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Pharyngealization in Tashlhiyt from kinematic and acoustic perspectives

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This study investigated the implementation of pharyngealization in Tashlhiyt, across various linguistic contexts VC̲V, VCC̲V, VC̲CV, and VCC̲CV. We analyzed articulatory and acoustic data from six male speakers who produced words containing these sequences with both plain ([d, z]) and pharyngealized target consonants ([dˤ, zˤ]). The investigation comprised dynamic analyses of kinematic and formant trajectories, as well as acoustic parameters of consonants and intrusive schwas. While pharyngealization did not affect the tongue tip, it did lead to a significant lowering of the tongue body. This lowering was not confined solely to the target consonants but was observed in larger domains, extending up to nearly the entire VCC̲CV items. The primary acoustic correlate of pharyngealization was identified as a lowered F2 of vowels and intrusive schwas, while acoustic properties of consonants remained unaffected. Consistent with observations in the articulatory domain, the lowering of F2 was not restricted solely to vowels adjacent to pharyngealized coronals; instead, it extended to larger domains, even when there were intervening consonants.

1. Introduction

Pharyngealization is a secondary articulation characterized by a constriction of the pharynx and a backward movement of the tongue towards the pharyngeal wall (Ghazeli, 1977). This articulation is lexically contrastive in some languages, notably in Arabic, where it is a prominent feature of certain sets of coronal segments (e.g., [tiːn] 'figs' vs. [tˤiːn] 'mud'). While the phonetic implementation of pharyngealization has been extensively studied in Arabic varieties, research on this topic in non-Semitic languages remains limited. Tashlhiyt is one such non-Semitic language where pharyngealization is phonemic and a feature of the entire set of coronals (e.g., [izi] 'fly' vs. [izˤi] 'gallbladder'). However, there is a lack of data on the phonetic implementation of pharyngealization in Tashlhiyt. This study aims to fill this research gap by providing a comprehensive, dynamic analysis of the articulatory and acoustic characteristics of pharyngealization in an Amazigh language.

The characteristics of pharyngealization, like other secondary articulations, are predominantly manifested in the formant structure of adjacent vowels (Ladefoged & Maddieson, 1996). Consequently, phonetic investigations of pharyngealization typically focus on plain and pharyngealized segments occurring within a vocalic context, with consonant-related measurements being of secondary importance. However, in Tashlhiyt, a language that makes frequent use of consonant clusters, it becomes crucial to understand how pharyngealization is manifested when the immediate phonetic context is either partially or completely occupied by consonants. To address this question, we will first establish a baseline by investigating pharyngealization in VC̲V words. Subsequently, we will explore three additional contexts, specifically VCC̲V, VC̲CV, and VCC̲CV structures, where C̲ marks the coronal target consonant. In these contexts, the underlined consonant can be either a plain or pharyngealized coronal, while V represents a low vowel /a/ or a high vowel /i/, and C a non-coronal consonant.

In the subsequent sections of this introduction, we will review the existing literature on pharyngealization, summarize previous findings from articulatory and acoustic studies, and provide a concise overview of the phenomenon of pharyngealization in Tashlhiyt.

1.1 Pharyngealization: A rare, but well-studied secondary articulation

Secondary articulations are defined as a simultaneous constriction of a lesser degree that accompanies another, stronger, primary constriction in another location in the vocal tract (Crystal, 2008; Laver, 1994; Proctor, 2022; Trask, 1996). The simultaneity of the primary and secondary constriction is an important criterion that distinguishes these segments from sequences, and the lower degree of the secondary constriction differentiates between double articulations (e.g., [k͡p] in Igbo) and secondary articulations (Van De Weijer, 2011). The secondary articulation is usually considered to be 'approximant-like' (Ladefoged & Maddieson, 1996, p. 354) or 'vowel-like' (Ladefoged & Johnson, 2011, p. 234).

The major types of secondary articulations are usually listed as labialization, palatalization, pharyngealization, and velarization (Ladefoged & Maddieson, 1996; see also Laver, 1994 for a discussion of other potential secondary articulations). About 25% of the phoneme inventories in the PHOIBLE dataset contain at least one secondary articulation (502/2177). Labialization is the most common (362 phoneme inventories), followed by palatalization (204); pharyngealization (24) and velarization (17) are the least common (Buech, Hermes & Ridouane, 2022). Pharyngealization is often associated with Arabic varieties where it is a prominent feature of a subset of coronal consonants. As a result, phonetic studies on pharyngealized consonants have been predominantly based on data from Arabic varieties such as Cairene Arabic (e.g., Hermes, 2018; Lehn, 1963), Qatari Arabic (Kulikov, 2021), Assiri Arabic (Shar & Ingram, 2010), Palestinian Arabic (Al-Adam, 2015), Saudi and Lebanese Arabic (Hermes et al., 2017), Moroccan and Jordanian Arabic (e.g., J. Al-Tamimi, 2017; Jongman et al., 2011), or Libyan Arabic (Laradi, 1983). Studies on pharyngealization beyond Arabic are comparatively rare, but cover languages like Nootka (Rose, 1979) and Hebrew (Laufer & Baer, 1988), and different Caucasian languages like Ubykh, Tsakhur, Udi and Tsez (see Beguŝ, 2020 for a review), Tŝilhqot'in (Bird & Onosson, 2023), and Kabyle Amazigh (Tigziri, 2013). A case where the pharyngealized vowels contrast with plain vowels is Northern Horpa (Chiu & Sun, 2020). While the primary emphasis of the majority of these studies was on the acoustics of pharyngealization, there were also articulatory studies that offered valuable insights into this phenomenon.

1.1.1 Articulatory correlates of pharyngealization

Several techniques have been used to investigate pharyngealization in Arabic from an articulatory perspective. These include X-ray measurements (Ghazeli, 1977), ultrasound (Alwabari, 2020; Chiu & Sun, 2020), real-time Magnetic Resonance Imaging (Hermes, 2018; Hermes et al., 2017), fiberscopy (Laufer & Baer, 1988; Zeroual, 1999), endoscopy (Zeroual et al., 2011), videofluorography (Ali & Daniloff, 1972; Laradi, 1983), and electromagnetic articulography (Embarki et al., 2011; Ouni, 2008). The studies consistently found that pharyngealization is caused by an additional constriction at the pharynx, resulting from a retraction of the tongue root (Ghazeli, 1977; Israel et al., 2012; Laufer & Baer, 1988; Zeroual et al., 2011).

The articulatory effects of the spread of pharyngealization were analyzed in several studies, including those by Alwabari (2019, 2020) and Hermes (2018). The study of Alwabari (2020) examined the production of bi- and multisyllabic words containing the sequence C_1VC_2, with C_1 as the underlying pharyngealized consonant and C_2 as labial ([b, f]), palatal ([j, ʃ]), or velar ([g, χ]) segments. She found that labials were produced with a strong tongue root retraction and a lowered tongue body, while [χ] was associated with a raised tongue body and a tongue root retraction. Palatals and [g] showed resistance to tongue dorsum modifications and tongue retractions. Hermes (2018) analyzed the production of CVC, CVCV, and VCVC items with varying positions of coronals and consonants ([b, f, j]). She found a pharyngeal constriction throughout the words containing pharyngealized coronals and a lowering of the tongue body for all vowels, regardless of height and quality. She also observed a stronger constriction at the pharynx in segments preceding the pharyngealized consonant than in segments following them, indicating a stronger leftward than rightward spread in Cairene Arabic.

1.1.2 Acoustic correlates of pharyngealization

As mentioned previously, the primary focus in acoustic studies on pharyngealization has been on analyzing the formant structure of adjacent vowels. The general finding is that pharyngealization induces an important lowering of F2 in the surrounding vowels. This finding is consistent across Arabic varieties (e.g., Al-Khairy, 2005; Hermes, 2018; Jongman et al., 2011; Kalaldeh & Al-Shdaifat, 2019; Shar & Ingram, 2010; Zeroual et al., 2011), and across non-Arabic languages (e.g., Beguŝ, 2020; Bird & Onosson, 2023; Chiu & Sun, 2020; Rose, 1979; Tigziri, 2013). The contribution of F1 is less clear, although the majority of studies report a raised F1 in adjacent vowels (e.g., Al-Adam, 2015; Freeman, 2021; Jongman et al., 2011; Rose, 1979). In contrast, Hermes found inconsistent results, and Bird and Onosson observed no difference except for a lowering in adjacent [i]. While F3 is not consistently considered in acoustic investigations due to its limited sensitivity to pharyngealization, certain studies, such as Al-Masri (2009) and Chiu and Sun, have reported a raising of this formant. Additionally, F. Al-Tamimi and Heselwood (2011) found that the effect on F3 was contingent upon the quality of the vowel involved. In general, formant differences appear to be biggest in /a/, followed by /i/, while the formant structure of /u/ seems to be least affected (Hermes).

The location of the highest formant differences within vowels is variable. In the case of F1, Al-Masri (2009) reported higher values throughout the vowel when preceded by a pharyngealized consonant. However, Kulikov et al. (2023) and Zeroual (1999) observed a higher F1 specifically at the onset of the following vowels, but not at their midpoint or offset. For F2, both Al-Masri and Kulikov et al. (2023) found lowered values throughout the entire vowels. Regarding F3, Kulikov et al. found raised values in the vicinity of the pharyngealized consonant in both preceding and following vowels. On the other hand, Al-Masri found a higher F3 only in the following vowel. When considering the highest difference of F2 in intervocalic coronals, Hermes (2018) found a stronger difference in the preceding vowels. Conversely, F. Al-Tamimi and Heselwood (2011) and Zawaydeh and de Jong (2011) observed a stronger lowering of F2 in the vowel following the pharyngealized segment.

The acoustic properties of pharyngealized consonants themselves have received relatively less attention when compared to adjacent vowels. Studies that have examined consonant-related measurements have primarily focused on temporal measurements. For example, Al-Khairy (2005) observed no difference in consonant duration between plain and pharyngealized fricatives. This is confirmed by Al-Masri (2009), but he observed a longer duration of pharyngealized stops than for plain ones in word-final position. Regarding stops, Voice Onset Time (VOT) has been reported to be shorter for pharyngealized coronal stops (Abudalbuh, 2011; Al-Adam, 2015; AlDahri, 2013; Khattab et al., 2006; Kulikov et al., 2023). Spectral characteristics of plain and pharyngealized obstruents have been investigated by Jongman et al. (2011), who found a lower Center of Gravity (COG) for pharyngealized [dˤ, tˤ] than for plain [d, t] , but no difference of the spectral mean in fricatives [ð, ðˤ, s, sˤ]. Bird and Onosson (2023), on the contrary, found a higher COG for [z] than for [zˤ]. Al-Masri found no effects of pharyngealization on other spectral properties, namely the standard deviation, skewness, and kurtosis.

Acoustic investigations of spread of pharyngealization have primarily focused on vowels, consistently revealing a lowered F2 in all vowels in up to four-syllable words (Ahmed & Grosvald, 2018; Al-Masri, 2009). However, studies specifically examining the acoustic effects of pharyngealization on consonants in the context of pharyngealization spread are limited. Kulikov (2021) conducted one of the rare investigations in this domain by a comparison of word-initial plain and pharyngealized in plain [tVC] and pharyngealized context [tVCˤ]. They found no impact on the VOT of initial plain coronal stops, but a lowered COG in pharyngealized contexts. Notably, research exploring the acoustic impact of pharyngealization on non-coronal consonants remains extremely scarce. To date, only one study by Al-Masri has been found, which analyzed the burst spectrum of /b/ in CVC syllables, but he did not report any discernible differences in the spectral moments.

1.2 Pharyngealization in Tashlhiyt Amazigh

Tashlhiyt includes the following set of pharyngealized consonants: /tˤ, tˤː, dˤ, dˤː, sˤ, sˤː, zˤ, zˤː, ʒˤ, ʒˤː, ɾˤ, ɾˤː, lˤ, lˤː/. This set is widely accepted because of the existence of various lexical items attesting to the underlying status of these segments and their lexical function in distinguishing words (Boukous, 1989; Dell & Elmedlaoui, 2002; El Moujahid, 1979; Elmedlaoui, 1985; Lasri, 1991). While other coronal consonants may also be considered underlyingly pharyngealized in specific words, the occurrence of these consonants is extremely rare. For instance, the pharyngealized [ʃˤː] in [amuʃˤː] ‘cat’ and [nˤː] in [mnˤːk] ‘to miss’, adapted from French ‘manquer’ /mɑ̃ke/’, are the only reported instances of these pharyngealized consonants. The presence of the pharyngealized /nˤː/ in the French adapted form [mnˤːk] could be attributed to the French back vowel adjacent to /n/, which is identified with the Tashlhiyt allophone [ɑ] in pharyngealized contexts. Therefore, this mapping is adapted into Tashlhiyt by pharyngealizing the adjacent consonant /nː/ (see Kenstowicz & Louriz, 2009, on the phenomenon of pharyngealization in loanword adaptation in Moroccan Arabic, where it was found to be systematic with French back vowels).

In Tashlhiyt, pharyngealization is a feature that any segment can display at the phonetic level. Similar to Arabic, it involves the spread of this secondary articulation from underlying pharyngealized coronals to neighboring sounds. For instance, in the forename /fatˤima/ ‘Fatima’, there is one underlying pharyngealized coronal /tˤ/. However, all the segments in the word have the potential to phonetically exhibit pharyngealization, resulting in the pronunciation [fˤaˤtˤiˤmˤaˤ]. Pharyngealized words may contain more than one coronal consonant, such as /ablˤadˤ/ ‘big stone’, or be composed solely of pharyngealized coronals, such as /dˤrˤ/ ‘fall’. In such instances, there is no established method of determining whether only one or more coronals are underlyingly pharyngealized.

Pharyngealization spread can be influenced by several factors, including speech style, speech rate, and the level of formality. Dell and Elmedlaoui (2002) highlight that a word like /tadˤːinga/ ‘wave’, typically pronounced as [tˤaˤdˤːiˤnˤga], can also be pronounced as [tadˤːiˤnga], where only the vowel following the pharyngealized /dˤː/ undergoes pharyngealization. However, this pronunciation is considered appropriate only in specific speech styles used by itinerant preachers and minstrels during certain forms of public speeches. Although there is a lack of consensus regarding the precise extent of pharyngealization spread in Tashlhiyt, it is generally admitted that the syllable serves as the minimum domain, while the word represents the maximum domain for this phenomenon. Nevertheless, irrespective of word boundaries, it is observed that onset-nucleus syllables can exhibit either pharyngealized or plain characteristics. Consider the following examples that showcase a phonological pun commonly found in the Tashlhiyt speaking area. This pun relies on a wordplay facilitated by the rule dictating that the onset-nucleus sequence /rˤi/ in (1a) must always be pharyngealized, even when the sequence spans a word boundary (in contrast to 1b).

