonemic contrast in vowel nasality, as well as patterns of N ⟶ V local nasal assimilation. This data suggests that the contrast between oral and nasal vowels in Kawaiwete dependent on the vowel's immediate segmental context, and that the information relevant to encoding it is dynamic over the time course of the vowel.

These findings come from a nasal airflow experiment, which showed that oral vowels between two oral consonants are realized as fully oral, while nasal vowels after nasal consonants are realized as fully nasal. Oral vowels between an oral and a nasal consonant, as well as nasal vowels after oral consonants, are both realized as partially nasal, with a cline in nasal airflow extending for the entire vowel's duration.

Kawaiwete differs from other languages for which vowel nasality has been studied instrumentally, as it provides evidence of both a contrast in vowel nasality, like French, as well as N ⟶ V local nasal assimilation, like English. The data from Kawaiwete provides crucial information regarding the realization of nasality in a language with both of these typological characteristics.

The data from Kawaiwete supports the need for a tripartite division of the phonological feature, as proposed by Lionnet (2017). Within this representational framework, features may be divided into three possible subfeatural values: [+nasal], [*x*nasal], and [–nasal]. The analysis presented here build on the representational framework laid out in Chapter 2, according to which segments may also be divided into three subsegments. Taken together, this representational schema is able to derive patterns of nasal-oral interpolation observed in Kawaiwete vowels.

Chapter 5

Conclusion

5.1 Summary

5.1.1 Empirical findings

In the preceding chapters, I have provided a detailed overview of various phonological processes involving local nasal and oral assimilation. I first laid out a cross-linguistic typology of all attested and unattested such processes, and I presented detailed case studies providing instrumental data on three of the major types of assimilation processes uncovered by this survey: (i) local oral assimilation, triggered by a vowel and undergone by a consonant; (ii) local nasal assimilation, triggered by a vowel and undergone by a consonant; and (iii) local nasal assimilation, triggered by a vowel and undergone by a consonant. The first two process types were illustrated with data from Panãra in Chapter 3, while the latter was illustrated with data from Kawaiwete in Chapter 4. The investigation of nasality from both a broad typological perspective, as well as a narrow, language-specific perspective made it possible to provide a unified analysis of these phenomena.

In Chapter 2, I showed that patterns of local nasal assimilation are much more widely attested than patterns of local oral assimilation. Whereas local nasal assimilation is attested as triggered by both vowels and consonants, patterns of local oral assimilation seem to be mostly restricted to having oral vowel triggers. The typology also reveals that edge of subsegments, or adjacent subsegments across a segment boundary, most commonly share the same value for the feature [nasal], which often gives rise to complex nasal segments, i.e. vowels or consonants containing both a nasal and an oral portion.

Patterns of local and nasal assimilation are largely predictable from a language's system of phonemic contrasts, where languages tend to make use of coarticulatory processes which avoid contrast neutralization. In addition, languages tend to follow a markedness hierarchy whereby grammars avoid certain types of segments which are less perceptually salient in favour of others. For instance, the typology reveals that complex segments of the type [CN] are significantly underattested, while complex segments of the type [NC] are very frequent. This suggests that languages tend to avoid assimilation processes that give rise to [CN] segments and favour those that give rise to [NC] segments. Building on Stanton's (2017, 2018) work, I also showed that, in languages for which vowel nasality is contrastive, grammars seem to favour assimilation processes that avoid decreasing the perceptual distance between oral and nasal vowels.

Chapter 3 presented phonetic data from two experiments (Lin & Lapierre 2019; Lapierre & Lin 2019), suggesting a robust distinction between two types of [NT]s arising from distinct phonological processes in Panãra. The results of the production experiment showed that native speakers of Panãra systematically produce [NT]s arising from post-oralization and pre-nasalization distinctly, where the former is realized with a longer proportion of nasal airflow than the latter. The results of the perception experiment show that native Panãra listeners can reliably identify a given [NT] token as arising from either post-oralization or pre-nasalization, suggesting that they are also able perceptually differentiate between the two structures. Taken together, the results of the two experiments support the need for distinct phonological representations for post-oralized and pre-nasalized [NT]s in Panãra.

