Phonetic evidence for contextual underspecification of nasality in A'ingae*

To appear in *Phonology*

Ryan Bennett[a], Shen Aguinda[b], Hugo Lucitante[c,d], and Scott AnderBois[e]

[a]University of California, Santa Cruz; [b]A'i-Cofán community of Dureno; [c]University of Texas at San Antonio; [d]A'i-Cofán community of Zábalo; [e]Brown University

Vowels are often nasalized before nasal consonants. Cohn (1993a) argued that contextually nasalized vowels in [VN] are unspecified for nasality in American English, and are only phonetically nasalized through anticipation of the following nasal. In contrast, Solé (1995) argued that nasalization is so extensive in English [VN] that nasalized vowels must be phonologically [+NASAL]. This disagreement reflects a broader problem: how do we determine the phonological specification of segments with phonetically intermediate values?

We contribute to this debate with data from A'ingae, a language spoken in the Ecuadorian and Colombian Amazon. A'ingae has a /V Ṽ/ contrast, along with left-to-right, phonological nasal spreading. We present aerodynamic data showing that A'ingae also has extensive, but nonetheless partial nasalization in [VN, V$^{\text{N}}$D]. This partial nasalization is phonetically distinct from contrastive /Ṽ/, and from nasal vowels derived by phonological spreading. From token to token, vowels in [VN, V$^{\text{N}}$D] range from fully nasal, to partly nasal, to essentially oral. We argue that these results are inconsistent with treating partially nasalized vowels as [+NASAL], or as specified for 'weak' or 'late' nasalization. Instead, we suggest that partial nasalization in A'ingae reflects surface underspecification.

1 Cross-linguistic patterns of contextual nasality

This paper investigates vowel nasality in A'ingae, an Indigenous language of the Ecuadorian and Colombian Amazon. We claim that surface forms in A'ingae may contain vowels which are either nasal, oral, or unspecified for nasality (= [∅NASAL]). To contextualize this claim, we first discuss some cross-linguistic facts about the phonetics and phonology of nasal (and nasalized) vowels.

In a survey of 224 languages, Hajek (2013) reports that 26% have contrastively nasal vowels, as in San Martín Peras Mixtec [kʷáà] 'blind' vs. [kʷã́ã̀] 'yellow' (Eischens & Hedding 2024). Nasal vowels are also commonly produced by assimilation to neighboring nasal sounds (1).[1]

*We are grateful to four anonymous reviewers, the Associate Editor, and the Editors of *Phonology* for their comments and guidance on this project. We also thank audiences at UCSC, NYU, UCLA, and the University of Maryland for their feedback. Special thanks to Amanda Rysling and Chelsea Sanker for their thoughtful comments and suggestions, particularly at the early stages of this project. This paper was improved by feedback from Rachel Walker, Jonathan Paramore, and John Kingston. We thank research assistants Katie Arnold, Mesa Diehl, Missy McReynolds, and especially Amenia Denson for help with data processing. We are grateful to the other members of the A'ingae Language Documentation Project team (Enma Chica, Martín Criollo, Jorge Mendua, Medardo Ortiz, Eloy Quenama, and Leidy Quenama) for discussions about nasality that provided the initial motivation for this study, and for their help reviewing potential stimuli. And very special thanks to all of the A'i participants in this research! We gratefully acknowledge the support of the NSF DEL/DLI #BCS-1911348/1911428 "Collaborative Research: Perspective Taking and Reported Speech in an Evidentially Rich Language" (to Scott AnderBois and Wilson Silva), and the Comparative Language Sciences Center (CLaS) at UC Santa Cruz (to Ryan Bennett).

[1]We use the symbol 'V' for vowels (often oral vowels specifically), 'Ṽ' for nasal vowels, 'N' for simple nasal stops like [n, m, etc.], and '$^{\text{N}}$D' for prenasalized stops and affricates like [ⁿd, ᵐb, ⁿd͡z, etc.]. Slash brackets '/ /' indicate underlying forms, square brackets '[ ]' surface forms. Abbreviations are defined in the appendix.

(1) Local nasal assimilation in Bengali: /V/ → [Ṽ] / ___ N
(Indo-Aryan, primarily Bangladesh and India; Lahiri & Marslen-Wilson 1991)

a. [pɑk] ‘cooking’ vs. [pɑ̃k] ‘slime’
b. /pɑ-ʃ/ → [pɑʃ] ‘you (familiar) get’
c. /pɑ-n/ → [pɑ̃n] ‘you (honorific) get’

Contextual vowel nasalization may neutralize phonemic contrasts, as in Bengali (1), but can also be purely allophonic and non-neutralizing, as in Sundanese (2).

(2) Unbounded L → R nasal spreading in Sundanese (spreading domain underlined)
(Austronesian, primarily Java, Indonesia; Robins 1957, 1953, Cohn 1993a,b, and references there)

a. /ŋ-ala/ → [<u>ŋã</u>la] ‘take (ACT.TR)’
b. /ŋ-pihak/ → [<u>mĩhã</u>k] ‘take sides (ACT.TR)’
c. /ŋ-saur/ → [<u>ŋãũ</u>r] ‘say (ACT.TR)’
d. /-al-, ŋ-saur/ → [<u>ŋ-ã</u>l-<u>ãũ</u>r] ‘say.PL (ACT.TR)’ (opaque V nasalization, cf. (2a,c))

Despite being non-neutralizing, nasal spreading in Sundanese has the hallmarks of a phonological process. First, nasality can spread over a potentially unbounded distance (2a-c): it continues, left-to-right, until it encounters a consonant other than [h ʔ]. Second, nasal spreading can be rendered opaque by infixation (2c,d), leading to the impression that nasal spreading has overapplied. Both of these properties imply that nasal spreading is part of the phonology: it is not just local, phonetic coarticulation for nasality (see e.g. McCollum 2019, Eischens 2022).

Contextual nasalization in Sundanese is also PHONETICALLY COMPLETE: nasalized vowels are strongly nasalized throughout. Fig. 1 reproduces a nasal airflow trace from Cohn (1990, 1993a,b), which shows that /a/ is fully nasalized to [ã] after /ŋ/ (see also Robins 1957). The fact that nasal airflow is lower for [ã] than for [ŋ] follows from aerodynamic principles: all airflow is nasal in [ŋ], while airflow is divided between the oral and nasal channels in [ã].

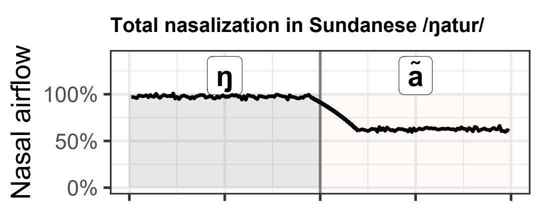


Figure 1: Nasal airflow trace for Sundanese [ŋã] from [<u>ŋã</u>tur] ‘arrange’ (Cohn 1993a:57).

Allophonically nasalized vowels in Sundanese are phonetically similar to contrastive nasal vowels in other languages. For example, nasal vowels are contrastive in European French (e.g. *beau* /bɔ/ ‘beautiful’ vs. *bon* /bɔ̃/ ‘good’) and also produced with substantial nasal airflow (Fig. 2, right).

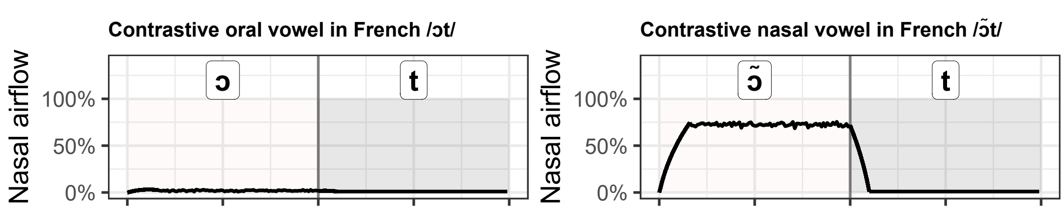


Figure 2: Nasal airflow traces for European French /ɔt/ from /bɔt/ ‘boot’ (left) and /ɔ̃t/ from /bɔ̃te/ ‘goodness’ (right) (Cohn 1993a:51-2).

European French is also a language in which vowels are typically realized as *oral* when preceding nasal consonants, rather than nasal (Fig. 3, Delvaux et al. 2008, Dow 2020).[2] Note the slight increase in nasal airflow at the end of the vowel: this is plausibly a brief coarticulatory effect, reflecting the articulatory transition from an oral vowel to a nasal consonant.

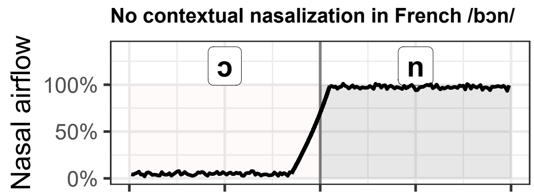


Figure 3: Nasal airflow trace for [ɔn] from European French [bɔn] 'good' (Cohn 1993a:51-2).

1.1 Partial nasalization in [VN]

In some languages, vowels may be only PARTIALLY NASALIZED when adjacent to nasal sounds (Fig. 4). In partial nasalization, a vowel is nasalized under the influence of an adjacent nasal, but nasal airflow is (i) only significant for part of the vowel, and (ii) is greater in duration and/or magnitude than what would otherwise be expected for a mechanical transition between oral and nasal sounds. Compare e.g. American English (Fig. 4) to European French (Fig. 3).

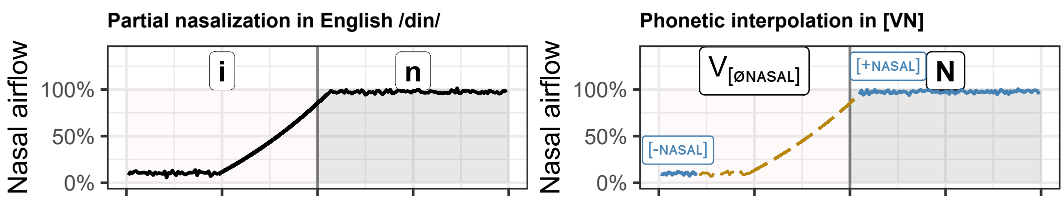


Figure 4: Left: Nasal airflow trace for [in] in English *dean* [dĩn] (Cohn 1993a:60). Right: partial nasality as phonetic interpolation. Solid lines indicate regions with specified targets for [NASAL], broken line indicates interpolation between targets. Initial [-NASAL] reflects preceding context.

Partial nasalization is widespread in [VN] sequences in American English, as documented by Cohn (1990, 1993a), Solé (1995, 2007), Beddor et al. (2018), Zellou (2022), and many others.

The phonological interpretation of partial nasalization has been a matter of debate. Cohn (1990, 1993a) argued that partially nasalized vowels in American English [VN] sequences are UNDERSPECIFIED for nasality: they lack any value or target for [NASAL] whatsoever. Underspecified vowels in [VN] may still be *phonetically* nasalized through INTERPOLATION. Specifically, Cohn (1990, 1993a) proposed that vowels in [VN] may show a cline-like pattern of increasing nasality simply because they intervene between a [-NASAL] and a [+NASAL] target.

Interpolation for nasality is schematized in Fig. 4 (right). Nasality begins low, reflecting the [-NASAL] specification of the preceding context. Nasality then rises gradually, peaking at the following nasal stop, which is [+NASAL]. This cline-like increase in nasality is possible precisely because the vowel itself does not have a target for [NASAL] — it 'doesn't care' about nasal airflow, or the position of the velum. Partial nasalization is thus conceptualized as a transition between phonetic targets which are separated by a targetless region.

Solé (1992, 1995) offers a different perspective on vowel nasalization in American English. First, Solé observes that nasalization in [VN] often begins much earlier in the vowel than necessary

[2]High vowels, which do not contrast for nasality in French, tend to be realized with more contextual nasalization (e.g. Rochet & Rochet 1991, Spears 2006, Delvaux et al. 2008, Desmeules-Trudel & Brunelle 2018, Dow 2020).

to anticipate the following nasal consonant. Second, the timing of nasalization during the vowel is correlated with duration: the *proportion* of the vowel which is nasalized remains roughly constant across changes in duration or speech rate (Solé 2007). Third, Solé (1992, 1995) shows that some [VN] tokens are nasalized throughout their entire duration.

These observations are surprising if vowel nasalization in [VN] reflects a transition from oral to nasal targets, over a targetless vowel. Instead, speakers of American English appear to be *intentionally producing* much more nasalization than necessary on vowels in [VN]. For that reason, Solé proposes that pre-nasal vowels in [VN] are phonologically [+NASAL], rather than underspecified for nasality (see also Pouplier et al. 2024).[3]

Partially nasalized vowels in English do not phonetically resemble [+NASAL] vowels in European French (Figs. 2, 4). To account for this fact, Solé (1995) proposes that the feature [+NASAL] may be implemented differently when contrastive (as in French) than when allophonic. However, this fails to explain why vowels are fully nasalized in Sundanese, since [+NASAL] is purely allophonic, and not contrastive, on vowels in that language (see also Krämer 2017).

In sum, the featural specification of partially nasalized vowels is largely unresolved. Here, we explore this issue with an analysis of nasality in A'ingae, an Indigenous language spoken in the western Amazon. Like French, A'ingae has contrastive vowel nasality (3a,b). Like Sundanese, A'ingae has a phonological process of left-to-right nasal spreading (3c). And like English, we show that A'ingae has extensive partial nasalization of vowels in /VN/ sequences (3d), as well as in /V$^{\mathrm{N}}$D/ sequences (3e).[4]

(3) Vowel nasality in A'ingae

a.	*athe* [ˈa.tʰe] 'saw'	(contrastive oral /V/)
b.	*anthe* [ˈã.tʰe] 'stopped, left'	(contrastive nasal /Ṽ/)
c.	*na'en* /naʔe/ → [ˈnã.ʔẽ] 'river'	(L→ R nasal spreading)
d.	*ana* [ˈã.nã] 'slept'	(partially nasalized [ṼN])
e.	*ande* [ˈã.ⁿde] 'land'	(partially nasalized [Ṽ$^{\mathrm{N}}$D])

This convergence of properties is useful, because it allows us to phonetically compare vowels in /VN, V$^{\mathrm{N}}$D/ sequences to phonologically oral and nasal vowels *within a single language*. We find that pre-nasal vowels in [ṼN, Ṽ$^{\mathrm{N}}$D] are phonetically distinct from (i) underlying [+NASAL] vowels, (ii) phonologically derived [+NASAL] vowels, and (iii) underlying oral vowels. Phonetically, vowels in [ṼN, Ṽ$^{\mathrm{N}}$D] range from fully nasal to fully oral, with many intermediate, partly nasal tokens. We conclude that, on the surface, vowels in [ṼN, Ṽ$^{\mathrm{N}}$D] are unspecified for nasality in A'ingae.

2 Language background

A'ingae is a linguistic isolate spoken in what is now northern Ecuador and southern Colombia. The term *a'i* (literally '(civilized) person') is used to refer to members of the ethnic group which

[3]Zellou (2022) reports that only 38% of the American English speakers in her study showed the timing patterns that Solé (1992, 1995, 2007) reports for American English. This highlights the fact that there may be considerable inter-speaker (and inter-dialectal) variation with respect to nasality in [VN] sequences, and in other contexts (see also Cohn 1990:2-3, Delvaux et al. 2012, Beddor et al. 2018, Bongiovanni 2021, Pouplier et al. 2024).

[4]As there is no widely used diacritic for partial nasalization, we transcribe partially nasalized vowels in forms like (3d,e) with the normal IPA diacritic for nasality, [Ṽ]. It should be borne in mind that vowels transcribed as [Ṽ] in surface forms may not be fully nasalized, especially in [ṼN, Ṽ$^{\mathrm{N}}$D] contexts.

traditionally speaks this language. The A'ingae language and A'i people are also commonly referred to as *Cofán* or *Kofán*, a term of uncertain origin.

A'ingae is spoken in communities along two main rivers and their tributaries: the Aguarico River in Sucumbíos province in Ecuador; and the San Miguel River, which forms the border between Ecuador and Colombia in this region. This geographic context, along with 4 major Ecuadorian A'i communities, is shown in Fig. 5 (Sinangoe being farthest upriver). A'ingae is spoken in 9 additional communities in Ecuador, as well as several communities in Colombia. A small amount of dialect variation has been noted for A'ingae: for example, Borman (1976) identifies some lexical items which are attested in Colombian A'ingae, but not in Ecuador. However, no significant phonological differences have so far been identified across varieties of A'ingae.

Figure 5: Ecuador (left), and 4 major A'i towns along the Aguarico River in the Ecuadorian Amazon (right). Green region overlapping eastern Ecuador is Amazon basin. Map data from Massicotte & South (2025), `data.humdata.org/dataset/hotosm_ecu_waterways` (Open Database License, `opendatacommons.org/licenses/odbl/1-0`), and `github.com/gamamo/AmazonBasinLimits`.

A'ingae has approximately 1500 speakers (although a robust census is lacking). In several communities (Zábalo, Chandia Na'en), the language remains entirely vital, being used in nearly all aspects of day-to-day life by community members of all ages. However, an ethnolinguistic vitality assessment by Pomilia (2025) finds a more mixed picture in other communities. While A'ingae is still acquired by most children in all A'i communities, Spanish may have begun to displace A'ingae in certain social contexts, especially in Duvuno, and to a lesser extent Sinangoe (Fig. 5). Overall, Pomilia (2025) finds the language to be relatively vital, though with some cause for long-term concern; especially so, given ongoing challenges to A'i territorial sovereignty posed by oil and other extractive industries, and the processes of colonization they have facilitated (see Cepek 2018). For summaries of prior research on the language, along with text and multimedia collections, see Dąbkowski (2021a, 2024) and `https://cofan-aldp.github.io/LingView/#/`.

This work is part of a long-term language documentation and revitalization project, called the A'ingae Language Documentation Project (ALDP; see again `https://cofan-aldp.github.io/LingView/#/`). The ALDP is a collaboration between academic linguists, A'i community linguists, and A'i educators and scholars from adjacent fields. Each of these groups are represented in the co-authorship team. Research decisions are made jointly, with authorship and intellectual leadership shared. The ALDP also provides training opportunities to help A'i researchers develop their own independent projects. The collaborative nature of this project affirms the A'i commitment to self-representation, and ensures that all research materials remain accessible to the A'i nation.

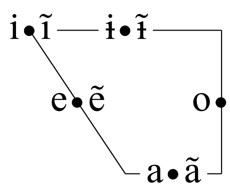
The research we present here has informed efforts to standardize A'ingae orthography, and has supported teacher training and the creation of educational materials for A'i schools. In addition to academic outputs, our findings have been presented to A'i members of the ALDP, as well as broader A'i audiences, including a meeting in July 2024 bringing together all educators working in Ecuadorian A'i communities, other educators from Colombian A'i communities, and officials from Secretaría de Educación Intercultural Bilingüe y la Etnoeducación [Secretary of Intercultural Bilingual Education and Ethnoeducation] in Ecuador (SEIBE). As native speakers of A'ingae, co-authors Aguinda and Lucitante ensured smooth communication with A'i community members, and managed project logistics through their long-standing family and community ties.

3 Phonology of nasal segments in A'ingae

In this section we outline the phonology of nasal vowels and consonants in A'ingae. For general information on the phonology of A'ingae, see Repetti-Ludlow et al. (2020), Fischer & Hengeveld (2023), Dąbkowski (2024), Sanker & AnderBois (2024) and references there. The A'ingae data we present in this paper is taken from those sources, two dictionaries (Borman 1976, ALDP ms), as well as our own extensive original fieldwork on the language, and the introspective judgments of two native speaker co-authors (Lucitante and Aguinda).

3.1 Contrastive vowel nasality

Nasality is contrastive on vowels in A'ingae, as evidenced by (near-)minimal pairs like *ji* [hi] 'came' vs. *hin* [hĩ] 'existed', or *uti* [oti] 'hammered' vs. *untin* [õtĩ] 'gadfly'. The phonemic vowel inventory is provided in Fig. 6.[5]



/ie, ĩẽ/	/ɨi, ɨ̃ĩ/	
/io, ĩõ/		/oi, õĩ/
/ia, ĩã/		/oe, õẽ/
/ei, ẽĩ/		/oa, õã/
/ai, ãĩ/	/ae, ãẽ/	/ao, ãõ/

Figure 6: Phonemic vowel inventory of A'ingae. Inventory of diphthongs from Dąbkowski (2024); cf. Repetti-Ludlow et al. (2020), Fischer & Hengeveld (2023), Sanker & AnderBois (2024).

3.2 Prenasalized stops

The phonemic consonants of A'ingae include both simple nasal stops /N/ and prenasalized stops /$^{\mathrm{N}}$D/ (Tab. 1). Prenasalized stops and affricates /$^{\mathrm{N}}$D/ are unitary segments in A'ingae, not clusters (see e.g. Riehl 2008, Riehl & Cohn 2011, Gouskova & Stanton 2021). First, prenasalized stops /$^{\mathrm{N}}$D/ are 'non-separable'. Prenasalized stops in A'ingae consist of a nasal interval [$^{\mathrm{N}}$] followed by a voiced stop interval [D]. However, voiced stops do not otherwise occur in the language. Hence, prenasalized /$^{\mathrm{N}}$D/ cannot be analyzed as a cluster of two independently occurring consonants.

Second, consonant clusters do not generally occur in native A'ingae words. Syllable structure is maximally [CV]; the only potential coda is /ʔ/ (e.g. *kan'chu* [kãʔ.t͡ʃo] 'binoculars, scope'), which can be analyzed as a prosodic feature instead (see Dąbkowski 2024). Syllable phonotactics thus argue against treating prenasalized /$^{\mathrm{N}}$D/ as a cluster. Word-initial prenasalized stops, as in *giyaen* [ˈᵑgi.jãẽ] 'cleaned', are especially bad candidates for clusters due to their sonority contour.

[5]The phonetic realization of phonemic /o õ/ ranges from [o õ]/[ɔ ɔ̃] to [u ũ]/[ʊ ʊ̃] in A'ingae. For the sake of consistency, we transcribe phonemic /o õ/ as a mid-back vowel throughout.

	Bilabial	Labio-dental	Alveolar	Post-alveolar	Palatal	Velar	Glottal
Stops	p p^h		t t^h			k k^h	ʔ
Prenasalized stops	^{m}b		^{n}d			^{ŋ}g	
Affricates			t͡s $t͡s^h$	t͡ʃ $t͡ʃ^h$			
Prenasalized affricates			^{n}d͡z	^{n}d͡ʒ			
Fricatives		f	s	ʃ			h
Nasals	m		n		ɲ		
Glides and rhotics		ʋ	ɾ		j	ɰ	

Table 1: Phonemic consonant inventory of A'ingae (Repetti-Ludlow et al. 2020, Fischer & Hengeveld 2023, Dąbkowski 2024, Sanker & AnderBois 2024).

