THE PHONETIC CORRELATES OF PHARYNGEALIZATION AND PHARYNGEALIZATION SPREAD PATTERNS IN CAIRENE ARABIC AN ACOUSTIC AND REAL-TIME MAGNETIC RESONANCE IMAGING STUDY

BY

ZAINAB HERMES

DISSERTATION

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Doctoral Committee:

Associate Professor Ryan K. Shosted, Chair
Professor Elabbas Benmamoun
Professor José Ignacio Hualde
Professor Brad Sutton

ABSTRACT

The major articulatory differences between plain and pharyngealized speech sounds in Arabic are a secondary posterior constriction and a lowered tongue body implicated in the production of the latter type. This articulatory configuration, *pharyngealization*, affects neighboring segments according to spread patterns that differ across different dialects in both direction and domain (distance). The most prominent acoustic consequence of this articulatory configuration is a lowering of the second formant frequency in surrounding vowels. The extent of the modification in the formant frequency is determined by the length and quality of the vowel. This study uses real-time magnetic resonance imaging (rtMRI) to investigate the acoustic and articulatory correlates of pharyngealization and pharyngealization spread in Cairene Arabic. The articulatory and acoustic correlates of pharyngealization and pharyngealization spread relate to phonetics and phonology, respectively. This study is thus at the interface of phonetics and phonology, presenting phonetic evidence for a phonological phenomenon. Four male native speakers of Cairene Arabic participated in the study. They were trained to repeat a carrier phrase inside the MRI scanner: /ʔal:aha: X ʔalf mar:a/ ('He told her X one thousand times', where X is the target word). Target words are monosyllabic minimal pairs of Cairene Arabic in which the plain-pharyngealized contrast occurs at the edges of the word, and in which the vowels immediately adjacent to the plain-pharyngealized contrast are /a:, i:, u:/ and /a, i, u/. The role of both vowel length and vowel quality in the extent of pharyngealization spread was examined, as well as the influence of rightward versus leftward spread of pharyngealization. The acquired rtMRI data is reconstructed using the Partial Separability model to achieve high temporal resolution (approximately 100 fps) and high spatial resolution (128 × 128 voxels (volume elements), with each voxel measuring 2.2 mm × 2.2 mm × 8.0 mm (through-plane depth). Midsagittal MRI frames are extracted at the middle of the consonants and vowels of the target words. They show the lingual and pharyngeal configuration during the articulation of each speech segment. An edge detection method is applied to identify the contours of the vocal tract from the glottis to the lips. These contours are analyzed in Matlab to examine the articulatory configuration of the sounds of interest. Two articulatory measures, 2D pharyngeal areas and 2D oral areas, are introduced to quantify the magnitude of the pharyngeal constriction and the oral cavity, respectively. These provide articulatory measurements of pharyngealization spread across different vowel qualities, different vowel lengths, and different directions. Results suggest that the magnitude of pharyngealization spread differs with respect to these three factors. Parallel acoustic data is acquired from the same four speakers in a sound attenuating booth and analyzed in Praat to examine the acoustic properties (i.e. the formant frequencies) of the sounds of interest. Results from articulatory measurements are corroborated with results from acoustic measurements of formant frequency modifications.

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Chapter 1: Overview

Pharyngealization is a phonemic feature of many living Semitic languages, including Arabic, Modern Aramaic, Modern South Arabian, and Ethiopic (Hetzron, 1998). This feature is articulated in Arabic with a secondary constriction in the posterior velopharyngeal and pharyngeal region of the vocal tract (Versteegh, 2001). The exact place of this secondary constriction varies according to a number of factors, including dialect, phonological context, and gender (Khattab et. al, 2006), and has thus been described as “velarization”, “uvularization”, and “pharyngealization” (Lehn, 1963). The presence of phonemically contrastive pharyngealized or velarized consonants (having a secondary constriction in the pharynx or near the velum respectively) is relatively rare across languages. Among the 451 languages in the UCLA Phonological Segment Inventory Database (UPSID; Maddieson & Precoda, 1990), only 8 are listed as having pharyngealized consonants (1.77% of the languages in the database) and only 13 are listed as having velarized consonants (2.88%). There is no category in the database for “uvularized” as a secondary articulation. This secondary constriction has the effect of modifying the auditory quality of the pharyngealized speech sound and surrounding vowels and consonants, resulting in an impressionistic auditory quality described as “dark”, “heavy”, “dull”, “thick” (Wahba, 1996) , and “intense” (Watson, 2002). The set of pharyngealized speech sounds in Arabic contrast with their *plain* counterparts, in which the secondary posterior constriction is not posited to occur. The set of pharyngealized consonants differs slightly across dialects. The various Arabic dialects combined distinguish five plain-pharyngealized coronal stops and fricatives: /t-tˤ, d-dˤ, ð-ðˤ, z-zˤ, s-sˤ/.

This study is an acoustic and real-time Magnetic Resonance Imaging (rtMRI) study for investigating the articulatory configuration and acoustic output associated with pharyngealization and pharyngealization spread in Cairene Arabic. Pharyngealization is an interesting topic for phoneticians because the secondary articulation occurs in the relatively inaccessible posterior velopharyngeal or pharyngeal region. Instrumental studies seek to obtain partial or holistic views of this region during speech production in order to precisely describe the articulation of these sounds. For phonologists, pharyngealization is an interesting suprasegmental phenomenon that spreads according to various patterns that differ across dialects. Differences include the domain and direction of the spread, as well as the presence and behavior of opaque elements (Davis, 1995). Pharyngealization spread has been described as a type of postvelar harmony and has received considerable attention in formal autosegmental approaches (Shahin, 2002, among others). This work presents a phonetic explanation to some of these phonological patterns. Pharyngealization is also of interest to sociolinguists, with studies reporting gender-driven and class-driven differences in the amount of pharyngealization and pharyngealization spread a speaker produces (Royal, 1985 and Wahba, 1996). Weaker pharyngealization is reported to mark feminine or effeminate speech and a greater level of social prestige (Royal, 1985). Pharyngealization is also implicated in historical and comparative Semitic linguistics. Pharyngealized consonants of Arabic correspond to glottalic egressive (ejective) consonants of South Semitic (languages spoken in the Southern part of the Arabian Peninsula and the Horn of Africa). This raises the question of which of the two realizations was original to Proto-Semitic. A precise description of the articulatory gestures implicated in the articulation of pharyngealized consonants, as well as of ejectives, will offer support for what is a more plausible evolution in terms of phonetics, and contribute to the discussion on the historical migration and settlement of peoples between the Horn of Africa and the Arabian Peninsula. Furthermore, by linking the articulatory configuration of the vocal tract during pharyngealization and pharyngealization spread with the corresponding acoustic properties, this work will also contribute to resolving the acoustic-to-articulatory inversion. The rtMRI data in this study provides high-resolution holistic images of the vocal tract in real-time and in a non-invasive manner that does not dramatically inhibit articulatory motion.

Chapter 2: Literature Review

2.1 The acoustic correlates of pharyngealization in Arabic

Arabic pharyngealized consonants are articulated with a secondary constriction in the back velopharyngeal and/or pharyngeal regions of the vocal tract. According to Perturbation Theory (Chiba & Kajiyama, 1941), the velopharyngeal region corresponds to a node (a point of maximum velocity) in the standing wave of the first formant frequency F1, and an anti-node (a point of maximum velocity) in the standing wave of the second formant frequency F2. Perturbation Theory predicts that the resonance frequency will increase if a constriction occurs at a node, and will decrease if the constriction occurs at an anti-node. Thus, in line with these predications, acoustic studies on Arabic pharyngealized consonants have reported a raised F1 and a lowered F2 in the onsets of vowels following the pharyngealized sound, and in the offsets of vowels preceding it (Jongman et. al., 2011; Khattab, 2006; Watson, 2002). These modifications in the formant frequencies have the effect of changing the auditory quality of the pharyngealized speech sound and the sounds surrounding it, yielding an auditory quality that has been impressionistically described as “dark”, “heavy” and “dull” (Wahba, 1996). Another term used by early Arab grammarians, and later by Jakobson (1957), is *mufaxxam* ‘intensified’ (Watson, 2002). They have also been described as “emphatic” in Western literature. Giannini & Pettorino (1982) suggest that the Western term “emphatic” was coined by de Sacy (1810) in reference to this “thick” or “heavy” quality of the speech sound. They quote his description of these sounds as being articulated:

> “avec une sorte d’emphase. Ce que j’appelle emphase ou articulation emphatique est une espèce de renflement qu’il n’est pas aisé de definir mais qui fait en quelque sorte entendre un o sourd après la consonne” (*with a sort of emphasis. What I call emphasis or emphatic*

> *articulation is a sort of enlarging that is not easy to define, but that leaves one somewhat hearing a hidden 'o' after the consonant*)" (de Sacy, 1810:20, cited in Giannini & Pettorino, 1982:10; translation my own).

The extent of the modification in the formant frequencies of adjacent vowels is determined by the length and quality of the vowel (Yeou, 1997). Yeou reports a greater effect of pharyngealization on F1 and F2 in the short vowels adjacent to pharyngealized consonants, relative to their long counterparts, i.e. he reports greater raising of F1 and greater lowering of F2 in the short vowels. The greatest modifications in F1 and F2 occur in the vowel /æ/, followed by /i/ and /u/ (Jongman et. al., 2011; Yeou, 1997). Yeou attributes this to the articulatory configuration associated with /æ/, which he reasons is "more compatible with the pharyngealization gesture" (Yeou, 1997:200) than the configuration of either /i/ or /u/. Jongman et. al. (2011) observe that the effect of an emphatic on /æ/ yields a vowel with a "distinctly different quality" (p. 86) that should be described as [ɑ]. This low back vowel, they point out, occurs in Arabic only in complementary allophonic distribution with /æ/ in the vicinity of a pharyngealized consonants (Jongman et. al., 2011), and in some dialects, in the vicinity of pharyngeal and/or uvular consonants as well. In contrast, the articulatory configurations associated with the high vowels /i/ and /u/ are at odds with the articulatory requirements of pharyngealization, namely the lowering of the tongue.