Chapter 4 presented oral and nasal airflow data from Kawaiwete, suggesting a distinction between fully oral, partially nasal, and fully nasal vowels in the grammar of the language. The results of the phonetic experiment showed that these three types of vowels are produced distinctly from one another by native speakers of Kawaiwete. Fully oral vowels between two oral consonants are realized with a low flat plateau of nasal airflow; oral vowels between an oral and a nasal consonant are realized with a positive slope in nasal airflow over the course of the vowel's duration; oral vowels between a nasal and an oral consonant are realized with a negative slope in nasal airflow over the course of the vowel's duration; nasal vowels after an oral consonant are realized with a positive slope in nasal airflow; and nasal vowels after a nasal consonant are realized with a high flat plateau in nasal airflow. The results of the experiment, then, suggest that fully oral vowels are realized without nasal airflow, fully nasal airflow are realized with sustained nasal airflow throughout their duration, and partially nasal vowels are realized with a dynamic slope of increasing or decreasing nasal airflow. On the basis of this production data, I argue in favour of distinct phonological representations for these three types of vowels in Kawaiwete.

5.1.2 The representational model

One of the main contributions of this study has been to deepen our understanding of phonological representations by combining two recent proposals for the representation of subsegments and subfeatures. Extending on proposals for Q Theory (Inkelas & Shih 2016; 2017; Shih & Inkelas 2014; 2019) and Subfeatural representations (Lionnet 2017), this study synthesizes a unified framework in which segments are divided into three quantized, temporally-ordered subsegments (q^1 q^2 q^3), and features are likewise divided into three quantized subfeatures [+/x/–nasal]. This representational architecture is illustrated schematically in Figure 1 below.

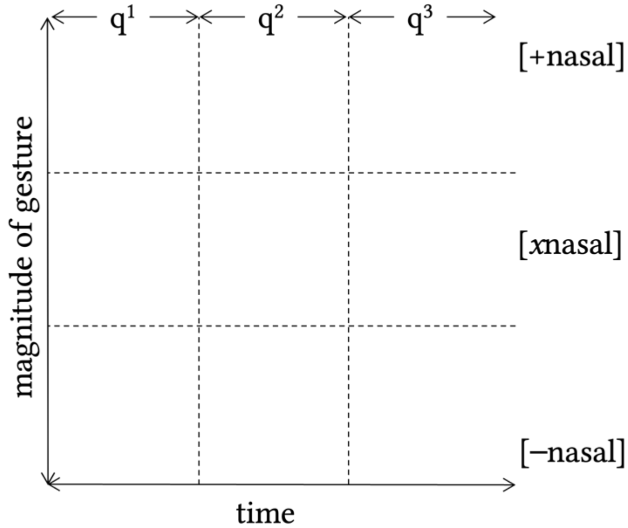

Figure 1: Temporally-defined subsegments and spatially-defined subfeatures

I argued that a model of phonological representations which makes use of both subsegments and subfeatures is able to capture the full range of phonological processes involving local nasalization or oralization laid out in Chapter 2. In addition, I showed that this representational architecture is able to account for the two case studies from Panãra and Kawaiwete. A tripartite subsegmental model of phonological representations is able to capture the distinction between post-oralized nasals and pre-nasalized stops in Panãra, where post-oralization is modeled with two [+nasal] subsegments, followed by a single [–nasal] subsegment; and pre-nasalized stops is modeled with two [–nasal] subsegments, followed by a single [+nasal] subsegment, as in (1a) and (1b), respectively.

(1) a. **Post-oralized nasals**

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

b. **Pre-nasalized stops**

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

A combined subsegmental and subfeatural model also provides the level of granularity necessary to distinguish between fully oral vowels, partially nasal vowels, and fully nasal vowels in Kawaiwete. This representational machinery derives the patterns of nasal-oral interpolation observed in Kawaiwete, where oral vowels between a nasal and an oral consonant are realized with a positive slope interpolation and represented with one [+nasal] subsegment, one [*x*nasal] subsegment, and one [–nasal] subsegment (2a); and oral vowels between an oral and a nasal consonant are realized a negative slope interpolation and represented with one [–nasal] subsegment, one [*x*nasal] subsegment, and one [+nasal] subsegment (2b).