(1) a. i-ħlb i-dˤrˤ i-gn [iħlbidˤrˤiˤgn]
3SG.MASC-eat 3SG.MASC-fall 3SG.MASC-sleep
‘he ate (something) with milk and fell asleep’

b. i-ħlb idˤrˤign [iħlbidˤrˤiˤgn]
3SG.MASC-eat diarrhea
‘he ate diarrhea with milk and fell asleep’

The phonetic characteristics of pharyngealization in Tashlhiyt have primarily been based on impressionistic data. However, due to the inherent limitations and ambiguities in acceptability judgments, experimental studies are crucial for obtaining an objective assessment of this phenomenon. This study aims to address this need by presenting an investigation that examines the articulatory and acoustic characteristics of pharyngealization in Tashlhiyt. It builds upon a previous study conducted by Buech, Ridouane and Hermes (2022), which focused on analyzing [aCa] logatomes spoken in isolation. This study showed that the main distinguishing articulatory parameter was a lowering of the middle of the tongue and tongue body during the production of pharyngealized consonants. In terms of acoustics, the primary acoustic parameter distinguishing plain and pharyngealized consonants was a significant decrease in F2 throughout both the preceding and the following vowels. The impact of pharyngealization on other formants was minimal in the case of F1 or varied, depending on the specific characteristics of the consonants in the case of F3.

Our current study primarily aims to understand the variations over time in kinematic and formant trajectories between pharyngealized and plain items. In order to do so, we have extended the research scope outlined in Buech, Ridouane and Hermes (2022). We have done this by including a collection of 28 real words contrasting pharyngealized and plain stops ([dˤ] and [d]) and fricatives ([zˤ] and [z]) in a variety of contexts. These contexts include instances where the target segments are not immediately adjacent to vowels (VC̲V, VCC̲V, VC̲CV, and VCC̲CV). This diverse range of contexts allows us to investigate the nature and extent of pharyngealization spread in a more comprehensive manner.

2. Methods

2.1 Participants

Six male native speakers of Tashlhiyt (32–50 years; mean = 44, standard deviation = 7; one is a co-author) were recruited for the experiment. None of them reported any speech or hearing-related issues. Each participant gave written consent.

2.2 Stimuli

The stimuli are displayed in Table 1. Target consonants included plain [d] and [z], and their pharyngealized counterparts [dˤ] and [zˤ]. These target consonants were positioned in four different word contexts: VC̲V, VCC̲V, VC̲CV, and VCC̲CV. Vowels varied between [i] and [a], and all the surrounding consonants were non-coronals. While most target words were real Tashlhiyt words, some pairs lacked appropriate plain or pharyngealized versions, so we used phonotactically well-formed non-words in those cases.

All target words were embedded in the carrier sentence (2):

(2) *Innajam ___ bahra*
i-nna-am ___ bahra
3SG.MASC.PAST-say-2SG.FEM ___ a_lot
'He told you (fem.) ___ a lot.'

The sentences were randomized and presented on a computer screen. The number of utterances in total was 784 ((28 words × 5 repetitions × 5 speakers) + (12 words × 7 repetitions × 1 speaker)). The stimuli for one speaker consisted of a subset of the words in Table 1, these were the pairs [idˤan – idan], [ibdˤa – ibda], [idˤgam – idgaln] and [izˤi – izi], [imzˤi – imzi], [imzˤmaz – imzman]. Twenty-nine utterances (3.7%) were discarded due to speech production errors. Thus, a total of 755 tokens went into the analyses. Table 2 gives an overview of the number of tokens retrieved for each sequence type by plain and pharyngealized productions.

target	structure	plain	meaning	pharyngealized	meaning
d/dˤ	VCV	idan	'intestines'	idˤan	'dogs'
	VCCV	ibda	'he started'	ibdˤa	'he divided'
	VCCV	idgaln	'widowers'	idˤgam	'yesterday'
	VCCCV	ibdgas	'it was wet for him'	ibdˤgas	nonce
	VCV	adan	'intestine'	adˤan	'disease'
	VCCV	abdaj	'beginning'	abdˤaj	'division'
	VCCV	adgal	'widower'	adˤgal	nonce
z/zˤ	VCV	izi	'fly'	izˤi	'gallbladder'
	VCCV	imzi	name of a hill	imzˤi	'be small'
	VCCV	izmaz	'periods'	izˤman	'scared'
	VCCCV	imzman	nonce	imzˤmaz	name of a city (pl.)
	VCV	aza	letter	azˤa	letter
	VCCV	amzaj	'smoothing'	amzˤaɾ	'rain'
	VCCV	azgaj	'harmony'	azˤgaj	nonce

Table 1: Stimuli by target consonant, structure and type.

context	type	N
VCV	plain	114
	pharyngealized	107
VCCV	plain	109
	pharyngealized	107
VCCV	plain	106
	pharyngealized	104
VCCCV	plain	56
	pharyngealized	52

Table 2: Number of tokens by context and type.

2.3 Recording procedure and data processing

Simultaneous recording of articulatory and acoustic signals was performed using the ElectroMagnetic Articulograph AG501 (EMA; Carstens Medizinelektronik GmbH). Sensor coils were placed at the vermillion border of the upper and lower lips (ULIP, LLIP), the tongue tip (TTIP), the middle of the tongue (TMID), and the tongue body (TBO). The stimuli were presented on a computer screen placed in a comfortable position in front of the speaker. The articulatory signal was sampled at 1250 Hz, filtered with a Butterworth low-pass (cut-off frequency: 25 Hz, order: 5). Acoustic data was acquired using an AKG C520L headset microphone (frequency response: 60 – 20.000 Hz) at a sample rate of 48 kHz and 16-bit resolution.

The Montreal Forced Aligner v.2.2.0 (McAuliffe et al., 2017) was used for an automatic annotation of the acoustic data. After a manual correction of the segmentation, the stop burst transients for the consonants [d, dˤ, g, b] were automatically identified using a simplification of the stop burst detection algorithm described in Ananthapadmanabha et al. (2014). Any necessary corrections were made afterwards. Stops without a clear stop burst in the waveform or spectrogram were classified as closures only. In stop-stop sequences where the release of the first stop was unclear, the presence of an intrusive schwa guided the annotation, with the offset of the first stop corresponding to the onset of the schwa's formant structure. In the cases where no schwa was present, the signal's intensity was used for annotation. Local intensity minima, which matched the number of stops and were separated by a visible transition, defined the segment boundaries. Sequences where the first stop could not be distinguished from the second, appearing only as a long closure, were excluded from the analysis.

2.4 Data analysis

Two main analyses are applied in this study: a dynamic analysis of the articulatory data and a combined dynamic and parametric analysis of the acoustic data. In our analysis of [aCa] sequences in Buech, Ridouane and Hermes (2022), we found that pharyngealization led to a lowering of the TMID and TBO sensors where the latter showed the strongest effect. Since this lowering manifested in differences which cannot be captured by classical-defined landmarks, such as gestural onset, peak velocity and target, we did not conduct a parametric analysis of the articulatory data. Instead, we relied on a dynamic analysis of the articulatory signal, where we used the kinematic trajectories of the vertical (high-low) positions of the TTIP for the primary articulation and the TBO for the secondary articulation. These trajectories were analyzed for each sequence type [VC̲V, VCC̲V, VC̲CV, VCC̲CV] at 10% intervals of each acoustic segment, including the preceding vowels' onset and the following vowels' offset.

For the dynamic analysis of the acoustic data, we measured the first three formants (F1, F2, and F3) at 5% intervals throughout both the preceding and following full vowels, including the vowels' onset and offset. In case of the vowel-approximant sequence [aj], we measured the formants in the same intervals from the onset to midpoint of the sequence. These formants were extracted using the Burg algorithm as implemented in Praat (Boersma & Weenink, 2023). Formant values were converted to Bark afterwards, using the formula (1) and their correction (2) from Traunmüller (1990).

$$z = 26.81f/(1960 + f) - 0.53 \tag{1}$$

$$z' = \begin{cases} z + 0.15(2z), & \text{if } z < 2.0 \\ z + 0.22(z20.1) & \text{if } z > 20.1 \end{cases} \tag{2}$$

We extracted additional, one-dimensional acoustic parameters for the coronal targets and non-coronal consonants and for intrusive schwas, if present within the consonant sequences. Intrusive schwas are usually short in duration, around 30–45 ms (Ridouane & Fougeron, 2011), making an analysis of format trajectories not suitable. Therefore, we measured F1, F2 and F3 at the midpoint of the schwas, along with their duration. For consonants, we measured the closure duration (CD) and release duration (REL) for stop segments ([b, g, d, dˤ]) and the consonant duration for non-stops [z, zˤ, m]. In addition, we measured the center of gravity (COG) and the standard deviation (SD) of the stop release and fricative spectra. For these measurements, we applied similar procedures from previous studies on stop and fricative spectra (e.g., Chodroff & Wilson, 2014; Forrest et al., 1988; Maniwa et al., 2009). The acoustic signal was resampled to 16 kHz. In addition, the resampled signal was pre-emphasized above 1000 Hz for stops. A high-pass filter with a cutoff frequency of 200 Hz was applied to both the pre-emphasized signal for stops and the resampled signal for fricatives in order to reduce the influence of low frequency pertubations. The COG and SD were measured based on Hamming windows centered at the fricatives' midpoint with a window size of 40 ms in order to obtain a high frequency resolution (Jongman et al., 2000). For the spectral measurements of stop releases, we did not use a fixed window size for the release spectra in order to reduce the influence of the closure or the following segment (e.g., vowels). Instead, in accordance with Jongman et al. (2011), we used Hamming windows with a variable size, spanning from the stop burst to the end of the release.

We conducted all measurements using a custom script written in Python (Van Rossum & Drake, 2009) version 3.10.11. The EMA sensor trajectories were extracted using the data extraction routine from ema2wav (Buech, Roessig, et al., 2022). Formant measurements were done using Parselmouth (Jadoul et al., 2018) in version 0.4.3, which interfaces with Praat v6.1.38 (Boersma & Weenink, 2023). Given that all speakers were male, we set the maximum formant frequency to 5000 Hz.

2.5 Statistical analysis

The statistical analysis was carried out in the Bayesian framework. Bayesian analyses lead to posterior distributions of possible values of the parameter estimates in the models.[1] For decision-making, we applied the HDI + ROPE decision rule (Kruschke, 2018). This rule consists of two key components: the Highest Density Interval (HDI) of the posterior distribution, and a Region Of Practical Equivalence (ROPE) and their relationship. The ROPE is a region that represents the null hypothesis (Kruschke, 2018). Three possible outcomes can result in the application of this rule and are depicted in Figure 1.

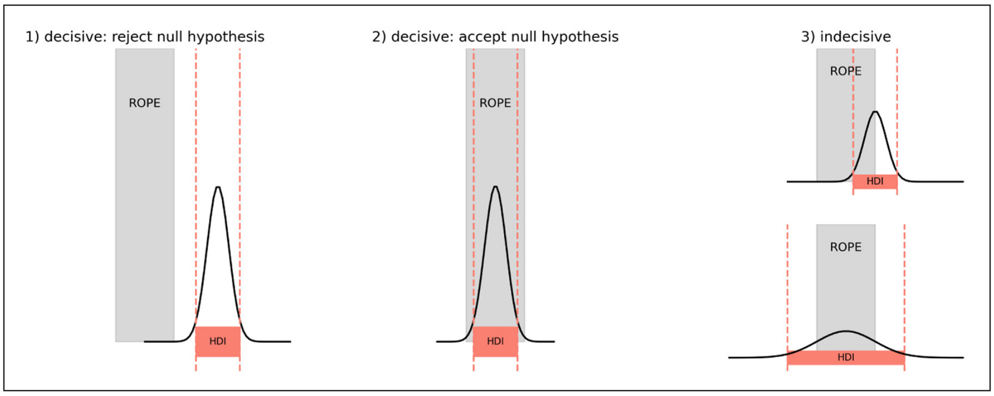

Figure 1: Possible outcomes of the HDI (red rectangles) + ROPE (gray areas) decision rule according to Krusche (2018, p. 272).

The model output is decisive in the case of (1), when the HDI is completely outside the ROPE, thus leading to a rejection of the null hypothesis and (2), when the HDI is completely inside the ROPE, leading to the acceptance of the null hypothesis. In any other cases (3), no decision can be made. The limits of the ROPE, since it captures the practical equivalence with the null, have to be adjusted according to underlying theory, data and/or model (Kruschke, 2018). Consequently, we tailored a specific ROPE for each domain of the statistical models below. The statistical analysis was performed using Bambi v. 0.11.0 (Capretto et al., 2022) utilizing PyMC v. 5.4.0 (Abril-Pla et al., 2023).

We describe the models for the dynamic analyses first. Since we want to capture differences in the articulatory and formant trajectories over time, we applied Gaussian Process (GP) regression analysis for this kind of data. GPs are non-parametric models that do not quantify parameter values but continuous functions. These GPs depend on a kernel function with a covariance described by the length scale and the width. Since GPs are computationally expensive, we used the Hilbert Space Gaussian Process (HSGP) approximation as described by (Riutort-Mayol et al., 2023) as implemented in PyMC.

[1] In contrast, frequentist methods lead to point estimates, confidence intervals and p-values.