In many Amazonian languages, prenasalized stops are allophones of either nasal consonants or oral stops (e.g. Stanton 2018, Lapierre 2023, Sanker & AnderBois 2024 and references there). This does not appear to be the case in A'ingae; see Dąbkowski (2024:13), Sanker & AnderBois (2024).

3.3 Nasal harmony

A'ingae has a pervasive process of left-to-right (progressive) nasal harmony. Nasality spreads rightward from nasal vowels (4)-(5). Laryngeal consonants [ʔ h] are transparent for nasal spreading (4a), (5a), and seem phonetically nasalized (Walker & Pullum 1999). Spreading across morpheme boundaries is blocked by non-laryngeal obstruents (4b) and the tap [ɾ] (though only one suffix, /-ɾi/ NOM, begins with [ɾ]). We indicate the domain of nasal spreading with underlining.[6]

(4) Nasal spreading from [Ṽ] in A'ingae: across morpheme boundaries

a. Laryngeal transparency across morpheme boundaries
ja'je /ha-ʔhe/ → [ˈhaʔ.he] 'go-IPFV'
tsun'jen /t͡sõ-ʔhe/ → [ˈt͡sõʔ.hẽ] 'do-IPFV'

b. Blocking by non-laryngeals across morpheme boundaries
jen'chu /hẽ-ʔt͡ʃo/ → [ˈhẽʔ.t͡ʃo] 'a sound (sounded-NMLZ)'

Inside roots, fricatives and plain (unaspirated) stops and affricates tend to pattern as transparent for nasal harmony (5b). Spreading inside roots is blocked by aspirated stops and affricates (5c). There are no alternations within roots, so 'spreading' is diagnosed by static co-occurrence patterns; see Dąbkowski (2024), Sanker & AnderBois (2024) for details.

(5) Nasal spreading from [Ṽ] in A'ingae: inside roots

a. Laryngeal transparency inside roots
ûnjin /ɨ̃hi/ → [ˈɨ̃.hɨ̃] 'rain'
in'jan /ĩʔha/ → [ˈĩʔ.hã] 'think, want'

[6] We use the terms 'spreading' and 'harmony' in a purely descriptive sense. We take no stance on whether these patterns are best analyzed with literal feature spreading, as in autosegmental phonology (Piggott & Van der Hulst 1997, Walker 2003), or with other devices such as agreement-by-correspondence (e.g. Rose & Walker 2004) or gestural blending (e.g. Smith 2018).

We reserve the term 'coarticulation' to refer to strictly phonetic processes involved in co-producing neighboring segments in physical time and space. Since we assume that phonetic processes may be language-specific (e.g. Keating 1984, Kingston & Diehl 1994), 'coarticulation' in this sense may be either intended (i.e. controlled), or mechanical (i.e. unavoidable), depending on the process.

b. Transparency of fricatives, plain stops and plain affricates inside roots
panshan /pãʃa/ → [ˈpã.ʃã] ‘passed’
unken /ũke/ → [ˈũ.kẽ] ‘goddaughter’

c. Blocking by aspirated stops and affricates inside roots
kankhe /kãkʰe/ → [ˈkã.kʰe] ‘town, city’
sinthû /sĩt͡ʰɨ/ → [ˈsĩ.tʰɨ] ‘bit’

Nasal harmony triggers alternations between glides and nasals. In native A’ingae words, the glides /ʋ j/ and tap /ɾ/ never follow a nasal vowel. When /ʋ j/ are placed after a nasal vowel through suffixation, they become nasal stops (6b), (7b). Harmony feeds glide nasalization (6c), (7c).[7]

(6) Glide nasalization after nasal vowels: /j/ → [ɲ]

a. *shakaye* /ʃaka-je/ → [ʃa.ˈka.je] ‘lack-INF’
b. *kañe* /kã-je/ → [ˈkã.ɲẽ] ‘look-INF’
c. *chavuen’jeña* /t͡ʃaʋa-ẽ-ʔhe-ja/ → [t͡ʃa.ˈʋõẽʔ.hẽ.ɲã] ‘buy-CAUS-IPFV-VER’

(7) Glide nasalization after nasal vowels: /ʋ/ → [m]

a. *thesive* /tʰesi = ʋe/ → [ˈtʰe.si.ʋe] ‘jaguar=ACC2’
b. *sin’ma* /sĩ-ʔʋa/ → [ˈsĩ-ʔ.mã] ‘bruise (lit. black-CLF:AREA)’
c. *kun’sime* /kõʔsi = ʋe/ → [ˈkõʔ.sĩ.mẽ] ‘woolly.monkey=ACC2’

The triggers for nasal harmony include both nasal vowels (6)-(7) and the simple nasal stops /m n ɲ/. Vowels following nasal stops are always, exceptionlessly nasal. That this is so can be shown by the fact that vowels following nasal consonants are themselves triggers for harmony (8b).

(8) Nasal spreading from [N] in A’ingae

a. *nae’sû* /naeʔ-sɨ/ → [ˈnãẽʔ.sɨ] ‘fish (river-ATTR)’
b. *semañe* /sema-je/ → [sẽ.mã.ɲẽ] ‘work-INF’

Left-to-right nasal harmony is a phonological process in A’ingae. First, it neutralizes the contrast between glides and homorganic nasal stops, as in (6b,c), (7b,c) and (8b). It is phonetically possible, in principle, to nasalize glides without changing their manner, /j ʋ/ → [j̃ ʋ̃] etc. (Cohn 1993b). The fact that harmony changes the manner of articulation of glides, as well as their nasality, supports the claim that it is a phonological process, not just phonetic coarticulation for nasality.

Second, harmony spreads nasality over a potentially unbounded distance (6c), (7c). This too is characteristic of a phonologically-controlled harmony process (e.g. McCollum 2019). Third, inside roots, harmony can spread nasality through plain stops and fricatives (e.g. *anchan* /ãt͡ʃa/ → [ˈã.t͡ʃã] ‘mosquito’), even though such segments are both oral and phonetically antagonistic to nasality (see also Walker 2000, Shosted 2006, Smith 2018).

Nasal vowels produced by phonological harmony provide an important comparison for the nasality of vowels *preceding* [N, ᴺD], to which we now turn.

[7]The velar glide /ɰ/ only occurs root-medially, and only after oral vowels. As such, /ɰ/ does not participate in alternations related to nasality. The velar nasal [ŋ] does not occur in A’ingae, which suggests that /ɰ/ never undergoes nasalization. The tap /ɾ/ is opaque to harmony, and does not undergo alternations related to nasality.

3.4 Pre-nasal vowels

Although vowel nasalization is contrastive in A'ingae, /V Ṽ/ contrasts are suspended before simple nasals [N] and prenasalized stops [$^{\text{N}}$D]: there are no hypothetical minimal pairs like [ˈa.mĩ] vs. [ˈã.mĩ], or [ˈa.$^{\text{ŋ}}$gi] vs. [ˈã.$^{\text{ŋ}}$gi]. In other words, the /V Ṽ/ contrast is neutralized before [N, $^{\text{N}}$D]. However, the surface *result* of neutralization in this context is not obvious. Impressionistically, there is some degree of nasalization on vowels preceding [N, $^{\text{N}}$D], e.g. words like *fuñu* [ˈfõ̱.ɲõ] 'skirt' and *kimbi* [ˈkĩ̱.$^{\text{m}}$bi] 'got tired' have audible nasality on the initial, stressed vowel. Nasalization before [N, $^{\text{N}}$D] is also clear when comparing morpho-syntactically related forms like those in (9):

(9) a. *thesi* [ˈt$^{\text{h}}$e.si̱] 'jaguar' vs. *thesinga* [ˈt$^{\text{h}}$e.sĩ̱=$^{\text{ŋ}}$ga] 'to the jaguar'
 b. *patû* [ˈpa.tɨ̱] 'rock' vs. *patûma* [ˈpa.tɨ̱̃=mã] 'rock=ACC'

At the same time, nasality on vowels before [N, $^{\text{N}}$D] sounds weaker than nasality on contrastively nasal vowels in words like *kanse* /ˈkã.se/ 'lived'. Indeed, native speaker judgments of nasality suggest that vowels preceding [N, $^{\text{N}}$D] may not be fully nasalized.

We have worked closely with (other) A'ingae speakers to codify their orthography, and produce community-oriented materials such as dictionaries and story collections. In general, A'ingae speakers have clear judgments of vowel nasality, particularly in stressed syllables. This is not surprising, given that vowel nasality is contrastive. However, many of our A'i collaborators and consultants have expressed the intuition that vowels preceding [N, $^{\text{N}}$D] are not fully nasal. Instead, vowels in this context are often described as 'only half-nasal'. In some cases, speakers are simply unsure as to the nasality of vowels preceding [N, $^{\text{N}}$D], or may disagree when given a binary choice between oral and nasal options. These judgments suggest that the neutralization of /V Ṽ/ contrasts before [N, $^{\text{N}}$D] may produce something other than a fully nasal vowel.[8]

There is thus a question as to whether nasality on vowels preceding [N, $^{\text{N}}$D] is complete (i.e. categorical) or partial (i.e. phonetically gradient). If nasalization before [N, $^{\text{N}}$D] is categorical, then it is reasonable to analyze it as part of the abstract, symbolic phonology of A'ingae. If nasalization before [N, $^{\text{N}}$D] is instead partial, it may be better understood as reflecting a gradient phonetic process, such as coarticulation for nasality between the vowel and a following [N] or [$^{\text{N}}$D].

To our knowledge, there is no *phonological* evidence that sheds light on the [NASAL] specification of vowels preceding [N, $^{\text{N}}$D]. Unlike nasal harmony (section 3.3), anticipatory nasalization before [N, $^{\text{N}}$D] is strictly local. It does not spread through laryngeals (10a), nor does it trigger glide ∼ nasal stop alternations (10b).

(10) Anticipatory nasalization is strictly local
 a. *ijima* /ihi=ma/ → [ˈi.h̲ĩ̲.m̲ã], *[ˈĩ̲.h̲ĩ̲.m̲ã] 'armadillo=ACC'
 b. *indiyembi* /i$^{\text{n}}$di-je-$^{\text{m}}$bi/ → [ĩ.$^{\text{n}}$di.ˈj̲ẽ̲.$^{\text{m}}$b̲i], *[ĩ.$^{\text{n}}$dĩ̲.ɲ̲ẽ̲.$^{\text{m}}$b̲i] 'grab-PASS-NEG'

These properties are consistent with treating anticipatory nasalization in [ṼN, Ṽ$^{\text{N}}$D] as either a phonetic or phonological process.

Phonetic phenomena, such as coarticulation, should not feed or bleed phonological rules. This follows from the assumption that in speech production, the phonetics interprets the output of the

[8]The perception of 'weaker' nasality in [ṼN, Ṽ$^{\text{N}}$D] could be a context effect: vowels are generally perceived as less nasal when adjacent to a nasal consonant (e.g. Beddor & Krakow 1999, Fowler & Brown 2000, Zellou 2017). However, this does not explain why vowels in [NṼ] are consistently identified as fully nasal by A'ingae speakers, at least in our informal experience. See Jeong (2012), Rysling (2017) for related discussion.

phonology, and so cannot ‘look backward’ to affect the application of phonological processes (see Eischens 2022, Bennett et al. 2023 for discussion and references). Indeed, anticipatory nasalization does not feed or bleed any known phonological process in A’ingae, nor is it blocked by any kind of phonotactic requirement (see e.g. Dąbkowski 2024). The lack of feeding and bleeding interactions certainly makes sense if anticipatory nasalization is a physical, phonetic process of coarticulation. Alternatively, anticipatory nasalization could be a phonological rule which just happens, by chance, not to interact with other rules or constraints in the phonology of the language.

The punchline is that we cannot assess the phonological vs. phonetic character of anticipatory nasalization in A’ingae based on phonological patterning. The available evidence is compatible with treating vowels in [ṼN, Ṽ$^{\text{N}}$D] as either [+nasal], [-nasal], or unspecified [∅nasal].

Given the lack of clear phonological evidence, in the remainder of the paper we turn to a phonetic study of vowel nasality in A’ingae. We will argue that vowels in [ṼN, Ṽ$^{\text{N}}$D] contexts are phonetically distinct from [-nasal] vowels, underlying [+nasal] vowels, and phonologically derived [+nasal] vowels. We conclude that underspecification for nasality, [∅nasal], best characterizes the phonetics and phonology of vowels preceding [N, $^{\text{N}}$D] in A’ingae.

4 Aerodynamic study

In the remainder of the paper we present a phonetic study of vowel nasality across several contexts, comparing pre-nasal [ṼN, Ṽ$^{\text{N}}$D] with underlying, contrastively oral /V/ and nasal /Ṽ/ as well as phonologically derived post-nasal /NV/ → [NṼ]. This section outlines the study. Section 5 presents the results, and section 6 argues that our findings are most consistent with treating vowels preceding [N, $^{\text{N}}$D] as phonologically and phonetically unspecified for nasality, [∅nasal].

4.1 Items

The items in our study consisted primarily of bisyllabic roots like those in Tab. 2. These roots were chosen to compare nasality on stressed vowels in four conditions: underlying oral /V/; underlying nasal /Ṽ/; phonologically derived post-nasal /NV/ → [NṼ]; and pre-nasal [ṼN, Ṽ$^{\text{N}}$D]. Since these vowels are in monomorphemic roots, they are all non-alternating (i.e. phonologically invariant), because their context never changes. We included a relatively large number of items in the [ṼN, Ṽ$^{\text{N}}$D] conditions, since these are the conditions of primary interest.

Item shape	**Description**	**Example**	# of items
[ˈCV̲.CV]	Contrastive oral /V/	*tufa* [ˈt̲o.fa] ‘lizard’	21
[ˈCṼ̲.CV]	Contrastive nasal /Ṽ/	*finfin* [ˈfĩ̲.fĩ] ‘fanned one’s self’	9
[ˈNV̲.CV]	Nasal [Ṽ] derived by L → R harmony (section 3.3)	*masha* [ˈmã̲.ʃa] ‘heron’	7
[ˈCṼ̲.NṼ]	Vowel preceding [N]	*china* [ˈt͡ʃĩ̲.nã] ‘daughter-in-law’	15
[ˈCṼ̲.$^{\text{N}}$DV]	Vowel preceding [$^{\text{N}}$D]	*thumbû* [ˈt$^{\text{h}}$õ̲.$^{\text{m}}$bɨ] ‘grasshopper’	18

Table 2: Sample items for each condition in the aerodynamic study. C = oral consonant, N = nasal stop, $^{\text{N}}$D = prenasalized stop. Stressed target vowels are underlined.

Our study also included some morphologically complex words like *khakenga* [ˈk$^{\text{h}}$a.k$^{\text{h}}$ẽ = $^{\text{ŋ}}$ga] ‘to the leaf’. These items were included to gather information about contextual nasalization across morpheme boundaries. However, we found it difficult to accurately measure nasality on unstressed, root-final vowels, which are often quite reduced in A'ingae. As such, in complex words like *khakenga* [ˈkʰa.kʰẽ = ᵑga], we only consider the nasality of the stressed vowel.

To summarize, the vowels analyzed here were always stressed; were typically root- and word-initial; and typically in the penultimate syllable. Less commonly, they were antepenultimate in morphologically complex words (on stress in A'ingae, see Dąbkowski 2021b, 2024).

Participants sometimes produced tokens which were different from what had been prompted, but which nonetheless fell into one of the conditions of interest of this study (e.g. producing *pûshesûnga* [pɨ.ˈʃe̠-sɨ̃ = ᵑga] 'to the woman' instead of the intended *pûshenga* [ˈpɨ̠.ʃẽ = ᵑga] 'to the wife'). The stressed vowels in such items were included in our data as long as they could be accurately transcribed and annotated.

Vowels preceding glottal stop [ʔ] or [h] were excluded from analysis, because of the difficulty involved in segmenting and analyzing vowels in these contexts (e.g. *cha'nditshi* [ˈt͡ʃã̠ʔ.ⁿdi-t͡sʰi] 'cold', *nuhan* [ˈnõ̠.hã] 'thorn', etc.). Items with diphthongs (whether oral or nasal) were similarly excluded to keep vowel measurements as comparable across items as possible.

Together, the preceding factors account for the uneven distribution of items across conditions in Tab. 2. A full list of items analyzed in this study is provided in the appendix.

Vowel height can affect the amount of nasal airflow in nasal vowels, for both articulatory and aerodynamic reasons (e.g. Bell-Berti 1993, Hajek 1997, Young et al. 2001, Gick et al. 2012:129-36, Kunay et al. 2022). We therefore tried to vary vowel quality, and particularly vowel height, for the stressed vowels in each condition. We also tried to vary the place and manner of the flanking consonants, in order to minimize any idiosyncratic influences on nasal airflow in the vowel (e.g. Bellavance et al. 2024). Some of the items in the /V/, /Ṽ/, and [ṼN, Ṽ$^{\mathrm{N}}$D] conditions lacked an initial consonant, e.g. *ansin* [ˈã.sĩ] 'salt'. Our ability to fully vary these factors was limited by (i) the number of items in each condition, which was chosen in part to keep recording sessions to a reasonable length; and (ii) a desire to use items consisting of relatively familiar bisyllabic roots, so as to minimize the difficulty of the task.

4.2 Participants

37 Participants were recruited via word of mouth in Zábalo and Lago Agrio, Ecuador (Fig. 5). All participants were native speakers of A'ingae who use the language as their primary means of daily communication with friends and family. The analysis consists of data from 15 speakers (7 male, 8 female; ages 19-63, mean = 38.4, median = 29, SD = 14). Thirteen participants lived in Zábalo at the time of recording, and 2 lived in Dureno (Fig. 5). All were born in either Zábalo or Dureno. We halted data annotation at 15 speakers because that was deemed to be a sufficient amount of data, based on comparable prior studies of nasal coarticulation.

4.3 Data collection

4.3.1 Recordings

Oral and nasal air pressure recordings were made with two Glottal Enterprises (GE) PT-2E pressure transducers, mounted on a GE oro-nasal mask. The GE oro-nasal mask has separate oral and nasal chambers, which allows oral and nasal air pressure to be recorded more-or-less independently.[9] The

[9]Recordings made with dual-chamber masks will often show small amounts of oral air pressure even in entirely nasal sounds (e.g. [m]), and small amounts of nasal air pressure even in entirely oral sounds (e.g. [v]) (Kochetov 2020; see e.g. Figs. 7, 8 for examples). This reflects the fact that the pressure transducers used for recording are

oral pressure transducer was mounted directly on the mask, and the nasal pressure transducer was mounted on a GE DRTH-1 mask handle connected to the mask.

The air pressure transducers were connected to a GE MS-110 pressure transducer unit with a GE BFC-2 cable. The GE MS-110 pressure transducer unit was connected to a computer via USB cable. The oral and nasal air pressure recordings were made at 11,025 Hz using Audacity. Modulation was turned off on both channels on the GE MS-110 pressure transducer unit.

Simultaneous audio recordings were made with an Audio-Technica AT831b cardioid condenser lavalier microphone and Zoom H5 solid-state portable recorder, at a 48 kHz sampling rate with 24 bit quantization. Our procedure for transcribing, segmenting, and annotating these recordings is described in more detail in the appendix.

4.3.2 Item presentation and recording procedure

Items were presented on a laptop screen, using a Python script which randomized the order of presentation for each session. Items were presented in A'ingae orthography in a large font, with a Spanish translation in smaller font below. Some participants preferred to use the contemporary (as of 2023) A'ingae orthography, while others preferred to use the older orthography found in sources like Borman (1976). The norms for writing vowel nasality are the same in both systems.

Participants were asked to repeat each item six times: twice without the oro-nasal air pressure mask in place; twice with the mask in place, speaking at a normal rate; and twice with the mask in place, speaking at a faster rate. The goal of manipulating speech rate was to elicit vowels of varying durations, so that we could investigate whether the proportion of the vowel which is nasalized in [ṼN, Ṽ$^{\mathrm{N}}$D] correlates (or not) with vowel duration (Solé 1992, 1995, 2007 and section 1.1). Participants sometimes repeated target items more often than requested, particularly at the beginning of each session as participants became accustomed to the recording setup. Any extra repetitions produced with the mask in place were included in our analysis (section 5). The mask-off repetitions were recorded to have clear audio of each item as a backup for analysis in case the airflow equipment or data was compromised; those audio recordings are not analyzed here.

During the recording session each participant held the mask by the handle, and raised it to their face as needed for recording. Participants were asked to place the mask gently but firmly on their face, forming a seal between their skin and the silicon ridge separating the oral and nasal chambers.

Participants completed an IRB-approved consent form in Spanish before participating. The contents of the consent form were first discussed in Spanish, and were then further discussed and clarified in A'ingae with the help of co-authors Aguinda and Lucitante. Participants typically arrived at recording sessions in family groups: the consent form, recording process, and project goals were discussed among these groups before any family members began their participation. At every stage, participants were reminded of their right to decline or withdraw from the study.

Recording sessions typically lasted 15-25 minutes. Participants were paid $15 US for enrolling in the study. All recordings took place in July 2023.

mounted on the same mask, and so any physical vibration of that mask caused by oral airflow may register slightly in the nasal pressure transducer, and vice-versa. We also cannot rule out some degree of leakage between the oral and nasal chambers. Phonologically oral sounds may be produced with small amounts of nasal airflow, which can additionally result in some amount of nasal pressure signal during oral sounds (e.g. Bell-Berti 1993).

4.4 Measurement and normalization of intensity and nasalance

A Praat script was used to extract intensity contours for the oral and nasal channels separately, using the `To Intensity` function, with the pitch floor set to 200 Hz, the time step set to one quarter of the effective window length (the default), and no mean subtraction. These intensity contours were then read into R (R Development Core Team 2025), and normalized to the range [0,1] for each speaker and channel separately.

The dependent measure of this study was NASALANCE (11), defined as the proportion of the total, combined oral and nasal intensity signals belonging to the nasal channel during each vowel.

(11) a. A_x = intensity of channel X
 b. Nasalance = $A_{nasal}/(A_{nasal} + A_{oral})$

Nasalance is a useful measure because it relativizes nasal air pressure to the sum total of air pressure in both the oral and nasal channels, expressed as a percentage. This helps control for the fact that *raw* nasal air pressure can be affected by changes to the overall volume of air leaving the vocal tract (e.g. when speaking loudly vs. quietly). Nasalance minimizes this confound. Additionally, it has been argued that the timecourse of nasalance is well-correlated with the timecourse of velar port opening (Siriwardena et al. 2024), though the initial phase of velum lowering can occur without significant acoustic effects (Bell-Berti 1993).

Nasalance values are dependent on both oral and nasal air pressure. Because of this, nasalance can vary as a function of vowel quality, in particular height. High vowels have a narrower oral constriction than low vowels, and thus tend to have less oral airflow. Nasal high vowels also tend to have more nasal airflow than nasal low vowels, because their narrow constrictions increase oral impedance, forcing more air through the nasal tract. As a consequence, even when overall airflow is held constant, high vowels will have higher nasalance values than low vowels (e.g. Hajek 1997, Young et al. 2001). In our statistical analysis, we try to factor out the effect of vowel quality on nasalance measurements.