(2) a. **Positive slope interpolation** b. **Negative slope interpolation**

$$\begin{array}{ccc} & [\overset{\times}{\mathrm{V}}] & \\ & \downarrow & \\ (\mathrm{V}^1 & \overset{\times}{\tilde{\mathrm{V}}}{}^2 & \tilde{\mathrm{V}}^3) \\ \begin{bmatrix} -\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} & \begin{bmatrix} x\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} & \begin{bmatrix} +\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} \end{array} \qquad \begin{array}{ccc} & [\overset{\times}{\mathrm{V}}] & \\ & \downarrow & \\ (\tilde{\mathrm{V}}^1 & \overset{\times}{\tilde{\mathrm{V}}}{}^2 & \mathrm{V}^3) \\ \begin{bmatrix} +\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} & \begin{bmatrix} x\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} & \begin{bmatrix} -\text{nasal} \\ +\text{syll.} \\ \dots \end{bmatrix} \end{array}$$

5.1.3 Constraint families

To account for the full range of nasal-oral alternations within the grammars of both Panãra and Kawaiwete, constraints that reference both subsegments and subfeatures are crucially needed. I showed that the combined representational model, embedded within the framework of Agreement-by-Correspondence, achieves this goal. Three major constraint families were introduced for this purpose.

The first is a INPUT-OUTPUT faithfulness constraint, which requires subsegments in the output to have the same value for a given feature [F] as their corresponding input subsegment, as in (3).

(3) **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].

The second is an OUTPUT-OUTPUT correspondence and agreement constraint family, which requires adjacent subsegments to have matching values for a given feature [F]. This constraint family is divided into two subfamilies: the first requires adjacent subsegments separated by a segment boundary to correspond and agree, as in (4); the second requires adjacent subsegments contained within the same segment to correspond and agree, as in (5).

(4) **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 [+/–F].

(5) **CORR-(qq)**: 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; *and*
iv. q_i and q_j do not agree in the feature [+/–nasal].

Finally, the third constraint family introduces the concept of *gradient agreement*, requiring that adjacent subsegments not differ by a value exceeding a certain threshold for a given feature [F]. As with the OUTPUT-OUTPUT correspondence and agreement constraint family above, gradient correspondence constraints can be divided into two subfamilies as well. The first requires correspondence and agreement between adjacent subsegments across a segments boundary (6), and the second requires correspondence and agreement between subsegments within the same segment (7).

(6) **GRAD-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 differ by a value exceeding *x* for the feature [nasal].

(7) **GRAD-CORR-(qq)**: 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; *and*
iv. q_i and q_j differ by a value exceeding *x* for the feature [nasal].

5.2 Future directions

This study has contributed to improving our understanding of the typology of nasality, as well as of theories of phonological representations. While this work has uncovered lots of empirical discoveries and provided new theoretical proposals, it also has generated a series of new questions. Here, I summarize some of the avenues of futures research that seem the most promising.

5.2.1 Distinctiveness vs. contrast

Throughout the discussion of the case studies in Chapters 3 and 4, I have discussed the notion of phonological distinctiveness, which is crucially different from the notion of phonological contrast. Distinctive structures are derived (as opposed to contrastive structures, which are present in the input), and they refer to elements that may be non-contrastive; that is, distributionally predictable but perceptually salient to speakers. There is general agreement in recent work that speakers encode very detailed phonetic knowledge (e.g. Kingston & Diehl 1994, Johnson 1997, Pierrehumbert 2001), and that distinctiveness should be accounted for by the suitable level of phonological representation in phonological models. However, the notion of distinctiveness remains relatively nebulous, and has traditionally been relegated to issues of the phonetics-phonology interface. The full range of typological and cognitive phenomena that can be characterized as distinctive in a linguistically meaningful way has yet to be determined.