In our analysis of the articulatory trajectories, we ran one model for the vertical dimension of each sensor (TTIP, TBO) and each sequence type (VC̲V, VCC̲V, VC̲CV, VCC̲CV). Prior to the analysis, we centered the data of each sensor around the mean per speaker. In the models we used one GP per word and included a by-speaker intercept as group-level effect. For example, the model for the vertical TBO trajectories in VC̲V contained estimates for idan, idˤan, adan, adˤan, izi, izˤi, aza and azˤa, separately. We used an exponential quadratic default kernel and Gamma priors with alpha and beta set to 2 for the length scale and width and with separate covariances. Furthermore, we used 8 basis vectors and set the extension factor to 1.5 for the HSGP approximation. The full specification of the model formula in Bambi is given in eq. (3), where $\textsc{Art}_{dim}$ was either the vertical TTIP or the vertical TBO trajectories.

$$\textsc{Art}_{\mathrm{dim}} \sim \mathrm{hsgp}(\mathrm{Timestep}, \mathrm{by} = \textsc{Word},\ \mathrm{m} = 8,\ \mathrm{c} = 1.5,\ \mathrm{share\_cov} = \mathrm{False}) + (1 \mid \textsc{Speaker}) \tag{3}$$

The remaining coefficients had default priors. We report the 95% HDI of the difference between the posterior mean estimates of the pharyngealized and the plain trajectories. We set a ROPE of [–1, 1] mm for decision-making, since this corresponds to the local precision of EMA devices including the AG501 (Savariaux et al., 2017).

For the formant trajectories, we used the same model structure as for the articulatory trajectories, and we ran these models for each formant, each position of the full vowel, and each sequence type. For example, the model for F2 of the following vowel in VC̲V sequences contained separate estimates for idan, ida̲n, idˤa̲n, ada̲n, adˤa̲n, izi̲, izˤi̲, aza̲ and azˤa̲. For length scale and width, we used the same priors (Gamma, alpha and beta set to 2) and adapted the length scale to Gamma (2,1) for one model. The prior for the common intercept was a normal distribution centered at the formant's mean and with sigma set to 2.5. Default priors were used for the remaining coefficients. The model specification is given in eq. (4), where the response variable $F\#_{pos}$ was either the bark-transformed $F1_{prec}$, $F2_{prec}$, $F3_{prec}$, $F1_{foll}$, $F2_{foll}$ or $F3_{foll}$ with the indices *prec* and *foll* indicating the position of the full vowel. Furthermore, we set the basis vectors to 4.

$$F\#_{\mathrm{pos}} \sim \mathrm{hsgp}(\mathrm{Timestep}, \mathrm{by} = \textsc{Word},\ \mathrm{m} = 4,\ \mathrm{c} = 1.5,\ \mathrm{share\_cov} = \mathrm{False}) + (1 \mid \textsc{Speaker}) \tag{4}$$

As for the models of the articulatory trajectories, we present the differences between the plain and pharyngealized trajectory estimates for F1, F2, and F3. It is a well-known fact that human frequency perception is logarithmic by nature, which means that we are more sensitive to small differences in lower frequency ranges than in higher ones. To address this, it would necessitate setting different ROPEs for different frequency regions, not only determined by each approximate range of the respective formants, but also for each time step of the measurements, given that the trajectories can vary over time. Instead of using complex and time-varying ROPEs, we simplified the process by converting frequency values from Hz to Bark units.

We set the ROPE for difference trajectories uniformly to 0.5 Bark, which corresponds to the difference between the center frequency of a critical band and the point of intersection to the adjacent critical bands. In addition to the dynamic analysis, we also took the peak differences of the difference trajectories and their location into consideration. The peak differences were distributions of the maxima of the absolute differences across samples and the location as the argument of these maxima.

For the analysis of the parametric acoustic measurements, we ran hierarchical linear regression models. All parameter values were z-scored prior to the analysis. Separate models were run for each parameter (F1, F2 and F3 and DUR for intrusive schwas; CD and REL for stops; DUR for non-stops, COG and SD for stops and fricatives). The model structure was as follows: We entered a common level effect for TYPE (plain, pharyngealized) and a by-speaker intercept and slope as group-level effects. The specification of the linear models is given in eq. (5), where the response variable was one of the acoustic parameters.

$$\text{Response} \sim \textsc{Type} + \left(1 + \textsc{Type} \,\middle|\, \textsc{Speaker}\right) \tag{5}$$

For the intercept and the common-level slope for TYPE, we used weakly informative Normal priors centered at 0 and with a standard deviation of 2.5. Similarly, we used a Normal prior with mean 0 and a HalfNormal hyperprior with a standard deviation of 2.5 for the by-speaker intercept and slopes as group-level effects. Since all values were standardized, we followed Cohen (1988) to set a uniform ROPE of [–0.1, 0.1] for all parameters.

All models for the dynamic analyses were sampled with four MCMC chains with 2000 draws and 2000 samples for tuning, thus resulting in 8000 samples for each model. The parametric models, on the other hand, were run also with four MCMC chains, but with 8000 draws and 8000 samples for tuning, leading to 32000 iterations of each model. We checked the convergence of all models by assuring that no $\hat{r}$ value was greater than 1. As described above, we graphically report the 95% HDI of the difference between the pharyngealized and plain posterior means of the GP models as well, as the location of these differences that fell outside the respective ROPEs. For the parametric models, we report the posterior mean (β), the lower and upper boundary of 95% HDI, as well as the probability of the posterior outside the ROPE ($P(\beta <> \text{ROPE})$) of the common level effect. If there was evidence for an effect of pharyngealization according to the HDI + ROPE decision rule, the parameter and their values were marked with bold fonts in the tables displaying these statistical results.

3. Results

The presentation of our results follows the following structure. First, we present the findings for the sequence V$\underline{\text{C}}$V, followed by the sequences VC$\underline{\text{C}}$V, V$\underline{\text{C}}$CV, and VC$\underline{\text{C}}$CV. For each sequence type, we present the results from the dynamic analysis of the articulatory and formant trajectories. Then, the parametric acoustic analysis will be presented. The dynamic analyses are reported for each pair along with aggregated trajectories.

3.1 VC̲V

The dynamic articulatory trajectories for VC̲V sequences in pharyngealized and plain contexts for the TTIP and TBO sensors in the vertical dimension (high-low) are displayed in Figure 2. The figure is divided into different panels for the TTIP (1), and the TBO (2). The larger panels show the 95% of the aggregated posterior estimates across pairs, while the smaller ones show the estimates for each pair (a-d). Each panel consists of two subplots: The upper plot depicts the plain (blue) and pharyngealized (red, hatched) estimates of the trajectories, and the lower one represents the difference between them. The grey hatched indicates the ROPE and the rose areas show the time range in which the difference is outside the ROPE.

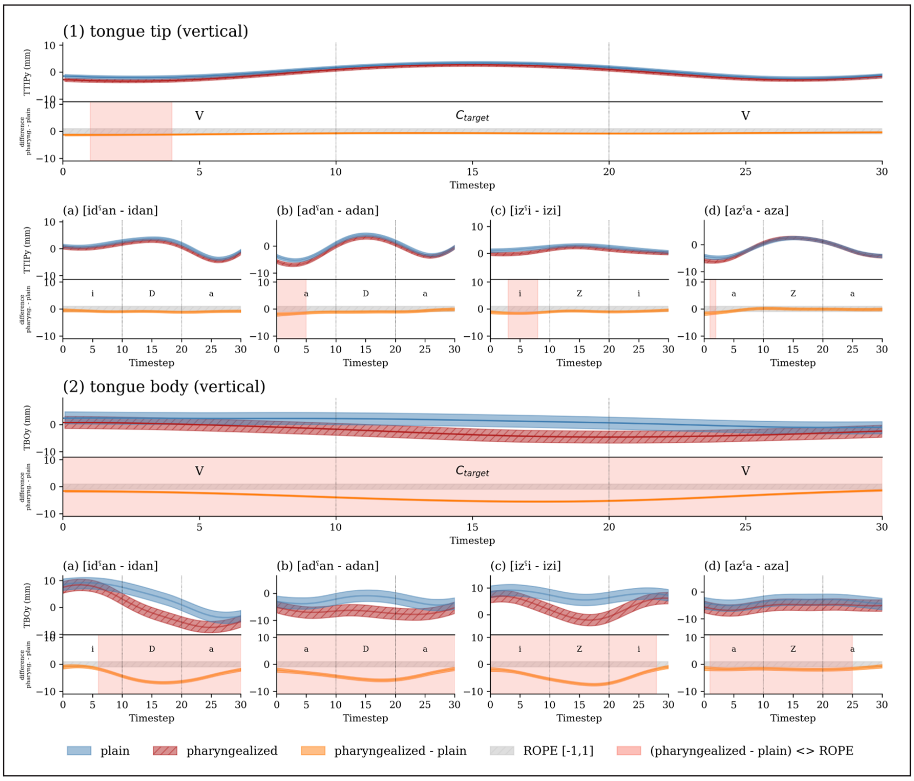

Figure 2: Vertical TTIP (1) and TBO (2) trajectories in VC̲V context for aggregated trajectories and estimates for each pair (a-d). Each panel shows the 95% posterior estimates for the plain (blue) and pharyngealized production (red) and their difference (orange), along with a ROPE of [–1, 1] (grey hatched area) and the time range in which the difference trajectory is outside the ROPE (rose area).

The TTIP movements showed overall no difference across time, except a small portion in the preceding vowel, indicating a slight lowering. The trajectories for TBO displayed substantial differences between pharyngealized and plain words. The pharyngealization consistently lowered the TBO in comparison to the plain productions and had its highest extent in the second half of the coronal target. This lowering was present already in the preceding vowel and continued through the coronal, followed by a slight rise into the following vowel, while still maintaining a difference of more than 1 mm. When looking at the word pairs in detail, this pattern is present in all pairs. A deviation can be observed for the pair [idˤan – idan] in (2a) where the lowering effect starts in the second half of the preceding [i]. Although already lowered in the beginning of the sequence, the difference trajectory for the pair [izˤi – izi] starts at a smaller difference at the onset of the preceding [i] and is less than 1 mm at the offset of the following [i]. Notably, the [azˤa – aza] pair in (2d) exhibited the least prominent difference, although it falls beyond the ROPE. Additionally, this pair did not display any discernible variation in the tongue contour compared to the other pairs, and it displayed a relatively consistent lowering over time.

The analysis of the formant trajectories are shown in Figure 3, where the results for the preceding full vowel are depicted in the left column and the results for the following full vowel are given in the right column. The figure shows a similar scheme like Figure 2: The formants analyses are divided into different panels, with panel (1) showing F3, panel (2) showing F2, and panel (3) showing F1. The larger panels represent the aggregated formant estimates across pairs, and the smaller panels (a-d) indicate the estimates for each pair. Color coding is according to Figure 2, that is, plain estimates are given in blue, the estimates for the pharyngealized trajectories are red hatched, and their differences are plotted in orange. Again, grey hatched areas represent the ROPE and rose areas indicate the time range where the difference is outside the ROPE.

Overall, no difference was found for F3 in both vowel positions at the vicinity of the coronal targets. However, pairs differed in this regard depending on vowel quality, where pharyngealization had a lowering effect on this formant in the case of [i] but not for [a]. Regarding F2, we found a lowering in both vowel qualities and in both positions. Vowel quality had an opposite impact than F3: While the F2 lowering persisted in the entire duration of [a] and the following [i], the preceding [i] resisted in portions around the vowel's midpoint. Overall, pharyngealization led to a decrease of F2 during the second half of the preceding vowel and the first 50% of the following vowel. Similar to F2, the F1 differences were highest in the vicinity of the coronal consonant. Differences in the temporal extent were found based on the manner of the coronal target: In the case of stops, F1 differences were limited to the vicinity of the coronal stop, regardless of vowel quality. For the coronal fricatives [z, zˤ], on the other hand, F1 differences spread nearly through the entire vocalic segments in the case of the pair [izˤi – izi] in (3c). Notably, there was no evidence for F1 modifications in the vowels of the [azˤa – aza] pair (3d).

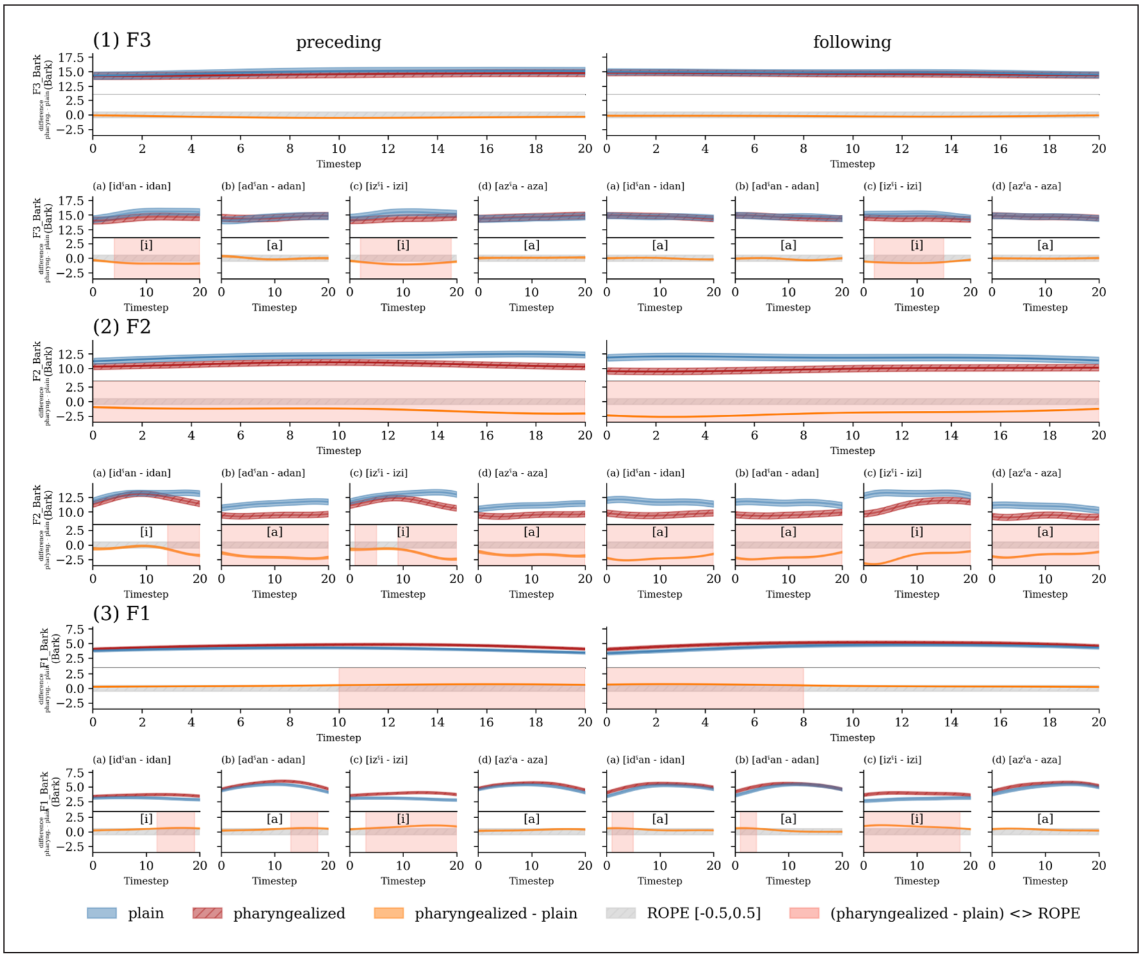

Figure 3: Formant trajectories in (1) F3, (2) F2, (3) F1 for VC̲V context with aggregated trajectories and estimates for each pair (a-d) by vowel position (columns). Each panel shows the 95% posterior estimates for the plain (blue) and pharyngealized productions (red) and their difference (orange), along with a ROPE of [–0.5, 0.5] (grey hatched area) and the time range in which the difference trajectory is outside the ROPE (rose area).

