Articulatory patterns in contrasting nasal-stop sequences in Panãra

Susan Lin & Myriam Lapierre
UC Berkeley

1 Introduction

In Panãra (ISO code: kre), a Northern Jê language spoken by approximately 630 people in the Brazilian Amazon, speakers produce surface nasal stop-oral stop sequences (hereafter, [NT]) that are perceived to be distinct to native listeners (Lapierre & Lin, 2019). Under Lapierre's (2019) phonological analysis, one sequence is the result of prenasalization of underlying oral obstruents /T/ when they appear after phonemically nasal vowels, as in (1), while the other is the result of postoralization of underlying nasal stops /N/ when they appear before a phonemically oral vowel, as in (2).

(1) Prenasalization: /T/ → [NT] / Ṽ __ e.g., /mĩ**t**ɛ/ → [mĩ**nt**ɛ]
(2) Postoralization: /N/ → [NT] / __ V e.g., /mĩ**n**ɔ/ → [mĩ**nt**ɔ]

The phonological inventory of the language is presented below, where Table 1 provides the inventory of consonants, and Table 2 provides the inventory of vowels (Lapierre, 2019). Crucial to Lapierre's analysis is that nasality is contrastive for both vowels and consonants in Panãra, which creates the relevant conditioning environments for the two phonological processes in (1-2).

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

Table 1. Consonant phonemes.

Short oral		
i	ɯ	u
e	ɤ	o
ɛ	a	ɔ

Short nasal		
ĩ	ɯ̃	ũ
ẽ	ɤ̃	õ

Long oral		
iː	ɯː	uː
eː	ɤː	oː
ɛː	aː	ɔː

Long nasal		
ĩː		
ẽː	ɤ̃ː	õː

Table 2. Vowel phonemes.

Since both surface sequences may be transcribed identically as [NT], a natural follow up question is in what ways do the productions of the sequences differ? Previous work shows that the acoustics of the two types of [NT]s differ in their relative duration of audible oral-to-nasal stop (Lapierre & Lin, 2018), where the duration of nasal murmur is lower for prenasalized stops and greater for postoralized nasals. This difference is illustrated in the two spectrograms in Figure 1, where the duration of nasality is very brief in /mĩtɛ/ → [mĩntɛ], and significantly longer for /mĩnɔ/ → [mĩntɔ].

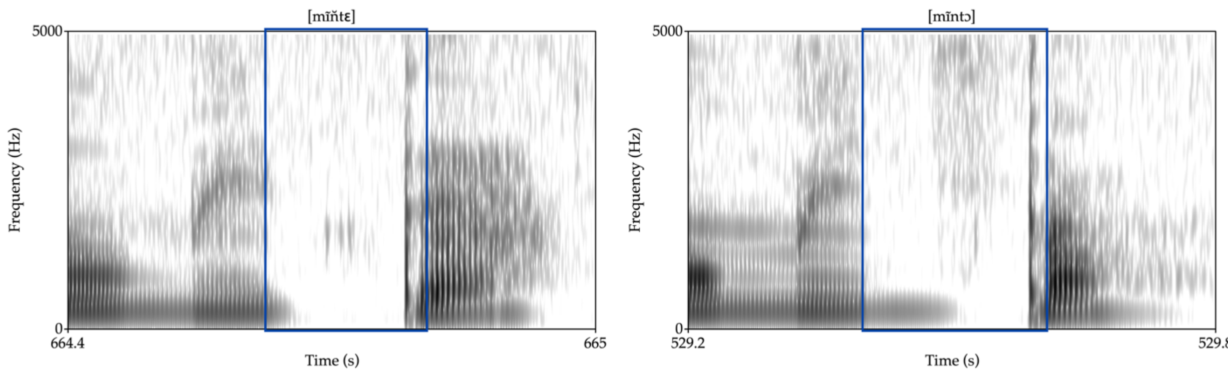

Figure 1. Spectrograms from the production the words /mĩ**t**ɛ/ → [mĩ**nt**ɛ] (left) and /mĩ**n**ɔ/ → [mĩ**nt**ɔ] (right), respectively, with [nt] sequence outlined by blue rectangles.

The goal of this paper is to describe the articulatory properties of these [NT] sequences that arise from prenasalization and postoralization, including the relative timing of the oral, glottal, and velic gestures in the two types of [NT] sequences.