To compute nasalance, the normalized intensity values produced in R were first exported to files in Praat's `.Intensity` format (following Stewart & Kohlberger 2017). Separate R and Praat scripts were used to compute nasalance at 17 equidistant, time-normalized steps for each vowel. Each step corresponds to the average nasalance in a window with duration equal to ¹⁄₁₇ of the duration of the vowel. These nasalance values were then imported into R for statistical analysis. Intensity values in dB (a logarithmic scale) were converted to Pascal (a linear scale) prior to processing. Nasalance was set to N/A for any point with nasal air pressure below 1% of that speaker's maximum nasal air pressure. In the discussion that follows, we will sometimes use the terms 'nasalance' and 'nasality' interchangeably when discussing our phonetic results.

Overall, we analyzed 3772 target vowels across conditions. The average number of observations per participant was 251 (range = [237, 260], SD = 5.5), including all items and repetitions. The average number of observations per item type (Tab. 2), per participant, was 50.3 (median 56) (range = [28, 72], SD = 15.7). The width of this range reflects the fact that we had more items in the crucial [ṼN, Ṽ$^{\mathrm{N}}$D] conditions than in other conditions. A breakdown of total observations per item type is provided in Table A1 in the appendix, along with a full list of items.

5 Results

In exploring our results, we first describe qualitative patterns based on individual tokens (section 5.1). We then statistically compare nasalance trajectories across conditions by means of generalized additive mixed models (GAMMs; section 5.2). Lastly, we fit sigmoid functions to individual nasalance trajectories to analyze the timing of nasality in [ṼN, Ṽ^{N}D] sequences (section 5.3).

5.1 Qualitative patterns

In general, surface oral vowels were produced with little to no nasal air pressure, and relatively low nasalance (Fig. 7, left).[10] Y-axis limits for nasalance reflect the range of nasalance values for that speaker. All plots were drawn with the `ggplot2` package in R (Wickham 2016).

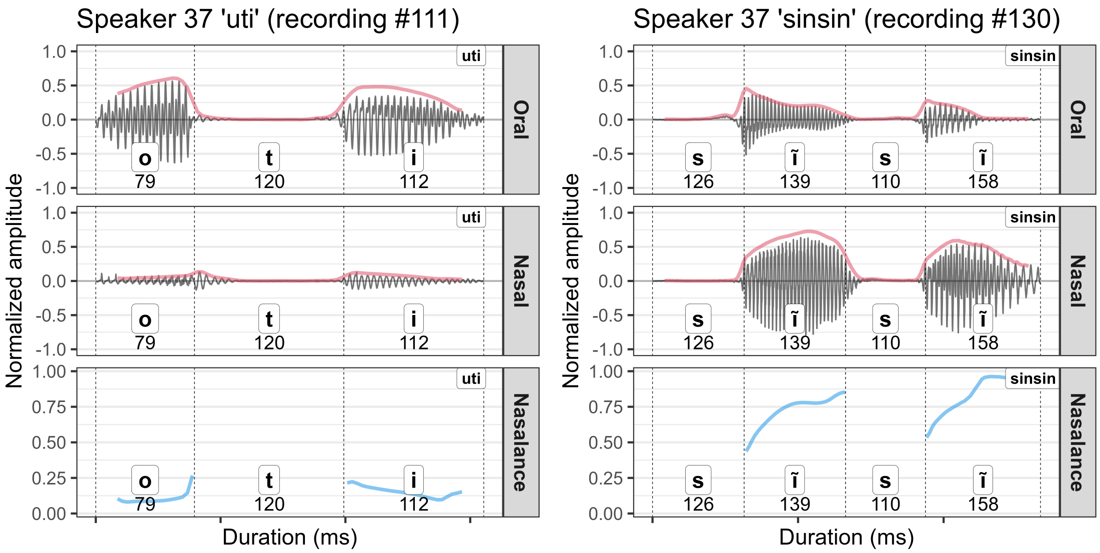


Figure 7: Sample token of a contrastive oral vowel /V/, *uti* [ˈo̠.ti] 'hammered' (left); and a contrastive nasal vowel /Ṽ/, *sinsin* [ˈsĩ̠.sĩ] 'louse' (right). Top panel shows oral air pressure and intensity, middle panel nasal air pressure and intensity, bottom panel nasalance (section 4.4).

Underlying, contrastive nasal vowels are generally produced with high levels of nasal airflow, and correspondingly, high nasalance (Fig. 7, right). Nasalance is typically high thoughout the entire vowel, though is often slightly depressed at the beginning of the vowel, presumably due to coarticulation with the preceding consonant, which was always oral (see also sections 5.2. 5.3, 6.1).

Phonologically derived nasal vowels in [NṼ] resemble underlying nasal vowels /Ṽ/: they are strongly nasalized throughout their entire duration, though nasalance sometimes dips at the juncture between the nasalized vowel and the following consonant, which was always oral (Fig. 8).

For vowels preceding [N, ^{N}D], we find patterns of variation, reminiscent of anticipatory nasalization in English (section 1). First, vowels preceding [N, ^{N}D] often show partial nasalization (Fig. 9): nasalance is low for roughly the initial ¼-½ of the vowel, then sharply increases, remaining relatively high until the onset following [N] or [^{N}D].

[10] We omit nasalance measures on obstruents in our plots because the low levels of overall air pressure during obstruents can lead to wild fluctuations in nasalance, which is misleading and visually distracting. Oral air pressure is low for fricatives in our data because of the 11,025 Hz sampling rate of the GE MS-110 pressure transducer unit, which cannot record higher-frequency noise components; see e.g. Fig. 7.

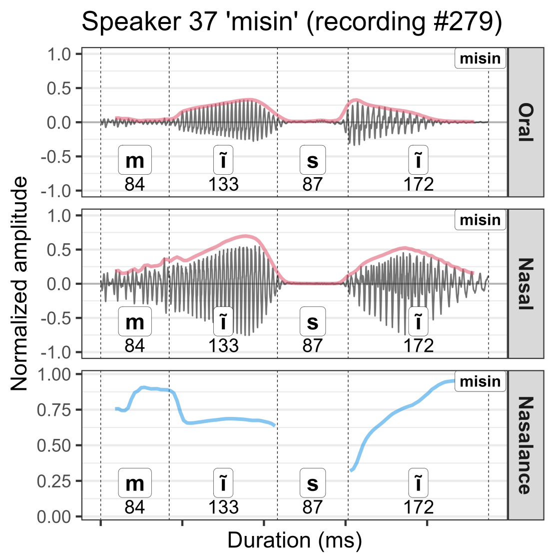


Figure 8: Sample token of a derived nasal vowel /NV/ → [NṼ], *misin* /misi/ → [ˈmĩ̠.sĩ] 'worm'.

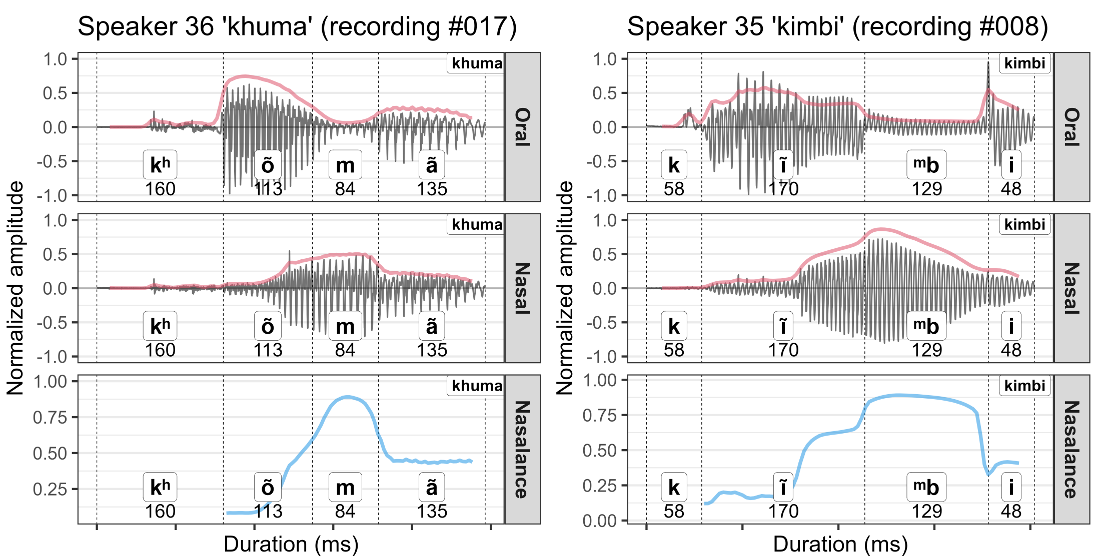


Figure 9: Sample token of a vowel with partial nasalization preceding [N], *khuma* /k$^{\text{h}}$oma/ → [ˈk$^{\text{h}}$õ̠.mã] 'chile' (left) and preceding [$^{\text{N}}$D], *kimbi* /ki$^{\text{m}}$bi/ → [ˈkĩ̠.$^{\text{m}}$bi] 'tired' (right).

Vowels may also show consistent, and relatively high levels of nasality preceding [N, $^{\text{N}}$D], rather than a cline-like increase (Fig. 10).

Lastly, some vowels preceding [N, $^{\text{N}}$D] are essentially oral for most of their duration (Fig. 11)

5.2 Statistical analysis using GAMMs

We modeled nasalance trajectories using a generalized additive mixed model (GAMM), following Winter & Wieling (2016), Sóskuthy (2017, 2021), Baayen et al. (2017), Wieling (2018) and Baayen & Linke (2021). GAMMs were fit using the `bam()` function in the `mgcv` package (Wood 2017).[11]

The dependent measure was vowel nasalance. Our goal was to model nasalance trajectories

[11] The `mgcv::bam()` function excludes tokens with missing values. Before fitting a GAMM, missing nasalance values were supplied using the `downup` imputation method of `tidyr::fill()` (Wickham et al. 2024).

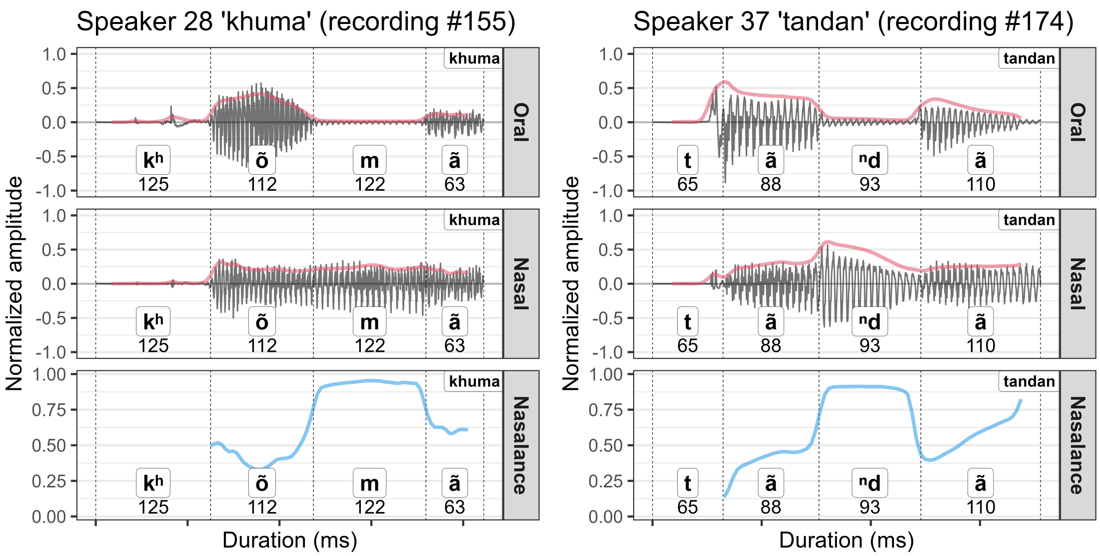


Figure 10: Sample token of a vowel with full nasalization preceding [N], *khuma* /k^{h}oma/ $\rightarrow$ [ˈk^{h}õ̲.mã] ‘chile’ (left) and preceding [^{N}D], *tandan* /ta^{n}dã/ $\rightarrow$ [ˈtã̲.^{n}dã] ‘tied’ (right).

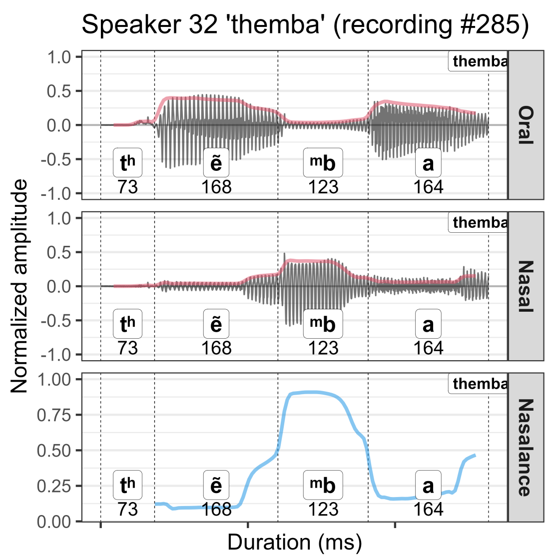


Figure 11: Sample token of a pre-nasal vowel with prolonged orality, *themba* [ˈt^{h}e^{m}ba] ‘branch’.

over time for vowels in each of our key experimental conditions: contrastive oral /V/; contrastive /Ṽ/; phonologically derived /NV/ $\rightarrow$ [NṼ]; and pre-nasal [ṼN, Ṽ^{N}D]. Here, we focus on the fixed-effects structure of the model; see the appendix for additional details of model fitting, including random effects.

Our fixed effects included a difference smooth for Nasality class, comparing nasalance across timesteps for contrastive oral /V/, contrastive /Ṽ/, phonologically derived /NV/ $\rightarrow$ [NṼ], and [ṼN, Ṽ^{N}D]. Following Sóskuthy (2017), we also included a reference smooth for Timestep, and a parametric term for Nasality class. All smooths used thin plate regression splines as the basis type (Wood 2003), with knots set at $k = 17$ (the maximum possible, given 17 timesteps).

We treated [ṼN] and [Ṽ^{N}D] as separate levels of Nasality class. This was to allow for the possibility that nasalance patterns might be different in [ṼN] and [Ṽ^{N}D]. Our results nonetheless suggest that nasalance patterns are comparable for [ṼN] and [Ṽ^{N}D].

The GAMM included parametric fixed-effects for several control predictors. First, vowel height is known to affect nasality, for both articulatory and aerodynamic reasons (sections 4.1, 4.4). This motivates the inclusion of a control predictor for V Quality in our models, with levels /a e i o ɨ/. The manner of articulation of the consonant in a [CṼ] sequence can also affect vowel nasalization (e.g. Bellavance et al. 2024). To control for this possibility, we included Preceding C as a parametric fixed-effect. The levels for this control predictor were Fricative, Plosive, Prenasalized ^{N}D, and # (= word-initial vowel). In the [NṼ] condition, the preceding consonant was always nasal: for vowels in this condition, the value for Preceding C was specified as the value of the *following* consonant instead (which was always an oral fricative or plosive).

We also included a smooth term for V duration (again using thin plate regression splines, knots set to $k = 9$). This was motivated by prior observations that vowel nasality may vary with speech rate and/or vowel duration (e.g. Solé 2007). We explore the potential effect of duration on vowel nasality in more detail in section 5.2.2.

Nasality class was treatment coded as an ordered factor with /Ṽ/ as the reference level. V quality and Preceding C were also treatment coded, with reference levels [a] and # (= word-initial vowel) respectively. V Duration and Timestep were mean-centered.

The model structure is summarized in Table 3. Since V quality and Preceding C are included primarily as controls, we omit detailed discussion of those predictors, and do not provide model estimates for their individual levels in Table 3.

Nasalance (%) ∼ Nasality class + V quality + Preceding C +
s(Duration, bs="tp", k=9) + s(Timestep, bs="tp", k=17) + s(Timestep, by = Nasality class, bs="tp", k=17) +
s(Word, bs="re") + s(Timestep, Speaker, bs="fs", m=1)

Parametric terms	Estimate	SE	t	p
(Intercept)	59.94	2.04	29.33	$< .001$*
Nasality class (reference = /Ṽ/)				$< .001$*
/NV/ → [NṼ]	2.84	1.78	1.60	.11
[ṼN]	-5.89	1.54	-3.83	$< .001$*
[Ṽ^{N}D]	-3.28	1.50	-2.19	$< .05$*
Oral [V]	-30.22	1.53	-19.73	$< .001$*
Preceding C				$< .001$*
V quality				$< .05$*

Smooth terms	edf	Ref. df	F	p
s(Timestep) (mean-centered)	13.79	14.38	40.74	$< .001$*
s(Timestep, by = Nasality class)				
/NV/ → [NṼ]	14.79	15.73	228.82	$< .001$*
[ṼN]	14.03	15.34	121.50	$< .001$*
[Ṽ^{N}D]	13.64	15.11	121.12	$< .001$*
Oral [V]	11.09	13.31	154.13	$< .001$*
s(Duration) (mean-centered)	4.19	5.21	6.43	$< .001$*

Table 3: Fixed-effects estimates for GAMM, fit to vowel nasalance at 17 time-normalized steps.

Fig. 12 shows the nasalance trajectories that the GAM model predicts for each segmental condition. These predicted trajectories are marginal effects, i.e. they are generalized over all other factors in the model (V quality, Preceding C, V duration, and the random effects).

Underlying nasal /Ṽ/ shows high levels of nasality throughout the vowel in Fig. 12, apart from

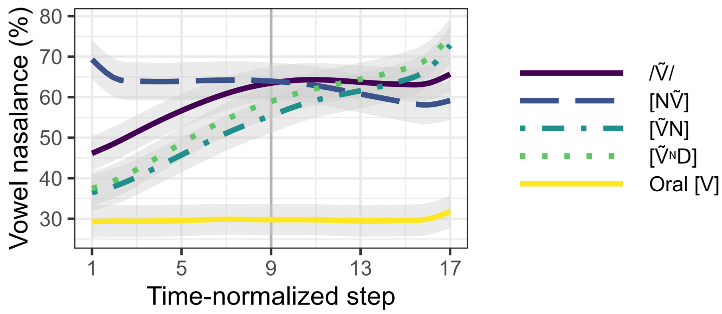


Figure 12: Model predictions for vowel nasalance by nasality class. Gray bands indicate confidence intervals around predicted values. Produced with `tidygam::predict_gam()` (Coretta 2024).

an initial rise which likely reflects coarticulatory influence from preceding oral consonants (see sections 5.3.1, 6.1 for more on [CṼ] coarticulation). Derived nasal vowels /NV/ → [NṼ] are consistently nasal throughout, with a slight initial drop in nasality reflecting the transition from the preceding nasal consonant. Oral vowels display low, unchanging nasality across their durations. Most importantly, vowels preceding [N, ᴺD] show a cline-like pattern of partial nasalization, beginning low, and rising gradually toward the following nasal consonant.

Fig. 13 shows difference smooths comparing pre-nasal [ṼN, ṼᴺD] to the other conditions in our study (contrastive nasal /Ṽ/, phonologically derived /NV/ → [NṼ], and contrastive oral /V/).

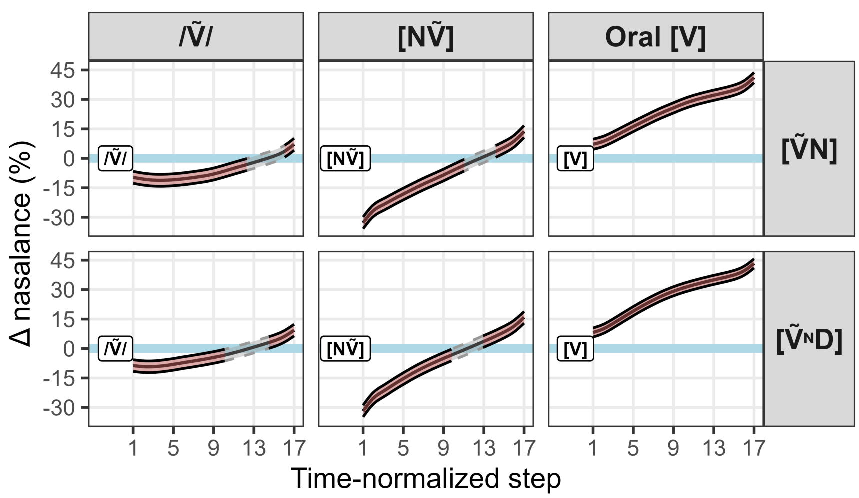


Figure 13: Difference smooths comparing nasalance across conditions. Positive values indicate greater estimated nasalance for [ṼN] or [ṼᴺD] (rows) relative to comparison category (columns); negative values indicate greater estimated nasalance for comparison category. Red regions with solid outlines correspond to significant differences between compared conditions; grey regions with dashed outlines indicate the lack of a significant difference. Produced with `tidygam::get_difference()` (Coretta 2024).

As implied by Fig. 12, pre-nasal [ṼN, ṼᴺD] have lower nasality than contrastive nasal /Ṽ/ up to somewhere around step 10-12 (≈ 60-70% of the vowel's duration). At the tail end of their trajectories, pre-nasal [ṼN, ṼᴺD] have higher nasality than contrastive nasal /Ṽ/, reflecting a transition into the following nasal consonant for [ṼN, ṼᴺD].

The same pattern holds for pre-nasal [ṼN, ṼᴺD] compared to phonologically derived /NV/ → [NṼ], though the magnitude of the difference in nasality is larger. This reflects the fact that derived /NV/ → [NṼ] begins with a nasal consonant, and so has the highest initial nasality of all vowel types in our study (Fig. 12).

Finally, pre-nasal [ṼN, Ṽ^{N}D] have higher nasality than contrastive oral /V/ at all time points, with the size of the difference growing substantially over time as nasality increases in [ṼN, Ṽ^{N}D].

5.2.1 Nasalance patterns by speaker

Fig. 14 shows smoothed nasalance trajectories for each condition, grouped by speaker. These smooths were fit over the raw data, rather than our model predictions; the by-speaker predictions of our model are comparable.