Table 3 presents the summary statistics from the parametric acoustic analyses, and Table 4 displayes the results of the linear regression analyses. The temporal measurements for VC̲V sequences comprised 114 tokens for the closure duration (CD) of stops, 48 tokens for the release duration (REL) of stops, and 107 tokens for fricatives. The results indicated no evidence that pharyngealization affected the CD, REL, or release spectra of [dˤ] compared to [d]. The CD and REL were nearly identical, and the COG and SD of the release spectra displayed substantial overlap. Similar to the findings for stops, the statistical analyses provided no evidence that pharyngealization influenced the fricative duration or the fricative spectra.

label	sequence	parameter	plain	pharyngealized
d/dˁ	iDa, aDa	CD (ms)	65 (8)	65 (10)
		REL (ms)	12 (4)	9 (4)
		COG (Hz)	1490 (1133)	1129 (853)
		SD (Hz)	1799 (650)	1365 (810)
z/zˁ	iZi, aZa	DUR (ms)	95 (18)	103 (16)
		COG (Hz)	1256 (1066)	1179 (1172)
		SD (Hz)	1600 (846)	1366 (841)

Table 3: Means and standard deviations (in brackets) for the acoustic measurements of the target consonats in VCV (CD = closure duration, REL = release duration, DUR = consonant duration, COG = center of gravity, SD = standard deviation). The sequence column lists the sequences under investigation (capital letters mark the coronal target, underlined segments indicate the segments' location).

label	sequence	measurement	parameter	mean	lower HDI	upper HDI	P (β < > ROPE)
d/dˁ	iDa, aDa	CD	Intercept	–0.05	–0.46	0.34	0.56
			TYPE[pharyng.]	0.07	–0.7	0.83	0.76
		REL	Intercept	0.34	–0.12	0.77	0.89
			TYPE[pharyng.]	–0.73	–1.41	–0.04	0.98
		COG	Intercept	0.25	–0.41	0.9	0.82
			TYPE[pharyng.]	–0.37	–1.04	0.3	0.88
		SD	Intercept	0.26	–0.37	0.86	0.83
			TYPE[pharyng.]	–0.43	–1.13	0.23	0.91
z/zˁ	iZi, aZa	DUR	Intercept	–0.2	–0.87	0.44	0.8
			TYPE[pharyng.]	0.45	0.01	0.87	0.96
		COG	Intercept	0.07	–0.73	0.81	0.76
			TYPE[pharyng.]	–0.18	–1.06	0.69	0.8
		SD	Intercept	0.16	–0.66	0.95	0.79
			TYPE[pharyng.]	–0.35	–1.0	0.28	0.88

Table 4: Common level effects of the linear regression models for the acoustic measurements of the target consonants in VCV sequences. Reported are the mean, the lower and upper boundaries of 95% HDI of the posterior, and the probability of the posterior falling outside the ROPE of [–0.1, 0.1]. The sequence column lists the sequences under investigation (capital letters mark the coronal target, underlined segments indicate the segments' location).

3.2 VC$\underline{C}$V

The analysis of the articulatory data of the vertical TTIP and TBO movements for VC$\underline{C}$V sequences is depicted in Figure 4. Again, the figure represents the estimated trajectories of pharyngealized and plain productions over time and their differences (differences outside the ROPE of [–1, 1] mm).

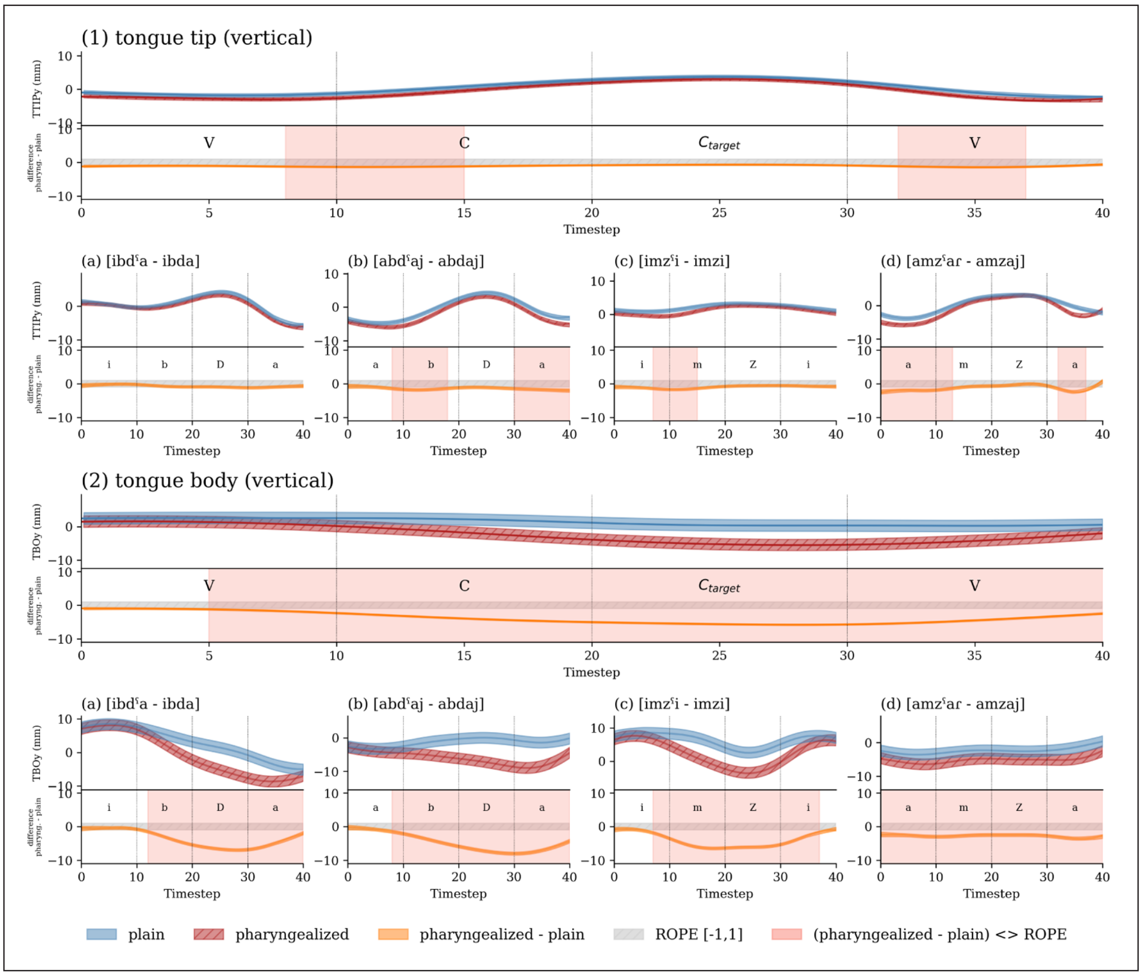

Figure 4: Vertical TTIP (1) and TBO (2) trajectories in VC$\underline{C}$V context for aggregated trajectories and estimates for each pair (a–d). Each panel shows the 95% posterior estimates for the plain (blue) and pharyngealized productions (red) and their difference (orange), along with a ROPE of [–1, 1] (grey hatched area) and the time range in which the difference trajectory is outside the ROPE (rose area).

We found an overall difference in the transition from the preceding full vowel to the pre-coronal consonant and in the center of the following vowel in the vertical TTIP trajectory. These differences were slightly more than 1 mm but absent in the pair [ibdˤa – ibda].

In the TBO movements, on the other hand, a consistent lowering was observed across all word pairs. Similar to our observations in the V<u>C</u>V context, this lowering extended beyond the target consonants, beginning at least in the preceding segment and extending into the following vowel. The overall peak difference was found in the second half of the coronal target. We noted a slight variation in the location of this peak difference: The pairs containing coronal stops showed the highest difference near the offset of the coronal target, while the pair [imzˤi – imzi] in (2c) had a rather plateau-like difference with a maximum difference in the middle of the preceding consonant but with a nearly equally substantial lowering in the target fricative. Similar to the behavior observed in the previous section for the pair [azˤa – aza], the pair [amzˤaɾ- amzaj] in (2d) also exhibited a consistent yet steady TBO lowering throughout the sequence.

Figure 5 illustrates the dynamic analyses for the formants, and the areas where these differences fall outside the ROPE of [–0.5, 0.5] Bark. The results indicate that F3 remained unaffected by pharyngealization, except for the pair [imzˤi – imzi] in (1c) in the midpoint of the preceding and the following vowel. Conversely, F2 was lowered in both vowel positions, whereby the difference between pharyngealized and plain productions was stronger in the following than in the preceding vowel. F2 in the preceding vowel consistently decreased and started increasing in the following vowel, indicating a more substantial F2 lowering with proximity to the target consonant. Vowel-specific differences were also observed, where [a] was affected by pharyngealization regardless of vowel positions, while [i] was impacted only in the final 25% in the pair [ibdˤa – ibda] in (2a). Regarding F1 in the preceding vowel, no discernible pattern was observed. This formant was raised only in the pairs [imzˤi – imzi] in (3c) and [amzˤaɾ- amzaj] in (3d), with their peak differences slightly above the ROPE at different locations. F1 differences between pharyngealized and plain productions in the following vowel were observed across the two vowel qualities and covered nearly the entire duration of the vowel, with the exception of the [a] in [ibdˤa – ibda] in (3a), where only the first 40% were affected.

Appendix A.1 presents the summary (Table A.1.1) and the linear regression results (Table A.1.2) of the consonant-related temporal and spectral characteristics, as well as the duration and the formants of intrusive schwas occurring within consonant sequences. A total of 69 out of 111 tokens for coronal stops and 58 out of 111 tokens for [b] had clear stop releases and went into the analysis. We found a total of 75 schwa instances between the pre-coronal consonant and the coronal target (e.g., between [b] and [dˤ] in [ibdˤa] or between [b] and [d] in [ibda]). The number of intrusive schwas by pair is given in Table 5. Overall, most schwas were found in pairs containing stops.

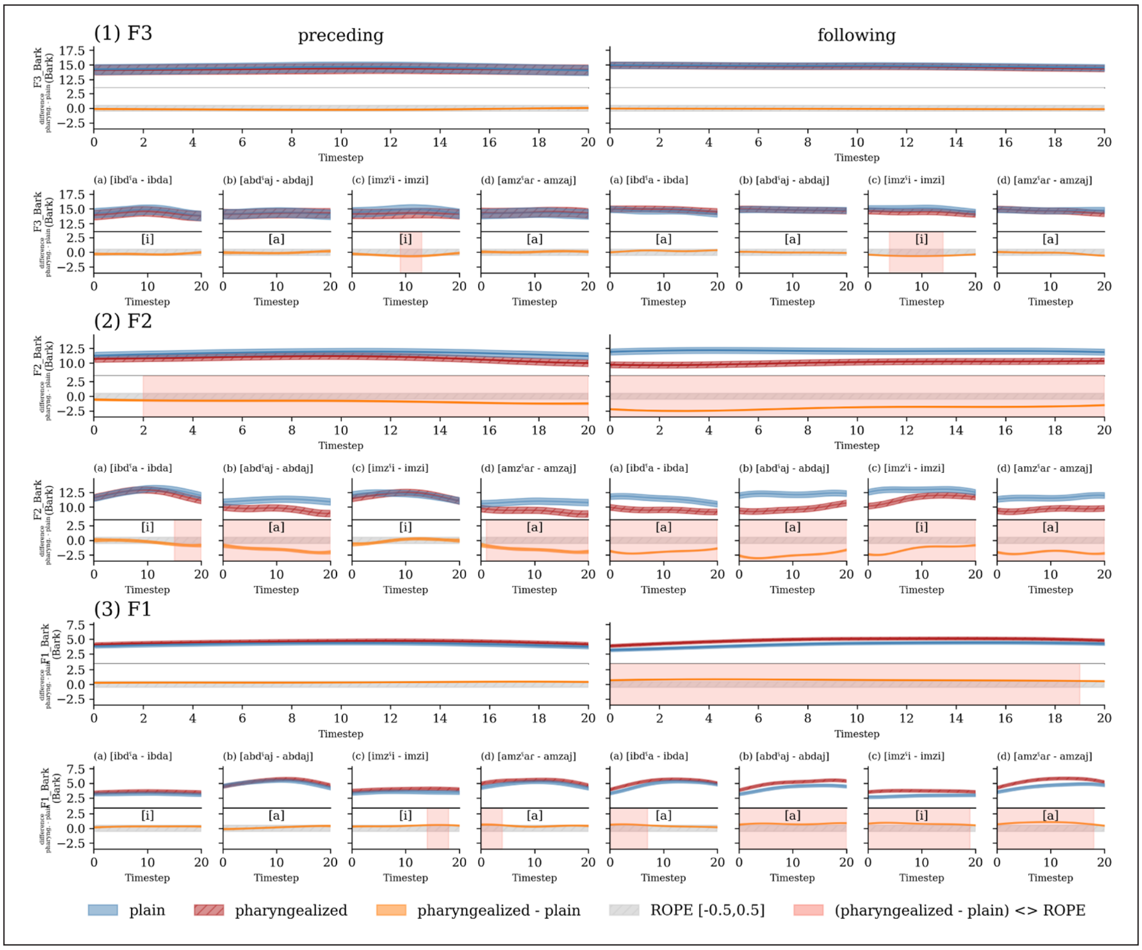

Figure 5: Formant trajectories in (1) F3, (2) F2, (3) F1 trajectories for VCC̲V context with aggregated trajectories and estimates for each pair (a–d) by vowel position (columns). Each panel shows the 95% posterior estimates for the plain (blue) and pharyngealized productions (red) and their difference (orange), along with a ROPE of [–0.5, 0.5] (grey hatched area) and the time range in which the difference trajectory is outside the ROPE (rose area).

pair	plain	pharyngealized
ibdˤa – ibda	19	20
abdˤaj – abdaj	16	19
imzˤi – imzi	0	0
amzˤaɾ – amzaj	1	0

Table 5: Number of schwa intrusions by pair in VCC̲V sequences.