5.2.2 The typology of long-distance nasal and oral assimilation

This study presented an overview of attested and unattested patterns of local nasal and oral assimilation. A natural extension of this work would be to survey attested and unattested patterns of long-distance nasal and oral assimilation, a class of phenomena that are also sometimes referred to as *nasal harmony*, and *oral harmony*, respectively. According to my preliminary typological work in this area, it appears that long-distance nasal assimilation is attested with both nasal vowel and nasal consonant triggers, and that these processes can target both vowels and consonants. To the best of my knowledge, no clear case of long-distance oral assimilation has been reported. Nasal assimilation, both local and long-distance, is overrepresented compared to patterns of oral assimilation (e.g., Herbert 1986, Steriade 1995, Hyman in press). I leave to future work laying out the details of the typology of long-distance nasal and oral assimilation, its interactions and interdependence on patterns of local nasal and oral assimilation. I also leave open the question of whether patterns of long-distance nasal and oral assimilation can be explained via the same mechanisms of contrast preservation and enhancement, and the same functional perceptual mechanism of segmental markedness.

Some of the data presented in Chapter 4 revealed a pattern of oral-nasal interpolation with a gradient cline beginning at the left edge of the syllable immediately preceding the triggering vowel, and with the peak of nasal airflow being attained at the right edge boundary of the triggering vowel. The process of long-distance nasal assimilation in the Kapiwat dialect of Kawaiwete, then, can be described as spanning two syllables. A clear avenue of investigation is to see whether long-distance interpolation can span a domain larger than two syllables, potentially including a multisyllabic phonological word. Though unattested as of yet, I suspect that the system of nasal harmony attested in Paraguayan Guaraní, another language of the Tupí-Guaraní family, may very well be of this type.

5.2.3 Hypothesized segment types

In Section 4.4.3, I laid out all of the logically possible segment types predicted by the proposed representational machinery. If segments can be decomposed into three subsegments, and features can be divided into three subfeatural values, this allows for 27 distinct segment types. As was noted, some of these segments types are attested, others are unattested. Of those that are as of yet unattested, I have formulated some hypotheses about which types of nasality systems may present evidence for such segment types. Here, I summarize some of these predictions.

If Paraguayan Guaraní, or another language of the Tupí-Guaraní family does indeed exhibit long-distance nasal harmony, realized as a slow and gradual interpolation from a raised velum to a lowered velum over the course of a multisyllabic phonological word, I expect that this language would exhibit vowels of the type in (8) with three [*x*nasal] subsegments, representing a segment with partial nasalization throughout its entire duration.

(8) (V̽^{1} V̽^{2} V̽^{3})

It was noted that the four segment types in (9a-d) are potentially attested in French, where the segment structure in (9a), with one [*x*nasal] and two [–nasal] subsegments, represents an oral vowel after a nasal consonant; the segment in (9b), with two [–nasal] and one [*x*nasal] subsegments, represents an oral vowel before a nasal consonant; the segment in (9c), with one [*x*nasal] and two [+nasal] subsegments, represents a nasal vowel after an oral consonant; and the segment in (9d), with two [+nasal] and one [*x*nasal] subsegments, represents a nasal vowel before an oral consonant. Whether the vowels of French could indeed be represented as with the structures below in the above-specified phonotactic environments has yet to be tested instrumentally.

(9) a. (Ṽ̽^{1} V^2 V^3) c. (Ṽ̽^{1} Ṽ^2 Ṽ^3)
b. (V^1 V^2 Ṽ̽^{3}) d. (Ṽ^1 Ṽ^2 Ṽ̽^{3})

Finally, I noted that the segment types in (10a) and (10b) are those that are attested in leftward non-iterative nasal harmony in Kawaiwete. The segment types in (10c) and (10d) represent the mirror pattern of nasal-oral interpolation spanning two segments, in a hypothetical system with rightward nasal harmony. The segment in (10c), with one [+nasal] and two [$x$nasal] subsegments, represents the vowel in the syllable immediately preceding the triggering vowel; and (10d), with two [$x$nasal] and one [–nasal] subsegments, represents the nasal vowel triggering the pattern of harmony itself. To the best of my knowledge, a language exhibiting non-iterative rightward spreading nasal harmony affecting only the syllable immediately following the trigger has not been documented, but this type of system seems perfectly plausible hypothetical human language. I leave the testing of this prediction to future work.