The observation that [ɑ] only occurs as an allophonic variant of /æ/ is contested by Youssef (2014) who lists some examples in Cairene Arabic of minimal pairs contrastive in /ɑ/ and /æ/. He therefore proposes that /ɑ/ be regarded as an independent phoneme in Cairene Arabic and a source that triggers pharyngealization spread in its own right.

Linguists generally consider the source of pharyngealization to be the pharyngealized consonants (Jongman et. al., 2011). Nonetheless, a perception study conducted by Jongman et. al. (2011) showed that the listeners' perception of pharyngealization relies on acoustic cues in the adjacent vowels (and non-target consonants) more than on acoustic cues from the pharyngealized consonant itself. Thus, information in the "rest of the word (vowel+non-target consonant)" is more crucial than information in the target consonant. In their study, Jongman et. al. (2011) cross-splice natural real-word C_1VC_2 minimal plain-pharyngealized pairs. In some of the words, C_1 is the target consonant (word-initial condition); in others C_2 is the target consonant (word-final condition). From all of the words, four stimuli were produced from cross-splicing the target consonant from one member of the pair with the VC segment (in the word-initial condition) or CV segment (in the word-final condition) from the other member of the pair. This generated two of the four stimuli. The remaining two were produced from cross-splicing the target consonant with the VC (or CV) segment of the same segments from different productions of the same word. Participants were presented with the cross-spliced stimuli and were required to determine whether the stimulus they heard corresponded to the word containing the pharyngealized consonant (i.e. the pharyngealized word) or the word containing the plain consonant (i.e. the plain word). Findings from that study showed that in both the word-initial and word-final conditions, participants tended to identify as pharyngealized, the stimuli in which the VC (or CV) segments came from the pharyngealized word, regardless of whether the target consonant was pharyngealized or plain.

This result is in line with previous studies that demonstrate that acoustic cues in the transitions from or into adjacent vowels of a consonant are possibly more essential in the perception of a given consonant (Cooper et. al., 1952, Delattre et. al., 1955).

2.2 The articulation of pharyngealization

2.2.1 Pharyngealization as described by early Arab Grammarians

The pharyngealization feature in Arabic was identified and described as early as the 8th century by Arab grammarians, who referred to the phenomenon as *iṭbāq* (spreading and raising of the back of the tongue), *isti ʿlā ʾ* (elevation of the dorsum), and *tafkhīm* (thickness or heaviness) (Lehn, 1963). Arab grammarians identified four pharyngealized sounds in Classical Arabic that they termed the *muṭbaqa* sounds, meaning 'covered' or 'enclosed': /tˤ, dˤ, sˤ, ðˤ/. All other speech sounds were termed *ghayr muṭbaqa* (not closed) or *munfatiħa* (opened). Sibawayh (d. 796) described the *muṭbaqa* sounds as having two places of articulation: one involving the front of the tongue rising to form the coronal constriction, and the other involving the back of the tongue rising up toward the velum, thus creating a configuration in which the sound is 'enclosed' between these two places. He noted that the secondary articulation is what distinguished the *muṭbaqa* (pharyngealized) sounds from their plain counterparts, and wrote, for example: "without *[iṭbāq]*, *sīn* [i.e. /s/] would be a *ṣād* [i.e. /sˤ/]" (Vollers, 1893:150). Ibn Sina (Avicenna; d. 1037) related the difference between the two sounds to the shape and volume of the oral cavity associated with each sound. He wrote:

> The production of /s/ is similar to (that) of /ṣ/[1] save that, (in /ṣ/) the passage of the air requires (the use) of a larger surface of the tongue both in length and breadth. A sort of

[1] Throughout this text, the transcription conventions of the IPA will be used, except in citations, in which case the citation will be presented in its original form with the transcription conventions chosen by its author. The IPA symbols different from those in the citation will then be presented in a footnote. Here, the symbol /ṣ/ corresponds to IPA /sˤ/.

hollow is formed in the tongue (surface) to give the rolling of the air a certain resonance. (Semaan, 1963:41).

To the *muṭbaqa* set of sounds, three additional sounds were added /q, x, ɣ/ to form a set of sounds having the property of *istiʿlāʾ* (elevation). The articulation of this set was defined as involving the elevation of the tongue toward *al-ħanak al-a'lā*, literally, *the upper palate*. Interestingly, as Bellem (2007) points out, this property was also defined as preventing the presence of another property *imāla* (inclining) which was defined as the fronting and raising of the vowel /a/ toward /i/. Thus, Bellem shows, that *imāla* was associated with fronting, whereas *istiʿlāʾ* was associated with backing. The *istiʿlāʾ* sounds are thus grouped together because they share an articulatory configuration that involves the elevation of the back of the tongue toward the upper palate, and because they block the fronting of an adjacent /a/. The auditory quality of the *istiʿlāʾ* sounds was referred to as *tafkhīm* meaning 'intensification' (Watson, 2002), 'aggrandizing', or 'puffing up' (Bellem, 2007). Thus, the seven *istiʿlāʾ* sounds were also *tafkhīm* sounds. Additionally /r/ and /l/ in certain contexts were described as having the *tafkhīm* quality (Al-Wohaibi, 1982 and Lehn, 1963).

Furthermore, varying degrees of *tafkhīm* were identified based on surrounding vowels, the strongest being when one of the seven sounds is followed by a long /a:/[2]. The weakest was when the sound is followed by a short /i/.

The early Arab grammarians also understood that the presence of a *tafkhīm* sound influenced especially the vowels immediately following it, and they identified and described an allophonic variant of /a/ having the *tafkhīm* quality when preceded by a *tafkhīm* sound. Some grammarians

[2] Unless otherwise explicitly stated, /a/ represents the front vowel.

also described longer distance pharyngealization spread to other consonants beyond the immediately adjacent vowels, such as al-Suyūṭī (d. 1505) in the following passage in Bellem (2007) that describes a right-to-left spread:

> Every *sīn* [/s/] which is followed by *ʿayn* [/ʕ/] or *ghayn* [/ɣ/] or *khāʾ* [/x/] or *qāf* [/q/] or *ṭāʾ* [/tˤ/] may be transformed into *ṣād* [/sˤ/], for instance *yusāqūna* and *yuṣāqūna*[3] …the condition for this is that the *sīn* [/s/] should precede these consonants (i.e. the elevated ones) not follow after them, and that these consonants should be close to it. (Bellem, 2007:25).

This right to left spreading pattern is observed in many dialects of Arabic such as Cairene (Youssef, 2014) and Palestinian (Herzallah, 1990).

McCarthy (1994) and Herzallah (1990) also examine the influence of pharyngealized consonants on *imāla*, described above, especially in a following feminine suffix (in Standard Arabic /a/). In Levantine Arabic, the underlying representation of the feminine suffix is the non-low /e/ or /i/ (McCarthy, 1994: 219). The fronting and raising of this feminine suffix, however, is blocked when it is preceded by pharyngealized (but also pharyngeal, laryngeal, and uvular) consonants. McCarthy cites the examples in Table 2.1 below from Syrian Arabic (from Cowell, 196:138, and Grotzfeld, 1965:45) to demonstrate this. All words are feminine, ending with the feminine suffix (underlyingly, the non-low /e/ due to *imāla*). In words in which the feminine suffix is preceded by pharyngealized consonants, it is observed that *imāla* is blocked, and the feminine suffix is realized as the low [a].

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[3] IPA yusa:qu:na and yusˤa:qu:na respectively.

Table 2.1: Syrian words illustrating imāla (fronting and raising of feminine suffix) and the blocking of it.

Word	Gloss	Word	Gloss
kbi:re	large (f)	madrase	school (f)
ʔəsˤsˤa	story (f)	ʕari:dˤa	wide (f)

2.2.2 Pharyngealization as described in more recent literature

Versteegh (2001) and others believe that the works of the medieval Arab grammarians were concerned mostly with describing Classical (standard) Arabic. Their biggest motivation seems to have been to preserve the original form of the language with which the Quran was recited, especially as the Arabic language spread to non-Arab populations. Some grammarians also documented ‘variants’ of certain speech sounds that existed alongside their standard realizations. In contrast, more recent phonetic and phonological studies on pharyngealized consonants are mostly concerned with describing the property in the spoken dialects of Arabic.

Emphasis is defined in the modern literature as a phonemic feature characteristic of Semitic languages. In Arabic, it is articulated with a secondary constriction in the posterior velopharyngeal region (Laufer & Baer, 1988), in addition to the primary coronal constriction. Thus, pharyngealized consonants having this secondary constriction are contrastive with their plain counterparts, in which this secondary constriction is typically considered absent. Al-Tamimi & Heselwood (2011), however, nuance this description and suggest that speakers not only refrain from forming the posterior constriction in the case of the plain sound, rather, they may actively be expanding their laryngopharynx. Thus, for them, the view that the plain sound has an identical configuration to the pharyngealized sound, but lacks the posterior constriction is imprecise and too simplistic. They also question whether the primary articulation is identical in both members, noting that in the pharyngealized member, the back of the tongue is retracted and raised, a configuration that may constrain the tongue tip from making the coronal constriction at the exact place as in the plain member. Rather, the expectation is that the tongue tip would form the coronal constriction at a more retracted place. Indeed, previous studies have cited a retracted tongue tip as an articulatory correlate of pharyngealized consonants (Lehn, 1963).