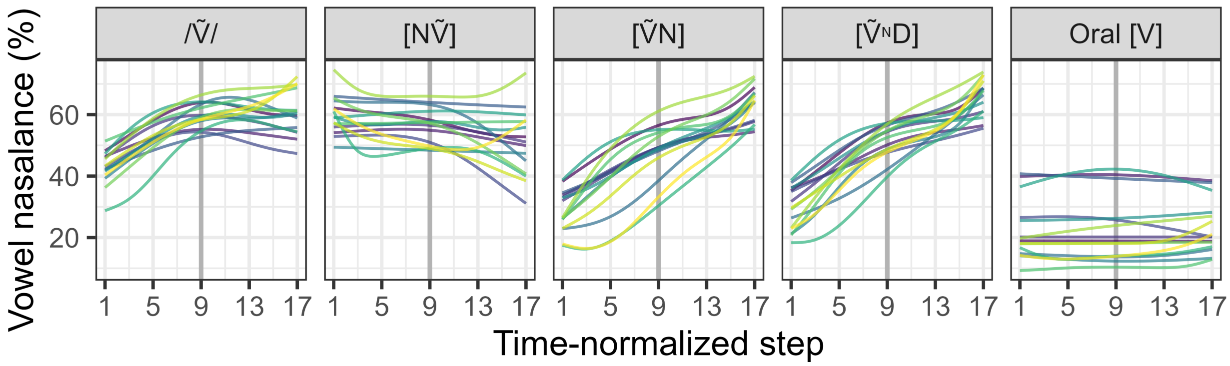


Figure 14: GAM smoothed nasalance traces over raw nasalance, by speaker and nasality class.

While the trajectories in Fig. 14 are not identical across speakers, they are generally quite similar, and clearly reflect the overall trends plotted in Figs. 12, 13.[12]

We conclude that the population-level patterns reported in our statistical analysis are broadly representative of how individual A'ingae speakers realize vowels across these contexts. We return to speaker-level patterns in section 5.3.5.

5.2.2 Effects of speech rate and vowel duration

Our speech rate manipulation (slow vs. fast productions) affected vowel duration as expected. The mean vowel duration for slow repetitions (154ms) was longer than the mean vowel duration for fast repetitions (124ms), according to a t-test ($p < .001$). The [2.5%, 97.5%] data range for duration was [84, 224]ms, mean = 139ms, median = 132ms, SD = 46ms.

To assess the potential effect of vowel duration on nasality, we added two fixed effects to the model described above: a smooth allowing the effect of duration to vary by timestep (= s(Timestep, Duration, bs="tp", k = 17)), and a smooth allowing the effect of duration at each timestep to vary depending on the condition (= s(Timestep, Duration, by = Condition, bs="tp", k = 17)).[13]

Fig. 15 shows how duration modulates — or mostly, fails to modulate — nasalance within each level of Nasality class. It is evident from Fig. 15 that vowel duration has essentially no predicted

[12] We speculate that inter-speaker differences in nasalance values for baseline oral vowels /V/ in Fig. 14 owe to anatomical variation, possibly related to gender and/or age. See e.g. Rochet et al. (1998), Young et al. (2001), Okalidou et al. (2011), Zellou (2022:28). It may also be that some speakers had greater leakage between the oral and nasal chambers of the air pressure mask than others.

[13] These duration-related fixed effects were not included in the initial GAMM because their addition increases concurvity above recommended levels. The results presented in Figs. 12, 13 are essentially unchanged when these duration-related predictors are included in the model. See the appendix for more discussion.

effect on the nasalance contours for contrastive nasal /Ṽ/, or pre-nasal [ṼN, Ṽ$^{\mathrm{N}}$D].

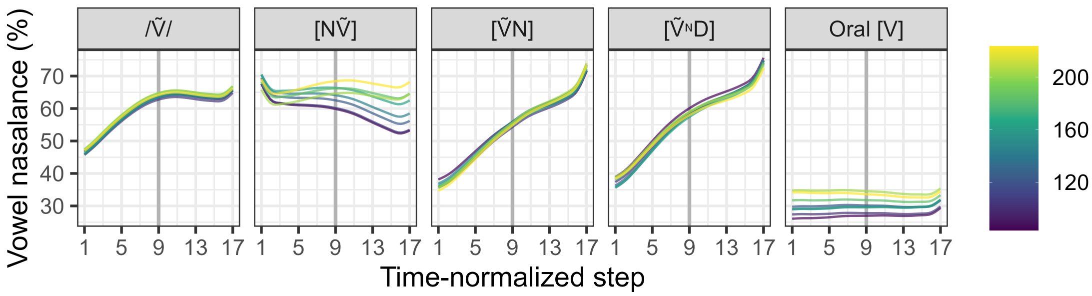


Figure 15: Model predictions for nasalance, as a function of vowel duration and nasality class. Lines correspond to 20ms increments in the range [84, 224]ms, the [2.5%, 97.5%] range for duration in our data. Confidence intervals omitted for readability. Produced with `tidygam::predict_gam()` (Coretta 2024).

At shorter durations, the nasalance contour for /NV/ → [NṼ] declines more strongly. We interpret this as an effect of coarticulation with the following oral consonant: a fixed amount of local coarticulation at the [Ṽ-C] transition in [NṼ.C] will have a greater *proportional* effect on shorter vowels. However, we do not know why the same effect is absent for contrastive /Ṽ/, as these vowels are also followed by oral consonants. Oral vowels slightly increase in nasality at longer durations.

These results hold even when (i) duration is replaced with a categorical predictor for Requested Speech Rate (fast vs. slow), or (ii) Requested Speech Rate is included alongside the duration-related predictors described above. In both cases, the nasalance contours that our GAM model predicts for [ṼN, Ṽ$^{\mathrm{N}}$D] are essentially insensitive to changes in vowel duration and/or speech rate, as in Fig. 15. (We omit plots demonstrating this finding for reasons of space.)

5.2.3 Discussion of GAMM results

These results align with our qualitative observation that pre-nasal vowels in [ṼN, Ṽ$^{\mathrm{N}}$D] are often produced with nasalization that is *partial* (increasing over time) when compared to contrastive /Ṽ/ or derived /NṼ/ → [NṼ]. Importantly, partial nasalization in [ṼN, Ṽ$^{\mathrm{N}}$D] does not appear to be conditioned by vowel duration or speech rate.

Our GAMM analysis confirms that vowels in [ṼN, Ṽ$^{\mathrm{N}}$D] are phonetically distinct from both contrastive [+nasal] vowels /Ṽ/ and allophonic [+nasal] vowels /NV/ → [NṼ]. Pre-nasal vowels in [ṼN, Ṽ$^{\mathrm{N}}$D] are also phonetically distinct from [-nasal] oral vowels /V/. This three-way phonetic distinction between [+nasal] vowels, [-nasal] vowels, and [ṼN, Ṽ$^{\mathrm{N}}$D] motivates our claim that vowels in [ṼN, Ṽ$^{\mathrm{N}}$D] contexts are phonetically and phonologically unspecified for nasality.

In the following section we build on these results by showing that the timing of nasality in [ṼN, Ṽ$^{\mathrm{N}}$D] is highly variable, consistent with the qualitative patterns in section 5.1, and with a formal analysis based on nasal underspecification.

5.3 The timecourse of nasality in [ṼN, Ṽ$^{\mathrm{N}}$D]

As observed in section 5.1, vowels in [ṼN, Ṽ$^{\mathrm{N}}$D] in A'ingae seem to vary from fully nasal, to partially nasal, to mostly oral. We illustrate this variation in Fig. 16 (see also Figs. 9, 10, 11, etc.).

To better understand how nasality is realized on vowels in [ṼN, Ṽ$^{\mathrm{N}}$D] in A'ingae, in this section we analyze the timecourse of vowel nasality in [ṼN, Ṽ$^{\mathrm{N}}$D] in quantitative terms. To do this, we used the `sicegar` package in R (Caglar et al. 2018) to fit sigmoidal ('s'-shaped) curves to measurements

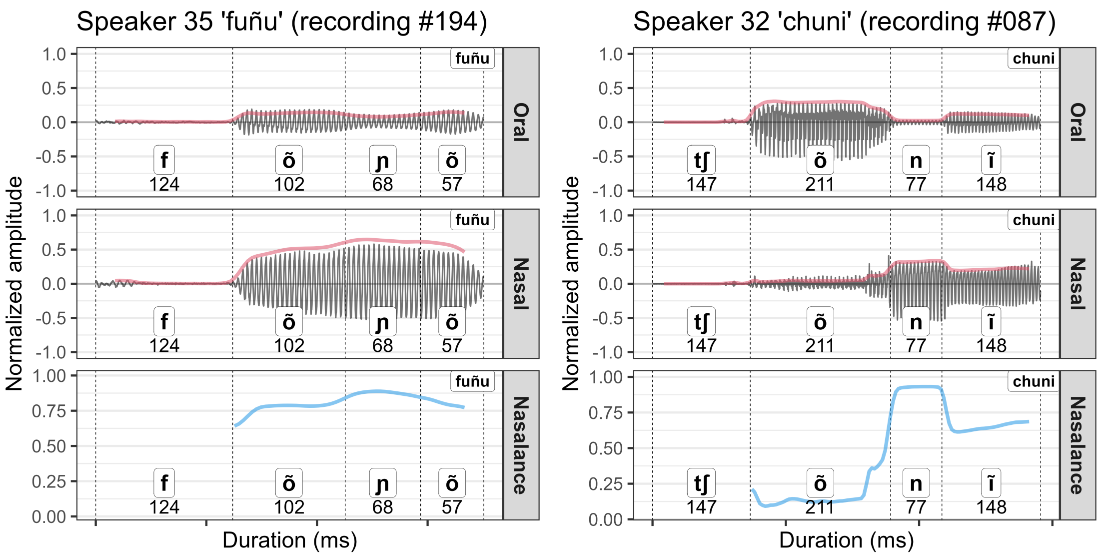


Figure 16: Sample tokens of pre-nasal vowels with early nasality, *fuñu* /foɲõ/ 'skirt' (left), and prolonged orality, *chuni* /t͡ʃoni/ 'nutria' (right).

of nasality over time (a method borrowed from Pouplier et al. 2024). The shape of these curves can then be used to estimate when nasality begins to rise (if at all) during any particular token.

The `sicegar` package attempts to classify whether time-varying data shows a pattern of change which resembles a sigmoidal curve. A sigmoidal ('s'-shaped) curve typically begins with a relatively flat set of values, which at some point steadily increases until reaching a maximum value (Fig. 17, left panel). The `sicegar` package can also classify tokens as having a double-sigmoidal curve, consisting of a sigmoidal rise followed by a sigmoidal fall (Fig. 17, center panel). Note that `sicegar` will fit 'sigmoids' which are close to linear (Fig. 17, right panel): these are sigmoids with a low value for the slope parameter k in the logistic function $y = \frac{Max(y)}{1+e^{-k(x-m)}}$, which is the basis of the sigmoids fit by `sicegar` (see Caglar et al. 2018 for additional details).

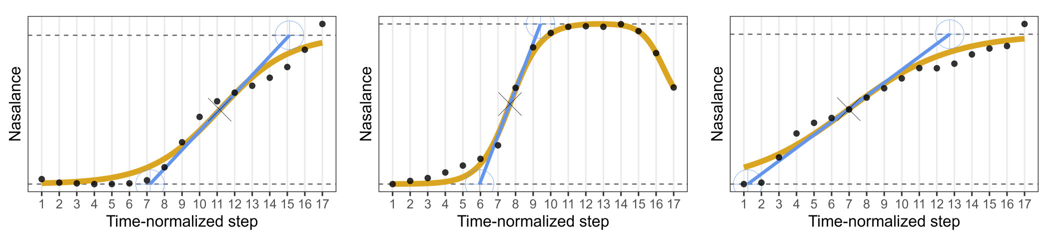


Figure 17: Sample sigmoidal (left), double sigmoidal (center), and quasi-linear (right) fits. Black dots indicate original measurements of nasalance. Blue lines are tangent to sigmoidal curve at midpoint of rise, marked with X. Estimated start time of rise is marked with bullseye intersecting minimum value of data; estimated end time is marked with bullseye intersecting maximum of curve.

The timing of a nasalance rise can be estimated by drawing a line tangent to the midpoint of the rising portion of the sigmoidal curve (Fig. 17). The intersection of this tangent with the line marking the minimum value of the input data provides an estimate of the start time of the rise. The intersection of this tangent with the line marking the maximum value in the sigmoidal curve provides an estimate of the end time of the rise.

Several parameter settings affect how the `fitAndCategorize()` function in `sicegar` detects rises, and how stringent it is about model fit for any given curve. We chose fairly strict parameter settings which were intended to report a rise only for vowels which truly had an oral-to-nasal transition, and not just any kind of increase in nasalance (e.g. a change from nasal to more strongly nasal). Our results are thus conservative, and may undercount the number of tokens which show a significant increase in nasality during the vowel. Details on the parameter settings used here are provided in the appendix. We manually classified oral vowels [V], and allophonically nasalized vowels produced by harmony /NV/ → [NṼ], as not having an oral-to-nasal rise (Figs. 12, 14).

5.3.1 Overall trends for oral-to-nasal transitions

Fig. 18 shows the number of tokens classified as having an oral-to-nasal rise in three conditions: contrastive /Ṽ/, [ṼN], and [Ṽ^{N}D]. As expected, oral-to-nasal rises are far more common for [ṼN, Ṽ^{N}D] (about 40% of tokens) than for contrastive /Ṽ/ (about 15% of tokens).

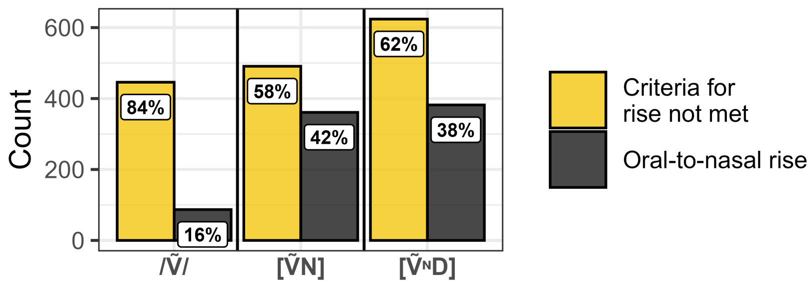


Figure 18: Barplot of nasalance traces classified as sigmoidal (black) vs. non-sigmoidal (yellow) with `sicegar` package in R, by condition. Percentages are within-condition.

Oral-to-nasal rises seem more gradual for [ṼN, Ṽ^{N}D] compared to contrastive /Ṽ/ (Fig. 19, dashed black lines). Peak nasality also occurs later in [ṼN, Ṽ^{N}D] than in /Ṽ/. Even for tokens which are identified as *lacking* an oral-to-nasal rise, the achievement of peak nasality is later in [ṼN, Ṽ^{N}D] than in /Ṽ/ (Fig. 19, solid yellow lines). These timing differences are consistent with our GAMM results (Figs. 12, 13). In general, contrastive nasal vowels /Ṽ/ seem to be fully nasalized by vowel midpoint or earlier, while full nasality in [ṼN, Ṽ^{N}D] occurs later (see also Huffman 1989).

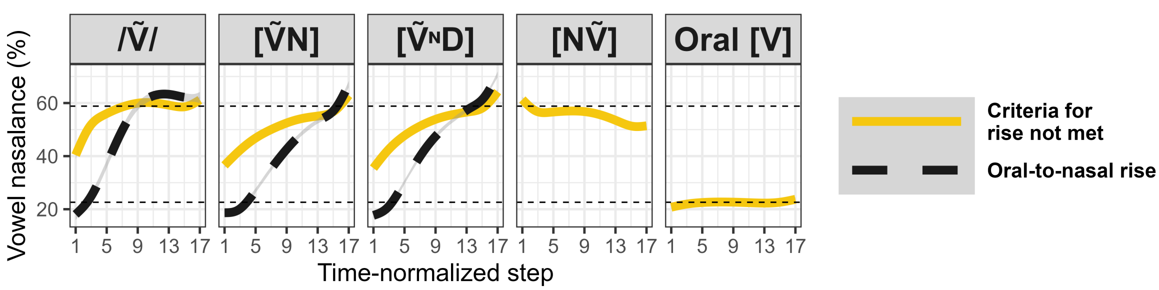


Figure 19: GAM-smoothed nasalance contours for tokens identified as having vs. lacking an oral-to-nasal rise, by condition. Dashed horizontal lines show mean nasalance for contrastively oral (lower) and nasal vowels /Ṽ/ (upper), taken across steps 6-12.

The presence of an oral-to-nasal rise does not appear to be tied to vowel duration. For contrastive /Ṽ/, [ṼN], and [Ṽ^{N}D], *t*-tests find no significant differences in duration between vowels identified as having vs. lacking an oral-to-nasal rise ($p > .085$ in all cases, largest mean difference = 6ms). These patterns are consistent with our finding above that duration is not a significant predictor of nasalance trajectories (section 5.2.2).

5.3.2 Start times of oral-to-nasal transitions

Fig. 20 shows the distribution of rise times for vowels identified as having an oral-to-nasal transition in /Ṽ/ and [ṼN, Ṽ^{N}D]. Almost all rises for /Ṽ/ begin before step 7, while there are many tokens of [ṼN, Ṽ^{N}D] with rises that begin later than step 7.[14]

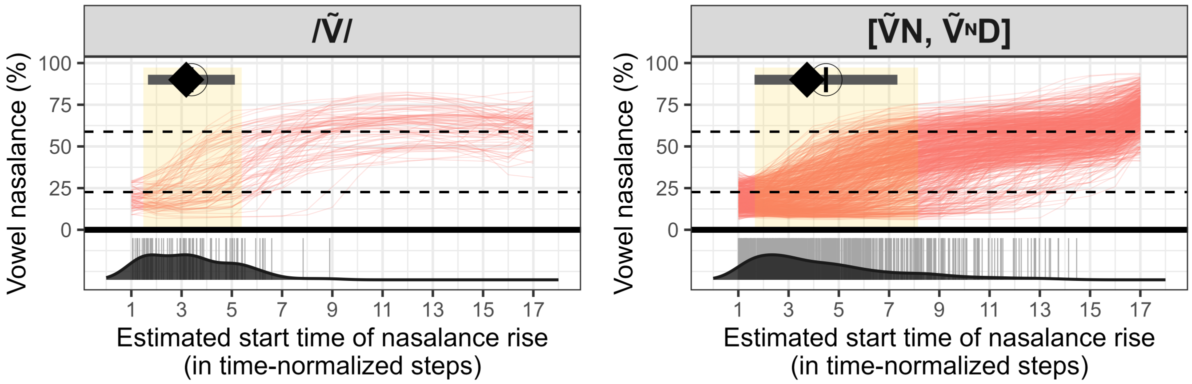


Figure 20: Start times for oral-to-nasal rises in /Ṽ/ and [ṼN, Ṽ^{N}D], in normalized time. Top of each figure (above 0 line): Individual nasalance traces shown in red. Dashed black lines mark mean nasalance for contrastive oral /V/ and nasal /Ṽ/ vowels (Fig. 19). Bottom of each figure (below 0 line): Vertical gray lines show estimated rise times for individual tracings. Density plot shows overall distribution. Shaded yellow regions cover middle 75% of rise times, [12.5%, 87.5%]. Open circles indicate means, diamonds medians, and grey horizontal bars ± 1 standard deviations from the mean.

For [ṼN, Ṽ^{N}D], most oral-to-nasal rises begin between time steps 2 and 8, i.e. in the first ≈45% of the vowel. There is a clump of values between steps 1-3, in the first ≈15-20% of the vowel. There is also a very long tail of estimated rise times, extending past the 14th time step (≈85% of the vowel).

It seems clear that nasality occurs relatively late in [ṼN, Ṽ^{N}D] when compared to contrastive /Ṽ/. Although there are some contrastive /Ṽ/ tokens which begin with low levels of nasality, they are infrequent: the vast majority of /Ṽ/ tokens begin with moderate-to-strong nasality (Figs. 18, 19). Even for those tokens of contrastive /Ṽ/ which do begin with low nasality, nasality increases early in the vowel. This is not the case for [ṼN, Ṽ^{N}D], which includes many tokens that have prolonged oral stretches before increasing in nasality (Figs. 19, 20).

We interpret the brief nasalance rises at the beginning of contrastive nasal /Ṽ/ as primarily reflecting coarticulation with the preceding oral consonant (e.g. Delvaux et al. 2008:592-5, Bellavance et al. 2024; see also Desmeules-Trudel & Brunelle 2018). In any event, it is clear that the timing of nasality is quite different in [ṼN, Ṽ^{N}D] than in /Ṽ/. Further, the source of these timing differences is not the preceding consonant, which was always either oral or prenasalized for both [ṼN, Ṽ^{N}D] and /Ṽ/. Nor can these timing differences be attributed to the influence of vowel height, because vowel height was varied in both conditions (e.g. Kunay et al. 2022).

In what follows, we focus our discussion on the results for [ṼN, Ṽ^{N}D]. There appears to be no

[14]Plots like Fig. 20 do not include tokens which are strongly nasal throughout (e.g. Fig. 28 below), or tokens which begin with intermediate nasality and then increase in nasality over time (e.g. Fig. 32 below). For these tokens, the phonetic onset of nasality is effectively step 1 (the earliest measurement point during the vowel), or potentially even earlier, during the preceding oral consonant (e.g. Delvaux et al. 2008). The existence of many such tokens should be borne in mind when interpreting our results; see also Figs. 18, 19.

correlation between vowel duration and estimated rise time in [ṼN, Ṽ$^{\mathrm{N}}$D]. Across vowel durations, rise times can be found which span essentially all timesteps (Fig. 21).

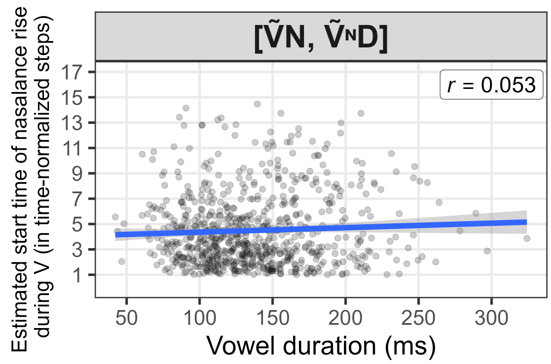


Figure 21: No correlation between V duration and start of oral-to-nasal rise (in time-normalized steps).

It seems that nasality may begin to rise at essentially any point during the vowel in [ṼN, Ṽ$^{\mathrm{N}}$D]. While there is a bias toward early rises, late rises are also quite common, even across changes in speech rate and duration.

Similar variability can also be observed if we consider rise times in physical ms, rather than normalized time (Fig. 22). Although oral-to-nasal rises *tend* to occur in the first ≈70ms after vowel onset, and/or around 150 to 50ms before vowel offset, there is a wide distribution of rise times in each case. (The mean vowel duration in our data is 139ms, SD = 46ms, median = 132ms.)