The statistical analyses in Table A.1.2 indicated no evidence that the durations of the pre-coronal consonants were affected by pharyngealization. As can be seen in Table A.1.1, the CD of [b] averaged at 59 ms and the REL had a mean of 10 ms in both pharyngealized and plain articulations. The duration of [m] was also similar with 75 ms before plain and pharyngealized consonants. In addition, there was no impact of pharyngealization on the COG and the SD of the release of pre-coronal [b]. The duration of schwas before plain coronals was also not different from schwas before pharyngealized coronals. Both were short in duration and had an average of 16 ms and 18 ms, respectively. Conversely, there was evidence that pharyngealization affected the formant structure of schwas regarding F1 and F2: F1 was 0.7 Bark higher and F2 was 1.9 Bark lower before pharyngealized coronals than before plain coronals. Regarding the coronal targets, there was no evidence that the duration of [zˤ] nor the CD or the REL of [dˤ] was different from their plain counterparts. Plain and pharyngealized fricatives had the same mean duration of 102 ms and the CD and REL of coronal stops differed marginally with an average of 52 ms and 56 ms for the closure and 13 ms and 17 ms for the release, respectively. Also, pharyngealization had no impact on the fricative or the stop release spectra, although the summary statistics in Table A.1.1 showed a tendency of a lower COG and SD.

3.3 VC̲CV

Figure 6 illustrates the vertical trajectories of TTIP and TBO in the VC̲CV contexts, along with their differences and the areas where these differences exceed the ROPE of [–1, 1] mm. The TTIP movements were not affected by pharyngealization during the coronal target or its immediate environment, but we found a difference in the following vowel. A closer inspection of the pairs showed that these differences were mainly carried by the pairs containing coronal stops. The pair [adˤgag – adgal] in (1d) exhibited a slight lowering of the TTIP at the onset of the preceding [a], and an abrupt lowering in the following vowel, which can be observed also in [idˤgam – idgaln] in (1a). The items containing fricative targets were mostly unaffected, except for a raising at the offset of the following [a] in the pair [azˤgan – azgaj] in (1d). These differences are most likely induced by the following segments, thus reflecting different places of articulation rather than an effect of pharyngealization. Echoing the findings for VC̲V and VCC̲V contexts, a consistent lowering in TBO was observed in all word pairs. This lowering initiated in the preceding vowel and remained consistent up to the following vowel. An inspection of each pair shows that the TBO lowering is in post-coronal [g] and disrupted in the pairs (2a, b). The observed differences in the following vowels' trajectories do not necessarily result from pharyngealization. These distinct patterns may arise from the articulatory distinctions in the final consonant, such as the higher tongue dorsum position for final [g] and the relatively lower position of this articulator for final [l] in the pair [adˤgag – adgal] in (2b), or the more fronted tongue position of the following [l] compared to [m] in [idˤgam – idgaln] in (2a).

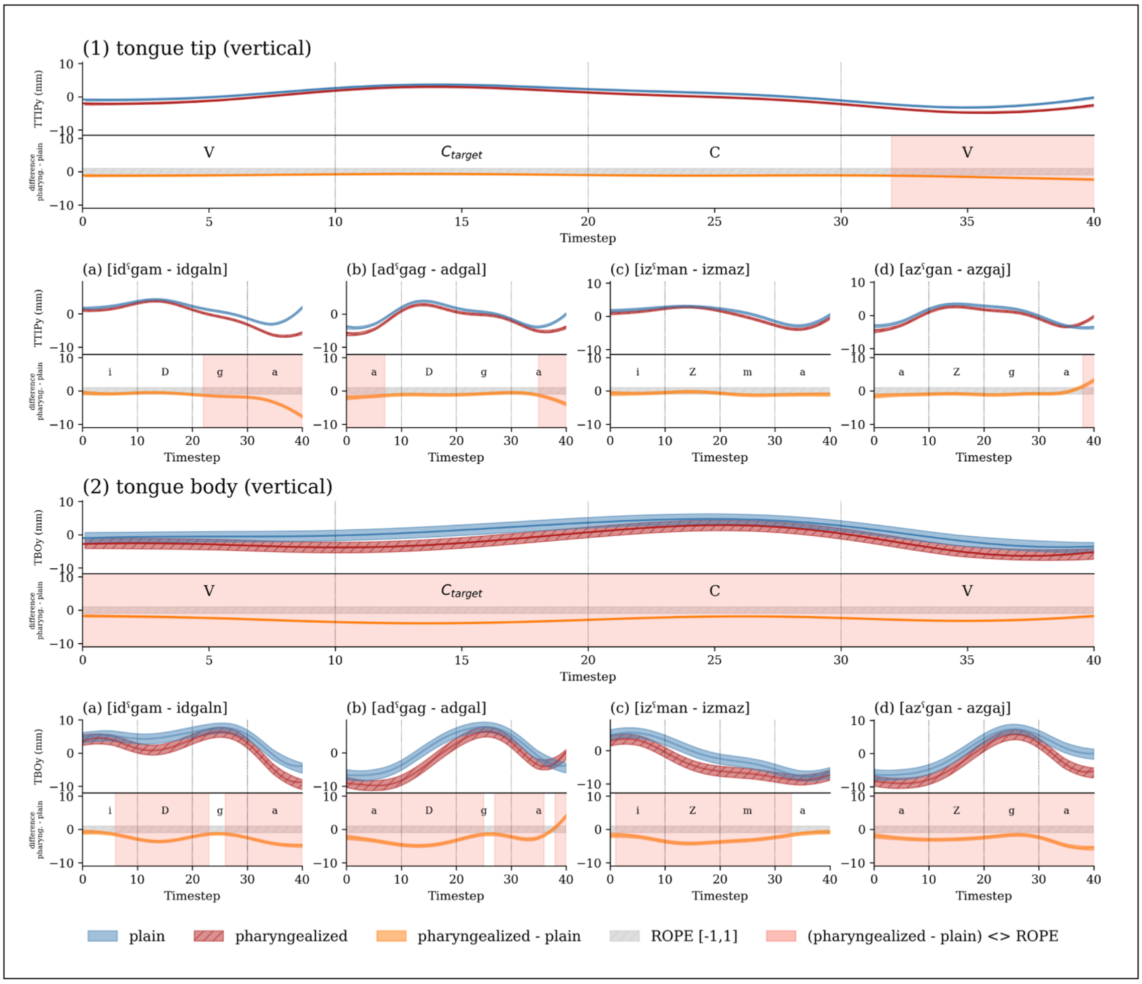

Figure 6: Vertical TTIP (1) and TBO (2) trajectories in VCCV context for aggregated trajectories and estimates for each pair (a–d). Each panel shows the 95% posterior estimates for the plain (blue) and pharyngealized production (red) and their difference (orange), along with a ROPE of [–1, 1] (grey hatched area) and the time range in which the difference trajectory is outside the ROPE (rose area).

Figure 7 displays the analyses of the F1, F2, and F3 trajectories of the full vowels, with their estimates, as well as the difference trajectories between pharyngealized and plain productions, and the regions where these differences fall outside the ROPE of [–0.5, 0.5] Bark. In VCCV contexts, F3 showed overall no modification in the pharyngealized condition. However, an inspection of the pairs showed vowel-specific differences, where F3 was lowered only for [i] preceding a pharyngealized coronal. Conversely, F2 was affected by pharyngealization in terms of a general lowering regardless of vowel quality. Notable divergences can be seen, however, in the temporal extent of these differences depending on vowel quality. While a lower F2 can be found throughout or in the largest part of [a] in both vowel positions, F2 was impacted only in the final portion of preceding [i]. Overall, pharyngealization had no impact on F1, except for a small portion at approximately 80% of the preceding vowel. Looking at each pair separately, F1 in the pair [idˤgam – idgaln] was not affected by pharyngealization. A raised F1 was found in the second half of the preceding vowel in [izˤman – izmaz] in (3c). F1 was also raised in following vowel in [azˤgan – azgaj] in (3d) and in the the second half of the following vowel in [adˤgag – adgal] in (3b) and in [izˤman – izmaz] in (3c). The lowered F2 and the raised F1 in the latter pair, especially in the second half of the following vowel, may be attributed to the difference between [a] and [aj] rather than to pharyngealization.

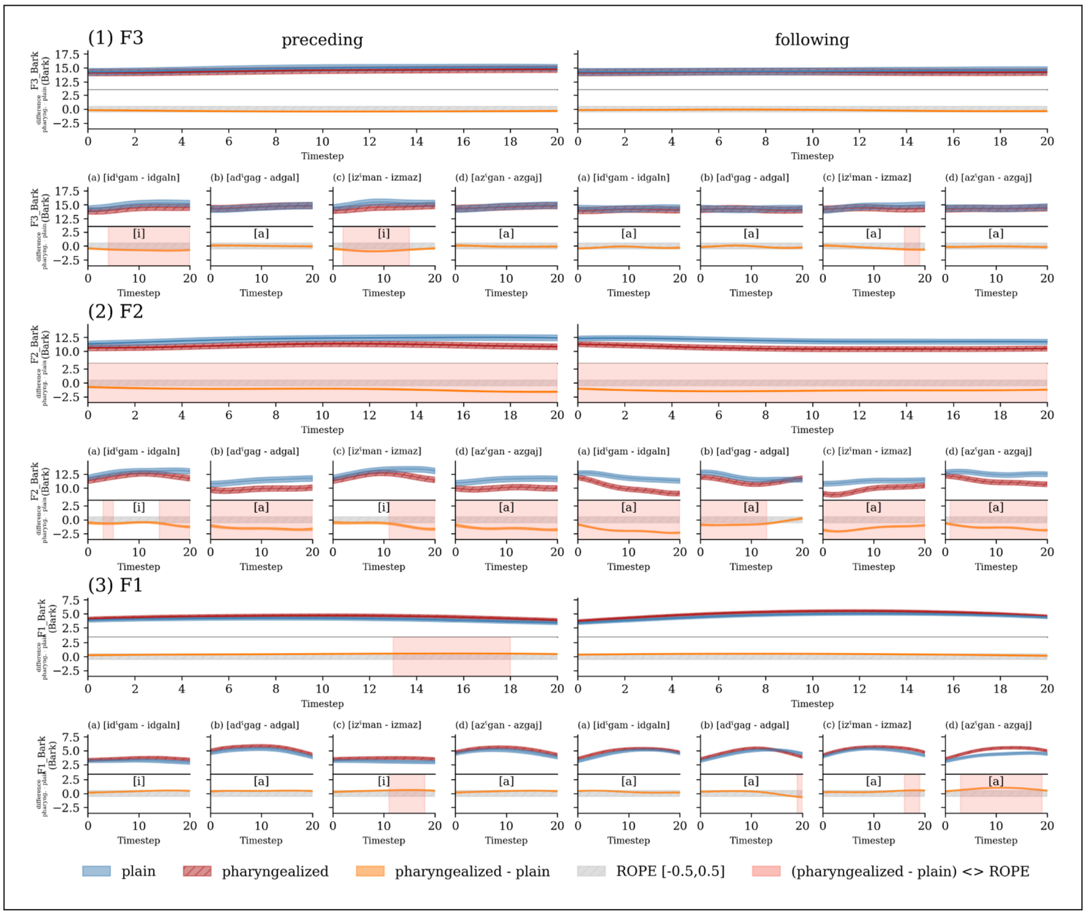

Figure 7: Formant trajectories in (1) F3, (2) F2, (3) F1 trajectories for VC̲CV context with aggregated trajectories and estimates for each pair (a–d) by vowel position (columns). Each panel shows the 95% posterior estimates for the plain (blue) and pharyngealized productions (red) and their difference (orange), along with a ROPE of [–0.5, 0.5] (grey hatched area) and the time range in which the difference trajectory is outside the ROPE (rose area).

The acoustic characteristics of the consonants and intrusive schwas (Table A.2.1), and the results of the linear regression analyses (Table A.2.2) are given in A.2. Stop releases were found for 63 out of 112 tokens of the coronal stops and for 124 out of 161 tokens of [g]. We found a total of 136 schwa segments and their distribution is listed in Table 6. The schwas occurred most often in stop-stop sequences.

pair	**plain**	**pharyngealized**
idˤgam – idgaln	26	30
adˤgag – adgal	21	23
izˤman – izmaz	3	11
azˤgan – azgaj	7	15

Table 6: Number of schwa intrusions by pair in VC̲CV sequences.

In line with our previous analyses for VC̲V and VCC̲V, there was no evidence that pharyngealization affected the duration of the coronal fricatives, schwas, and the post-coronal and coronal stops in VC̲CV. The mean duration of [zˤ] was similar to [z] with 92 ms and 91 ms, respectively. The CD ([dˤ] = 58 ms, [d] = 56 ms) and REL ([dˤ] = 10 ms, [d] = 16 ms) of coronal stops and post-coronal [g] (CD: plain = 51 ms, pharyngealized = 52 ms, REL: plain = 15 ms, pharyngealized = 13 ms) did not differ between pharyngealized and plain articulations. The same observation holds for post-coronal [m] with a mean duration of 70 ms after plain or 69 ms after pharyngealized fricatives. In contrast, pharyngealization had an impact on the formant structure of intrusive schwas. While F3 was not modified, F2 was 1.6 Bark lower and F1 was 0.4 Bark higher in pharyngealized compared to plain productions.