Various experimental methods have been employed to observe the place of the posterior secondary constriction in different dialects of Arabic. These studies suggest that its exact place differs across dialects (Norlin, 1987; Obrecht, 1968; Al-Tamimi & Heselwood, 2011), and across different phonological environments within the same the dialect (Obrecht, 1968; Al-Tamimi & Heselwood, 2011). Thus, in Jordanian Arabic, the secondary articulatory gesture associated with pharyngealization is described as a constriction in the lower oropharynx involving the folding and backward retraction of the epiglottis, in a motion comparable to that implicated in the production of pharyngeal consonants (Al-Tamimi & Heselwood, 2011 and Heselwood & Al-Tamimi, 2011). This is the literal definition as pharyngealization. The oropharynx is defined in Zemlin (1998) as having a superior limit at the level of the soft palate, and a lower boundary at the level of the hyoid bone (Zemlin, 1998:227). In the context of the back vowel /u:/, the articulation of pharyngealized consonants is described as uvularization, involving the approximation of the back of the tongue with the uvula (Heselwood & Al-Tamimi, 2011). A study of Lebanese Arabic described this secondary articulation as velarization (Obrecht, 1968). Additional more anterior articulatory gestures that are reported to be implicated in pharyngealization include labialization and the lowering and concavity of the tongue body (Lehn, 1963 and Watson, 2002).

Norlin (1987) had summed up the observation that the strategy with which pharyngealization is realized differs according to dialect with the following:

> The modern dialects show a wide spectrum of phonemic contrasts in their segments, both among themselves and vis-à-vis Standard Arabic. It should by no means be impossible that [pharyngealization], although certainly a universal phenomenon in all forms of Arabic, might be realised in different ways and degrees in different dialects. (Norlin, 1987:13)

In addition to the dialect, and the phonological context, Khattab et. al. (2006) suggest that the gender of the speaker may also factor in determining the secondary place:

> There is no consistent single articulatory exponent of [pharyngealization]. Rather, speakers have a range of articulatory strategies at their disposal, including how high in the pharynx to create a constriction. Which strategy a speaker uses will depend on several factors that may include not only native dialect and phonological context, but also gender and possibly other social variables. (Khattab et. al, 2006:140)

Studying the secondary articulation of pharyngealization can be especially challenging because of the posterior and relatively inaccessible place in which this articulation occurs. Experimental techniques that have been previously employed include nasoendoscopy, videofluoroscopy, magnetic resonance imaging (MRI), ultrasound imaging, and electromagnetic articulogrophy (EMA). What follows is a brief description of these techniques, some phonetic studies that have applied them for the purpose of describing the articulation of pharyngealization in Arabic, and a discussion of their strengths and limitations.

Nasoendoscopy involves inserting a flexible tube through the subject's nostril and passing it down to the pharynx. A small camera and light are attached to the tube. The images captured by the camera present a lateral view of the pharynx and the epiglottis, but the relative distance between the articulators and the camera can be difficult to control. This technique is a clinical procedure and must be administered by a doctor. It is also invasive as it involves inserting something into the subject's body. These issues make this a relatively costly experiment, and limit the number of participants that normally take part in it.

Thus, for their nasoendoscopy study on pharyngealization in Jordanian Arabic, Al-Tamimi & Heselwood (2011) recruited four speakers. Using this technique, they were able to observe an epiglotto-pharyngeal constriction formed by the downward and backward folding of the epiglottis toward the pharyngeal wall. They report that this secondary constriction is comparable to the primary constriction they observed in another study they conducted on Arabic pharyngeal fricatives (Heselwood & Al-Tamimi, 2011). They, accordingly, conclude that the secondary articulation for these speech sounds in Jordanian Arabic is, indeed, best described as pharyngealization. Their findings, they maintain, show that the epiglottis is implicated in the pharyngeal constriction, but they make no claims about its ability to move independently from the tongue root. This observation is in line with Laufer & Baer (1988) who arrive at the same conclusion with regards to the motion of the epiglottis and its implication in the articulation of pharyngealization.

In a similar nasoendoscopic study on Moroccan Arabic, Zeroual et. al. (2011a) report a raising of the back of the tongue during /tˤ/ to a height intermediate between the height during uvular /q/ (which is higher), and during plain /t/ (which is lower).

In their study on pharyngealization in Jordanian Arabic, Al-Tamimi & Heselwood (2011) also conduct a videofluoroscopic experiment. **Videofluoroscopy**, or motion X-ray, is another technique in which real-time X-ray images are acquired during speech. This is also a clinical procedure conducted in the radiology department of a hospital. Images from this technique show a midsagittal view of the vocal tract, including the pharynx. As with nasoendoscopy, this is a costly technique that requires medical supervision, and consequently, the number of participants in such a study is relatively limited. Furthermore, this technique requires exposing the participants to continuous and high levels of radiation, something that may further discourage participants from taking part in such an experiment. The ionizing radiation, therefore, make this technique better suited for medical diagnosis and therapy as well as image-guided surgery (Gick, et. al., 2013:140). Nonetheless, two participants took part in the videofluoroscopic study by Al-Tamimi & Heselwood (2011). Their results further support nasoendoscopic findings suggesting that the secondary articulation of pharyngealization in Jordanian Arabic is an epiglotto-pharyngeal constriction for most of their data. When the vowel adjacent to the pharyngealized consonant is /u:/, however, they report that, due to coarticulation, the constriction is higher in the pharynx and that the overall articulatory configuration is best described as uvularization.

Embarki et. al. (2011b) studied the articulation of pharyngealization in Tunisian Arabic using **electromagnetic articulagrophy** (EMA). In this technique, sensors are attached to discrete points on the orofacial articulators including the lips, tongue, and jaw. As the participant speaks, the EMA system records the Cartesian coordinates of the discrete points in three-dimensional space. This allows for tracking the motion of these discrete points during speech articulation. This method differs from the previous ones discussed above in that one does not directly observe the articulatory configuration, rather one tracks the motion of discrete points, and, consequently, infers the overall articulatory configuration. Furthermore, this method is not a clinical procedure and, thus, does not require medical supervision. It is, therefore, less costly in comparison with the other methods, and more likely to include more participants. There is a limitation, however, on the region of the vocal tract that can be studied with this technique. Because this technique involves attaching sensors on the points of interest in the speaker's vocal tract, how far back in the vocal tract a sensor is placed is determined by the point at which the faucal gagging reflex is excited. In one study, this seems to have been the point just opposite of the uvula on the tongue (Emarki et. al., 2011b). Thus, this method allows for studying the articulatory configuration of the tongue blade up to the anterior part of the tongue dorsum, but not the tongue root, epiglottis, or pharynx. It is an effective technique for examining the primary articulation and the "hollowing" of the tongue associated with pharyngealized speech sounds. In a study conducted by Emabarki et. al. (2011b), four sensors were glued along the tongue of the one speaker in their experiment. The furthest sensor was placed at approximately 7 cm from the tongue tip, (in the schematic illustration in their paper, the location of this sensor appears to be just opposite of the uvula on the tongue). The speaker was required to utter a number of words containing V_1CV_2 sequences in which the intervocalic consonant varied between pharyngealized and plain pairs. Results from their study show rearward horizontal displacement of the sensors during the pharyngealized consonant when compared with the displacement of the sensors during the plain counterpart. They also show slight lowering of the tongue during the pharyngealized member in the context of /a/.

Zeroual et. al. (2011a) also conducted an EMA study on one speaker of Moroccan Arabic. Three sensors were placed on the tip, middle, and dorsum of the tongue, though no precise measurements were given of the exact locations along the tongue. The target words included items with pharyngealized-plain contrasts in C_1VC_2 syllables in which the word-initial C manifested the pharyngealized-plain contrast. Like the previous EMA study, results from this study show that the sensors placed on the middle of the tongue and at the dorsum of the tongue experience more rearward horizontal displacement and more downward vertical displacement during the pharyngealized members than during their plain counterparts.

These results are in line with results from another EMA study on three speakers of Lebanese Arabic (Hermes et. al., 2015). In that study, three sensors were placed along the midline of the tongue 1, 2, and 3 cm from the tongue tip. The speakers were required to repeat target words contrastive in the pharyngealized-plain speech sound. The pharyngealized-plain speech sound occurred in various phonological environments word-initially, word-medially, and word-finally, and surrounded by various vowels. That study found that the vertical displacements of the middle sensor and back sensors were significantly lower during the pharyngealized member than during the plain one, suggesting that the tongue is lowered during pharyngealization. Results further suggested that the tongue blade assumes a concave shape during the pharyngealized member in line with observations in the literature (Watson, 2002).

In an **ultrasound** experiment, a probe is fixed on the throat, beneath the chin and just above the larynx. Ultra-high frequency sound ranging from 3 – 16 MHz (Gick et. al., 2013:160) then travels through the tongue and is reflected back to a transducer. From these signals, it is possible to reconstruct a midsagittal view of the tongue (Gick et. al., 2005). This technique has many advantages in that it is safe, non-invasive, and does not require medical supervision. One limitation, however, is that it cannot directly image the palate and the pharyngeal wall implicated in the secondary articulation of pharyngealization (Stone, 2010). Nonetheless, Zeroual et. al. (2011a) apply this method to look at the configuration of the tongue during pharyngealization. One speaker of Moroccan Arabic participated in their study, and was required to repeat isolated words containing /t, tˤ, χ, k, q, ħ, h/ among other speech sounds. They report observing a more elevated tongue back during /χ, q/ due to the uvular constriction required for producing these speech sounds. /ħ/ and /t/ are reported to have a lower tongue back, and /tˤ/ is reported to be at an intermediate elevation between these two sets. These results support the notion that the tongue assumes a concave shape during pharyngealization, having a lowered tongue body, a relatively raised back, and a raised tip or blade (to achieve the primary constriction).

In another ultrasound study, Zeroual et. al. (2011b), examine the secondary articulation in a set of Moroccan labialized dorsal and labial speech sounds as produced by one native speaker of this dialect. By comparing the lingual configuration during the labialized speech sounds and their plain counterparts, they conclude that the more precise description of the secondary articulation is labiovelarization. They report that the back of the tongue is more retracted and more raised in the labialized member. Their observations, they maintain, are in accordance with a general observation by Ladefoged & Maddieson (1996): "in the great majority of cases where lip rounding is employed as a secondary articulation, there is also an accompanying raising of the back of the tongue, i.e. a velarization gesture. […] This double secondary articulation type is sometimes called labiovelarization".