2 Methods

We designed a production experiment to test in what way these two [NT]s differ in their articulation by native Panãra speakers. In the summer of 2017, prior to data collection, the plan to conduct the experiment and collect data was presented to community leaders in the Panãra village of Nãnsêpotiti by the researcher (the second author), located inside the Panará Indigenous Land. Community leaders spread the word, as did others who heard about the experiment, and those who were interested in participating presented themselves at the researcher's house. A total of 34 native speakers of Panãra between the ages of 15 and 38 years (mean age = 26 years; 15F) participated. The data analyzed and discussed here is from 4 male and 3 female speakers.

On completion of the experiment, each participant was compensated 83 grams of Czech beads. Note that this type of remuneration was used upon request of the community, as the economic system in place inside of the Panará Indigenous Land is mostly dependent on trade. Czech beads are used to create ornaments that are worn during village festivities and often sold in nearby towns and are among the most valued goods.

2.1 Stimuli and equipment

The stimuli for this experiment consisted of 38 disyllabic words containing one of the eight phonotactic forms in Table 3, which represent every possible combination of nasality/orality in a VCV sequence. To the extent possible given the lexicon of the language, target words were

Type	Form	Example target word	Gloss
	/VTV/	/ko**pɔ**/ → [ko**pɔ**]	‘paddle’
Prenasalization	/VTṼ/	/mĩ**tɛ**/ → [mĩ**(^{n})tɛ**]	‘caiman leg’
	/ṼTV/	/a**tõ**/ → [a**tõ**]	‘gun’
Prenasalization	/ṼTṼ/	/põ**põ**/ → [põ**(^{m})põ**]	‘crane’
Postoralization	/VNV/	/paː**nɔ**/ → [paː**n^{t}ɔ**]	‘toe’
Postoralization	/VNṼ/	/mĩ**nɔ**/ → [mĩ**n^{t}ɔ**]	‘caiman eye’
	/ṼNV/	/ka**mĩ**/ → [ka**mĩ**]	‘porridge’
	/ṼNṼ/	/sõ**ɲĩ**ː/ → [sõ**ɲĩ**ː]	‘vomit’

Table 3. Examples of the eight target forms.

balanced for place of articulation and quality of target consonants and vowels. Participants were prompted to say all target words inside of the carrier phrase [kjẽ hẽ ka sũ X] ‘I say the word X’, where X represents the target word.

Using an EGG-D800 produced by Laryngograph, which has two separate pressure transducers, we captured nasal and oral airflow data. The EGG-D800 device was paired with the use of a handheld Oro-Nasal Rothenberg mask with two isolated chambers, thus allowing for oral and nasal airflow to be captured separately. We chose to use the Rothenberg mask specifically because its design results in relatively clear speech audio, which we recorded using an ECM-500L/SK microphone connected to the auxiliary input of the EGG-D800. All three channels were recorded simultaneously to a single WAV file.

2.2 Experimental procedures

Participants were instructed in Panãra by the researcher, a functional and fluid speaker of the language, to hold the mask tightly over their nose and mouth, and the researcher provided feedback on the position of the mask so as to minimize leakage of airflow. Each target word was presented visually on an individual slide in a PDF slide deck so as to eliminate the risk of creating an enumeration effect on prosody. Target words embedded inside the relevant carrier phrase, were presented in orthography alongside a picture depicting the target word in order to help illiterate participants to identify the target word. Target words were presented five times each in semi-randomized blocks.

As even the literate participants do not read in a fluid manner representative of natural speech, the researcher guided the participants through the task by producing the entire carrier phrase for each token, and participants were asked to repeat what had been said. This was done to reduce the complexity of the task, as Panãra speakers are not generally familiar with experimental language research procedures. This particular method allowed them to feel more at ease and to make it clear to them that the task did not involve any evaluation of their reading abilities. The experiment took approximately 20 minutes to complete.

3 Analysis

The audio speech recording from each speaker was annotated by hand by trained undergraduate research assistants. They annotated the audio recordings for the onset and offset of all targe sequences. Only [ṼNTV] sequences were selected for the analysis presented in this paper, as this is the only phonotactic environment in which both types of [NT] sequences are found.