3.4 VCC̲CV

The analysis of the articulatory trajectories for plain and pharyngealized coronals in inter-consonantal position, i.e., VCC̲CV, are presented in Figure 8. Overall, the TTIP movement was not modified by pharyngealization. The inspection of the pairs showed that a lowering of slightly more than 1 mm was found at the transition of the preceding vowel to the pre-coronal segment in the pair [imzˤmaz – imzman] in (1b), while the other pair was unaffected. The vertical TBO trajectory, on the other hand, exhibited a continuous lowering in pharyngealized productions, which started already in the preceding vowel and spread to the end of the following vowel. A closer view revealed that the TBO lowering in the pair [ibdˤgas – ibdgas] in (2a) started in preceding [b] and was interrupted in the middle of the following [g], while this modification started in the second half of the preceding [i] in [imzˤaz- imzman] (2b) and remained above 1 mm until the end of the sequence.

The analyses of the formants trajectories are depicted in Figure 9. We found no modification of F1 and F3 in both vowel positions, neither in the aggregated trajectories nor in the specific pairs. A F2 lowering was found in the second half of the preceding vowel in the pair [ibdˤgas – ibdgas] in (2a), but not for the pair [imzˤmaz – imzman] in (2b). In case of following [a], F2 was lowered nearly during the entire vowel duration in both pairs.

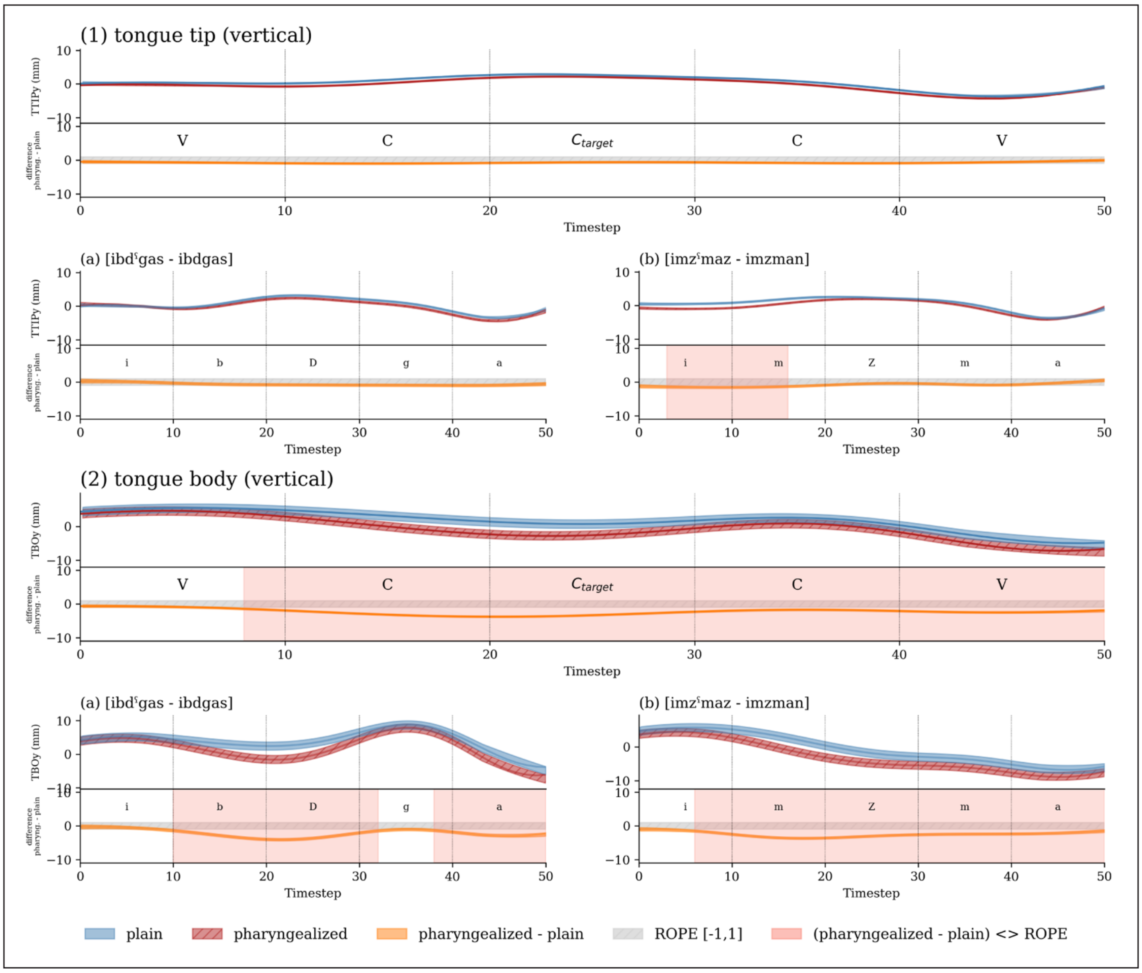

Figure 8: Vertical TTIP (1) and TBO (2) trajectories in VCCV context for aggregated trajectories and for each pair (a–b). Each panel shows the 95% posterior estimates for the plain (blue) and pharyngealized production (red) and their difference (orange), along with a ROPE of [–1, 1] (grey hatched area) and the time range in which the difference trajectory is outside the ROPE (rose area).

Out of a total of 108 tokens for VCCCV items, we observed 77 intrusive schwas within the consonant sequences. Table 7 gives an overview of the occurences of these schwas. Ninety-seven percent of the schwas were found in tokens for the pair [ibdˤgas – ibdgas].

The summary statistics (Table A.3.1) and regression analyses (Table A.3.2) of the acoustic parameters for the coronal targets, the surrounding consonants and the intrusive schwas are presented in A.3. Stop releases were found for 33 out of 46 coronal stops, 13 out of 46 [b] tokens, and 31 out of 46 [g] tokens.

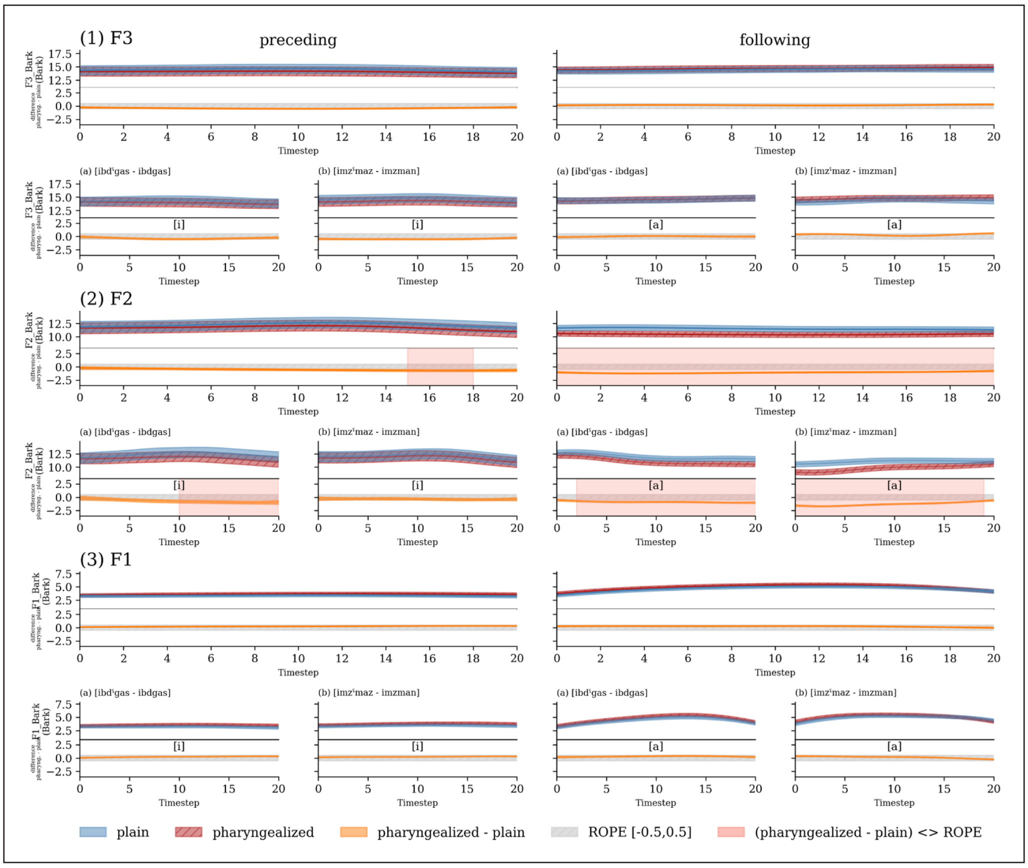

Figure 9: Formant trajectories in (1) F3, (2) F2, (3) F1 trajectories for VCCV context with aggregated trajectories and estimates for each pair (a–b) by vowel position (columns). Each panel shows the 95% posterior estimates for the plain (blue) and pharyngealized productions (red) and their difference (orange), along with a ROPE of [–0.5, 0.5] (grey hatched area) and the time range in which the difference trajectory is outside the ROPE (rose area).

pair	position	plain	pharyngealized
ibdˤgas – ibdgas	pre-coronal	22	20
	post-coronal	17	16
imzˤmaz – imzman	pre-coronal	2	0
	post-coronal	0	0

Table 7: Number of schwa intrusions by pair in VCCCV sequences.

There was no evidence that pharyngealization affected the temporal domain of pre-coronal [b] and [m], the coronal targets, post-coronal [g] and [m] and the intrusive schwas. The closure of pre-coronal [b] was nearly identical in both plain (51 ms) and pharyngealized articulations (50 ms). The REL of [b] (plain = 13 ms, pharyngealized = 14 ms) as well as the duration of pre-coronal [m] (plain = 70 ms, pharyngealized = 68 ms) did not differ with respect to the articulation of the coronal targets. Similarly, the CD ([dˤ] = 49 ms, [d] = 52 ms) and REL ([dˤ] = 14 ms, [d] = 19 ms) of coronal stops and the duration of coronal fricatives (zˤ = 100 ms, [z] = 102 ms) were virtually identical. The same holds for the temporal characteristics of post-coronal [g] (CD: plain = 49 ms, pharyngealized = 54 ms, REL: plain = 14 ms, pharyngealized = 15 ms) and [m] (plain = 71 ms, pharyngealized = 75 ms). The duration of schwas was identical before coronal in plain and pharyngealized articulations were identical before coronal targets and averaged at 19 ms before. Schwas after pharyngealized coronal consonants had a mean duration of 24 ms and 23 ms after plain coronals. Regarding spectral characteristics, the statistical analyses revealed that pharyngealization had no impact on the COG or the SD of coronal and non-coronal obstruents. However, this was not the case for the intervening schwas. There was evidence that pharyngealization led to a lowering of F2 in the pre-coronal schwa, where it was more than 1 Bark lower compared to plain productions. As can be seen in Table A.3.1, F1 and F3 of the schwas in this position were comparable, with a mean F1 of 2.8 Bark and a mean F3 of 14.8 Bark in plain productions, and a mean F1 of 3.2 Bark and 14.7 Bark for F3 in pharyngealized articulations. In post-coronal schwas, both F1 and F2 were affected by pharyngealization: These schwas had a higher F1 and a lower F2 after pharyngealized consonants than after plain coronals.

4. Discussion and Conclusion

This study aimed to explore the implementation of pharyngealization in Tashlhiyt. In the V$\underline{\text{C}}$V condition, used as a baseline, our results showed that the tongue body was already lowered in the preceding vowel. This lowering reached its maximum during the consonant, and subsequently continued into the following vowel, with a decreasing intensity. Acoustically, F2 was lowered for both preceding and following vowels, but consonant-internal acoustics were not affected by pharyngealization. We specifically investigated the way pharyngealization was realized if the segments surrounding the coronal targets involved consonants, in VC$\underline{\text{C}}$V, V$\underline{\text{C}}$CV and VC$\underline{\text{C}}$CV contexts. We found that the tongue body lowering peaked in the pharyngealized coronal segment in all contexts, showing it is the anchor of pharyngealization. Furthermore, this lowering extended beyond the target segments, implicating that the scope of pharyngealization is larger and decreases with increasing distance to the coronal anchor. Acoustically, we found that the lowering of F2 was present in full vowels as well as in intrusive schwas present within consonant sequences. A notable behavior regarding these articulatory and acoustic correlates was found for [g] and [i], where the tongue body lowering was reduced for [g], and the effect on F2 was less important for [i]. In the following, we discuss these findings starting with the articulatory and acoustic characteristics of pharyngealization, followed by the spread and direction of pharyngealization across the different contexts.

4.1 Phonetic correlates of pharyngealization

The defining articulatory correlate for pharyngealization is a backward movement of the tongue root towards the pharyngeal wall, leading to a narrowing of the pharyngeal cavity (Ali & Daniloff, 1972; Ghazeli, 1977; Hermes, 2018). Although electromagnetic articulography does not allow for tracking sensors on the tongue root near the pharynx's location, our data can shed light on the tongue modifications in the production of the plain – pharyngealized contrast. In the VC̲V position, we observed that a lowering of the tongue, which started in the preceding vowel, had its peak at the coronal target, and propagated with decreasing amplitude into the following vowel. These findings are in line with previous investigations on Arabic that observed that this lowering coincides with the formation of a pharyngeal constriction by the tongue back (Ali & Daniloff, 1972; Alwabari, 2020; Embarki et al., 2011; Hermes, 2018; Laufer & Baer, 1988; Zeroual et al., 2011). The systematic lowering of the tongue was not only observed in the baseline, i.e., the VC̲V contexts, but also in the other contexts under investigation.