Another ultrasound study (Lapinskaya, 2013) described differences in the lingual configuration between pharyngealized-plain stops and fricatives of Cairene Arabic as exemplified in the speech of one native speaker of this dialect. The speaker was required to repeat several iterations of meaningful words contrastive in the pharyngealized-plain speech sound. The pharyngealized-plain consonants all occurred in the /a_a/ environment. The results for the lingual configuration associated with the pharyngealized members show a lowered tongue body in the palatal region and a retracted dorsum, in line with previous results.

Perhaps the most powerful technique for studying pharyngealization **is magnetic resonance imaging** (MRI). This is because this technique can provide several simultaneous views of the vocal tract: midsagittal, lateral, coronal, as well as other oblique angles specified by the researcher. In the midsagittal view, this technique provides a full view of the vocal tract including the posterior velopharyngeal region of interest in the study of pharyngealized consonants. This technique is also non-invasive and does not need to be administered by a medical doctor. The limitations, however, are that it is relatively more costly, and, though it is non-invasive and does not involve subjecting the speakers to radiation, it is still sometimes intimidating for some speakers. Thus, recruiting participants for an MRI study can be challenging.

A number of studies on Arabic speech sounds in which the pharyngeal region is implicated have employed MRI. Shar and Ingram (2011) compared pharyngeal width and laryngeal height during Arabic gutturals (uvulars, pharyngeals, and glottals). Five native speakers of Saudi Arabic (spoken in the southern Assiri region) were recruited for this study. The study employed static MRI. Thus, the 5 participants were trained to maintain the speech sounds of interest for 11 seconds, the duration required to acquire a static MRI scan in this experiment. Two pharyngeal width measurements were computed: one at the level of the tongue root; another at the level of the epiglottis. The laryngeal height was computed as the vertical distance between a fixed horizontal reference line and two stable vertebrae. The results show narrowing in the pharyngeal diameters at the level of the tongue root during the articulation of uvulars, and at the level of the epiglottis during the articulation of glottals, and pharyngeals. Epiglottis retraction is also observed during the voiceless uvular fricative /χ/. Laryngeal raising (increased height) is observed during the production of pharyngeals; the maximum raising is observed during the approximant /ʕ/. Furthermore, a higher larynx is observed during the voiceless uvular fricative /χ/.

Shosted et. al. (2011) also use static and dynamic MR imaging to study the role of the posterior constrictions in pharyngeal and pharyngealized speech sounds of Arabic. One speaker of Jordanian Arabic and one of Moroccan Arabic took part in the study. In the static MRI acquisition, the speakers were required to utter and sustain the speech sounds of interest for a duration of 20 seconds. The pharyngeal areas were then computed from the transverse (midsagittal) images as a function of the distance from the glottis. These pharyngeal area functions showed considerable differences in the place and extent of pharyngeal constrictions in glottal and pharyngeal fricatives. A pharyngeal expansion was also observed in the articulation of the /ʕ/ at about 50 mm above the glottis. Furthermore, a pharyngeal constriction in the upper pharynx is attested in the pharyngealized consonants, and absent in their plain counterparts. Real-time dynamic MR images (rtMRI) were also acquired. For this part of the study, the speakers were required to repeat words containing the target speech sounds and embedded in a carrier phrase. For each MRI frame throughout the duration of the target speech sound, five areas were demarcated: laryngeal, hypopharyngeal, epiglottal, oropharyngeal, and nasopharyngeal. The average pixel intensities (API) in those areas were calculated, and used in a principal components analysis (PCA). The results of the PCA revealed that two principal components (PCs) are sufficient to account for 85% of the variation in the data, suggesting that the variation in pharyngeal width between these speech sounds of Arabic is mostly significant in two regions of the pharynx: an upper pharynx comprising the oropharyngeal and nasopharyngeal regions, and a lower region comprising the remaining laryngeal, hypopharyngeal, and epiglottal regions.

Israel et. al. (2012) also used real-time MRI (rtMRI) to study the posterior constriction associated with pharyngealization and the suprasegmental spread of pharyngealization in Lebanese Arabic as manifested in the speech of one female speaker. They implemented a semi-automatic algorithm (Proctor et. al., 2010) to extract the lingual contours in the midsagittal MRI frames. The extracted contours were manually corrected in cases where the algorithm failed. Tract-normal gridlines extended from the glottis and ran through the vocal tract to a point beyond

the lips to quantitatively compare between the tongue contour displacement as well as the degree of constriction. Results showed that the phonetic correlates of pharyngealization for the female Lebanese Arabic speaker are a constriction in the upper pharynx formed by the approximation of the tongue dorsum to the upper rear pharyngeal wall approximately 40 mm above the glottis.

2.3 Pharyngealization as a phonological feature

2.3.1 A discussion of coarticulation, coproduction, and spread

Classic phonological theories build on the notion of abstract, mental representations of speech sounds (phonemes) associated with a standard articulation or 'motor plan' (Kühnert & Nolan, 1999). Coarticulation accounts for the observation that these units of sound are not realized identically in all phonological environments, rather are influenced by surrounding segments. A classic example is of the phoneme /k/, associated with an articulation that involves raising the back of the tongue toward the soft palate to form a complete constriction. This standard articulation is probably the one observed in the word [kæt], for example. In the context of a high front vowel, however, such as in the word 'key', the place of the constriction will be more forward on the palate, thus, the realization will be closer to [k̟i:]. Thus, the adjustment in the articulation of the phoneme /k/ is a consequence of coarticulation with the neighboring /i/. Many studies in speech science have described and modelled coarticulation, attributing it in part to the physiological constraints of the vocal mechanism, especially in real-time, such that it is not possible to instantaneously jump from one articulatory configuration to another, but also accounting for the setup of our perceptual system and the observation that parallel processing of the acoustic properties of more than one phoneme at once facilitates rapid perception of speech (Kühnert & Nolan, 1999).

Coarticulation can be viewed from the perspective of spatial or temporal targets. In the former, the articulatory configuration of a phoneme or segment is modified from its target place due to the influence of surrounding segments. In the latter, the articulatory configuration is modified due to the relative beginning and ending times of the phonemes and their duration (Kühnert & Nolan, 1999). Thus, in the former, there are overlaps in the spatial targets, while in the latter, there are overlaps in the temporal targets.

It is noteworthy to point out that the term coarticulation has also been used in reference to speech sounds that have two simultaneous places of articulation, such as the Arabic pharyngealized consonants – the object of this study – that have a primary coronal place and a simultaneous back (velar, uvular, or pharyngeal) place.

The motor constraints of the speech mechanism described above represent *phonetic* constraints that cause coarticulation. Cross-linguistic studies of coarticulation have further revealed that coarticulatory patterns vary according to language-specific *phonological* constraints. Findings by Manuel & Krakow (1984) show that languages with considerably larger vowel inventories, such as English, exhibit less coarticulatory effects on vowels. They attribute this to the necessity of maintaining the distinctiveness of vowels in such languages. In contrast, the languages that had relatively fewer distinct vowels in their study (Swahili and Shona) exhibited more coarticulatory effects. They thus argue that coarticulation is determined not only by constraints of motor planning and execution, but also by constraints defined by phonology (here, the size of the phonemic vowel inventory). Thus, it is important to distinguish between coarticulatory effects that are a consequence of the speech producing mechanism in general, and those that are language-specific. The latter correspond to phonological spread patterns. There is thus here an interface between phonetic coarticulatory patterns and phonological patterns.

With regards to vowel inventory, the number of distinct Cairene Arabic vowels (in terms of quality) is the same as the number of distinct Swahili vowels – five. Like Standard Arabic, Cairene Arabic contrasts /i/, /u/, and /a/, but Cairene Arabic includes two additional close-mid vowels /e/ and /o/ (Gadalla, 2000). In both Standard and Cairene Arabic, vowel length is contrastive for /i/, /u/, and /a/ - thus, both varieties of Arabic contrast /i:/-/i/, /u:/-/u/, and /a:/-/a/. /e/ and /o/ in Cairene Arabic have no short counterparts (Gadalla, 2000).

Yeou (1997) argues that in Arabic, the pharyngealized consonants are the most resistant consonants to coarticulatory effects from adjacent vowels due to the greater constraints on the tongue body required for their articulation. These are the constraints required for achieving 1) the primary (coronal) articulation, and simultaneously 2) the back pharyngeal constriction. He compares this with the English velarized approximant [lˠ] (dark l), the production of which requires the back of the tongue to be raised toward the velum in addition to maintaining the alveolar constriction. This, he argues, makes it more resistant to coarticulatory effects from adjacent vowels. In contrast, the palatal [l^j] (light l) is less resistant to coarticulation because of the lesser demands – defined here by the number of gestures – imposed on the tongue to produce this sound. These findings are in line with findings from Embarki et. al. (2011a) and Embarki et. al. (2011b). Both studies investigate the coarticulation patterns triggered by the pharyngealized and contrastive non-pharyngealized consonants across the Yemeni, Kuwaiti, Jordanian, and Moroccan dialects of Arabic. They use Locus equations (Yeou, 1997) to measure the amount of coarticulation at consonant-vowel boundaries. In this method, onset F2 values of the vowels (i.e. in the transitions) are plotted against F2 values measured at the middle of the vowels (i.e. in the steady state), and the slope is computed. A relatively flat slope is indicative of maximal coarticulatory resistance of the preceding consonants, while a relatively steep slope is indicative of minimal coarticulatory resistance of the preceding consonants. Their findings report maximal coarticulatory resistance of the pharyngealized consonants to vowel effects across all dialects. They further investigate the influence of speech 'style' on coarticulatory effects, thus comparing coarticulatory effects on pharyngealized consonants as produced by speakers in their native regional dialects against those produced by the same speakers in Standard Arabic. They report flatter slopes during Standard Arabic than during dialectal Arabic, suggesting stronger resistance of the pharyngealized consonants to coarticulatory effects from adjacent vowels in the Standard Arabic variety. This may perhaps be interpreted as hyperarticulation in Standard Arabic.