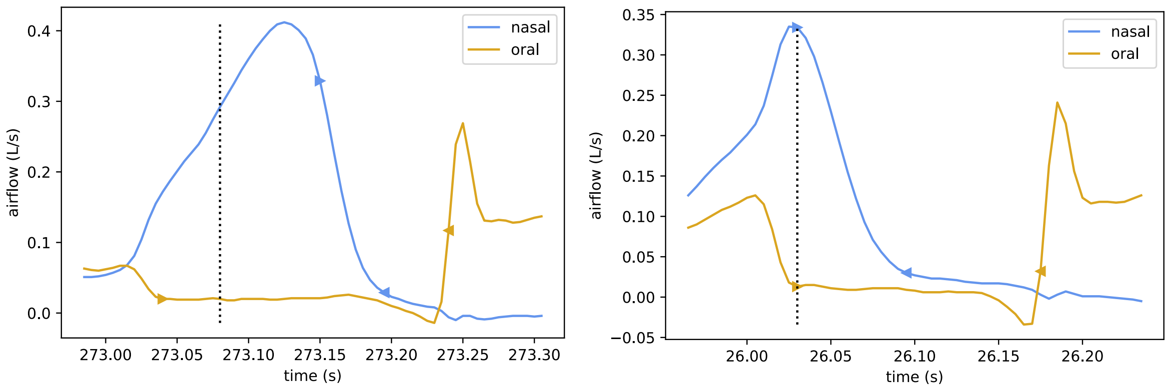

Figure 2. Oral (orange) and nasal (blue) airflow channel during the production of the [ṼNTV] sequences in the word /mĩ**nɔ**/ → [mĩ**ntɔ**] 'caiman eye' (post-oralization, left) and /mĩ**tɛ**/ → [mĩ**nt**ɛ] 'caiman leg' (pre-nasalization, right) by a female speaker. Arrows indicate articulatory landmarks, as determined by inflection points in the oral and nasal airflow curves, and dotted black lines indicate end of vocal fold vibration.

Comparisons between the velic and oral articulations in [NT] sequences and those found in [ṼNṼ] and [VTV] sequences are planned, but are outside the scope of the current work.

For each utterance, we tracked activity of three articulators: the glottis, the velum, and the oral articulator. Figure 2 shows nasal and oral airflow from two example utterances, for /mĩnɔ/ (left) and /mĩtɛ/ (right). The vertical dotted line in each plot represents the end of audible voicing, which we determined by calling Praat's PointProcess object within the [ṼNTV] span (Boersma & Weenink, 2008). We calculated articulatory landmarks relating to velic movement and oral cavity constriction by finding the inflection points (local minima and maxima of the second derivative) in the nasal and oral airflow curves. Achievement of complete velic (left pointing blue arrow) and oral (right pointing orange arrow) constriction was operationalized as the inflection point with negative slope and zero nasal and oral airflow respectively. In contrast, onset of velic and oral release was operationalized as the inflection point with negative slope and non-zero nasal and oral airflow respectively.

We then determined the relative alignment of particular articulatory landmarks with respect to one another by calculating the time interval between the following three pairs of articulatory landmarks illustrated below in Figure 3:

i. oral lag = *onset of velum closure* – *achievement of oral constriction*;
ii. velum raising = *achievement of velum closure* – *onset of velum closure*; and
iii. voicing lag = *achievement of velum closure* – *offset of vocal fold vibration*.

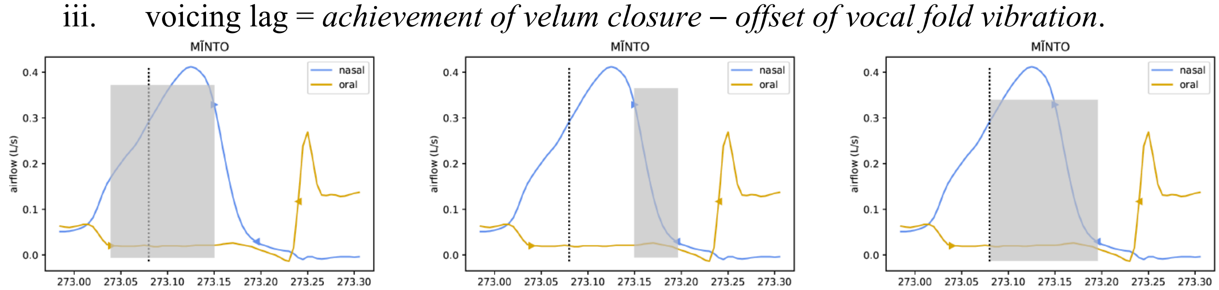

Figure 3. Oral lag (left), velum raising (center), and voicing lag (right) during the production of the target word /mĩ**nɔ**/ → [mĩ**ntɔ**] 'caiman eye' by a female speaker.