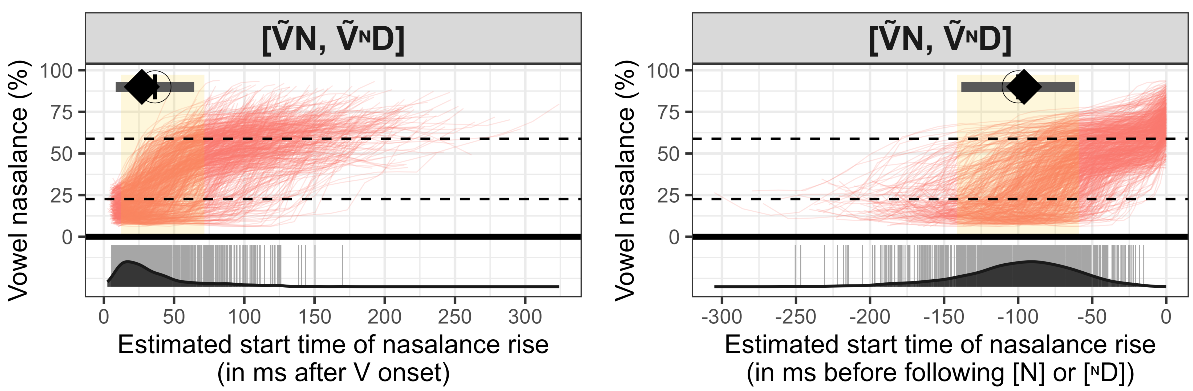


Figure 22: Start times for oral-to-nasal rises in [ṼN, Ṽ$^{\mathrm{N}}$D], in ms after vowel onset (left) and before vowel offset (right). See Fig. 20 for more details.

Pouplier et al. (2024) estimate that "25 ms [is] needed minimally to arrive at peak [velar] opening" for a nasal stop. The majority (73%) of oral-to-nasal rises for [ṼN, Ṽ$^{\mathrm{N}}$D] begin more than 75ms before the following nasal consonant (Fig. 22, right panel). Though it is hard to pin down what a truly minimal amount of coarticulation for nasality would be in a [VN] or [V$^{\mathrm{N}}$D] sequence, it is clear that the onset of nasality in [ṼN, Ṽ$^{\mathrm{N}}$D] in our data typically exceeds any plausible threshold for mechanical coarticulation with the following [N] or [$^{\mathrm{N}}$D].

5.3.3 End times of oral-to-nasal transitions

The same patterns of variability can be observed for the estimated *end* points of the nasalance rises in [ṼN, Ṽ$^{\mathrm{N}}$D] (Fig. 17). First, the estimated end points span the entire range of time-normalized steps, with little evidence of clustering around any particular value (Fig. 23). And again, there is no apparent correlation between vowel duration and the end point of the rise.

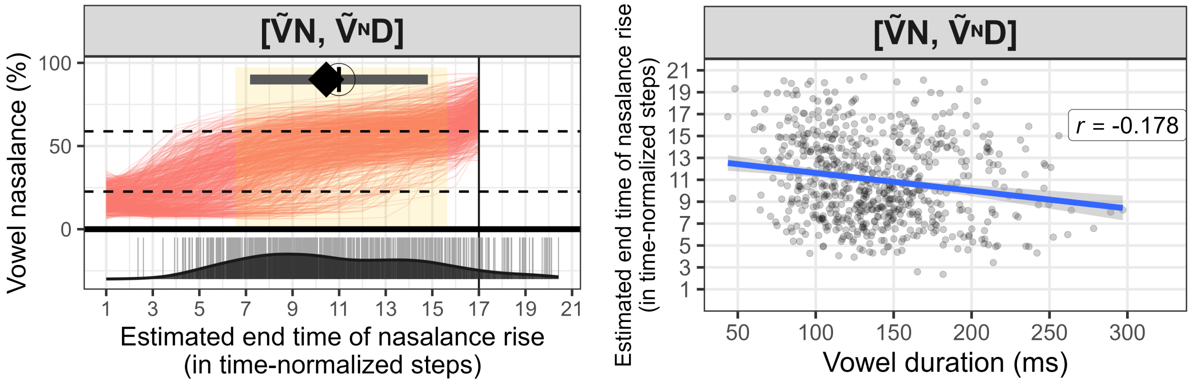


Figure 23: End times for oral-to-nasal rises in [ṼN, Ṽ$^{\text{N}}$D], in normalized time (left), and correlated with V duration (right). Estimated end points larger than 17 imply that nasalance reaches a peak *after* vowel offset.

In physical ms, the same patterns hold (Fig. 24). The end of a nasalance rise in [ṼN, Ṽ$^{\text{N}}$D] does not lag the beginning or end of the vowel by any consistent amount of time.

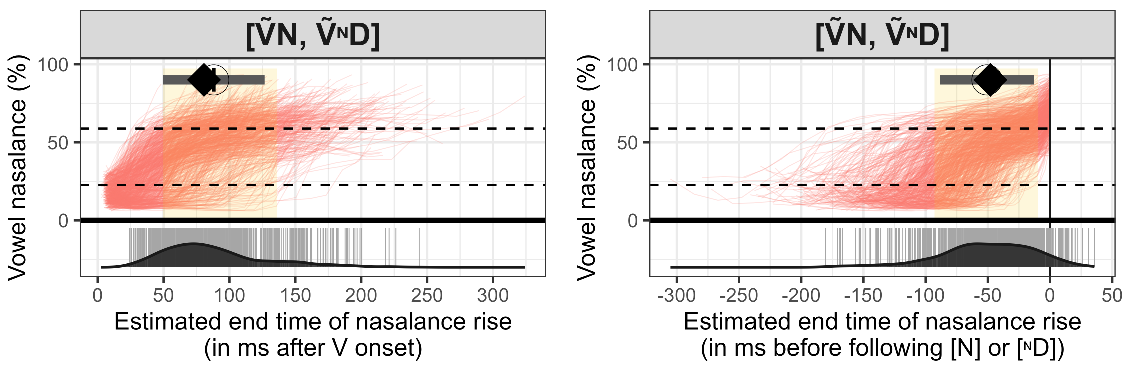


Figure 24: End times for oral-to-nasal rises in [ṼN, Ṽ$^{\text{N}}$D], in ms after vowel onset (left) and before vowel offset (right) (see Fig. 20 for more details). Estimated end points larger than 0 in right panel imply that nasalance reaches a peak *after* vowel offset.

5.3.4 Interim summary of timing patterns for nasality in pre-nasal [ṼN, Ṽ$^{\text{N}}$D]

The timecourse of nasality in [ṼN, Ṽ$^{\text{N}}$D] sequences in A'ingae is quite variable. The onset of nasality may occur at essentially any point; the same is true for the achievement of peak nasality. Vowels in [ṼN, Ṽ$^{\text{N}}$D] may be fully nasalized, nasalized fairly early, or nasalized quite late. While certain outcomes are more common than others, all of these outcomes are robustly attested in our data. Variation in the time course of nasalization appears to be unrelated to vowel duration.

5.3.5 Speaker-level timing patterns for pre-nasal [ṼN, Ṽ$^{\text{N}}$D]

In this section we explore timing patterns for nasality in [ṼN, Ṽ$^{\text{N}}$D] at the level of individual speakers (see also Beddor et al. 2018, Zellou 2022). Caution must be taken in interpreting speaker-level data, because the amount of data we have for each speaker is limited (= 118-129 tokens of [ṼN, Ṽ$^{\text{N}}$D] per speaker). There is a risk that spurious patterns might occur in a particular speaker's dataset, as an artifact of data sparsity in our modestly-sized samples. Still, we believe we have enough data to claim that individual speakers show approximately the same patterns of timing variability reported in aggregate in section 5.3.2.

Fig. 25 shows the start points for oral-to-nasal transitions in [ṼN, Ṽ^{N}D], grouped by speaker.

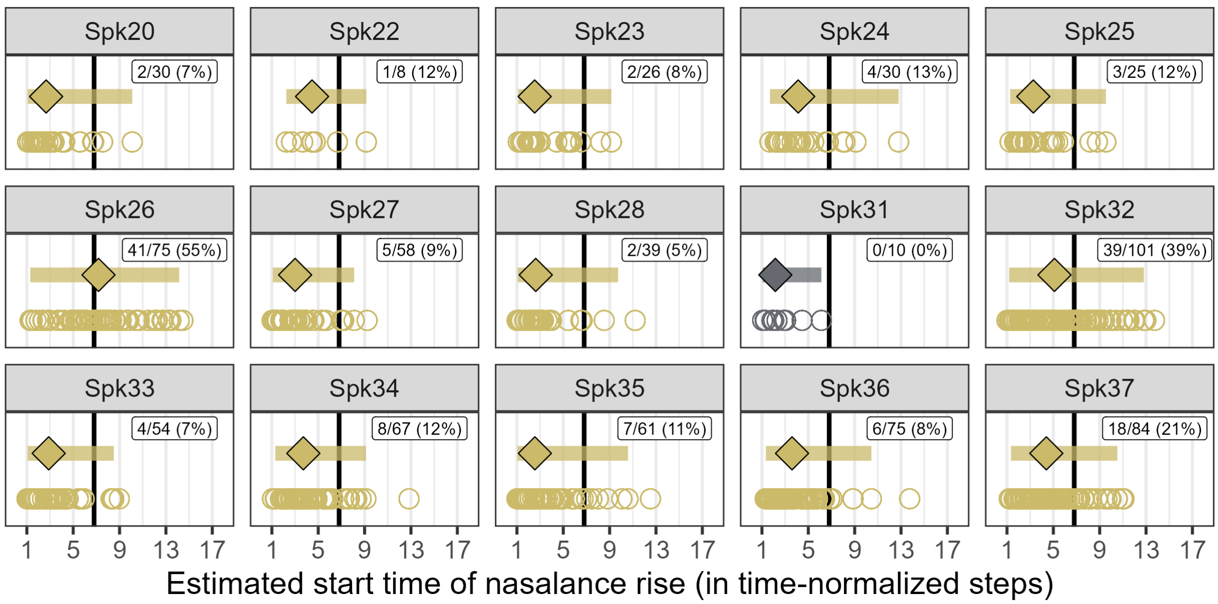


Figure 25: Start times for oral-to-nasal transitions in [ṼN, Ṽ^{N}D] by speaker (time-normalized). Diamonds indicate median values, horizontal bands [2.5%, 97.5%] data range. Open circles mark start times for individual observations. Vertical black line marks 40% of time- normalized vowel duration. Boxed numbers tally [ṼN, Ṽ^{N}D] tokens classified as having late rises for each speaker, and associated percentage of that speaker's total oral-to-nasal rises.

If the [2.5%, 97.5%] data range for a given speaker extended past 40% of time-normalized vowel duration (= step 6.8) we classified that speaker as having at least *some* [ṼN, Ṽ^{N}D] tokens with significantly delayed nasality. Otherwise, we classified that speaker as having only early rises in nasality in [ṼN, Ṽ^{N}D].

The 40% threshold was chosen somewhat arbitrarily as reflecting a fairly late onset of vowel nasality. Since the data points in Fig. 25 correspond to the estimated *onset* of an oral-nasal transition, rather than the achievement of significant nasality, we believe this is a reasonably stringent criterion for counting as a vowel with 'late' nasality (see Figs. 19-24).

By this criterion, 14/15 of our speakers had at least some [ṼN, Ṽ^{N}D] tokens with significantly delayed nasality. For 3 speakers (26, 32, and 37), late rises were very common, constituting 21-55% of all oral-nasal transitions. For 5 speakers (22, 24, 25, 34, 35), late rises were a minority pattern, but nonetheless corresponded to at least 10% of each speaker's oral-nasal transitions. For the remaining speakers, late rises constituted 0-10% of the total.

The same patterns are evident in physical ms, as shown in Fig. 26. We set a somewhat arbitrary threshold of 50ms as the criterion for a 'late' onset of vowel nasality (= 38% of the 132ms median vowel duration for [ṼN, Ṽ^{N}D] in our study). By this criterion, all speakers in our study had at least some late rises (though the proportion varies, as with the time-normalized data in Fig. 25). And again, these rise times indicate the *onset* of vowel nasality, rather than the ultimate achievement of target nasality later in the vowel.

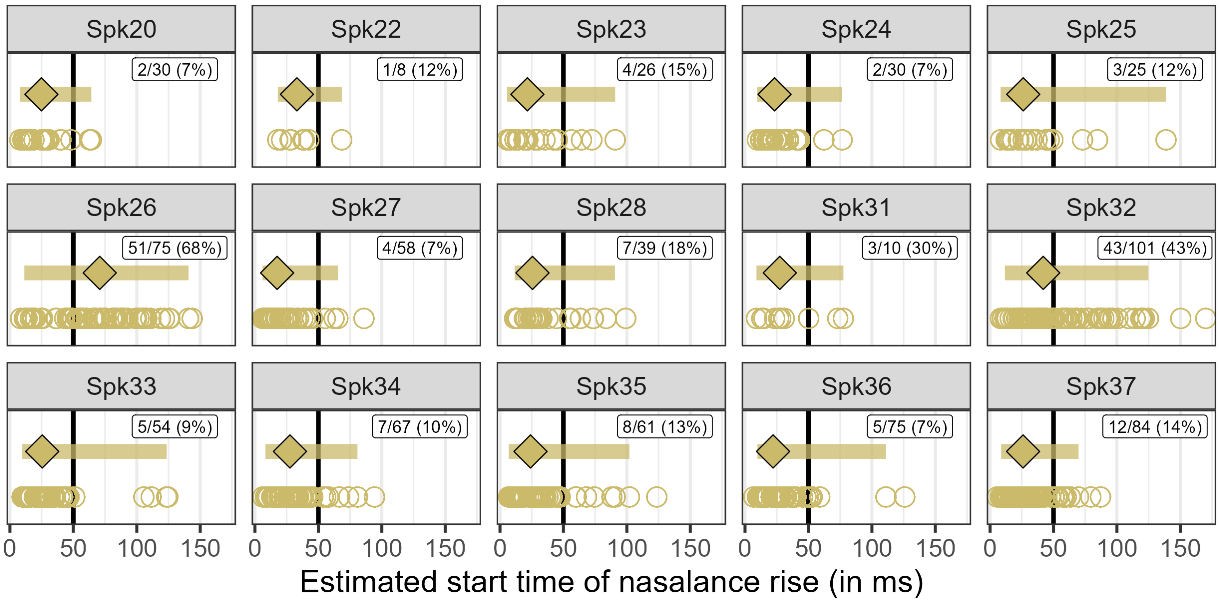


Figure 26: Start times for oral-to-nasal transitions in [ṼN, Ṽ$^{\mathrm{N}}$D] by speaker (in ms). Criterion for 'late' rise: start time $\geq$ 50ms. See Fig. 25 for more details.

We conclude that variability in the timing of nasality in [ṼN, Ṽ$^{\mathrm{N}}$D] is not an artifact of pooling across speakers with different, stable timing patterns. The same timing variability seen in macro, across speakers, can also be seen in micro, at the level of individual speakers. Similarly, timing variability is not an artifact of time-normalization, as the same variability is evident in physical ms.

6 Formal analysis: contextual underspecification of nasality

Phonologically, there is no contrast between oral /V/ and nasal /Ṽ/ preceding [N, $^{\mathrm{N}}$D], even though vowel nasality is otherwise robustly contrastive in A'ingae. In other words, the /V Ṽ/ contrast is contextually neutralized before [N, $^{\mathrm{N}}$D]. But are these vowels neutralized to [+NASAL], to [-NASAL], or to [∅NASAL]?

There are no phonological facts known to us which clearly speak to the [NASAL] specification of vowels preceding [N, $^{\mathrm{N}}$D] (section 3.4). But phonetically, vowels preceding [N, $^{\mathrm{N}}$D] are distinct from (i) underlying oral vowels /V/, (ii) underlying nasal vowels /Ṽ/, and (iii) phonologically derived nasal vowels produced by left-to-right spreading, /NV/ → [NṼ]. In particular, the onset of nasality varies in [ṼN, Ṽ$^{\mathrm{N}}$D] between early, delayed, or very late. These timing patterns correspond to fully nasal, partially nasal, and essentially oral realizations of the vowel in [ṼN, Ṽ$^{\mathrm{N}}$D].

These phonetic facts are consistent with our claim that vowels in [ṼN, Ṽ$^{\mathrm{N}}$D] sequences are *unspecified* for nasality in A'ingae: they do not have a nasal specification or target of their own. Underspecification for nasality then produces the three-way, surface phonetic distinction between oral [V] (= [-NASAL]), nasal [Ṽ] (= [+NASAL]), and pre-nasal [ṼN, Ṽ$^{\mathrm{N}}$D] (= [∅NASAL]) that we observe in our data.[15]

[15] To produce a three-way distinction in nasality by means of underspecification, [±NASAL] must be binary rather than unary/privative. See also Cohn (1993b), Trigo (1993) and references there.

We propose that contextual underspecification is the result of a process like (12): vowels are predictably underspecified for nasality (= [∅NASAL]) when preceding nasal consonants of any kind (= {N, ᴺD}). This is true whether the vowels in question are taken to be underlyingly oral /V/ or underlyingly nasal /Ṽ/.[16] Rule (11) is neutralizing, because it collapses oral /V/ and nasal /Ṽ/ vowels into a single surface output, underspecified $\mathrm{V}_{[\varnothing\textsc{nasal}]}$. Rule (11) thus accounts for the lack of an oral /V/ vs. nasal /Ṽ/ contrast preceding [N, ᴺD] in A'ingae.

(12) Neutralization of /V Ṽ/ contrast through contextual underspecification
/V, Ṽ/ → [∅NASAL] / ___ {N, ᴺD}

In the following sections we consider alternative analyses of these facts, arguing in favor of the simple underspecification analysis in (12).

6.1 Against [+NASAL] with coarticulation

Given the significant nasalization on many vowels preceding [N, ᴺD], the question arises as to whether such vowels could be treated as [+NASAL] rather than underspecified [∅NASAL], following Solé's (1995) proposal for anticipatory nasalization in American English (section 1.1).

An obvious challenge for this approach comes from partial nasalization. In many tokens in our data, vowels in [ṼN, ṼᴺD] begin with very low nasal air pressure, growing more nasal over time (e.g. Fig. 27). Partial nasalization is *not* characteristic of underlying nasal vowels /Ṽ/ or nasal vowels derived by left-to-right spreading in [NṼ] in A'ingae. If vowels preceding [N, ᴺD] are [+NASAL], it is unclear why they do not have the phonetic characteristics of contrastive /Ṽ/ or phonologically derived [NṼ].

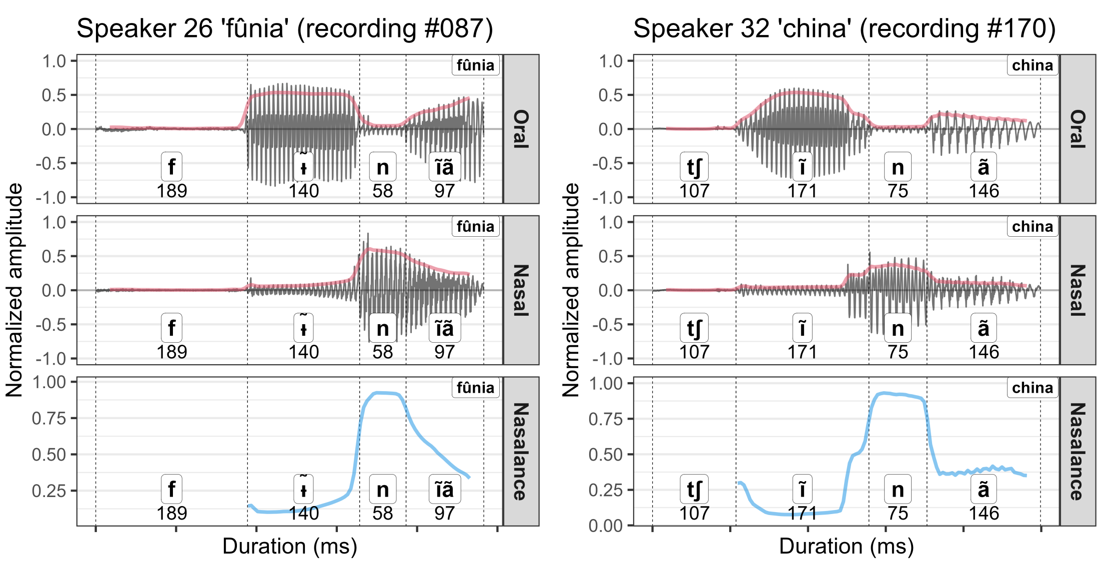


Figure 27: Sample tokens of mostly oral vowels in [ṼN], *fûnia* /fɨ̠nia/ 'round' (left), and *china* /t͡ʃi̠na/ 'daughter-in-law' (right).

[16] Rule (12) should apply equally to morpheme-internal /VN, VᴺD/ sequences and cross-morpheme /V-N, V-ᴺD/ sequences. The data in this paper bear only on morpheme-internal /VN, VᴺD/; we leave the phonetics of cross-morpheme /V-N, V-ᴺD/ for future research, but retain the strong version of rule (12) for the time being. See section 6.4.2 for some suggestive evidence regarding nasalization across morpheme boundaries.

Partial nasalization in [ṼN, Ṽ^{N}D] cannot be attributed to coarticulation with the preceding oral consonant (e.g. *pindu* [ˈpi.^{n}du] ‘hawk’). First, partial nasalization in [CṼN, CṼ^{N}D] is more extreme than the local coarticulatory effects observed in contrastive /CṼ/ (e.g. *finfin* [ˈfĩ.fĩ] ‘fanned one’s self’). Nasality can occur quite late in the vowel in [ṼN, Ṽ^{N}D] (Figs. 11, 16, 27, etc.). Nasality begins much earlier in contrastive /Ṽ/, even when slightly delayed by coarticulation (Figs. 7, 12, 19, etc.). Second, partial nasalization is far more frequent for [ṼN, Ṽ^{N}D] than for contrastive /Ṽ/ (Fig. 18), despite the fact that the preceding consonants are comparable in both conditions.

We conclude that coarticulation with a preceding oral consonant is not sufficient to explain partial nasalization in [CṼN, CṼ^{N}D], particularly in tokens with a very late onset of nasality like Fig. 27. It follows that treating vowels in [CṼN, CṼ^{N}D] as [+NASAL] does not provide an account of their phonetic differences from contrastive /Ṽ/ and phonologically derived /NV/ → [NṼ]

6.2 Against [-NASAL] with coarticulation

Alternatively, it might be possible to treat vowels preceding [N, ^{N}D] as phonologically [-NASAL]. This would straightforwardly distinguish those vowels from contrastive /Ṽ/ and derived /NV/ → [NṼ], which are unambiguously [+NASAL]. Partial nasalization could then be attributed to local phonetic coarticulation for nasality with the following [N, ^{N}D] (see also Pouplier et al. 2024).