Yeou (1997) remarks that speech sounds that are resistant to coarticulation induce greater coarticulatory effects on adjacent segments. This type of coarticulation would thus correspond to phonological spread. Thus, the coarticulatory effects of pharyngealized consonants are described phonologically as the spread of the pharyngealization feature.

2.3.2 Phonological studies on the spread of the pharyngealization feature

It has been noted that the phonemic inventories differ slightly across Arabic dialects. In addition to the phonemic inventories, Embarki et. al. (2011b) also note that the "gestural and temporal adjustments during larger units" also differ across dialects:

> [P]honetic sets […] differ regularly from one Arab country to another. This concerns not only the ways in which the phonemes are produced, but also the gestural and temporal adjustments during larger units such as syllables, phonological words, and other prosodic domains. It is therefore reasonable to assume that coarticulation, which is the result of gestural and temporal adjustments, may differ significantly from one [Arabic dialect] to another." (Embarki et. al., 2011b:195-196)

Consequently, the patterns observed for pharyngealization spread differ across dialects. This includes differences in the direction of the spread, the domain (distance) of the spread, and the presence and type of opaque elements and their behavior.

Moreover, the segments that trigger this spread also vary. Segments that are described as underlyingly or intrinsically pharyngealized, i.e. pharyngealized speech sounds that are phonemically contrastive with plain counterparts, always trigger pharyngealization spread. For some dialects, additional segments have been included as triggers for pharyngealization spread, such as [$r^{ʕ}$] in Egyptian Arabic (Youssef, 2014) and in Palestinian Arabic (Younes, 1993). The speech sounds /χ/, /ʁ/, and /q/ have also been grouped in the same class with pharyngealized consonants on the count that they, too, trigger the same or similar phonological patterns (Lehn, 1963 and Watson, 2002). It was also suggested that the pharyngeals /ħ/ and /ʕ/ be grouped with pharyngealized consonants within the same emphatic class (Heselwood & Al-Tamimi, 2011 and

Watson, 2002). Proponents of this view maintain that the pharyngeals /ħ/ and /ʕ/ are emphatic counterparts of the laryngeals /h/ and /ʔ/ respectively, a proposal also suggested by Jakobson (1957). They argue that the pharyngeal constriction in /ħ/ and /ʕ/ is a secondary, not a primary articulation, and that the primary articulation occurs below the pharynx and involves larynx raising as well as gestures implicating the aryepiglottic folds, the ventricular bands, and the arytenoid cartilages in the case of /ʕ/ (Heselwood, 2007 and Heselwood & Al-Tamimi, 2011). In the case of /ħ/, Heselwood & Al-Tamimi (2011) cite Esling (1996) and Esling (1999) and speculate that the friction of this fricative is generated "in the narrow space between the arytenoids and the base of the retracted epiglottis, and between the aryepiglottic folds and the upper part of the epiglottis at the laryngeal aditus (2011:124). They further cite Ghazeli's conclusion that "the friction during /ħ/ is created by intralaryngeal adjustments" (Ghazeli, 1977:49) as well as observations by Yeou & Maeda (2011) that the friction during /ħ/ is generated at the glottis. A similar observation may have also been alluded to in Ibn Sina's (Semaan, 1963) articulatory description of /ħ/ below in which he reports a narrower opening between the "two lower cartilages":

> Although /ħ/ shares with /ʕ/ (the place and fashion of articulation), it differs from it in the form of the point of articulations, in the (amount) of obstruction […] and in the place where the air is released. The opening between the two lower cartilages is narrower (than it is in the production of /ʕ/). (Semaan, 1963:36)

According to Heselwood & Al-Tamimi (2011), these gestures and adjustments below the pharynx explain why the 'secondary' pharyngeal constriction in /ħ/ and /ʕ/ is observed in many studies to be lower in the pharynx than the secondary pharyngeal constriction in the pharyngealized coronals: the secondary constriction is closer to the primary articulation. Thus, when the primary articulation is coronal, the pharyngeal constriction is higher in the pharynx; when the primary articulation is below the pharynx, the pharyngeal constriction is lower in the pharynx.

Additionally, in support of the proposal to treat pharyngeals as emphatic counterparts of laryngeals, they point to the constraints on the occurrence of homorganic consonants in adjacent radicals in the tri-consonant roots. McCarthy (1994) shows that a plain-emphatic (i.e. plain-pharyngealized) coronal pair does not occur in adjacent radicals in a tri-consonant root. His data also show a similar infrequency in the occurrence of a pharyngeal-laryngeal pair in adjacent radicals.

Thus, there are differing views on which speech sounds should be included within the set of emphatic sounds and which trigger pharyngealization spread. For Egyptian (Cairene) Arabic, Youssef (2014) argues that the set of segments that trigger pharyngealization spread consists of the coronals /$t^ʕ$, $d^ʕ$, $s^ʕ$, $z^ʕ$, $r^ʕ$/, and he argues for treating the low back vowel /ɑ/ as an independent phoneme (the opposing view treats it as an allophone of /a/ ([ɑ])), and thus includes it as a segment that triggers pharyngealization spread. In this view then, the pharyngeal quality of /ɑ/ is intrinsic rather than a consequence of spread from surrounding back segments. He also shows that pharyngealization spread in this dialect is bidirectional with no opaque elements. The domain of this spread is the syllable as well as the phonological word including all prefixes and suffixes. He observes an interesting pattern with emphatic /$r^ʕ$/ that it "loses its emphatic feature where it comes in direct tautosyllabic contact with a non-inflectional allophone of /i/" (Youssef, 2014:463), suggesting a morphological factor in this phonological pattern.

In another study on pharyngealization spread in Abha Arabic (spoken in the Southwestern part of Saudi Arabia), Younes (1991) reports that pharyngealization rarely spreads beyond adjacent vowels. In a study on a northern Palestinian dialect of Arabic, Herzallah (1990) reports leftward spread of pharyngealization from the trigger to the beginning of the word. Rightward spread, however, does not extend beyond the following vowel. Thus, any consonant following this vowel, except the set of pharyngeals /ɦ, ʕ, h, ʔ/, effectively blocks the spread of pharyngealization. The presence of any of these consonants after the vowel allows the pharyngealization to spread further to the following vowel. Davis (1995) reported bidirectional pharyngealization spread within the phonological word in two Palestinian dialects (a northern and a southern dialect), but noted asymmetries in the spread patterns. Leftward spread is generally unbounded; rightward spread, however, is reported to be blocked by a different set of opaque elements in each dialect. In the northern dialect, the opaque elements are /ʃ, j, w/; in the southern dialect, they are /ʃ, ʒ, j, i/.

Bukshaisha (1985) also reports bidirectional pharyngealization spread in Qatari Arabic, and notes that in cases where the pharyngealized consonant occurs word-initially, pharyngealization may spread leftward across the word-boundary to the adjacent word. This phenomenon was also observed in certain cases of Cairene Arabic (Youssef, 2014).

Israel et. al. (2012) used dynamic real-time MRI (rtMRI) to study the posterior constriction associated with pharyngealization in Lebanese Arabic as exemplified in the speech of the one female speaker in their experiment. They also examined the suprasegmental spread of pharyngealization. In their study, the term ‘emphaticized’ refers to a speech segment to which the pharyngealization (emphasis) spreads, in contrast to the term ‘emphatic’ which refers to the pharyngealized segment, i.e. the speech segment having the posterior secondary articulation. Thus, in the word /$t^ʕ$alab/, initial /$t^ʕ$/ is (intrinsically) emphatic and final /b/ is emphaticized, because the emphasis (i.e. pharyngealization) spreads to it.

The speaker was required to repeat several verbs contrasting plain and emphatic consonants embedded in a carrier phrase. Target words were in the form of CVCVC or CVCCVC. The consonants of interest are at the edges: the plain-emphatic contrast occurs word-initially, and the plain-emphaticized contrast occurs word-finally. Medial consonants varied between palatal and non-palatal, to examine the opacity (blocking) effects of intervening palatals on pharyngealization spread.

In the midsagittal MRI frames corresponding to the speech sounds of interest, a semi-automatic algorithm was applied to extract the lingual contours (Proctor et. al., 2010). The extracted contours were manually corrected in cases where the algorithm failed. Forty-one tract-normal gridlines were defined extending from the glottis and running through the vocal tract to a point beyond the lips. The gridline normal to the vocal tract at the glottis was defined as gridline 0, and the last gridline at the point beyond the lip was defined as gridline 41. The remaining 39 gridlines were separated by 4.8 mm intervals. These gridlines allowed the authors to quantitatively compare between the tongue contour displacement as well as the degree of constriction.

Results show that for their speaker of Lebanese Arabic, the phonetic correlates of pharyngealization are a constriction in the upper pharynx formed by the approximation of the tongue dorsum to the upper rear pharyngeal wall. This constriction is located at gridline 8, approximately 40 mm above the glottis, and the mean pharyngeal aperture at this place is 3.84 mm. Their results also show that pharyngealization spreads in both direction. Thus, they compare the lingual contours of the intrinsically emphatic /$d^ʕ$/ in /$bajjad^ʕ$/ with the tongue contour of the final /d/ in /$ts^ʕ$ajjad/ (intrinsically non-emphatic, but emphaticized in this context due to the rightward spread of emphasis (pharyngealization) from emphatic /$s^ʕ$/). Both lingual contours are also compared against the non-emphatic and non-emphaticized /t/ in /bajjat/. They report that the emphaticized /d/ is articulated with a depressed and retracted tongue body just as emphatic /dˤ/, but that the depression and retraction in the emphaticized /d/ are "less pronounced":

> [E]mphaticized segments typically exhibit the same characteristics observed in intrinsically emphatic segments, but these characteristics appear to be less pronounced. (Israel et. al., 2012: 2177).