4 Results

The results of our analysis show that, as expected, Panãra speakers systematically produce the two types of [NT]s distinctly with respect to all three metrics: namely oral lag, velum raising, and voicing lag. The statistics presented in this section are the result of a linear mixed effects regression model using the lme4 package in R (Bates et al., 2015), with participant and word included as random effects.

As shown in Figure 4 (left), oral lag is significantly greater in postoralized nasal stops relative to prenasalized oral stops ($\beta = 0.0729$; $t = 7.655$; $p = 0.0003$). The model's estimated duration of oral lag over all speakers is 100 ms for post-oralized nasals, and 27 ms for pre-nasalized stops. This suggests that the velic and oral gestures occur close to one another in the production of prenasalized stops, while onset of velum raising occurs much later than oral stop closure is achieved in postoralized nasals. Thus, nasal airflow persists during a greater proportion of the stop closure for postoralized nasals relative to prenasalized stops, which is expected given their underlying representation as /N/, as well as previously reported differences in the durations of the audible nasal component.

Furthermore, as shown in Figure 4 (right), voicing lag is also significantly greater in postoralized nasal stops (78 ms) than in prenasalized oral stops (43ms; $\beta = 0.0354$; $t = 4.75$; $p = 0.0032$). This indicates that the velic and glottal gestures occur close together in the production of prenasalized stops, whereas onset of velum raising gesture occurs much later after the vocal folds cease to vibrate in the case of postoralized nasals. This finding indicates that nasal airflow does persists during a greater proportion of the stop closure for post-oralized nasals relative to pre-nasalized stops.

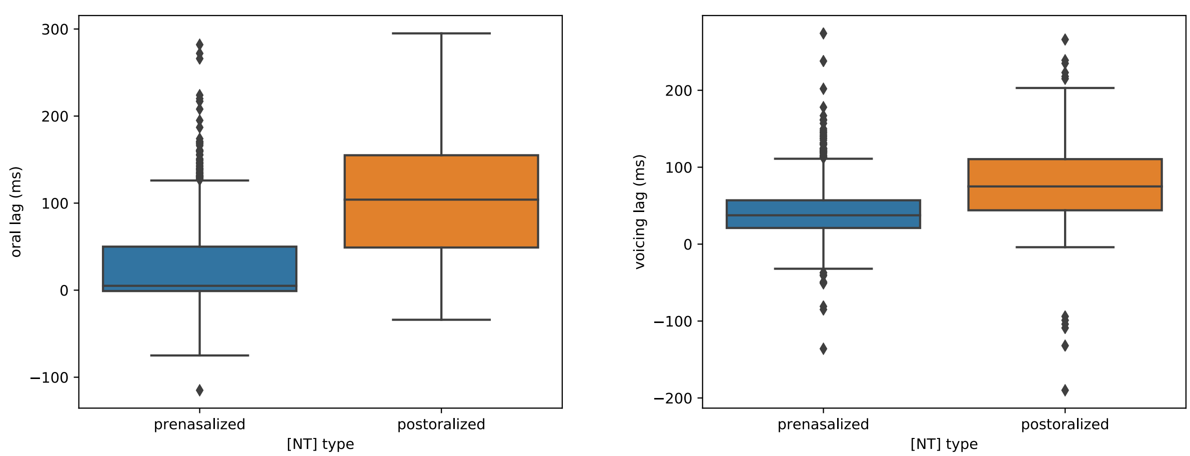

Figure 4. Model estimate of oral lag (left) and voicing lag (right) for prenasalized /T/ (left) and postoralized /N/ (right).

Finally, as shown in Figure 5, our results also demonstrate that at 83 ms and 51 ms, the velum takes significantly longer to complete its rise during the production of postoralized nasal stops relative to prenasalized oral stops ($\beta = -0.0319$; $t = -4.006$; $p = 0.0070$). This suggests a slower moving velum in production of postoralized nasal stops than prenasalized oral stops.