A challenge for this analysis comes from the fact that many tokens of [ṼN, Ṽ^{N}D] in our data are *fully* nasalized, even at fairly long durations (e.g. Fig. 28). This is surprising if those vowels are [-NASAL], given that [-NASAL] vowels in languages like French show only limited coarticulation with a following nasal consonant (section 1).[17]

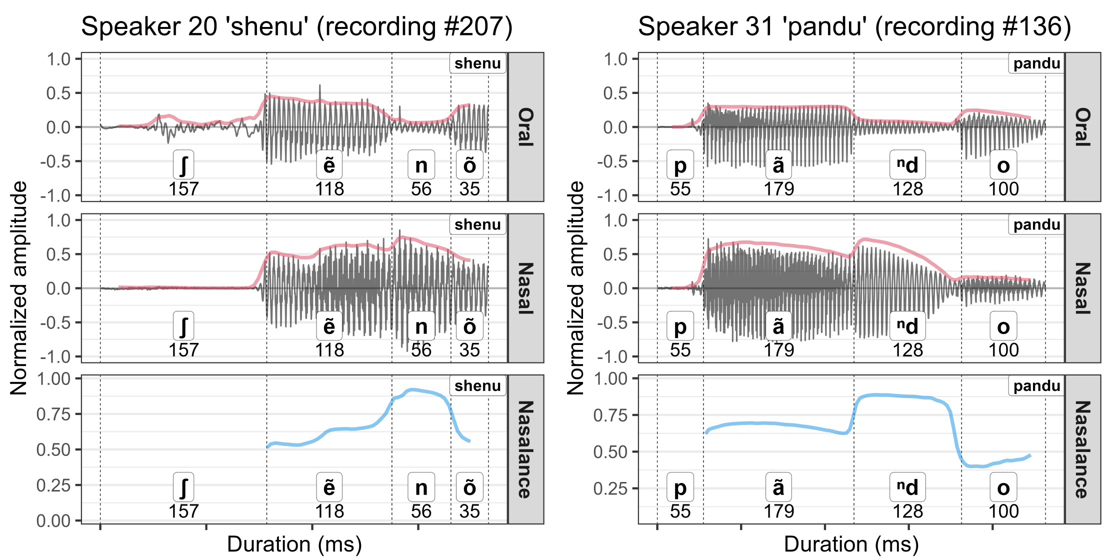


Figure 28: Sample tokens of mostly nasal vowels in [ṼN, Ṽ^{N}D], *shenu* /ʃeno/ ‘sister’ (left), and *pandu* /pa^{n}do/ ‘fox, tayra (*Eira barbara*)’ (right).

[17]Pouplier et al. (2024) report that nasalization can occur early in /(V #) lVN/ sequences in European French. However, such ‘early’ nasalization appears to be comparatively weak, about half as intense as anticipatory nasalization in English /VN/. Early nasalization in A’ingae [ṼN, Ṽ^{N}D] is often comparable to contrastive /Ṽ/, and hence does not resemble the weaker coarticulatory nasality that Pouplier et al. (2024) report for French. For work which finds limited nasal coarticulation in French /VN/, see Cohn (1990), Rochet & Rochet (1991), Spears (2006), Delvaux et al. (2008), Proctor et al. (2013), Desmeules-Trudel & Brunelle (2018), Dow (2020), Zellou & Chitoran (2023) and references there.

In our view, nasalization is too extensive in vowels preceding [N, ^{N}D] to plausibly reflect an active specification for an oral (= [-NASAL]) target. We believe this is true even in theories of the phonetics-phonology interface which only require a loose correspondence between phonological features and phonetic events. For example, Huffman (1989) proposes that phonologically [-NASAL] vowels are only required to be oral in the vicinity of the vowel midpoint. This allows some wiggle-room for nasal coarticulation with neighboring nasal consonants. However, in our data, vowels preceding [N, ^{N}D] are often substantially nasalized at vowel midpoint; this is true for both fully and partially nasalized tokens (e.g. Figs. 9, 10, etc.). This is incompatible with [-NASAL], even in the relatively permissive framework laid out by Huffman (1989) (see also Cohn 1990). We conclude that treating vowels preceding [N, ^{N}D] as [-NASAL] is untenable on phonetic grounds.

6.3 Against multivalued [NASAL]

We have so far assumed that [NASAL] is a binary feature, with two values ([+NASAL] and [-NASAL]), and the possibility of underspecification ([∅NASAL]). It has also been proposed that features may be multivalued, with three or more values along a scale (see e.g. Gnanadesikan 1997, Lionnet 2017, McCollum 2019, Sande & Oakley 2023 for references and discussion).

For the sake of simplicity, we consider a theory with a three-valued [NASAL] feature: oral [-NASAL], nasal [+NASAL], and intermediate, weakly nasal [≈NASAL]. Could vowels preceding [N, ^{N}D] bear this latter, intermediate [≈NASAL] value?[18]

There is both typological and language-internal evidence against this approach. Typologically, no language is reported to make a three-way contrast in vowel nasality (Ladefoged & Maddieson 1996:135). Adopting a multivalued [+/-/≈NASAL] feature incorrectly predicts that such a contrast should be possible (e.g. Hall 2007).[19]

Furthermore, there are no cases known to us in which a putative intermediate value for [NASAL] shows the behavior of a bona fide phonological feature, such as spreading or assimilation. Indeed, A'ingae-internal evidence against this approach comes from the interaction between vowels and simple nasal stops [N]. Nasal stops are uncontroversially [+NASAL], particularly since they spread the feature [+NASAL] to the following vowel, /NV/ → [NṼ] (section 3). So if vowels preceding nasal stops [ṼN] are [≈NASAL], where do they acquire that feature specification from? It cannot be via spreading from the following nasal [N], because nasal stops are fully [+NASAL], not weakly [≈NASAL]. But treating vowel nasalization in [ṼN] as the result of something *other* than spreading misses a clear generalization about the source of nasality in [ṼN].

An intermediate [≈NASAL] specification also fails to explain why vowels preceding [N, ^{N}D] are often strongly nasalized in our data (e.g. Fig. 28). The feature [≈NASAL] should correlate with *consistent* weak nasality, but what we find is a range of variation from partially to completely nasalized vowels, as well as vowels that are mostly oral. Such variability is more naturally accommodated by contextual underspecification [∅NASAL] than by a specified, but weak [≈NASAL] target.

While we have couched our critique here in terms of a ternary [+/-/≈NASAL] feature, we believe the same basic arguments (particularly, the last one) also apply to more sophisticated theories using multivalued features, including theories which use continuous, numerically-specified feature values

[18]A three-way contrast in nasality could also be produced using two binary features, e.g. [±NASAL] and [±ORAL].

[19]Three-way contrasts in vowel nasality have been reported for varieties of Chinantec and Chatino, both Oto-Manguean languages. It is possible to analyze these contrasts as a distinction between oral /V/, nasal /Ṽ/, and oral-nasal diphthongs /V͜Ṽ/ (Ladefoged & Maddieson 1996:299-300, Merrifield & Edmondson 1999), or between oral /V/, nasal /Ṽ/, and nasal /Ṽ/ followed by a nasal coda /ŋ/. See Chávez-Peón (2014) for details and further references.

like [0.4 nasal] (e.g. Lionnet 2017, McCollum 2019 and references there).

6.4 Against sub-segmental spreading

6.4.1 Sub-segmental spreading in Q theory

It has been proposed that information about the internal, temporal structure of segments is present in phonological representations. For example, in Q theory, segments are discretized into three semi-independent sub-units: roughly, the onset, center, and offset of those segments (Shih & Inkelas 2018, Lapierre 2023 and references there). Each of these three sub-segmental units can be specified for different feature values. With this type of representation, it becomes possible to generate sub-segmental spreading: the [+nasal] feature associated with [N] or [^{N}D] can spread leftward to some, but not all of the sub-segmental units associated with the preceding vowel (Fig. 29). This produces a phonological representation with an oral-to-nasal transition inside a single segment — in other words, partial nasalization.

$$\begin{array}{ccccccccc} & \mathrm{V} & & \mathrm{N}/{}^{\mathrm{N}}\mathrm{D} & \longrightarrow & & \mathrm{V} & & \mathrm{N}/{}^{\mathrm{N}}\mathrm{D} \\ (\mathrm{v}^1 & \mathrm{v}^2 & \mathrm{v}^3) & & & (\mathrm{v}^1 & \boxed{\mathrm{v}^2} & \boxed{\mathrm{v}^3}) & \\ [\text{-nas}] & [\text{-nas}] & [\text{-nas}] & & & [\text{-nas}] & [\text{+nas}] & [\text{+nas}] & \end{array}$$

Figure 29: Partial nasalization in Q theory

Q-theoretic representations are thus capable of representing partial vowel nasalization as a kind of oral-to-nasal contour segment or diphthong (as is also possible in Autosegmental Phonology; Sagey 1986, Jardine et al. 2021).

To the extent that Q-theoretic representations like Fig. 29 make predictions about the timecourse of phonetic nasality, they predict that the *proportion* of the vowel which is nasalized should be relatively consistent across tokens. Q theory may also predict that velum lowering should be roughly synchronous with some articulatory landmark in the vowel, given that sub-segmental units in Q theory have been explicitly (though only approximately) equated with major gestural landmarks like onset, plateau, and release (e.g. Lapierre 2023 and references there).[20]

The timing results discussed in section 5.3 argue against the claim that partial nasality reflects sub-segmental spreading of a [+nasal] feature (section 6.4). The proportion of the vowel which is nasalized in [ṼN, Ṽ^{N}D] is highly variable. Further, we find a wide and continuous distribution of start and end times for the nasalance rise in [ṼN, Ṽ^{N}D], which do not appear to cluster around any particular landmark (Figs. 20-24). While there is a tendency for nasality to begin early in the vowel in [ṼN, Ṽ^{N}D], this is by no means an ironclad rule.

If the extent of sub-segmental spreading of [+nasal] is variable, optionally targeting either 1, 2, or 3 of the preceding sub-segments (Fig. 29), we should find a multimodal distribution of start or end times. But again, we find a broad distribution of start and end times instead.

6.4.2 Sub-segmental spreading in Articulatory Phonology

Partial nasalization can also be modeled with the abstract gestural representations of Articulatory Phonology (e.g. Browman & Goldstein 1986, 1989, Gafos 2002, Smith 2018 and references there).

[20] Since Q-theoretic representations are abstract and phonological, one could object that they make no predictions at all about the timecourse of phonetic nasality inside segments. In that case, we know of no evidence that bears on the plausibility of a Q-theory approach to this data: the phonological evidence alone simply does not shed enough light on the matter (section 3.4). See e.g. Lapierre (2023) for work which explicitly links the number of [+nasal] sub-segmental units in Q theory to the proportion of a segment which is phonetically realized as nasal.

In Articulatory Phonology, segments are decomposed into their component articulatory gestures. These gestures are represented abstractly in the phonology itself. This allows for phonological representations which include information about the timecourse of articulator movements. Conventionally, the timecourse of an articulatory gesture (e.g. velum lowering) is expressed with an open trapezoid, as in Fig. 30.

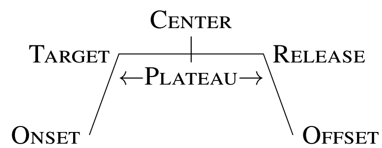


Figure 30: Major gestural landmarks in Articulatory Phonology

Gestures belonging to neighboring segments may overlap with each other, depending on how they are coordinated. Overlap between gestures can be represented by fixing the relative timing of their respective articulatory landmarks (Fig. 30). Fig. 31 shows how gestural representations could be used to specify partial or total nasalization of vowels preceding [N] or [^{N}D]. Essentially, the velar lowering gesture associated with [N] or [^{N}D] extends and/or shifts leftward to generate significant overlap with the preceding vowel, thereby nasalizing it. Since overlap can be partial, nasalization can be too.

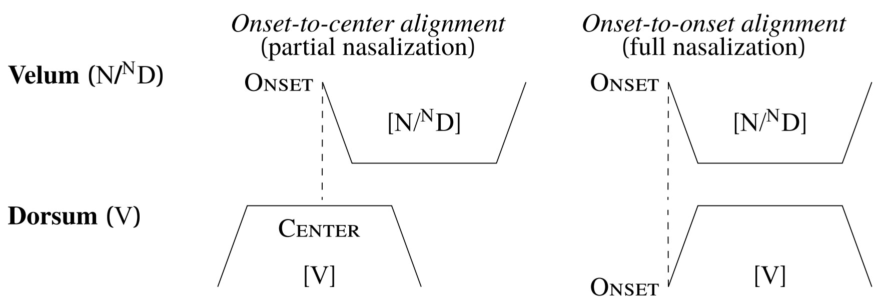


Figure 31: Gestural timing patterns for anticipatory nasalization. Gestural trapezoid for velum position is inverted to emphasize lowering of the velum for nasalization.

Gestural representations like those in Fig. 31 predict that the timing of velum lowering should be relatively stable with respect to some landmark in the vowel's articulation (e.g. Solé 1995, Krakow 1999, Byrd et al. 2009, etc.). But again, our results are at odds with the claim that nasality in [ṼN, Ṽ^{N}D] is tightly bound to any particular landmark in the pre-nasal vowel.

Many pre-nasal vowels are fully nasalized, or nasalized quite early, somewhere near the [CV] transition in [CṼN, CṼ^{N}D]. This implies that nasality is synchronized with the release of the oral consonant in [CṼN, CṼ^{N}D] (that is, with the acoustic onset of the vowel). But as is clear from the long, right tail in Figs. 20 and 22 (left), the association between C release and the onset of nasality is, at best, quite loose. Instead of a discrete, unimodal pattern, we find a broad and essentially continuous distribution for the timing of nasalization, albeit with a tendency toward earlier onset times.

Relatedly, the timing of nasality in [ṼN, Ṽ^{N}D] is *different* from the timing pattern seen for contrastive /Ṽ/. It has been argued that the onset of velum lowering in contrastively nasal vowels is coordinated with consonant release in [CṼ] in both European and Brazilian Portuguese (Meireles et al. 2015, Cunha et al. 2021; see also Proctor et al. 2013:578 on European French). Our timing results for contrastive /Ṽ/ seem consistent with that assumption (Figs. 18, 19). But the timing of nasality is different in [CṼN, CṼ$^{\text{N}}$D] when compared to /CṼ/. This difference also suggests that nasality is *not* tightly coordinated with consonant release in [CṼN, CṼ$^{\text{N}}$D].

It may be possible to produce these results in Articulatory Phonology with the use of phase windows (Byrd 1996) (see also Keating 1990, Zsiga 2000). Byrd (1996) proposes that timing relationships between articulatory gestures may be relatively tight (narrow phase window) or relatively loose (wide phase window; see also the related notion of 'coupling strength', e.g. Mücke et al. 2020). If we assume that (i) the onset of nasality is timed relative to oral C release in [CṼN, CṼ$^{\text{N}}$D], and (ii) that this timing relation is relatively loose, then wide, continuous timing distributions like those in Figs. 20-22 are likely to result.

However, assuming a wide phase window for the timing of nasality in [CṼN, CṼ$^{\text{N}}$D] is tantamount to underspecification, stated over the time domain. It also expresses the basic intuition that vowels in [ṼN, Ṽ$^{\text{N}}$D] are more or less 'indifferent' to the time course of nasality in [ṼN, Ṽ$^{\text{N}}$D]. For that reason, we do not view the phase window approach as a competing analysis of our data: instead, it is an alternative means of expressing the same essential claim that vowels in [ṼN, Ṽ$^{\text{N}}$D] are relatively free to vary in their nasality because they do not have a robust specification for the timing and/or magnitude of velum opening.

To be sure, we are not claiming that wide phase windows are *equivalent* to underspecification for [∅nasal]. These conceptual tools are embedded in very different theories, and so cannot be straightforwardly equated. But at a higher level of abstraction, they share the the property of relative 'indifference' suggested by our results.

Contemporary work in Articulatory Phonology often dispenses with both phase windows and landmark-to-landmark coordination (see Hall 2017 for an overview; but cf. Shaw 2022 and references there). Instead, coordination between gestures is specified to be either *in-phase* (simultaneous initiation) or *anti-phase* (sequential initiation). Gestures in syllable onsets are specified for in-phase timing, i.e. for simultaneity between oral and velar gestures in onset nasals in [NV] (Krakow 1999). All else being equal, velum lowering in [V.NV] should initiate with the nasal consonant itself, and nasalization of the preceding vowel should be fairly minimal.

However, the precise timing of in-phase gestures can be perturbed through competition with other gestural specifications. Of particular interest here is Byrd et al.'s (2009) finding that in American English, the velar gesture of the nasal in [ˈV.NV] appears to be 'attracted' to the stressed vowel, such that velar lowering occurs earlier in [ˈV.NV] than in [V.ˈNV]. This effect could be responsible for the significant anticipatory nasalization found in our study, given that the pre-nasal vowels we investigated were always stressed [ˈṼ.NV] or [ˈṼ.$^{\text{N}}$DV].

This analysis appears to make the wrong predictions about anticipatory nasalization in *un*stressed vowels in A'ingae. Although we have not provided a quantitative analysis of nasality in unstressed vowels, our data does include many examples of unstressed vowels which are strongly nasalized before [N, $^{\text{N}}$D], even when relatively long in duration (Fig. 32).

The attraction of velum lowering to a preceding stressed vowel does not, by itself, explain the significant nasalization of *un*stressed pre-nasal vowels in [V.NV] or [V.$^{\text{N}}$DV] in examples like Fig. 32. Of course, more work is needed to confirm this tentative result. Assuming the nasalization of unstressed pre-nasal vowels is systematic in A'ingae — as it appears to be, both impressionistically and in our initial data here — it would support our claim that anticipatory nasalization is produced by underspecification of [nasal], rather than by stress-sensitive coarticulation. While more intricate patterns of gestural coordination in [Ṽ.NV], [Ṽ.$^{\text{N}}$DV] may be able to produce these results, we

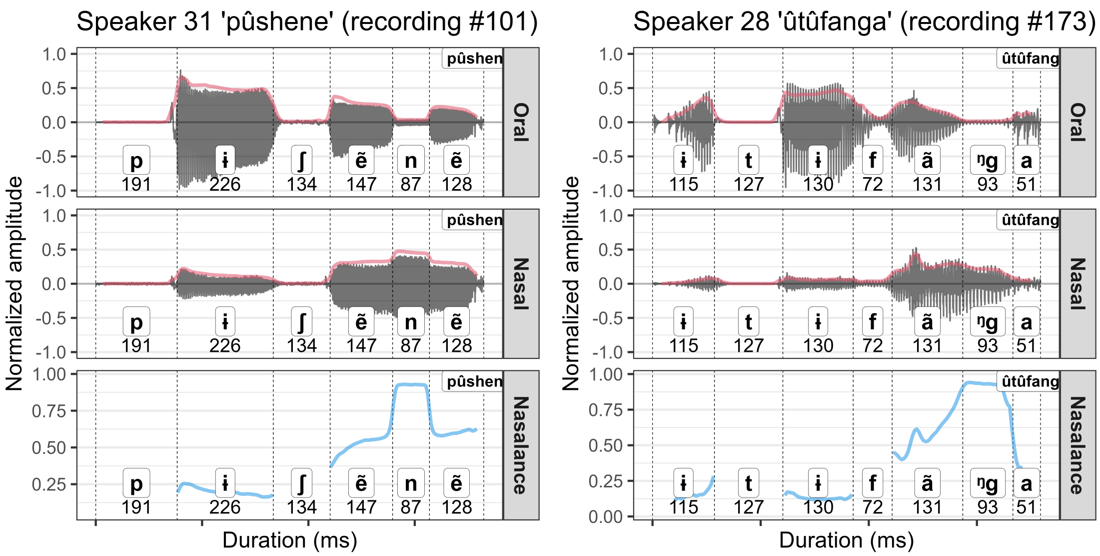


Figure 32: Anticipatory nasalization for phonetically long, unstressed pre-nasal vowels. Left: *pûshene* /pɨʃe̠=ne/ → [ˈpɨ.ʃẽ̠.nẽ] 'about the wife'. Right: *ûtûfanga* /ɨtɨfa̠=ᵑga/ → [ɨ.ˈtɨ.fã̠.ᵑga] 'to the corner'.

leave a fuller evaluation of such possibilities to future work.

In any case, the mechanism responsible for partial nasalization in [ṼN, Ṽ^{N}D] in A'ingae must, to some extent, be specific to this particular language. Anticipatory nasalization is frequent and extensive in [ˈVNV] sequences in A'ingae. But in Spanish, Italian, Greek, and several languages of Australia, among others, anticipatory nasalization in [ˈVNV] appears to be much more limited (e.g. Solé 1995, 2007, Diakoumakou 2004, Delvaux et al. 2008:596, Stoakes et al. 2020 and work cited there). The active control of anticipatory nasalization in /VNV/ is further underscored by the fact that nasalization in /VN/ appears to vary across speakers and dialects of the same language (e.g. Delvaux et al. 2012, Beddor et al. 2018, Bongiovanni 2021, Zellou 2022).

Lastly, it bears mentioning that gestural dynamics like the above do not themselves account for the fact that oral vs. nasal /V Ṽ/ contrasts are suspended before [N, ^{N}D] in A'ingae. Some kind of neutralizing rule or process, like our rule (12), is still required to implement this generalization.

7 Discussion

On the basis of phonetic and phonological evidence, we have argued that partially nasalized vowels in A'ingae should be analyzed as phonologically unspecified for nasality, [∅NASAL]. Key to our argumentation is the fact that A'ingae has *both* contrastive [+NASAL] vowels and phonologically derived [+NASAL] vowels produced by harmony, alongside [-NASAL] oral vowels. This allows us to compare partially nasalized vowels to vowels that are unambiguously [+NASAL] and [-NASAL], while also controlling for the possibility that underlying and derived instances of [+NASAL] might be produced with different patterns of phonetic nasality (Solé 1995 and section 1.1).

To date, partial nasality has only been examined in languages which do not allow for this full range of comparisons. As such, it has not been possible to definitively conclude whether partially nasalized vowels are [+NASAL], [-NASAL], or [∅NASAL] in those languages. The phonological structure of A'ingae resolves this ambiguity, and does so in favor of Cohn's (1990) proposal that partial nasalization may reflect phonological underspecification for nasality.

7.1 The phonetics of [∅NASAL]

We have said very little about how vowels lacking a specification for nasality, [∅NASAL], are mapped to speech production targets. We concur with Solé (1995) that the many cases of full nasalization on [ṼN, Ṽ^{N}D] in our data are at odds with a naive target interpolation model which simply implements a gradual transition between [-NASAL] and [+NASAL] targets over an intervening, underspecified span (section 1.1). More sophisticated models of interpolation are of course conceivable, and might suffice (see e.g. Liberman & Pierrehumbert 1984 for discussion). It is also possible that phonetic mechanisms *other* than interpolation are called for here (e.g. phase windows, section 6.4). Lastly, whatever mechanisms are responsible for the phonetics of [∅NASAL] vowels, those mechanisms could either be universal, or to some extent specific to A'ingae (e.g. Keating 1984, Kingston & Diehl 1994, Zsiga 2000, etc.). We leave a more detailed exploration of these issues to future work. What is clear, however, is that nasalization in [ṼN, Ṽ^{N}D] is more extensive than simple, mechanical coarticulation for nasality — it must be under speaker control in some sense (e.g. Solé 1992, 1995, 2007).