The authors also briefly refer to the disagreement over the presence of opaque elements that block the spread of pharyngealization. Previous phonological studies suggested that an intervening high palatal /j/ may block the spread of pharyngealization in this dialect. Thus, in their study, they also investigate this issue. Their findings show that for Lebanese Arabic, and for this speaker, high segments do not, in fact, block pharyngealization; they report that the quantified emphaticization measured after a high segment is weaker, but is nonetheless significant.

2.4 Pharyngealization as a social marker

Sociolinguistic studies report that pharyngealization in Arabic is a social marker and identify interesting trends and preferences among speakers. Royal (1985) reported on gender-driven differences in the degree of pharyngealization a speaker produces. In her study of Egyptian Arabic, she reports that women had a consistent tendency to produce weaker pharyngealization than men. She notes that "women who pronounce pharyngealized consonants too strongly are perceived as 'unfeminine'" (Royal, 1985:93). She notes that "the social meanings of femininity and effeminacy are shared by both front pronunciations and weak pharyngealization, while back pronunciation and strong pharyngealization are both associated with 'tough', 'male' behavior". (Royal, 1985: 96). Interestingly, she observes that "many [Egyptian] jokes and puns turn on feminine or effeminate confusion of pharyngealized and non-pharyngealized consonants", and that this "shows that 'weak' pharyngealization is […] stereotypically associated with female speech" (Royal, 1985:93-94).

Other sociolinguistic studies on gender-related differences in pharyngealization in Egyptian (Alexandrian) Arabic (Wahba, 1996), and in Jordanian Arabic (Khattab et. al., 2006; and Abdubalbuh, 2011) reach similar conclusions: female and effeminate speech is generally characterized by less pharyngealization than male speech. An earlier study on Cairo Arabic by Harrell (1957), and cited in Royal (1985), makes the following generalization:

> the general attitude seems to be that if one's normal pronunciation of a morpheme is emphatic, the non-emphatic seems affected and effeminate. If one's usual pronunciation is non-emphatic, the emphatic form may seem variously overly formal, pompous, or crude and hick-like (Harrell, 1957:81)

Furthermore, this interesting exchange with an Egyptian male participant in the study is cited:

> "Question: Would you ever say /raʃʃa:ʃa/ instead of /raʃʃa:ʃa/ [i.e. non-emphaticized vs. emphaticized; 'water sprinkler']?
>
> Answer: Well, *I* wouldn't.
>
> Question: Why not?
>
> Answer: Because I am not a woman." (Harrell, 1957:81).

In addition to the gender-driven differences, Royal (1985) also observed class-driven differences in the extent of pharyngealization produced, with less pharyngealization indicative of a more refined social class. Royal examined the speech of two groups: one from Heliopolis, an affluent region in Cairo, and another group from Gammaliya, a poorer area in Cairo. Her results show that the men of Heliopolis produce stronger pharyngealization in their speech than the women of Heliopolis, but interestingly, the men of Heliopolis produce weaker pharyngealization than both the men and women of Gammaliya. Thus, she concludes, speakers may have a tendency to produce weaker pharyngealization to convey a level of prestige. Royal reports that "some upper-class suburbanites ruefully acknowledge that they do not always pronounce pharyngealized consonants 'strongly enough'" (Royal, 1985:94).

To measure the "strength" of pharyngealization for a consonant, Royal measured the duration of the transition of the second formant (F2) to a steady state (or peak) in an /i/ vowel following the consonant. Longer transitions suggested stronger pharyngealization. From an articulatory point of view, this was explained in terms of the strong coarticulatory resistance of the front vowel /i/ to the backing of a preceding pharyngealized consonant. Thus, the tongue assumes a back position during the pharyngealized consonant, and then moves forward to articulate the vowel /i/. The transition of the tongue from the back position to a front position is reflected in a longer transition duration of the F2 formant in /i/. She cites Ghazeli (1977):

> If the vowel following the pharyngealized consonant is palatal ([i] or [e]) and long, the back of the tongue gradually moves forward to achieve the target position of the palatal vowel … it takes longer to move the mass of the tongue to reach the steady state of [i] from [Ç̣] [a pharyngealized consonant] than from [C] [its non-pharyngealized counterpart]. This difference in distance is translated into a long transition characteristic of palatal vowels adjacent to pharyngealized consonants (Ghazeli, 1977:79)

Chapter 3: Problem Statement

This study describes and quantifies the acoustic and articulatory correlates of pharyngealization and pharyngealization spread in Cairene Arabic and compares the strength of pharyngealization spread in different directions and across vowels of different lengths and different qualities. This is done in both the articulatory and acoustic domains.

In the articulatory domain, a relatively new technique, real-time Magnetic Resonance Imaging (rtMRI) is used. Magnetic Resonance Imaging (MRI) has the unique advantage of providing holistic views of the vocal tract, including the relatively inaccessible posterior region implicated in pharyngealization. Furthermore, real-time MRI allows for viewing the vocal tract in motion at a relatively high frame rate. Beyond describing the articulatory configuration associated with pharyngealization and pharyngealization spread, this study quantifies it by introducing a number of 2D area measures. By quantifying pharyngealization, this study is able to thus compare the extent of pharyngealization that occurs in different vowel qualities and vowel lengths, as well as examine whether pharyngealization spread in one direction is stronger than in another. In addition to the articulatory correlates, the study examines the acoustic correlates of pharyngealization and pharyngealization spread by measuring and comparing modifications in formant frequencies. Results observed in the acoustic domain are then linked with those observed in the articulatory domain.

Understanding the articulatory and acoustic cues of pharyngealization and of its spread patterns has broader applications in acoustic-to-articulatory mapping and language pedagogy. It is also implicated in distinguishing between the various dialects of Arabic and in the study of diachronic and synchronic sound change.

Chapter 4: Methodology

4.1 Articulatory data acquisition

Real-time dynamic Magnetic Resonance Imaging (rtMRI; Fu et. al., 2015) is used to investigate the articulatory configuration associated with pharyngealization and pharyngealization spread in Cairene Arabic. The major strength of rtMRI (Fu et. al., 2015) is that it provides holistic imaging of the vocal tract with high spatiotemporal resolution, which allows for capturing the complex dynamics of natural speech (Lingala et. al., 2016). High temporal resolution is necessary for capturing the fast-varying dynamics of speech; while high spatial resolution is necessary for capturing the fine features of the articulators implicated in natural speech (Fu et. al., 2015). In order to achieve high spatiotemporal resolution, an MR image must be acquired at twice the highest component frequency in the dynamic signal, according to the Nyquist sampling theorem. This requirement is difficult to achieve with limited MR imaging speed. The method developed by Fu et. al. (2015), however, makes use of the Partial Separability (PS) model to evade this sampling requirement and allows for decomposing the dynamic signal into partially separable spatial and temporal components. This method meets requirements of the 2014 Speech MRI Summit (Lingala et. al., 2016). Hermes et. al. (2017) worked with rtMRI data collected using an earlier version of this method to investigate the articulation of ejectives in Tigrinya, and, in another study, to examine and compare the posterior pharyngeal constriction implicated in the production of pharyngeal and pharyngealized consonants in Jordanian, Lebanese, and Saudi Arabic. The temporal resolution achieved by this method (i.e. the reconstructed sampling frequency) is approximately 100 fps. The spacial resolution achieved for each reconstructed frame is 128 × 128 voxels (volume elements), with each voxel measuring 2.2 mm × 2.2 mm × 8.0 mm (through-plane depth) (Carignan et. al. 2015).

Articulatory rtMRI data was collected from four male native speakers of Cairene Arabic. The choice of male speakers for this study was made because, as shown in the review of relevant literature above, studies have reported that males produce stronger and more pharyngealization than females (Royal, 1985). Table 4.1 lists demographic information about the four participants in this study. The rtMRI data was collected during September 2016.

Table 4.1 Demographic information for participants in this study

Speaker	Age at the time of data collection	Years spent in Cairo	Hometown
SP1	26	8	Biala
SP2	26	25	Giza
SP4	28	25	Giza
SP5	26	26	Cairo

Data was also collected from a fifth speaker (SP3) but had to be discarded. The first speaker (SP1) did not produce the target words /azinn/ and /az^{ʕ}inn/.

Acquisition of the rtMRI data was conducted at the Beckman Institute for Advanced Science and Technology at the University of Illinois at Urbana-Champaign in the Biomedical Imaging Center. Prior to the acquisition, each participant was familiarized with the task of repeating the required test material described in detail in section 3.3 in their most native Cairene dialect. After training, the participant lies supine inside the Magnetom Trio 3T scanner and repeats the test materials for approximately 90 seconds (i.e. 1.5 minutes). The reconstruction algorithm identifies the regular changes that occur in the vocal tract, and by focusing on those specific changes, the algorithm is able to achieve high resolution.

Inside the scanner, the speaker's head is fitted with a head/neck coil and rests on a NoMoCo support system (NoMoCo Pillow, Inc., San Diego, CA). This is in order to reduce movement. As for the effect of posture on the dimensions of the upper airway, a previous study by Jan et. al. (1994) had found that pharyngeal cross-sectional areas slightly decrease when the speaker assumes a supine position. Measurements of the perimeter at the oropharyngeal junction drop from 1.65 +/- 0.6 cm to 1.31 +/- 0.07 cm. This suggests that the study of pharyngealization (and vocal dynamics in general) would be better suited to upright MRI technology. Given the limited availability of such scanners, speech imaging researchers have largely accepted this limitation. Furthermore, the speaker lies supine throughout the entire acquisition, and thus, it is reasonable to assume that the consequence of this posture will affect all the speech segments in the same manner. Thus, upon comparing the pharyngeal articulatory configuration in a given target word having a pharyngealized segment, with the pharyngeal articulatory configuration having the contrastive non-pharyngealized (plain) counterpart, the assumption is that the difference represents the effect of the pharyngealization, the object of this study. This is the case even if, initially, both articulatory configurations are influenced by the supine posture of the speaker.