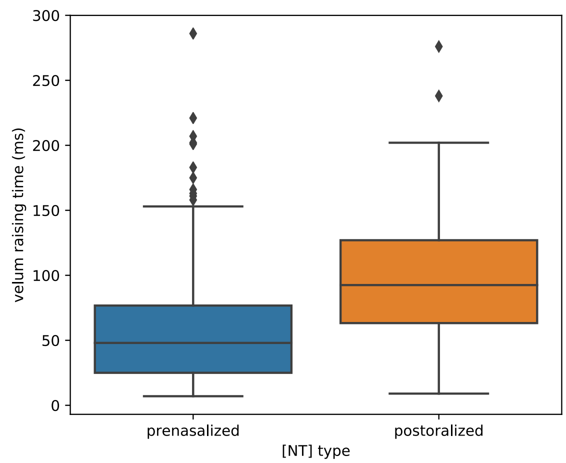

Figure 5. Model estimates of velum raising time for prenasalized /T/ (left) and postoralized /N/ (right).

5 Discussion

5.1 Gestural synchrony and asynchrony

Taken together, the results of our production experiment show that the oral, nasal, and glottal articulations of prenasalized [NT]s are significantly more closely aligned with one another than those in postoralized [NT]s. Considering the timing and the typical duration of articulator movement, it is plausible that the gestures of prenasalized [NT]s may be planned synchronously. In contrast, these same three gestures of postoralized [NT]s are almost certainly asynchronous. In postoralized [NT]s, achievement of oral constriction occurs first, followed by the offset of vocal fold vibration, followed finally by the release of the velum. In Figure 6, we present a schematization of the alignment between the oral, nasal, and glottal gestures in prenasalized stops (left) and asynchrony of these same gestures for postoralized nasals (right).

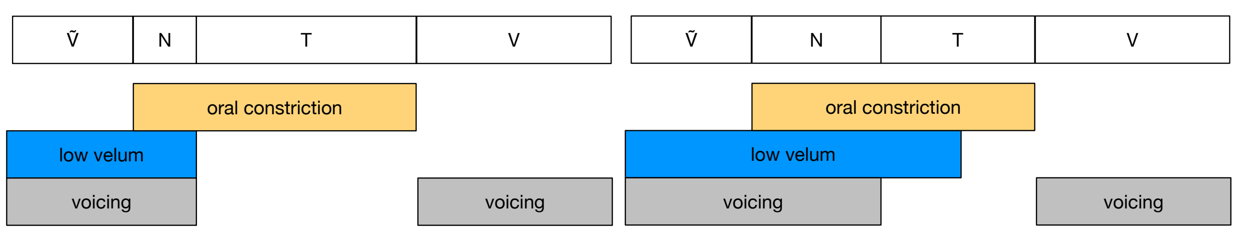

Figure 6. Gestural scores for a prenasalized /T/ (left) and postoralized /N/ (right).

The relative synchrony of gestures in prenasalized /T/ and relative asynchrony of gestures in postoralized /N/ would be most consistent with an analysis in which prenasalization is a fixed phonological process and postoralization is a gradient phonetic process. However, previous analyses have suggested exactly the opposite (Lapierre, 2019). Prenasalization is variably applied, both by and within speaker, and speakers' productions of prenasalization are highly variable in their duration; in contrast, postoralization is a consistently applied process, resulting in relatively consistent N:T duration ratios within a given speaker's productions (Lapierre & Lin, 2018).

5.2 Voicing asynchrony and oral air pressure

Another puzzle is the fact that vocal fold vibration ceases before velum raising is achieved. This is typologically unexpected, given the extensive literature discussing the markedness of [NT] segments compared to [ND]. It is generally understood that without deliberate abduction of the vocal folds during the production of an [ND] segment, the natural state of the glottis during the oral portion of a partially nasal segment is to be vibrating (Hayes & Stivers, 2000; Ohala, 1993, 2011). However, our analysis shows that the vocal folds must be abducted while the velopharyngeal port is still open during the production of postoralized /N/. For the vocal folds to not be vibrating, they must either be abducted sufficiently to prevent vibration, or they must be completely adducted. That the pneumotachograph registers nasal airflow is evidence against adduction. Crucially then, this implies that the lack of voicing during the closure phase of the postoralized nasals cannot be the result of passive aerodynamic constraints and must be due to the deliberate abduction of the glottis. We wonder then, what motivates this abduction?