References

ALDP, A'ingae Language Documentation Project. ms. Diccionaro a'ingae – kukamangae. Unpublished manuscript draft version from July 17, 2024.

Baayen, R. Harald & Maya Linke. 2021. Generalized additive mixed models. In *A practical handbook of corpus linguistics*, 563–591. Cham: Springer. doi:10.1007/978-3-030-46216-1_23.

Baayen, R. Harald, Shravan Vasishth, Reinhold Kliegl & Douglas Bates. 2017. The cave of shadows: Addressing the human factor with generalized additive mixed models. *Journal of Memory and Language* 94. 206–234. doi:doi.org/10.1016/j.jml.2016.11.006.

Beddor, Patrice & Rena Krakow. 1999. Perception of coarticulatory nasalization by speakers of English and Thai: Evidence for partial compensation. *Journal of the Acoustical Society of America* 106(5). 2868–2887.

Beddor, Patrice Speeter, Andries Coetzee, Will Styler, Kevin McGowan & Julie Boland. 2018. The time course of individuals' perception of coarticulatory information is linked to their production: Implications for sound change. *Language* 94(4). 931–968. doi:10.1353/lan.2018.0051.

Bell-Berti, Fredericka. 1993. Understanding velic motor control: studies of segmental context. In Marie K. Huffman & Rena A. Krakow (eds.), *Nasals, nasalization, and the velum,* 63–85. San Diego: Academic Press.

Bellavance, Sarah Rose, Amanda Eads, Aidan Katson, José Álvarez Retamales, Alden McCollum, Auromita Mitra & Lisa Davidson. 2024. Vowel nasalization does not cue ambisyllabicity in American English nasals: Evidence from nasometry. *JASA Express Letters* 4(7).

Bennett, Ryan, Robert Henderson & Meg Harvey. 2023. Vowel deletion as grammatically controlled gestural overlap in Uspanteko. *Language* 99(3). 399–456. doi:10.1353/lan.2023.a907008.

Bongiovanni, Silvina. 2021. On covariation between nasal consonant weakening and anticipatory vowel nasalization: Evidence from a Caribbean and a non-Caribbean dialect of Spanish. *Laboratory Phonology* 12(1). doi:10.16995/labphon.6444.

Borman, Marlytte Bubs. 1976. *Vocabulario cofán: Cofán-castellano, castellano-cofán*. Quito, Ecuador: Instituto Lingüístico de Verano.

Browman, Catherine & Louis Goldstein. 1986. Towards an articulatory phonology. *Phonology yearbook* 3(21). 219–252. doi:10.1017/S0952675700000658.

Browman, Catherine & Louis Goldstein. 1989. Articulatory gestures as phonological units. *Phonology* 6(2). 201–251. doi:10.1017/S0952675700001019.

Byrd, Dani. 1996. A phase window framework for articulatory timing. *Phonology* 13(2). 139–169.

Byrd, Dani, Stephen Tobin, Erik Bresch & Shrikanth Narayanan. 2009. Timing effects of syllable structure and stress on nasals: A real-time MRI examination. *Journal of Phonetics* 37(1). 97–110.

Caglar, M. Umut, Ashley I. Teufel & Claus O. Wilke. 2018. Sicegar: R package for sigmoidal and double-sigmoidal curve fitting. *PeerJ* 6. e4251. doi:10.7717/peerj.4251.

Cepek, Michael. 2018. *Life in oil: Cofán survival in the petroleum fields of Amazonia*. Austin, TX: University of Texas Press.

Chávez-Peón, Mario Ernesto. 2014. Nasalidad en lenguas otomangues: aproximación a sus contrastes y tipología. In Ryan Bennett, Rikker Dockum, Emily Gasser, Dolly Goldenberg, Ryan Kasak & Patrick Patterson (eds.), *Proceedings of the workshop on the sound systems of Mexico and Central America*, Yale University. `https://campuspress.yale.edu/ssmca/files/2025/01/ChavezPeon-2014-Otomangues-SSMCA.pdf`.

Cohn, Abigail. 1990. *Phonetic and phonological rules of nasalization*. Los Angeles: University of California, Los Angeles dissertation. `https://escholarship.org/uc/item/1xq3d5hr`.

Cohn, Abigail. 1993a. Nasalisation in English: phonology or phonetics. *Phonology* 10(1). 43–81.

Cohn, Abigail. 1993b. The status of nasalized continuants. In Marie K. Huffman & Rena A. Krakow (eds.), *Nasals, nasalization, and the velum*, 329–367. San Diego: Academic Press.

Coretta, Stefano. 2024. *tidygam: Tidy prediction and plotting of generalised additive models*. `https://CRAN.R-project.org/package=tidygam`. R package version 1.0.0.

Cunha, Conceição, Nuno Almeida, Jens Frahm, Samuel Silva & António Teixeira. 2021. Data-driven analysis of nasal vowels dynamics and coordination: Results for bilabial contexts. In *IberSPEECH 2021*, 215–219. doi:10.21437/IberSPEECH.2021-46.

Dąbkowski, Maksymilian. 2021a. A'ingae (Ecuador and Colombia) – language snapshot. *Language Documentation and description* 20. 1–12. doi:10.25894/ldd28.

Dąbkowski, Maksymilian. 2021b. Dominance is non-representational: evidence from A'ingae verbal stress. *Phonology* 38(4). 611–650. doi:10.1017/S0952675721000348.

Dąbkowski, Maksymilian. 2024. The phonology of A'ingae. *Language and Linguistics Compass* 18(3). e12512. doi:10.1111/lnc3.12512.

Delvaux, Véronique, Didier Demolin, Bernard Harmegnies & Alain Soquet. 2008. The aerodynamics of nasalization in French. *Journal of Phonetics* 36(4). 578–606.

Delvaux, Véronique, Kathy Huet, Myriam Piccaluga & Bernard Harmegnies. 2012. Inter-gestural timing in French nasal vowels: A comparative study of (Liège, Tournai) Northern French vs. (Marseille, Toulouse) Southern French. In *Proceedings of Interspeech 2012*, 2682–2685. doi:10.21437/Interspeech.2012-666.

Desmeules-Trudel, Félix & Marc Brunelle. 2018. Phonotactic restrictions condition the realization of vowel nasality and nasal coarticulation: Duration and airflow measurements in Québécois French and Brazilian Portuguese. *Journal of Phonetics* 69. 43–61. doi:10.1016/j.wocn.2018.05.001.

Diakoumakou, Evanthia. 2004. *Coarticulatory vowel nasalization in Modern Greek*. Ann Arbor, MI: University of Michigan dissertation.

Dow, Michael. 2020. A phonetic-phonological study of vowel height and nasal coarticulation in French. *Journal of French Language Studies* 30(3). 239–274.

Eischens, Ben. 2022. *Tone, phonation, and the phonology-phonetics interface in San Martín Peras Mixtec*. Santa Cruz, CA: University of California, Santa Cruz dissertation.

Eischens, Ben & Andrew Hedding. 2024. San Martín Peras Mixtec. *Journal of the International Phonetic Association* 54. 811–852. doi:10.1017/S0025100324000124.

Fischer, Rafael & Kees Hengeveld. 2023. A'ingae (Cofán). In Patience Epps & Lev Michael (eds.), *Amazonian languages: An international handbook*, vol. 1, 65–124. Berlin: De Gruyter Mouton. doi:10.1515/9783110419405-002.

Fowler, Carol & Julie Brown. 2000. Perceptual parsing of acoustic consequences of velum lowering from information for vowels. *Perception & Psychophysics* 62. 21–32. doi:10.3758/BF03212058.

Gafos, Adamantios. 2002. A grammar of gestural coordination. *Natural Language & Linguistic Theory* 20(2). 269–337.

Gick, Bryan, Ian Wilson & Donald Derrick. 2012. *Articulatory phonetics*. Malden, MA: Wiley-Blackwell.

Gnanadesikan, Amalia Elisabeth. 1997. *Phonology with ternary scales*. Amherst, MA: University of Massachusetts, Amherst dissertation.

Gouskova, Maria & Juliet Stanton. 2021. Learning complex segments. *Language* 97(1). 151–193.

Hajek, John. 1997. *Universals of sound change in nasalization*. Oxford, UK: Blackwell.

Hajek, John. 2013. Vowel nasalization (v2020.3). doi:10.5281/zenodo.7385533. Available online at https://wals.info/chapter/10.

Hall, Daniel Currie. 2007. *The role and representation of contrast in phonological theory*: University of Toronto dissertation.

Hall, Nancy. 2017. Articulatory phonology. In S.J. Hannahs & Anna Bosch (eds.), *The Routledge handbook of phonological theory*, 530–552. Abingdon: Routledge. doi:10.4324/9781315675428.

Huffman, Marie K. 1989. *Implementation of nasal: timing and articulatory landmarks*. Los Angeles, CA: University of California, Los Angeles dissertation.

Jardine, Adam, Nick Danis & Luca Iacoponi. 2021. A formal investigation of Q-theory in comparison to autosegmental representations. *Linguistic Inquiry* 52(2). 333–358.

Jeong, Sunwoo. 2012. Directional asymmetry in nasalization: a perceptual account. 음성음운형태론연구 18(3). 437–469.

Keating, Patricia. 1984. Universal phonetics and the organization of grammars. In *UCLA working papers in phonetics*, vol. 59, 35–49. Los Angeles: University of California, Los Angeles.

Keating, Patricia. 1990. The window model of coarticulation: articulatory evidence. In John Kingston & Mary Beckman (eds.), *Papers in laboratory phonology I: Between the grammar and the physics of speech*, 451–470. Cambridge, UK: Cambridge University Press.

Kingston, John & Randy Diehl. 1994. Phonetic knowledge. *Language* 70(3). 419–454.

Kochetov, Alexei. 2020. Research methods in articulatory phonetics II: Studying other gestures and recent trends. *Language and Linguistics Compass* 14(4). e12371. doi:10.1111/lnc3.12371.

Krakow, Rena A. 1999. Physiological organization of syllables: a review. *Journal of Phonetics* 27(1). 23–54.

Krämer, Martin. 2017. Is vowel nasalisation phonological in English? A systematic review. *English Language & Linguistics* 23(2). 405–437.

Kunay, Esther, Philip Hoole, Michele Gubian, Jonathan Harrington, Arun Jospeh, Dirk Voit & Jens Frahm. 2022. Vowel height and velum position in German: Insights from a real-time magnetic resonance imaging study. *Journal of the Acoustical Society of America* 152(6). 3483–3501. doi:https://doi.org/10.1121/10.0016366.

Ladefoged, Peter & Ian Maddieson. 1996. *The sounds of the world's languages*. Malden, MA: Blackwell.

Lahiri, Aditi & William Marslen-Wilson. 1991. The mental representation of lexical form: A phonological approach to the recognition lexicon. *Cognition* 38(3). 245–294.

Lapierre, Myriam. 2023. Two types of [NT]s in Panãra: Evidence for temporally ordered subsegmental units. *Glossa* 8(1).

Liberman, Mark & Janet Pierrehumbert. 1984. Intonational invariance under changes in pitch range and length. In Mark Aronoff & Richard Oehrle (eds.), *Language sound structure: studies in phonology presented to Morris Halle by his teacher and students*, 157–233. Cambridge, MA: MIT Press.

Lionnet, Florian. 2017. A theory of subfeatural representations: the case of rounding harmony in Laal. *Phonology* 34(3). 523–564.

Massicotte, Philippe & Andy South. 2025. *rnaturalearth: World map data from natural earth*. doi:10.32614/CRAN.package.rnaturalearth. `https://CRAN.R-project.org/package=rnaturalearth`. R package version 1.1.0.

McCollum, Adam. 2019. *Gradience and locality in phonology: Case studies from Turkic vowel harmony*. San Diego, CA: University of California, San Diego dissertation.

Meireles, Alexsandro, Louis Goldstein, Reed Blaylock & Shrikanth Narayanan. 2015. Gestural coordination of Brazilian Portugese nasal vowels in CV syllables: A real-time MRI study. In The Scottish Consortium for ICPhS 2015 (ed.), *Proceedings of the 18th International Congress of the Phonetic Sciences,* 1–5. Glasgow: University of Glasgow. Available online at https://www.internationalphoneticassociation.org/icphs-proceedings/ICPhS2015/Papers/ICPHS0526.pdf.

Merrifield, William & Jerold Edmondson. 1999. Palantla Chinantec: Phonetic experiments on nasalization, stress, and tone. *International Journal of American Linguistics* 65(3). 303–323.

Mücke, Doris, Anne Hermes & Sam Tilsen. 2020. Incongruencies between phonological theory and phonetic measurement. *Phonology* 37(1). 133–170.

Okalidou, Areti, Asimina Karathanasi & Eleni Grigoraki. 2011. Nasalance norms in Greek adults. *Clinical linguistics & phonetics* 25(8). 671–688. doi:10.3109/02699206.2010.549993.

Piggott, Glyne & Harry Van der Hulst. 1997. Locality and the nature of nasal harmony. *Lingua* 103(2-3). 85–112.

Pomilia, Mateo. 2025. *The ethnolinguistic vitality of A'ingae in Ecuador*. University of Arizona MA thesis.

Pouplier, Marianne, Francesco Rodriquez, Justin J.H. Lo, Roy Alderton, Bronwen G. Evans, Eva Reinisch & Christopher Carignan. 2024. Language-specific and individual variation in anticipatory nasal coarticulation: A comparative study of American English, French, and German. *Journal of Phonetics* 107. 101365. doi:10.1016/j.wocn.2024.101365.

Proctor, Michael, Louis Goldstein, Adam Lammert, Dani Byrd, Asterios Toutios & Shrikanth Narayanan. 2013. Velic coordination in French nasals: a real-time magnetic resonance imaging study. In *Proceedings of Interspeech 2013*, 577–581. doi:10.21437/Interspeech.2013-159.

R Development Core Team. 2025. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing Vienna, Austria. Version 4.5.1, retrieved from http://www.R-project.org/.

Repetti-Ludlow, Chiara, Haoru Zhang, Hugo Lucitante, Scott AnderBois & Chelsea Sanker. 2020. A'ingae (Cofán). *Journal of the International Phonetic Association* 50(3). 431–444.

Riehl, Anastasia. 2008. *The phonology and phonetics of nasal obstruent sequences*. Ithaca, NY: Cornell University dissertation.

Riehl, Anastasia & Abigail Cohn. 2011. Partially nasal segments. In Marc van Oostendorp, Colin Ewen, Elizabeth Hume & Keren Rice (eds.), *The Blackwell companion to phonology,* 550–576. Malden, MA: Wiley-Blackwell.

Robins, Robert H. 1953. The phonology of the nasalized verbal forms in Sundanese. *Bulletin of the School of Oriental and African Studies* 15(1). 138–145. doi:10.1017/S0041977X00087309.

Robins, Robert H. 1957. Vowel nasality in Sundanese: a phonological and grammatical study. In *Studies in linguistics (special volume of the Philological Society)*, 87–103. Oxford, UK: Basil Blackwood.

Rochet, Anne & Bernard Rochet. 1991. The effect of vowel height on patterns of assimilation nasality in French and English. In *Proceedings of the XIIth International Congress of Phonetic Sciences*, vol. 3, 54–57. Aix-en-Provence: Université de Provence.

Rochet, Anne, Bernard Rochet, Elizabeth Sovis & Dallyce Mielke. 1998. Characteristics of nasalance in speakers of western Canadian English and French. *Journal of Speech Language Pathology and Audiology* 22. 94–103.

Rose, Sharon & Rachel Walker. 2004. A typology of consonant agreement as correspondence. *Language* 80(3). 475–531.

Rysling, Amanda. 2017. *Preferential early attribution in segmental parsing*. Amherst, MA: University of Massachusetts, Amherst dissertation.

Sagey, Elizabeth. 1986. *The representation of features and relations in non-linear phonology*: Massachusetts Institute of Technology dissertation.

Sande, Hannah & Madeleine Oakley. 2023. A typological survey of the phonological behavior of implosives: Implications for feature theories. *Phonological Data and Analysis* 5(7). 1–46.

Sanker, Chelsea & Scott AnderBois. 2024. Reconstruction of nasality and other aspects of A'ingae phonology. *Cadernos de etnolingüística* 11(1). e110101.

Shaw, Jason. 2022. Micro-prosody. *Language and Linguistics Compass* 16(2). e12449. doi:10.1111/lnc3.12449.

Shih, Stephanie & Sharon Inkelas. 2018. Autosegmental aims in surface optimizing phonology. *Linguistic Inquiry* 50(1). 137–196. doi:10.1162/ling_a_00304.

Shosted, Ryan. 2006. *The aeroacoustics of nasalized fricatives*. Berkeley, CA: University of California, Berkeley dissertation.

Siriwardena, Yashish M., Suzanne E. Boyce, Mark K. Tiede, Liran Oren, Brittany Fletcher, Michael Stern & Carol Y. Espy-Wilson. 2024. Speaker-independent speech inversion for recovery of velopharyngeal port constriction degree. *Journal of the Acoustical Society of America* 156(2). 1380–1390. doi:10.1121/10.0028124.

Smith, Caitlin. 2018. *Harmony in gestural phonology*. Los Angeles: University of Southern California dissertation.

Solé, Maria-Josep. 1992. Phonetic and phonological processes: The case of nasalization. *Language and Speech* 35(1-2). 29–43.

Solé, Maria-Josep. 1995. Spatio-temporal patterns of velopharyngeal action in phonetic and phonological nasalization. *Language and Speech* 38(1). 1–23.

Solé, Maria-Josep. 2007. Controlled and mechanical properties in speech. In Maria-Josep Solé, Patrice Beddor & Manjari Ohala (eds.), *Experimental approaches to phonology*, 302–321. Oxford, UK: Oxford University Press.

Sóskuthy, Márton. 2017. Generalised additive mixed models for dynamic analysis in linguistics: a practical introduction. doi:10.48550/arXiv.1703.05339. `https://arxiv.org/abs/1703.05339`.

Sóskuthy, Márton. 2021. Evaluating generalised additive mixed modelling strategies for dynamic speech analysis. *Journal of Phonetics* 84. 101017. doi:10.1016/j.wocn.2020.101017.

Spears, Abby. 2006. *Nasal coarticulation in the French vowel /i/: a phonetic and phonological study*. University of North Carolina MA thesis. Available online as ROA-889, Rutgers Optimality Archive, http://roa.rutgers.edu/.

Stanton, Juliet. 2018. Environmental shielding is contrast preservation. *Phonology* 35(1). 39–78.

Stewart, Jesse & Martin Kohlberger. 2017. Earbuds: A method for analyzing nasality in the field. *Language Documentation & Conservation* 11. 49–80.

Stoakes, Hywel M, Janet M Fletcher & Andrew R Butcher. 2020. Nasal coarticulation in Bininj Kunwok: An aerodynamic analysis. *Journal of the International Phonetic Association* 50(3). 305–332.

Trigo, Rosario Lorenza. 1993. The inherent structure of nasal segments. In Marie K. Huffman & Rena A. Krakow (eds.), *Nasals, nasalization, and the velum*, 369–400. San Diego: Academic Press.

Walker, Rachel. 2000. *Nasalization, neutral segments and opacity effects*. New York: Garland.

Walker, Rachel. 2003. Reinterpreting transparency in nasal harmony. In Jeroen van de Weijer, Vincent J. van Heuven & Harry van der Hulst (eds.), *The phonological spectrum: Volume I: Segmental structure*, 37–72. Amsterdam: John Benjamins.

Walker, Rachel & Geoffrey K. Pullum. 1999. Possible and impossible segments. *Language* 75(4). 764–780.

Wickham, Hadley. 2016. *ggplot2: Elegant graphics for data analysis*. Springer-Verlag New York. `https://ggplot2.tidyverse.org`.

Wickham, Hadley, Davis Vaughan & Maximilian Girlich. 2024. *tidyr: Tidy messy data*. `https://CRAN.`

`R-project.org/package=tidyr`. R package version 1.3.1.

Wieling, Martijn. 2018. Analyzing dynamic phonetic data using generalized additive mixed modeling: A tutorial focusing on articulatory differences between L1 and L2 speakers of English. *Journal of Phonetics* 70. 86–116. doi:10.1016/j.wocn.2018.03.002.

Winter, Bodo & Martijn Wieling. 2016. How to analyze linguistic change using mixed models, growth curve analysis and generalized additive modeling. *Journal of Language Evolution* 1(1). 7–18. doi:10.1093/jole/lzv003.

Wood, Simon N. 2003. Thin-plate regression splines. *Journal of the Royal Statistical Society* (*B*) 65(1). 95–114.

Wood, Simon N. 2017. *Generalized additive models: an introduction with R*. New York: Chapman and Hall 2nd edn.

Young, Lisa H., David J. Zajac, Robert Mayo & Celia R. Hooper. 2001. Effects of vowel height and vocal intensity on anticipatory nasal airflow in individuals with normal speech. *Journal of speech, language, and hearing research* 44(1). 52–60.

Zellou, Georgia. 2017. Individual differences in the production of nasal coarticulation and perceptual compensation. *Journal of Phonetics* 61. 13–29. doi:10.1016/j.wocn.2016.12.002.

Zellou, Georgia. 2022. Coarticulation in phonology. *Cambridge Elements in Phonology* doi:10.1017/9781009082488.

Zellou, Georgia & Ioana Chitoran. 2023. Lexical competition influences coarticulatory variation in French: comparing competition from nasal and oral vowel minimal pairs. *Glossa* 8(1). doi:10.16995/glossa.9801.

Zsiga, Elizabeth. 2000. Phonetic alignment constraints: consonant overlap and palatalization in English and Russian. *Journal of phonetics* 28(1). 69–102.

Appendix

Abbreviations

ACC = accusative, ACC2 = accusative 2, ACT = active, ATTR = attributive, CAUS = causative, CLF = classifier, INF = infinitive, IPFV = imperfective, MANN = manner, NEG = negation, PASS = passive PL = plural, NMLZ = nominalizer, TR = transitive, VER = veridical.

V = (oral) vowel, Ṽ = nasal vowel, N = simple nasal stop, ^{N}D = prenasalized stop.

Item list and summary of observations per nasality class

NASALITY CLASS	Oral [V]	/Ṽ/	Derived [NṼ]	[ṼN]	[Ṽ^{N}D]	**Total**
COUNT	954	533	427	852	1006	3772

Table A1: Number of observations per nasality class in the study.