The acoustic analysis showed that a significant drop of F2 in the surrounding vowels is the primary correlate of the plain – pharyngealized contrast in Tashlhiyt. This finding adds to the growing body of evidence suggesting that the lowering of F2 is a universal feature of pharyngealization, irrespective of the language. This has been confirmed across various typologically diverse languages, including different Arabic varieties (see Embarki et al., 2011, for a review), Hebrew (Laufer & Baer, 1988), Nootka (Rose, 1979), Tŝilhqot'in (Bird & Onosson, 2023), Kabyle Amazigh (Tigziri, 2013), Northern Horpa (Chiu & Sun, 2020), as well as several Caucasian languages such as Ubykh, Tsakhur, Udi, and Tsez (see Beguŝ, 2020, for a review). Furthermore, we also found detailed differences in formants dependent on vowel quality. F1 was raised in both [a] and [i] when immediately preceding or following a pharyngealized coronal. However, the temporal extent to which this effect was observable differed by vowel quality. While F1 was raised for [a] nearly throughout the vowel, this pattern occurred for [i] only in the immediate vicinity of a pharyngealized coronal. The effect on F3 on the other hand, was less clear. We found no modification of F3 for [a] in either of the tested items. In contrast, this formant was lowered for [i], although only when this vowel was immediately in contact with the pharyngealized coronal target. The effect of pharyngealization on F3 has not been well explored, since most acoustic studies take only F1 and F2 into consideration. The few studies that investigated F3 reported diverse results. Some studies (e.g., Abudalbuh, 2011; Chiu & Sun, 2020; Jongman et al., 2011) found a raised F3 in pharyngealized productions, while F. Al-Tamimi & Heselwood (2011) observed no differences. However, it must be noted that our approach in this study was based on formants in the Bark scale, while previous studies used uniform data based on Hertz for their statistical analyses. Results for F3 may thus not be comparable. When comparing the formant values in Hertz and Bark in F. Al-Tamimi and Heselwood (2011), it can be seen that differences of F3 in Bark are marginal and are usually around or less than 0.5 Bark, which we used as a threshold for our statistical analysis. In any case, the transformations from Hertz into Bark do not explain our finding that F3 is lowered for [i] in a pharyngealized context.

Contrary to some studies that examined the temporal characteristics of pharyngealized coronals (e.g., F. Al-Tamimi et al., 2021; Khattab et al., 2006; Kulikov, 2021), we found no statistically relevant effects of pharyngealization on the closure, release, consonant duration, or fricative spectra of coronal targets. Likewise, pharyngealization did not induce any modifications in these acoustical parameters in the adjacent non-coronal consonants [m, b, g], regardless of their position and context. The present study is one of the few studies that has included consonant-related acoustic measurements of non-coronals in the analysis. The only other study we are aware of that has done so is Al-Masri (2009), which found no change in the temporal and spectral characteristics for [b] in a pharyngealized context.

Our data show that the main articulatory attribute of pharyngealization is the lowering of the tongue dorsum while the main acoustic attribute is the lowering of F2. Although these attributes occur in parallel, they are not in a causal relationship, given that tongue body lowering is known to cause a raising of F1 and not a drop of F2 (e.g., Lindblom & Sundberg, 1971; Stevens, 2000). A significant observation arises when comparing the pairs [azˤa – aza] with other V$\underline{\text{C}}$V pairs. As illustrated in Figure 2, the differences in tongue body position for the [azˤa – aza] pair were notably smaller and remained relatively constant, unlike the more dynamic changes observed in the other pairs. If there was a causal relationship between tongue body lowering and F2 lowering, we would anticipate a smaller F2 difference in /a/ vowels of the [azˤa – aza] pair. However, as shown in Figure 2, the formant differences were similar across all pairs that included [a], consistently starting at approximately –2.5 Bark at the onset of the following [a]. This strongly suggests that the lowering of the tongue body is not the cause of a drop of F2, although clearly correlated. Therefore, the source of these characteristic F2 differences likely lies elsewhere.

The increased lowering of the mandible for the vowel [a] may explain its distinct pattern compared to [i], particularly regarding the extent of the F2 drop and its evolution over time. Since [a] typically involves a more open jaw position, the F2 drop resulting from the backward movement of the tongue is intensified by the lowering of the mandible, leading to a significant difference in F2 throughout the duration of the vowel. Conversely, the vowel [i], which is characterized by a closed jaw position (Keating et al., 1994), may not exhibit the same degree of F2 lowering. Additionally, the lowering of the tongue dorsum due to tongue root retraction is at odds with the higher tongue dorsum position of [i]. As a result, changes in the vertical tongue dorsum and their impact on F2 become evident only from the middle of the preceding [i] into the following pharyngealized coronal. This pattern is similarly observed during the transition from the pharyngealized coronal to the subsequent vowel, where both the tongue body and F2 exhibit a steeper decrease, as the tongue body must reach a higher position to produce [i].

In addition to this speaker-oriented explanation, another potential reason for why [i] appears to be less affected by pharyngealization compared to [a] could be perceptual factors, as discussed by Flemming (1995) (see also Jongman et al., 2011, for Jordanian Arabic). This different pattern could stem from the absence of contrast in backness for the low vowel [a]. Essentially, while a significant lowering of F2 for [i] might compromise the contrast between [i] and [u], a similar lowering for [a] would not introduce any acoustic overlap or perceptual confusion, as there is no phonemic low back vowel in Tashlhiyt vowel system. Regardless of the reasons for this F2 drop in neighboring vowels, it remains the primary acoustic correlate indicating pharyngealization. The concurrent lowering of the tongue dorsum remains consistent across our item pairs and contexts, although the degree and progression over time may vary depending on vowel quality.

4.2 Pharyngealization spread

A particular focus of this study was the investigation of the implementation and the spread of pharyngealization in target words bigger than VC̲V. The spread of pharyngealization is not a phenomenon inherent to this secondary articulation, as there are languages with pharyngealization but without pharyngealization spread (see, e.g., Beguŝ, 2020; Bird & Onosson, 2023). It is, however, a prominent characteristic occurring in Arabic (Davis, 1995). Pharyngealization spread has also been reported in Tashlhiyt, where it is argued that it may extend from the CV level as the smallest domain to encompass the entire word as the largest domain, contingent upon speech timing, or speech style (Boukous, 1989; Dell & Elmedlaoui, 2002). However, these claims are mostly based on subjective impressions rather than experimental evidence. Therefore, experimental studies are crucial for providing an objective assessment of this phenomenon, especially considering the limitations and ambiguities in acceptability judgments.

Our results showed that pharyngealization in Tashlhiyt manifests in domains larger than VC̲V, both in acoustics and in articulation. In articulation, the tongue body was lowered during pharyngealized productions. This tongue body lowering was evident not only in VC̲V items, but also extended to VCC̲V, VC̲CV, and VCC̲CV items. Figure 10 illustrates this observation, depicting the time ranges of these differences outside the ROPE by sequence type. Importantly, the tongue body lowering was not limited to the segments immediately preceding or following the underlyingly pharyngealized segment, whether they were vowels or consonants. Instead, it was observed in larger domains, extending up to nearly the entire VCC̲CV items. This finding provides clear articulatory support to the claim that pharyngealization spread in Tashlhiyt can encompass an entire word.

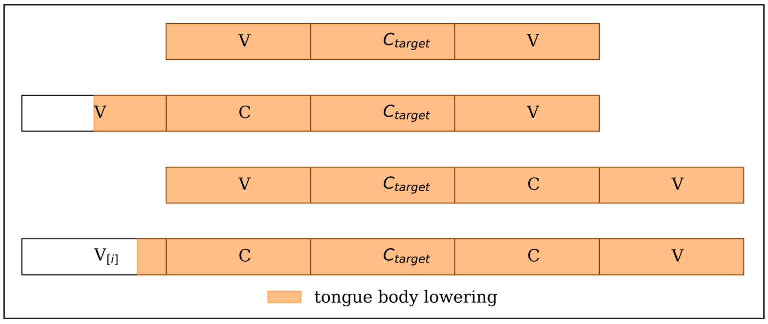

Figure 10: Extent of the tongue body lowering across segments in four different sequences.

Studies on Arabic, particularly those examining multisyllabic words, documented a lowering effect on F2 not only within the syllable containing the pharyngealized coronal segment, but also in neighboring syllables, extending even to longer distances in the case of three or four syllable words (e.g., Ahmed & Grosvald, 2018; Al-Masri, 2009; Hassan & Esling, 2011). Our study provided similar results. Figure 11 illustrates the extent of F2 lowering across the vowels within the tested items. Vowel-specific differences can be noted between [a] and [i]. In the case of [a], the F2 lowering is not confined solely to vowels adjacent to pharyngealized coronals; instead, it extends to larger domains, even when there is an intervening consonant. The effect of pharyngealization in [i] diverges according to the vowel's position: F2 lowering occurs through the vowel if it follows the pharyngealized coronal. However, in pre-coronal position the F2 drop occurs only partially in the vowel segment, or does not occur at all if there was a consonant between this vowel and the pharyngealized consonant. Another interesting finding is that transitional schwas occurring within consonant sequences also bear the same lowered F2 when adjacent to pharyngealized coronals.

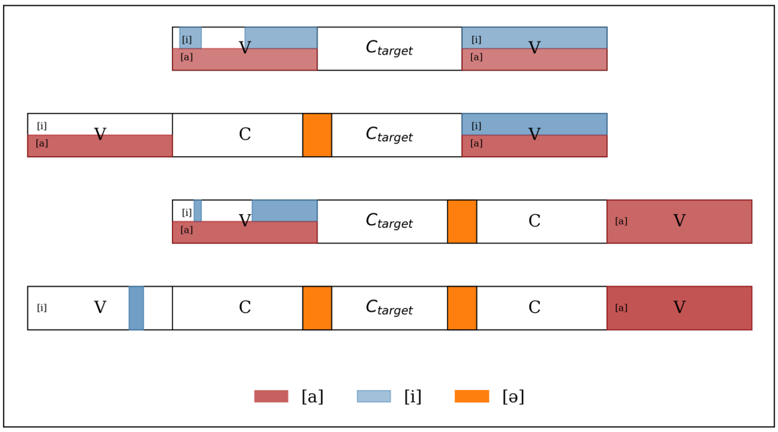

Figure 11: Extension of F2 lowering by vowel quality and position (including intrusive schwas) in four different sequences.

A special remark must be made on the phonetic properties of [i] and [g] in the context of pharyngealization. We observed in our data that the tongue lowering during these segments was either reduced in the case of [i] or blocked in the case of [g]. Here too, similar findings have been reported on data from Arabic. Hassan and Esling (2011) and Jongman et al. (2011) observed that the vowel [i] exhibits a smaller F2 drop in pharyngealized contexts compared to the vowel [a]. In terms of articulation, Hermes (2018) showed in a rtMRI study that the difference in the pharyngeal area for [iː] was less than for [aː], indicating a lesser degree of tongue root retraction and lesser narrowing of the pharyngeal cavity for the high vowel. Additionally, Alwabari (2020) showed that the tongue shape for [g] did not change when co-articulated with a pharyngealized consonant compared to a plain context, suggesting that [g] resisted pharyngeal co-articulation. Alwabari described this as a same-articulator conflict, meaning the required tongue root retraction for pharyngealization was inconsistent with the more forward position of the tongue root necessary for [g].

The production of both [i] and [g] requires a high position of the tongue dorsum. In both cases, a more advanced tongue root is needed to create a constriction by the elevated tongue dorsum. As Alwabari (2020) highlighted, this mechanism is at odds with the more retracted tongue root configuration for pharyngealization, which therefore results in a weakening or obstruction of pharyngealization spread. Further evidence for vowels can be found in Hermes (2018), who discovered an even lesser degree of pharyngeal width for [u], another high vowel. Alwabari analyzed also [χ, ʃ, j] with a more advanced tongue root. All these consonants were produced with a high tongue body position and, in the case of [ʃ, j], with a more advanced tongue root. Although this was not the case for [χ], the high tongue body position required conflicts with the retraction of the tongue root, leading to an inter-gestural antagonism that reduces, but does not eliminate, the dorsal lowering caused by the pharyngealized gesture (Alwabari, 2020).

The high dorsum position required by a certain set of segments can introduce a level of resistance to pharyngeal coarticulation: The higher the tongue dorsum position, and consequently, the tighter the constriction, the greater the resistance to the spread of pharyngealization. This relationship may not be complete, however. To fully account for the spread of pharyngealization, it would thus require the incorporation of at least two additional dimensions. The first one involves the backing of the tongue root since this is the primary articulatory correlate for pharyngealization. This dimension would interact with the tongue dorsum height such that a higher dorsal position or a stronger dorsal closure results in a more advanced tongue root, and thus a smaller narrowing of the pharyngeal cavity. The second dimension would take into account the temporal extent or distance to the pharyngealized coronal. As evidenced by our data and prior research, the effect of pharyngealization spread fades as the speech sounds move further from the underlyingly pharyngealized segment.

In conclusion, the results of this study show that the effect of pharyngealization as a secondary articulation is not restricted to the underlying pharyngealized consonant itself, but can be tracked into larger domains. Furthermore, we showed that articulatory modifications can be observed in non-vocalic surrounding segments, where overtly acoustic vowel-related correlates are absent. In addition, the results that the segments specified by a high tongue body position show resistance to co-articulated pharyngealization may guide future research to incorporate a wider variety of segments. This may inform theoretical approaches on pharyngealization spread not only in Tashlhiyt, but also in other languages by providing a more in-depth understanding of this phenomenon, factoring in aspects such as tongue body height and distance to the coronal anchor.