During scans, the speaker also wears an MR-compatible headset with an attached optical noise-cancelling microphone (Dual Channel-FOMRI, Optoacoustics, Or Yehuda, Israel) to record simultaneous acoustic data. A noise cancellation method is applied to attenuate some of the background noise produced by the MR scanner during acquisition. This acoustic data is used to determine the start and end times of the individual speech sounds of interest in Praat (Boersma & Weenink, 2013).

The rtMRI method allows for the acquisition of several simultaneous views of the vocal tract, including views from the sagittal, lateral (transverse), and coronal planes, as well as planes at other oblique angles specified by the researcher. For the purpose of this study, only sagittal images were acquired. This plane provides a holistic view of the vocal tract, including the back pharyngeal and velopharyngeal regions, as well as the lingual contour in the oral cavity. Both the pharyngeal and the lingual configurations are implicated in the study of pharyngealization. The sagittal views were, more precisely, midsagittal views, i.e. a sagittal plane that passes through the middle of the head. This midsagittal plane was located after acquiring a three-dimensional scan of the head. Using this imaging volume, coronal and axial views were used to interactively place the sagittal slice at the prescribed location. Figure 4.1 shows an example of a midsagittal view acquired from SP1.

Figure 4.1: An illustration of a midsagittal view acquired from SP1.

4.2 Acoustic data acquisition

As mentioned in section 4.1 above, acoustic data is acquired while the speaker is inside the MRI scanner. This acoustic data is synchronized with the rtMRI articulatory data and is used to determine the MR images corresponding to the speech segments of interest. The MR scanner produces considerable background noise during acquisition. A noise cancellation method is applied to attenuate some of this background noise. The resulting acoustics are used to identify the start and end times of the speech segments. While formant frequencies are visible in these acoustics, the acoustics remain somewhat noisy. Additional (cleaner) acoustic data is collected in a sound-attenuated recording facility at the Phonetics and Phonology Lab at UIUC from the same four speakers. The speaker lies supine in the booth in a similar fashion as he did in the MRI scanner, to control for effects of gravity on the aperture of the pharynx, as discussed in section 4.1 above. An AKG C520 head-worn condenser microphone is positioned at the corner of the speaker's mouth, approximately 3 cm away to reduce the effects of turbulent airflow. Speech is recorded on a Marantz PMD570 recorder outside of the booth.

4.3 Test materials

To elicit natural speech, the speakers are required to repeat a sentence comprised of target words embedded in the carrier phrase of Cairene Arabic: /ʔallaha X alf marra/ ('He told her X one thousand times' where X is the target word). The carrier phrase is constructed such that the words immediately preceding and following the target item contain no posterior sounds (the vowel /a/ in the words preceding and following the target word is fronted in this context). This is to avoid any potential effect back vowels may have on the target word, minimizing the risk of postvelar harmony due to the tongue root retraction associated with a low back vowel. The target words are selected in order to allow for examining the following:

1) the role of the **quality** of the vowel in the amount of pharyngealization spread
2) the role of the **length** of the vowel in the amount of pharyngealization spread
3) the influence of rightward versus leftward spread of pharyngealization

The target words are real-word minimal pairs contrastive in the plain-pharyngealized consonants, and in which the vowels immediately adjacent to the plain-pharyngealized contrast are /a:, i:, u:/ and /a, i, u/. In most of the cases, the target words are monosyllabic, with the plain-pharyngealized contrasts occurring at the edge of the word (i.e. at the beginning of the word, or at the end of the word). Where it was not possible to find real monosyllabic minimal pairs, bisyllabic words were used. In these cases, the vowel in the other syllable was controlled to be /a/, except in one pair, in which the vowel was /u/. The plain-pharyngealized contrast in the bisyllabic words also occurred at the edge of the words. All target words used in this study are listed in Table 4.2 below.

The same target words were used during the acquisition of both the articulatory and the acoustic data. As mentioned in section 4.1 above, each speaker was asked to repeat the carrier phrase for a duration of 90 seconds. There were, naturally, different speaking rates for each speaker. Thus, a different number of repetitions was produced by each speaker for each target word. Thus, this study only included the first 20 valid repetitions from each speaker in order to ensure an equal amount of data from each speaker.

Table 4.2: Target words contrastive in a plain-pharyngealized consonant that occurs word-initially or word-finally. The adjacent vowels are long and short /a, i, u/.

condition	word-initial		condition	word-final	
#Ca:	/sˤa:b/	he hit [a target]	a:C#	/ba:sˤ/	bus
	/sa:b/	he let go		/ba:s/	he kissed
#Ci:	/sˤi:n/	China	i:C#	/bi:dˤ/	white (adjective, plural)
	/si:n/	The Arabic name of the letter /s/		/bi:d/	exterminate (imperative)
#Cu:	/tˤu:b/	stones	u:C#	/bu:zˤ/	rot/damage (imperative)
	/tu:b/	repent (imperative)		/bu:z/	muzzle
#Ca	/sˤabb/	he poured	#Ca	/basˤsˤ/	he looked
	/sabb/	he insulted		/bass/	enough!
#Ci:	/azˤinn/	I think	iC#	/fa:yidˤ/	remaining
	/azinn/	I whine		/fa:yid/	a town in Egypt
#Cu	/tˤubb/	come unexpected	uC#	/yuʕudˤdˤ/	he bites
	/tubʔa/	will become		/yuʕud/	he sits

4.4 Articulatory data analysis

The acoustic data that was acquired simultaneously with the articulatory rtMRI data was segmented in Praat (Boersma & Weenink, 2013). The segmentation was based on visual inspection of the waveforms and the wide-band spectrograms associated with them, as well as on auditory inspection of the acoustics. From every repetition of each target word, three segments were identified: C1, V, C2. The plain-pharyngealized contrast was either C1 or C2. Accordingly, the start and end times of these segments were extracted. Figure 4.2 shows an example of this segmentation.

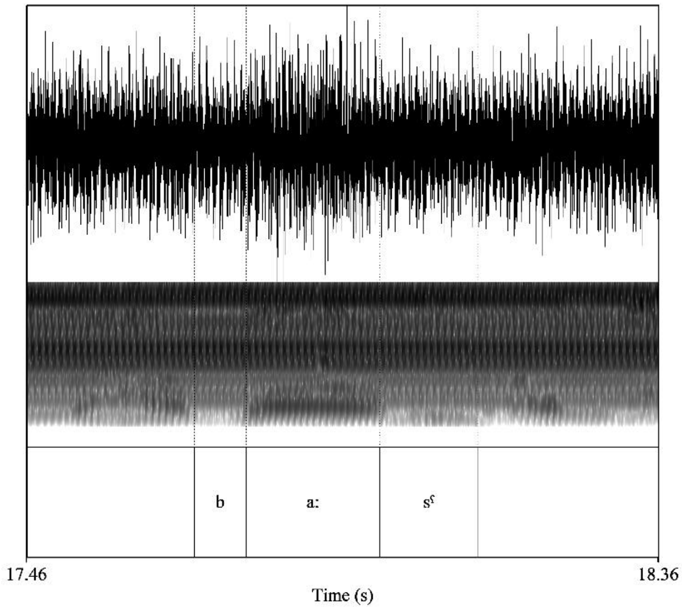


Figure 4.2: Segmentation of the target word /ba:sˤ/ (bus) extracted from the phrase /ʔallaha ba:sˤ alf marra/ (He told her bus one thousand times). This acoustic data is acquired inside the MR scanner

A Matlab (R2015a) script was written to identify the MRI frames corresponding to the segmented speech sounds based on the start and end times. The middle frame within this sequence was selected because it corresponds to the temporal midpoint of the speech sound and can therefore be a good representative of the shape of the vocal tract during that speech sound.

After identifying MRI frames of interest, a Matlab interface developed by Proctor et. al. (Proctor et. al., 2015; Narayanan et. al., 2014; and Israel et. al., 2012)[4] was used to automatically detect the contours of the vocal tract from the glottis to the lips in those frames. In this application, the interface of which is shown in Figure 4.3, the user is presented with an MR image and manually

[4] Downloaded from: http://mproctor.net/software.html

clicks on four anatomical landmarks: the glottis, the highest point on the palate, a point on the alveolar ridge, and a point midway (vertically) between both lips.

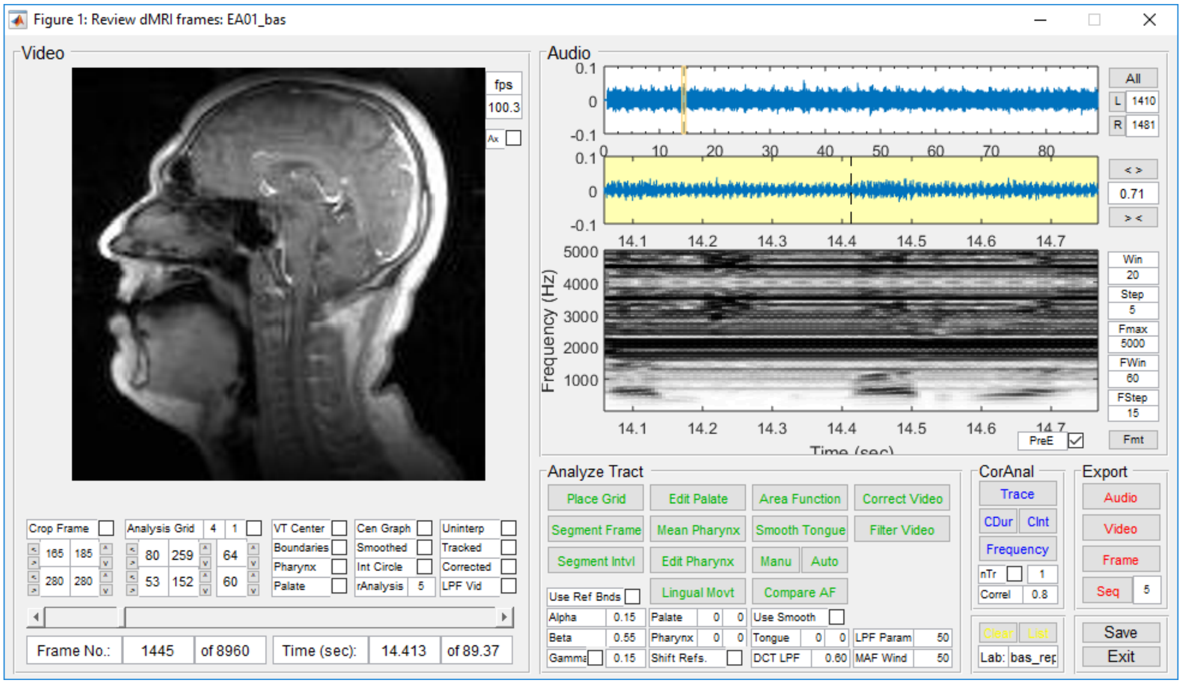


Figure 4.3: The Matlab interface developed by Proctor et. al. (Proctor et. al., 2015; Narayanan et. al., 2014; and Israel et. al., 2012). The user will manually click on the MRI frame on the left to identify the required anatomical landmarks. The MRI frame is an arbitrarily selected frame from the first speaker (SP1).