(10) a. (V^1 Ṽ̽^{2} Ṽ̽^{3}) c. (Ṽ^1 Ṽ̽^{2} Ṽ̽^{3})
b. (Ṽ̽^{1} Ṽ̽^{2} Ṽ^3) d. (Ṽ̽^{1} Ṽ̽^{2} V^3)

5.2.4 Other phonological phenomena

The work presented here discussed processes of nasalization and oralization as a test case for the proposed model of subsegmental and subfeatural representations. Indeed, nasality provided a rich and fruitful empirical ground for the testing of these hypotheses. A natural extension of this work is to see which other features might exhibit partial [xF] values, in addition to both [+/–F]. Lionnet's (2017) original work on subfeatural representations argues convincingly that Laal, an isolate language spoken in Chad, provides evidence of partial rounding best represented phonologically as [$x$round]. I suspect that the partially rounded vowels of Laal are akin to the partially nasal vowels of Kawaiwete, in that they represent an interpolation from an unrounded to a rounded segment over the course of the duration of the vowel. Lionnet's work provided instrumental measures at the mid-point of partially rounded vowels, which would be taken in the middle of the interpolation slope, were this empirical pattern to be confirmed. Carrying out additional measure on both earlier and later timepoints in the partially rounded vowels of Laal would confirm whether the partially rounded vowels can be represented as parallel to the partially nasal vowels of Kawaiwete, namely with a gradient cline of increasing or decreasing values of F2 over the course of the vowel's duration.

In addition, work by McCollum (2019) shows evidence of long-distance backness vowel harmony in Uyghur, suggesting that the assimilatory effect of this process is gradient, petering out over the course of the word, with back vowels being realized as increasingly fronted in non-initial syllables. In addition, McCollum's (2016) on Kazakh rounding harmony suggests similar patterns of gradient interpolation over a long-distance domain. I suspect that an analysis of word-medial vowels within a long-distance interpolation harmony domain could best be represented with three [$x$back] and three [$x$round] subsegments in Uyghur and Kazakh, respectively.

5.2.5 Directional constraints

In Chapter 2, I noted that languages may exhibit multiple patterns of nasal and oral assimilation in different phonotactic contexts. For instance, French exhibits C → V nasal assimilation the case of an /NV/ input sequence, as well as V → C nasal assimilation in the case of an input /ṼD/ sequence. There is also some evidence that French may exhibit C → V oral assimilation in the case of an input /DṼ/ sequence, suggesting that French assimilation may be determined by rightward spreading of a [+/−nasal] feature, regardless of whether the trigger is a vowel or a consonant, and specified as oral or nasal in the input. Indeed, patterns of local nasal and oral assimilation in French may be best described as prioritizing the rightward spread of any [+/−nasal] feature.

The implementation of directionality to the structure of Agreement constraints within the framework of Agreement-by-Correspondence has benefitted from a lot of investigation. Implementing rightward or leftward anchored directionality within a framework of ABC that makes use of both subsegmental and subfeatural representations seems like a fruitful area of investigation to best model the systems of nasal and oral assimilation attested in languages such as French, and likely, many others.

5.2.6 Factorial typology

Another promising avenue of research is to generate a factorial typology using all of the constraints summarized in Section 5.1.3. While this represents no small test, testing the predictive power of a grammar making use of such constraints and comparing it to the systems of attested and unattested local nasal and oral assimilation presented in Chapter 2 will inform future work on subsegmental and subfeatural representations. Are the systems predicted by the factorial typology indeed attested in natural languages? Does the factorial typology fail to predict a type of system which is indeed attested in natural languages? I leave these questions to future work.

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