One possibility is that it serves as an opportunity for Panãra speakers to enhance the perceptual distance between prenasalized and postoralized [NT]s. This asynchrony of the oral and nasal gestures should result in lower air pressure build up in the oral cavity before the release of the postoralized [NT]. This reduced air pressure behind the oral constriction, in turn, would result in a reduction of the amplitude of the oral stop burst. This proposal is consistent with the results of a perception experiment showing that Panãra listeners make use of at least three acoustic cues in distinguishing between the two types of [NT]s during identification and discrimination tasks, namely (i) amplitude of the nasal murmur; (ii) relative duration of the nasal and oral components during stop closure; and (iii) presence or absence of a stop burst (Lapierre & Lin, 2019). Presence of a stop burst resulted in greater proportion of underlying /T/ responses (relative to underlying /N/ responses), suggesting that the stop burst of postoralized nasals may indeed be less perceptually salient than that of prenasalized stops.

6 Conclusion

In this paper, we presented the results of a production experiment aimed at determining the relative alignment of the oral, nasal and glottal gestures during the production of [NT]s arising from either postoralization of a nasal stop /N/ or prenasalization of an oral obstruent /T/ in Panãra. We predicted that nasal airflow and vocal fold vibration would persist during a greater proportion of the stop closure duration of postoralized nasals, relative to pre-nasalized stops. All of the relevant measurements and calculations show significant differences in the realization of postoralized nasals and prenasalized stops in the directions expected. We conclude that the two types of [NT]s differ significantly in their articulation, as evidenced by oral and nasal airflow data, as well as voicing offset as determined by analysis of acoustic recordings. However, under most implementations of gestural phonology (e.g. Browman & Goldstein, 1989, 1992; Gafos, 2002), the relative synchrony of tracked gestures in prenasalized /T/s vs asynchrony of the same gestures in postoralized /N/s suggest that prenasalization is a phonological process while postoralization is a phonetic process, exactly the opposite of what previous analyses of Panãra have pointed to (Lapierre, 2019; Lapierre & Lin, 2018).

We also discussed one interesting puzzle uncovered in our data – the timing of the ends of voicing and nasality in postoralized /T/s, which cannot be due to passive aerodynamic constraints. This suggests that the asynchrony between the devoicing gesture and the velic gesture in these [NT]s is deliberate, and we speculate that this asynchrony may have developed as a strategy of perceptual contrast enhancement (for further discussion of contrast enhancement in Panãra, see Lapierre, 2020).

References

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1), 1–48.

Boersma, P., & Weenink, D. (2008). *Praat: Doing phonetics by computer [Computer Program]. Version 5.0.14.*

Browman, C., & Goldstein, L. (1989). Articulatory gestures as phonological units. *Phonology*, *6*, 201–251.

Browman, C., & Goldstein, L. (1992). Articulatory Phonology: An Overview. *Phonetica*, *49*(3–4), 155–180.

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

Hayes, B., & Stivers, T. (2000). Postnasal voicing. *Ms., UCLA*.

Lapierre, M. (2019). *A phonological analysis of Panãra* [Qualifying paper]. University of California, Berkeley.

Lapierre, M. (2020). Postoralized and devoiced nasals in Panãra (Jê): ND > NT. In D. Enke, L. Hyman, J. Nichols, G. Seiler, & T. Weber (Eds.), *Language Change for the Worse* (pp. 53–88). Language Science Press.

Lapierre, M., & Lin, S. (2018). *Patterns of nasal coarticulation in Panará* [Poster]. 16th Conference on Laboratory Phonology, Lisbon, Portugal.

Lapierre, M., & Lin, S. (2019). Cues to Panãra Nasal-Oral Stop Sequence Perception. In S. Calhoun, P. Escudero, M. Tabain, & P. Warren (Eds.), *Proceedings of the 19th International Congress of Phonetic Sciences* (pp. 310–314). Australasian Speech Science and Technology Association Inc.

Ohala, J. J. (1993). The phonetics of sound change. In C. Jones (Ed.), *Historical Linguistics: Problems and Perspectives* (pp. 237–278). Longman.

Ohala, J. J. (2011). Accommodation to the Aerodynamic Voicing Constraint and its Phonological Relevance. *Proceedings of the 17th International Congress of the Phonetic Sciences*, 64–67.