A Appendix

A.1 VCCV

position	sequence	segment	parameter	plain	pharyngealized
pre-coronal	ibDa, abDa	b	CD	59 (11)	59 (14)
			REL	10 (6)	10 (5)
			COG	857 (670)	949 (929)
			SD	1127 (758)	1133 (681)
	imZi, amZa	m	DUR	75 (13)	75 (16)
inter-consonantal	ibDa, abDa, amZa	ə	DUR	16 (5)	18 (7)
			F3	14.9 (0.4)	15.0 (0.4)
			F2	11.9 (0.4)	10.0 (1.1)
			F1	2.6 (0.3)	3.3 (0.7)
coronal	ibDa, abDa	d/dˤ	CD	52 (14)	56 (17)
			REL	13 (10)	17 (15)
			COG	1618 (1010)	1474 (971)
			SD	1855 (740)	1797 (807)
	imZi, amZa	z/zˤ	DUR	102 (23)	102 (20)
			COG	1416 (1175)	1192 (1042)
			SD	1678 (859)	1486 (930)

Table A.1.1: Means and standard deviations (in brackets) for the acoustic measurements (CD = closure duration, REL = release duration, DUR = consonant duration, COG = center of gravity, SD = standard deviation) of the pre-coronal consonant, intervening schwa, and the coronal target in VCCV sequences. The sequence column lists the sequences under investigation (capital letters mark the coronal target, underlined segments indicate the segments' location).

position	sequence	segment	measurement	parameter	mean	lower HDI	upper HDI	P (β < > ROPE)
pre-coronal	ibDa, abDa	b	CD	Intercept	0.04	–0.57	0.69	0.68
				TYPE[pharyng.]	–0.02	–0.81	0.77	0.76
			REL	Intercept	–0.0	–0.47	0.48	0.66
				TYPE[pharyng.]	–0.01	–0.64	0.62	0.74
			COG	Intercept	0.03	–0.75	0.85	0.76
				TYPE[pharyng.]	–0.01	–0.66	0.64	0.73
			SD	Intercept	0.11	–0.78	1.07	0.8
				TYPE[pharyng.]	–0.16	–0.85	0.57	0.77
	imZi, imZa	m	DUR	Intercept	–0.0	–0.68	0.64	0.71
				TYPE[pharyng.]	–0.04	–0.56	0.47	0.66
inter–consonantal	ibDa, abDa, amZa	ə	DUR	Intercept	–0.17	–0.77	0.43	0.75
				TYPE[pharyng.]	0.23	–0.38	0.81	0.81
			F3	Intercept	–0.04	–0.99	0.93	0.8
				TYPE[pharyng.]	0.17	–0.77	1.0	0.82
			F2	**Intercept**	**0.86**	**0.46**	**1.39**	**1.0**
				TYPE [pharyng.]	**–1.34**	**–2.17**	**–0.4**	**0.99**
			F1	Intercept	–0.76	–1.69	–0.06	0.99
				TYPE [pharyng.]	**0.98**	**0.1**	**1.73**	**0.99**

(Contd.)

position	sequence	segment	measurement	parameter	mean	lower HDI	upper HDI	P (β < > ROPE)
coronal	ibDa, abDa	d/dˤ	CD	Intercept	–0.18	–0.74	0.37	0.76
				TYPE[pharyng.]	0.29	–0.16	0.74	0.86
			REL	Intercept	–0.1	–0.59	0.4	0.69
				TYPE[pharyng.]	0.21	–0.39	0.81	0.8
			COG	Intercept	0.05	–0.61	0.73	0.72
				TYPE[pharyng.]	–0.14	–0.82	0.53	0.77
			SD	Intercept	–0.01	–0.82	0.79	0.76
				TYPE[pharyng.]	–0.05	–0.9	0.84	0.78
	imZi, amZa	z/zˤ	DUR	Intercept	0.02	–0.62	0.69	0.71
				TYPE[pharyng.]	–0.02	–0.49	0.43	0.64
			COG	Intercept	0.11	–0.72	0.97	0.79
				TYPE[pharyng.]	–0.27	–0.7	0.17	0.85
			SD	Intercept	0.11	–0.82	1.05	0.81
				TYPE[pharyng.]	–0.31	–0.69	0.08	0.9

Table A.1.2: Common level effects of the linear regression models for the acoustic measurements of the pre-coronal consonants, the intervening schwas, and the coronal targets in VCCV sequences. Reported are the mean, the lower and upper boundaries of 95% HDI of the posterior, and the probability of the posterior falling outside the ROPE of [–0.1, 0.1]. Bold fonts indicate an effect for the respective parameter. The sequence column lists the sequences under investigation (capital letters mark the coronal target, underlined segments indicate the segments' location).

A.2 VCCV

position	sequence	segment	parameter	plain	pharyngealized
coronal	iDga,	d/dˤ	CD	56 (13)	58 (10)
	aDga		REL	16 (12)	10 (5)
			COG	1684 (1256)	1515 (1119)
			SD	1849 (706)	1814 (865)
	iZma,	z/zˤ	DUR	91 (16)	92 (17)
	aZga		COG	838 (750)	955 (754)
			SD	1234 (775)	1366 (807)
inter-consonantal	iDga,	ə	DUR	26 (10)	25 (10)
	aDga,		F3	14.5 (0.7)	14.2 (0.7)
	iZma,		F2	12.9 (0.6)	11.3 (1.4)
	aZga		F1	2.7 (0.3)	3.1 (0.4)
post-coronal	iDga,	g	CD	51 (13)	52 (11)
	aDga,		REL	15 (8)	13 (5)
	aZga		COG	2115 (1058)	1708 (808)
			SD	1646 (451)	1507 (498)
	iZma	m	DUR	70 (12)	69 (14)

Table A.2.1: Means and standard deviations (in brackets) for the acoustic measurements (CD = closure duration, REL = release duration, DUR = consonant duration, COG = center of gravity, SD = standard deviation) of the coronal target, intervening schwa, and the post-coronal consonants in VCCV sequences. The sequence column lists the sequences under investigation (capital letters mark the coronal target, underlined segments indicate the segments' location).

position	sequence	segment	measurement	parameter	mean	lower HDI	upper HDI	P (β < > ROPE)
coronal	iDga, aDga	d/dˤ	CD	Intercept	–0.12	–0.46	0.24	0.63
				TYPE[pharyng.]	0.2	–0.47	0.89	0.79
			REL	Intercept	0.17	–0.6	0.95	0.79
				TYPE[pharyng.]	–0.51	–1.22	0.22	0.94
			COG	Intercept	0.04	–0.65	0.74	0.73
				TYPE[pharyng.]	–0.21	–0.76	0.36	0.8
			SD	Intercept	0.02	–0.72	0.76	0.75
				TYPE[pharyng.]	–0.16	–0.72	0.4	0.76
	iZma, aZga	z/zˤ	DUR	Intercept	–0.0	–0.76	0.74	0.72
				TYPE[pharyng.]	0.03	–1.05	1.15	0.81
			COG	Intercept	–0.08	–1.14	0.98	0.82
				TYPE[pharyng.]	0.15	–0.55	0.89	0.77
			SD	Intercept	–0.08	–1.22	1.04	0.83
				TYPE[pharyng.]	0.16	–0.55	0.85	0.77

(Contd.)

position	sequence	segment	measurement	parameter	mean	lower HDI	upper HDI	$P\ (\beta <> \mathrm{ROPE})$
inter-consonantal	iDga, aDga, iZma, aZga	ə	DUR	Intercept	–0.17	–0.93	0.64	0.79
				TYPE[pharyng.]	0.05	–0.33	0.45	0.59
			F3	Intercept	0.18	–0.78	1.11	0.83
				TYPE[pharyng.]	–0.51	–1.25	0.29	0.93
			F2	**Intercept**	**0.67**	**0.32**	**1.03**	**1.0**
				TYPE [pharyng.]	**–1.21**	**–1.89**	**–0.54**	**1.0**
			F1	**Intercept**	**–0.67**	**–1.13**	**–0.2**	**0.99**
				TYPE [pharyng.]	**1.13**	**0.64**	**1.59**	**1.0**
post–coronal	iDga, aDga, aZga	g	CD	Intercept	–0.07	–0.58	0.48	0.66
				TYPE[pharyng.]	0.07	–0.37	0.51	0.64
			REL	Intercept	0.12	–0.35	0.58	0.67
				TYPE[pharyng.]	–0.18	–0.64	0.29	0.76
			COG	Intercept	0.16	–0.62	0.96	0.79
				TYPE[pharyng.]	–0.35	–0.77	0.07	0.92
			SD	Intercept	0.1	–0.55	0.77	0.73
				TYPE[pharyng.]	–0.2	–0.68	0.32	0.78
	iZma	m	DUR	Intercept	0.02	–0.88	0.9	0.77
				TYPE[pharyng.]	–0.05	–0.94	0.75	0.77

Table A.2.2: Common level effects of the linear regression models for the acoustic measurements of the coronal targets, the intervening schwas, and the post-coronal consonants in VCCV sequences. Reported are the mean, the lower and upper boundaries of 95% HDI of the posterior, and the probability of the posterior falling outside the ROPE of [–0.1, 0.1]. Bold fonts indicate an effect for the respective parameter. The sequence column lists the sequences under investigation (capital letters mark the coronal target, underlined segments indicate the segments' location).

A.3 VCCCV

position	sequence	segment	parameter	plain	pharyngealized
pre-coronal	ibDga	b	CD	51 (10)	50 (13)
			REL	13 (10)	14 (8)
			COG	621 (276)	467 (160)
			SD	858 (414)	612 (285)
	imZma	m	DUR	70 (17)	68 (18)
inter-consonantal	ibDga, imZma	ə	DUR	19 (10)	19 (9)
			F3	14.8 (0.7)	14.7 (0.5)
			F2	12.4 (0.6)	11.2 (1.0)
			F1	2.8 (0.3)	3.2 (1.3)
coronal	ibDga	d/dˤ	CD	52 (19)	49 (14)
			REL	19 (14)	14 (11)
			COG	2123 (1577)	1384 (1398)
			SD	1977 (881)	1570 (825)
	imZma	z/zˤ	DUR	102 (14)	100 (13)
			COG	1380 (1231)	1232 (940)
			SD	1616 (817)	1602 (847)
inter-consonantal	ibDga	ə	DUR	23 (7)	24 (9)
			F3	14.4 (0.6)	14.1 (0.4)
			F2	12.7 (0.7)	11.7 (0.8)
			F1	2.6 (0.3)	2.9 (0.2)
post-coronal	ibDga	g	CD	49 (12)	54 (10)
			REL	14 (5)	15 (5)
			COG	1784 (814)	1895 (622)
			SD	1489 (432)	1463 (415)
	imZma	m	DUR	71 (11)	75 (11)

Table A.3.1: Means and standard deviations (in brackets) for the acoustic measurements (CD = closure duration, REL = release duration, DUR = consonant duration, COG = center of gravity, SD = standard deviation) of the pre- and the post-coronal consonant, intervening schwas, the coronal target in VCCCV sequences. The sequence column lists the sequences under investigation (capital letters mark the coronal target, underlined segments indicate the segments' location).

position	sequence	segment	measurement	parameter	mean	lower HDI	upper HDI	P (β < > ROPE)
pre-coronal	ibDga	b	CD	Intercept	0.02	–0.59	0.64	0.7
				TYPE[pharyng.]	–0.03	–0.8	0.77	0.78
			REL	Intercept	–0.05	–1.26	1.18	0.85
				TYPE[pharyng.]	0.08	–1.45	1.73	0.89
			COG	Intercept	0.25	–1.0	1.51	0.87
				TYPE[pharyng.]	–0.64	–1.84	0.65	0.94
			SD	Intercept	0.28	–0.93	1.58	0.87
				TYPE[pharyng.]	–0.7	–1.89	0.54	0.95
	imZma	m	DUR	Intercept	0.06	–0.58	0.69	0.72
				TYPE[pharyng.]	–0.06	–0.77	0.63	0.75
inter-con-sonantal	ibDga, imZma	ə	DUR	Intercept	–0.06	–1.08	0.97	0.81
				TYPE[pharyng.]	0.04	–0.68	0.73	0.74
			F3	Intercept	0.21	–0.8	1.29	0.83
				TYPE[pharyng.]	–0.33	–1.29	0.62	0.86
			F2	Intercept	0.59	0.02	1.17	0.98
				TYPE [pharyng.]	**–1.25**	**–2.13**	**–0.44**	**1.0**
			F1	Intercept	–0.21	–0.75	0.34	0.78
				TYPE[pharyng.]	0.4	–0.61	1.4	0.89

(Contd.)

position	sequence	segment	measurement	parameter	mean	lower HDI	upper HDI	P (β < > ROPE)
coronal	ibDga	d/dˤ	CD	Intercept	0.08	–1.01	1.06	0.81
				TYPE[pharyng.]	–0.17	–1.1	0.8	0.82
			REL	Intercept	0.16	–0.5	0.84	0.77
				TYPE[pharyng.]	–0.39	–1.34	0.51	0.88
			COG	Intercept	0.21	–0.74	1.19	0.83
				TYPE[pharyng.]	–0.44	–1.24	0.41	0.9
			SD	Intercept	0.22	–0.77	1.23	0.83
				TYPE[pharyng.]	–0.45	–1.23	0.33	0.9
	imZma	z/zˤ	DUR	Intercept	0.04	–0.8	0.94	0.78
				TYPE[pharyng.]	–0.19	–0.76	0.4	0.78
			COG	Intercept	0.02	–0.82	0.88	0.78
				TYPE[pharyng.]	–0.13	–0.66	0.4	0.73
			SD	Intercept	–0.06	–1.08	0.96	0.82
				TYPE[pharyng.]	–0.02	–0.43	0.39	0.59

(Contd.)

position	sequence	segment	measurement	parameter	mean	lower HDI	upper HDI	P (β < > ROPE)
inter-con-sonantal	ibDga	ə	DUR	Intercept	–0.06	–1.12	0.98	0.81
				TYPE[pharyng.]	0.2	–0.57	0.95	0.8
			F3	Intercept	0.22	–0.91	1.36	0.85
				TYPE[pharyng.]	–0.55	–1.35	0.23	0.94
			F2	Intercept	0.34	–0.79	1.44	0.88
				TYPE [pharyng.]	**–0.87**	**–1.49**	**–0.27**	**0.99**
			F1	Intercept	–0.53	–1.48	0.43	0.93
				TYPE [pharyng.]	**1.04**	**0.3**	**1.8**	**0.99**
post-coronal	ibDga	g	CD	Intercept	–0.21	–1.18	0.78	0.84
				TYPE[pharyng.]	0.48	–0.18	1.15	0.93
			REL	Intercept	–0.24	–1.34	0.86	0.84
				TYPE[pharyng.]	0.11	–1.44	1.8	0.87
			COG	Intercept	–0.26	–1.51	0.99	0.86
				TYPE[pharyng.]	0.09	–1.49	1.64	0.86
			SD	Intercept	–0.04	–0.94	0.81	0.77
				TYPE[pharyng.]	0.02	–1.54	1.58	0.86
	imZma	m	DUR	Intercept	–0.2	–0.74	0.38	0.77
				TYPE[pharyng.]	0.42	–0.61	1.48	0.89

Table A.3.2: Common level effects of the linear regression models for the acoustic measurements of the pre- and post-coronal consonants, the intervening schwas, and the coronal targets in VCCCV sequences. Reported are the mean, the lower and upper boundaries of 95% HDI of the posterior, and the probability of the posterior falling outside the ROPE of [–0.1, 0.1]. Bold fonts indicate an effect for the respective parameter. The sequence column lists the sequences under investigation (capital letters mark the coronal target, underlined segments indicate the segments' location).

Data availability

The data tables and analysis scripts are available under https://osf.io/zkd4b/.

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Competing interests

The authors have no competing interests to declare.

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