Practical	IPA	Gloss	Practical	IPA	Gloss
andeni	[ˈã.ⁿdẽ.nĩ]	‘on land’	ansi	[ˈã.si]	‘sweet’
ansin	[ˈã.sĩ]	‘salt’	asi	[ˈa.si]	‘fish w/ a hook’
atsane	[ˈa.t͡sã.nẽ]	‘about avocado’	binshin	[ˈᵐbĩ.ʃĩ]	‘dog flea’
chanatshi	[ˈt͡ʃã.nã.t͡sʰi]	‘very white’	chanditshi	[ˈt͡ʃã.ⁿdi.t͡sʰi]	‘clear, crystaline’
changu	[ˈt͡ʃã.ᵑgo]	‘hole’	chapetshi	[ˈt͡ʃa.pe.t͡sʰi]	‘soft, smooth’
chharatshi	[ˈt͡ʃʰa.ɾa.t͡sʰi]	‘clear, bright’	china	[ˈt͡ʃĩ.nã]	‘daughter-in-law’
chuni	[ˈt͡ʃõ.nĩ]	‘nutria’	fambi	[fã.ᵐbi]	‘electric eel’
finfin	[ˈfĩ.fĩ]	‘fanned one’s self’	fûnia	[ˈfɨ̃.nĩã]	‘round’
fuñu	[ˈfõ.ɲõ]	‘skirt’	geñu	[ˈᵑgẽ.ɲõ]	‘banana’
kani	[ˈkã.nĩ]	‘yesterday’	khake	[ˈkʰa.kʰe]	‘leaf’
khakenga	[ˈkʰa.kʰẽ.ᵑga]	‘to the leaf’	khuma	[ˈkʰõ.mã]	‘chili pepper’
kimbi	[ˈkĩ.ᵐbi]	‘tired’	kûña	[ˈkɨ̃.ɲã]	‘achiote’
kungû	[ˈkõ.ᵑgɨ]	‘sweet potato’	kungun	[ˈkõ.ᵑgõ]	‘rotted’
kungûnga	[ˈkõ.ᵑgɨ̃.ᵑga]	‘to the sweet potato’	masha	[ˈmã.ʃa]	‘heron’
matshan	[ˈmã.t͡sʰã]	‘roasted’	metshi	[ˈmẽ.t͡sʰi]	‘empty, having none’
misin	[ˈmĩ.sĩ]	‘worm’	mûsin	[ˈmɨ̃.sĩ]	‘hugged’
nathe	[ˈnã.tʰe]	‘dentón (type of fish)’	ñutshi	[ˈɲõ.tsʰi]	‘good’
paña	[ˈpã.ɲã]	‘heard, understood’	pandu	[ˈpã.ⁿdo]	‘fox, tayra (*Eira barbara*
patû	[ˈpa.tɨ]	‘rock’	patûni	[ˈpa.tɨ̃.nĩ]	‘at the rock’
pindu	[ˈpĩ.ⁿdo]	‘eagle’	pindune	[ˈpĩ.ⁿdõ.nẽ]	‘about the eagle’
pûshe	[ˈpɨ.ʃe]	‘wife’	pûshene	[ˈpɨ.ʃẽ.nẽ]	‘about the wife’
pûshenga	[ˈpɨ.ʃẽ.ᵑga]	‘to the wife’	pûshesûnga	[pɨ.ˈʃe.sɨ̃.ᵑga]	‘to the woman’
sema	[ˈsẽ.mã]	‘worked’	shenu	[ˈʃẽ.nõ]	‘sister’
sime	[ˈsĩ.mẽ]	‘afternoon’	simene	[ˈsĩ.mẽ.nẽ]	‘about afternoon’

sina	[ˈsĩ.nã]	‘mushroom’	sinsin	[ˈsĩ.sĩ]	‘louse’
sûmbi	[ˈsɨ̃.ᵐbi]	‘dumb’	tandan	[ˈtã.ⁿdã]	‘tied’
tansintshi	[ˈtã.sĩ.t͡sʰi]	‘correct, upright’	themba	[ˈtʰẽ.ᵐba]	‘branch’
thembane	[ˈtʰẽ.ᵐbã.nẽ]	‘about the branch’	thesi	[ˈtʰe.si]	‘jaguar’
thesinga	[ˈtʰe.sĩ.ᵑga]	‘to the jaguar’	thûkhûni	[ˈtʰɨ.kʰɨ̃.nĩ]	‘in the room’
thumbû	[ˈtʰõ.ᵐbɨ]	‘grasshopper’	tsampi	[ˈt͡sã.pi]	‘forest’
tsampini	[ˈt͡sã.pĩ.nĩ]	‘in the forest’	tsanda	[ˈt͡sã.ⁿda]	‘thunder’
tsifu	[ˈt͡si.fo]	‘throat’	tufa	[ˈto.fa]	‘lizard’
untin	[ˈõ.tĩ]	‘horsefly’	untin	[ˈõ.tĩ]	‘gray hair’
uti	[ˈo.ti]	‘nailed’	ûtûfanga	[ɨ.ˈtɨ.fã.ᵑga]	‘to the river side’
utafanga	[o.ˈta.fã.ᵑga]	‘to the river side’ (variant)			

Table A2: Items analyzed in the study.

Data annotation

Audio recordings were first transcribed in the A’ingae orthography. These orthographic transcriptions were then converted to IPA transcriptions using the Python script `translate04.py` (Cohen Priva et al. 2021), and a customized A’ingae ruleset for grapheme-to-phoneme conversion. The IPA transcribed recordings were then segmented into time-aligned word- and phone-level annotations using the Montreal Forced Aligner (McAuliffe et al. 2017). The segmentations produced by forced alignment were subsequently hand-corrected by a team of undergraduate research assistants.

Hand-corrected segmental boundaries were determined in Praat (Boersma & Weenink 2020), following the recommendations of Turk et al. (2006) and Machač & Skarnitzl (2009). Since A’ingae syllable structure is strictly [(C)V] (apart from post-vocalic [ʔ], which we exclude here), segmentation consisted in finding appropriate boundaries between vowels and flanking consonants. Segmental boundaries were marked at points of significant amplitude change (particularly in the F2 region and above), which often coincided with sudden changes in the overall quality of the acoustic spectrum (e.g. the appearance of aperiodic noise for fricatives). Approximate boundaries were determined using spectrograms, then refined with reference to waveforms. Tokens which were disfluent or too severely reduced to accurately annotate were excluded from analysis.

Transitions between nasal vowels and oral stops or fricatives sometimes produced an excrescent nasal stop, e.g. *tsampi* /t͡sãpi/ → [t͡sã$\boxed{\text{m}}$pi] ‘forest, nature’. We discuss these excrescent nasals (also known as ‘nasal appendices’) in more detail in the next section; for the purposes of annotation, they were excluded from the preceding vowel (as in Desmeules-Trudel & Brunelle 2018).

After annotating the audio recordings, the time lag between the audio and oral/nasal air pressure recordings was estimated. This was done by finding 8 readily identifiable, corresponding acoustic events in each pair of recordings: typically, these were the initial glottal pulses of vowels in [#CV] sequences, as in *patû* /patɨ/ ‘stone’. The timestamps of these events were taken down for each audio recording and paired oral/nasal air pressure recording. The average discrepancy between these timestamps was used to create time-shifted Praat TextGrid files for the analysis of the oral/nasal air pressure data. Visual inspection of the time-shifted TextGrids confirmed the effectiveness of this method.

Nasal ‘appendices’

Nasalized vowels were sometimes produced with nasal ‘appendices’ in our recordings (e.g. Desmeules-Trudel & Brunelle 2018, Lapierre 2023): these are periods of overlap between a nasal vowel and a following oral consonant which resemble a nasal stop, e.g. *tsampi* /t͡sãpi/ → [t͡sã$\boxed{\text{m}}$pi] ‘forest, nature’ (we place nasal appendices inside a box to distinguish them from the first portion of prenasalized stops). Nasal appendices occur in our data following both contrastively nasal vowels and derived, predictable nasal vowels (Fig. A3). They can be identified in diagrams like Fig. A3 as periods of time in the latter half of a vowel with little to no oral air pressure, but significant nasal air pressure. This matches the aerodynamic profile of a nasal stop like [m n] (e.g. Fig. A3, right).

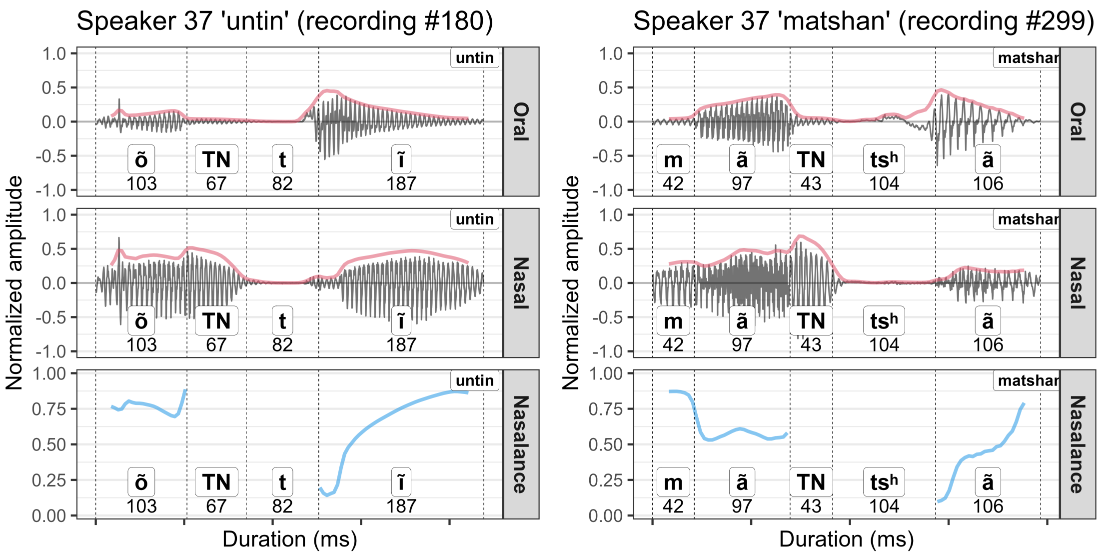


Figure A3: Nasal appendices in *untin* /õtĩ/ → [ˈõ$\boxed{\text{n}}$tĩ] ‘gadfly’ (left) and *matshan* /mat͡sʰã/ → [ˈmã$\boxed{\text{n}}$t͡sʰã] ‘grilled (like a plantain)’ (right). Nasal appendices coded ‘TN’ for ‘transitional nasal’.

We analyze nasal appendices in A’ingae as resulting from phonetic processes of gestural timing and overlap. Nasal appendices are variable in our data, occurring only some of the time. The appearance of nasal appendices is variable both within and across speakers. Additionally, since A’ingae does not have coda consonants, and does not have voiceless prenasalized phonemes like [$^{\text{n}}$t] or [$^{\text{n}}$t͡sʰ] (Fig. A3), there is no phonological analysis of nasal appendices which is consistent with the basic phonotactics of the language. Lastly, nasal appendices also occur following nasal vowels in pre-pausal position, as in Figs. A3 (left) and Fig. 7. We assume that this reflects a transition into non-speech breathing or some other rest position: the mouth is closed after speaking, but the velum remains lowered and nasal airflow continues, producing an excrescent final nasal (e.g. Barnes 2006:Ch. 3.6.4, Johnson et al. 2007). These observations are consistent with the view that nasal appendices are non-phonological.[1]

Nasal appendices were coded ‘TN’ in the TextGrids corresponding to oral/nasal air pressure

[1] This is not to imply that nasal appendices in A’ingae are ‘merely phonetic’, in the sense of reflecting a mechanical transition from a nasal vowel to an oral stop (e.g. Solé 2007). As John Kingston points out to us, nasal appendices in our data are often too long to result from simple coarticulation (mean = 44ms, comparable to values reported by Desmeules-Trudel & Brunelle 2018 and Lapierre 2023). Instead, a language-specific, controlled pattern of articulatory timing may be involved here (e.g. Kingston & Diehl 1994, Gafos 2002, Delvaux et al. 2012, Bennett et al. 2023 and references there). Suggestive evidence for this conclusion comes from the fact that the lexical item *tsampi* /t͡sãpi/ ‘forest, nature’ seems to be produced with a nasal appendix more often than other lexical items, at least impressionistically.

recordings. In our statistical analysis of vowel nasality (section 5), nasal appendices were excluded from the interval containing the preceding vowel, as in Desmeules-Trudel & Brunelle (2018).

Details of GAMM fitting procedure

We first fit an intercept-only model with random intercepts for word, and a by-step factor smooth for speaker (Baayen et al. 2017). We used this initial model to estimate an approximate value for ρ, the autocorrelation parameter used to reduce autocorrelation of residuals with an AR(1) term. The inclusion of additional random effects, such as by-condition factor smooths for each speaker, led to elevated concurvity in the model. Concurvity is the GAMM analog of multicollinearity in linear models. High concurvity implies that two or more predictors are competing for the same variance: this makes it difficult to isolate the independent contributions of those predictors, and can also lead to instability in model estimates. For that reason, we follow the advice of Baayen et al. (2017), Matuschek et al. (2017), Tomaschek et al. (2018), Wieling (2018), and Baayen & Linke (2021), and retain the simpler random effects structure described above.

We then fit a model the incorporating fixed effects described in section 3, along with the random effects described above. We compared this initial model to a model omitting the difference smooth for Nasality class, using the `compareML()` function in the `itsadug` package (van Rij et al. 2022). A χ^2 test of ML scores suggested that the inclusion of a difference smooth for Nasality class was statistically justified ($p < .0001$). We then re-estimated the autocorrelation parameter ρ, and re-fit the initial model. We assessed model fit using the `gam.check()`, `k.check()`, and `concurvity()` functions in the `mgcv` package. The model structure was determined to be appropriate according to these checks. The residuals in the model were approximately normally distributed.

If we ignore the above-mentioned concurvity issues, and fit an expanded model with by-condition factor smooths for Nasality Class for each speaker (i.e. s(Timestep, Speaker, by=Nasality Class, bs="fs", m=1)), along with the additional duration-related parameters discussed in section 5.2.2, this has essentially no effect on the model predictions visualized in Figs. 12, 13.

Details of sigmoid fitting with the `sicegar` package

The `sicegar` algorithm compares many different curves to each token, assesses their degree of fit, and eventually chooses the best-fitting curve, if there is one (see Caglar et al. 2018, `https://cran.r-project.org/web/packages/sicegar/vignettes/fitting_individual_models.html`, and `https://cran.r-project.org/web/packages/sicegar/vignettes/categorizing_fits.html` for details). The algorithm can return several classifications: 'sigmoidal', 'double-sigmoidal', 'ambiguous', or 'no signal'. 'No signal' means that no (sigmoidal) rise was detected over the course of the token. 'Ambiguous' means that a rise in nasalance was detected, but the algorithm is not confident as to whether a sigmoidal or double-sigmoidal curve provides a better fit. For ambiguous fits, we selected the simpler sigmoidal model as the optimal one. Both sigmoidal and double-sigmoidal fits indicate that nasalance increases substantially at some point in the token being analyzed. For that reason, we lumped double and single sigmoidal fits into a single, sigmoidal rise category.

We fit our nasalance data using `fitAndCategorize()` function in `sicegar`. Each token was required to have at least 600 successful fitting attempts (= `n_runs_min_(d)sm`) and at most 1200 fitting attempts (= `n_runs_max_(d)sm`) for sigmoidal and double-sigmoidal models. The maximum number of iterations (= `n_iterations_(d)sm`) was set at 1024. The AIC threshold for accepting a fit as 'successful' was set at 20, which was determined by trial-and-error.

For a token to be classified as sigmoidal or double-sigmoidal, a number of other conditions had to be met. The goal in setting these conditions was to focus on sigmoidal rises which plausibly reflect a transition from oral to nasal states, rather than a within-category transition. The nasalance value of the fitted sigmoid at the first time step (= `threshold_t0_max_int`) had to be no larger than 27.5%. The lower threshold for the maximum nasalance value of the data (= `threshold_minimum_for_intensity_maximum`) was set at 45%. Lastly, the lower threshold for the range between the minimum and maximum nasalance values of the data (= `threshold_intensity_range`) was set to 35%.

All other parameter settings were left at their default values; see `https://www.rdocumentation.org/packages/sicegar/versions/0.2.4/topics/fitAndCategorize`.

Before fitting sigmoidal models, missing nasalance values in individual tokens were supplied via data imputation using the `downup` method of the `fill()` function in the `tidyr` package (Wickham et al. 2024). This was done to prevent the `fitAndCategorize()` function from identifying spurious 'rises' from missing values at steps 1-2 to following steps. Tokens with estimated rise points below 1 were classified as not having an oral-to-nasal rise during the vowel itself.

Sigmoidal fits for [ṼN, Ṽ$^{\mathrm{N}}$D] and /Ṽ/ were manually inspected. Any sigmoidal fit with an estimated rise time that was obviously inaccurate by a wide margin was re-classified as lacking a sigmoidal rise. This led to the reclassification of 9 tokens of [ṼN, Ṽ$^{\mathrm{N}}$D].

The remaining sigmoidal fits were subject to further screening criteria. If the raw data for time-normalized steps 1 or 2 was above 32.5% (= `threshold_t0_max_int` + 5%), that token was reclassified as lacking a sigmoidal oral-nasal rise. If a token had a residual sum of squares error higher than the 97.5% quantile, indicating a relatively poor fit between data and sigmoidal model, that token was reclassified as lacking a sigmoidal oral-nasal rise (see also Pouplier et al. 2024).

References

Baayen, R. Harald & Maya Linke. 2021. Generalized additive mixed models. In *A practical handbook of corpus linguistics*, 563–591. Cham: Springer. doi:10.1007/978-3-030-46216-1_23.

Baayen, R. Harald, Shravan Vasishth, Reinhold Kliegl & Douglas Bates. 2017. The cave of shadows: Addressing the human factor with generalized additive mixed models. *Journal of Memory and Language* 94. 206–234. doi:doi.org/10.1016/j.jml.2016.11.006.

Barnes, Jonathan. 2006. *Strength and weakness at the interface: positional neutralization in phonetics and phonology*. Berlin: Mouton de Gruyter.

Bennett, Ryan, Robert Henderson & Meg Harvey. 2023. Vowel deletion as grammatically controlled gestural overlap in Uspanteko. *Language* 99(3). 399–456. doi:10.1353/lan.2023.a907008.

Boersma, Paul & David Weenink. 2020. Praat: doing phonetics by computer (version 6.1.05). Computer program. Retrieved from http://www.praat.org/.

Caglar, M. Umut, Ashley I. Teufel & Claus O. Wilke. 2018. Sicegar: R package for sigmoidal and double-sigmoidal curve fitting. *PeerJ* 6. e4251. doi:10.7717/peerj.4251.

Cohen Priva, Uriel, Emily Strand, Shiying Yang, William Mizgerd, Abigail Creighton, Justin Bai, Rebecca Mathew, Allison Shao, Jordan Schuster & Daniela Wiepert. 2021. *The cross-linguistic phonological frequencies (xpf) corpus manual*. Accessible online, `https://cohenpr-xpf.github.io/XPF/manual/xpf_manual.pdf`.

Delvaux, Véronique, Kathy Huet, Myriam Piccaluga & Bernard Harmegnies. 2012. Inter-gestural timing in French nasal vowels: A comparative study of (Liège, Tournai) Northern French vs. (Marseille, Toulouse) Southern French. In *Proceedings of Interspeech 2012*, 2682–2685. doi:10.21437/Interspeech.2012-666.

Desmeules-Trudel, Félix & Marc Brunelle. 2018. Phonotactic restrictions condition the realization of vowel nasality and nasal coarticulation: Duration and airflow measurements in Québécois French and Brazilian Portuguese. *Journal of Phonetics* 69. 43–61. doi:10.1016/j.wocn.2018.05.001.

Gafos, Adamantios. 2002. A grammar of gestural coordination. *Natural Language & Linguistic Theory* 20(2). 269–337.

Johnson, Keith, Christian DiCanio & Laurel MacKenzie. 2007. The acoustic and visual phonetic basis of place of articulation in excrescent nasals. In *UC Berkeley Phonology Lab annual report*, 529–561. Department of Linguistics, UC Berkeley. Available online at http://escholarship.org/uc/item/0n17f74x.

Kingston, John & Randy Diehl. 1994. Phonetic knowledge. *Language* 70(3). 419–454.

Lapierre, Myriam. 2023. Two types of [NT]s in Panãra: Evidence for temporally ordered subsegmental units. *Glossa* 8(1).

Machač, Pavel & Radek Skarnitzl. 2009. *Principles of phonetic segmentation*. Prague: Epocha.

Matuschek, Hannes, Reinhold Kliegl, Shravan Vasishth, R. Harald Baayen & Douglas Bates. 2017. Balancing Type I error and power in linear mixed models. *Journal of Memory and Language* 94. 305–315. doi: 10.1016/j.jml.2017.01.001.

McAuliffe, Michael, Michaela Socolof, Sarah Mihuc, Michael Wagner & Morgan Sonderegger. 2017. Montreal Forced Aligner: trainable text-speech alignment using Kaldi. In *Proceedings of the 18th conference of the international speech communication association*, 498–502.

Pouplier, Marianne, Francesco Rodriquez, Justin J.H. Lo, Roy Alderton, Bronwen G. Evans, Eva Reinisch & Christopher Carignan. 2024. Language-specific and individual variation in anticipatory nasal coarticulation: A comparative study of American English, French, and German. *Journal of Phonetics* 107. 101365. doi:10.1016/j.wocn.2024.101365.

Solé, Maria-Josep. 2007. Controlled and mechanical properties in speech. In Maria-Josep Solé, Patrice Beddor & Manjari Ohala (eds.), *Experimental approaches to phonology,* 302–321. Oxford, UK: Oxford University Press.

Tomaschek, Fabian, Peter Hendrix & R. Harald Baayen. 2018. Strategies for addressing collinearity in multivariate linguistic data. *Journal of Phonetics* 71. 249–267. doi:10.1016/j.wocn.2018.09.004.

Turk, Alice, Satsuki Nakai & Mariko Sugahara. 2006. Acoustic segment durations in prosodic research: A practical guide. In Stefan Sudhoff, Denisa Lenertova, Roland Meyer, Sandra Pappert, Petra Augurzky, Ina Mleinek, Nicole Richter & Johannes Schließer (eds.), *Methods in empirical prosody research,* 1–28. Berlin: De Gruyter.

van Rij, Jacolien, Martijn Wieling, R. Harald Baayen & Hedderik van Rijn. 2022. itsadug: Interpreting time series and autocorrelated data using gamms. R package version 2.4.1.

Wickham, Hadley, Davis Vaughan & Maximilian Girlich. 2024. *tidyr: Tidy messy data*. `https://CRAN.R-project.org/package=tidyr`. R package version 1.3.1.

Wieling, Martijn. 2018. Analyzing dynamic phonetic data using generalized additive mixed modeling: A tutorial focusing on articulatory differences between L1 and L2 speakers of English. *Journal of Phonetics* 70. 86–116. doi:10.1016/j.wocn.2018.03.002.