The xy-coordinates of these landmarks are registered, and tract-normal semi-polar gridlines (orthogonal to the midline of the vocal tract) are generated from the lips to the glottis. Based on changes in pixel intensity, tissue boundaries along the vocal tract are detected. These include the contours of the palate, the back pharyngeal wall, the tongue root (forming the anterior pharyngeal wall), and the contour of the tongue body as shown in Figure 4.4. These contours provide information about the pharyngeal configuration, as well as the lingual oral configuration.

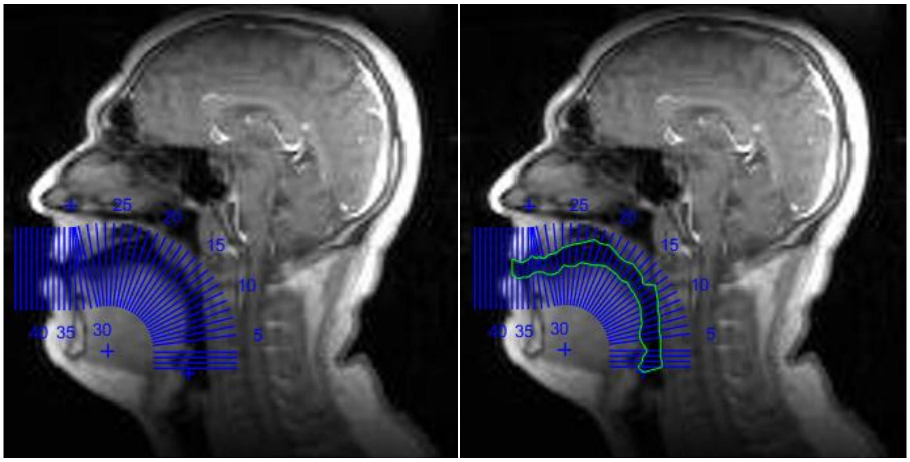


Figure 4.4: a. (left) Semi-polar gridlines superimposed on an arbitrarily selected MRI frame from SP1 running from the lips to the glottis. b. (right) Automatically-detected vocal tract contours in the same MRI frame in a.

Results from the edge detection method implemented are dependent on the visual quality of the MRI image. Specifically, it is dependent on the contrast between the vocal contours and the (black) vacuum in the vocal tract. If this contrast is clear and sharp, the algorithm is able to identify the edge well. Thus, the first step in using this application involves selecting two scalars that determine the brightness and contrast in the MR image. After several trials, the scalar values of 1.0 and 1.5 were used, because they appeared to yield the best contrast and therefore the best detection of the lingual contours. Some of the trials are presented in Figure 4.6. The edge detection is conducted on the same arbitrarily-selected frame for the same speaker (frame 868, SP5). The trials shown in Figure 4.6 vary scalar 1 from 0.1 – 1.0, and scalar 2 from 2.0 – 3.0. The result from the trial with scalar values that were ultimately selected (1.0 and 1.5) is presented in Figure 4.5. These same two scalar values were applied to all the data for every speaker.

The application allows the user to manually modify the results that the edge-detection method automatically yields, i.e., it is possible to adjust the vocal tract contours that are automatically detected. However, manual adjustments were avoided here for the obvious reasons that manual adjustment is subjective, and hence not reproducible. It was thus decided to avoid any manual intervention and work with the results that the automatic detection method produced. As there are several repetitions of each segment of interest, the assumption is that the effect of a possible detection error in one repetition will be will be attenuated, and possibly cancelled out, in averages across all the repetitions.

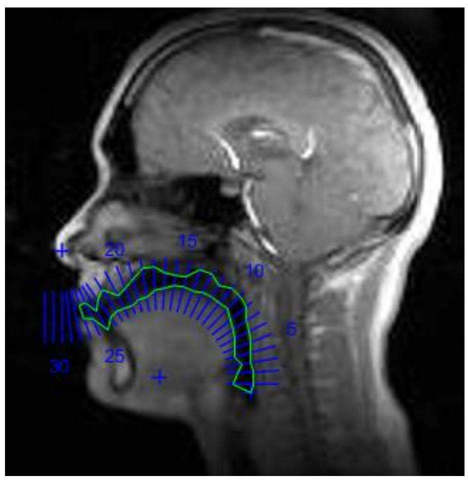


Figure 4.5: Result of the automatic edge-detection method conducted on the arbitrarily-selected MRI frame 868 from SP5 with scalar values 1.0 and 1.5.

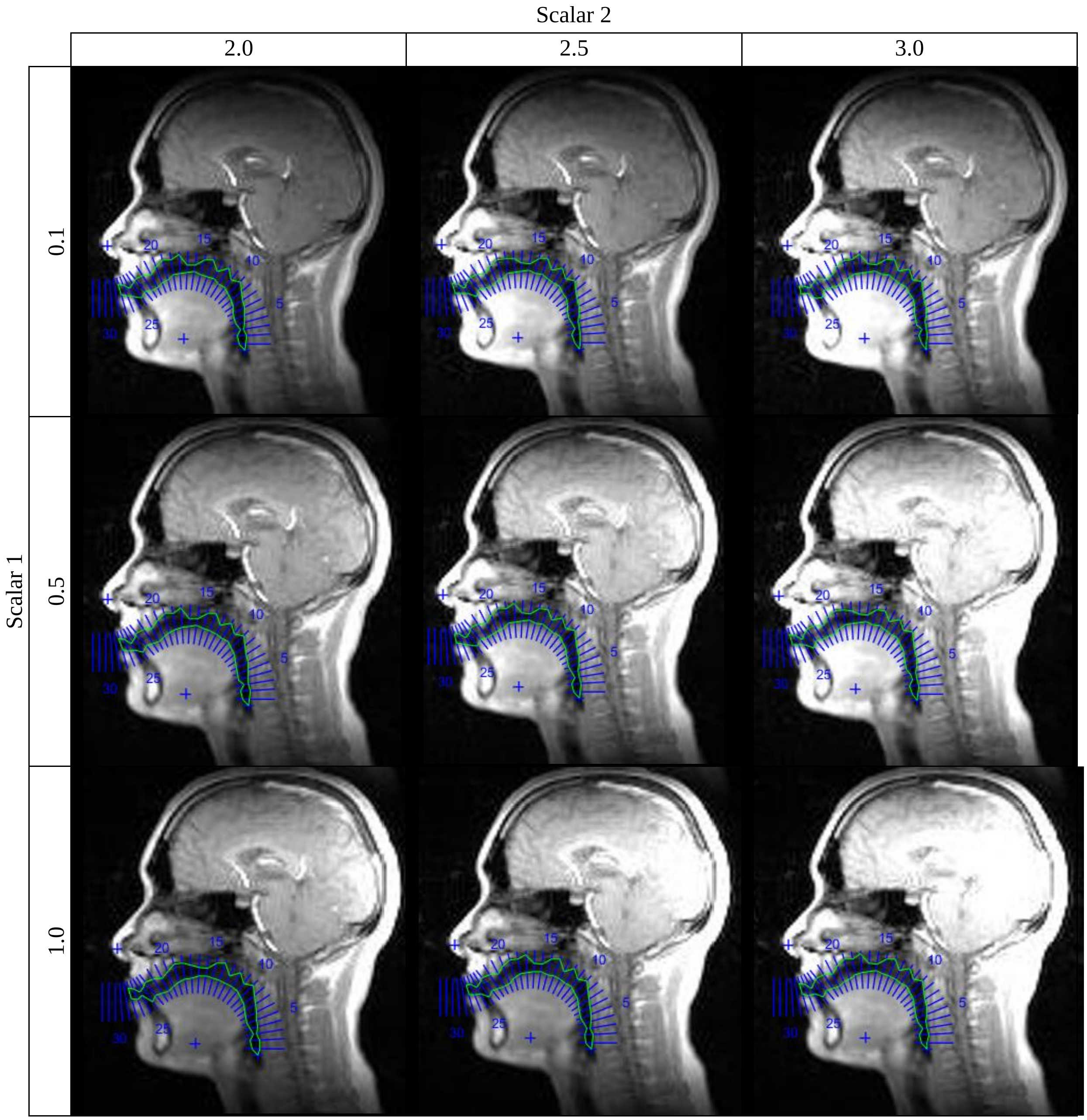


Figure 4.6: Results from the automatic edge-detection conducted on the arbitrarily-selected MRI frame 868 from SP5. The scalar values vary.

The lingual and pharyngeal contours for every sound of interest in every repetition of the target words were extracted and plotted. An example of this from SP5 is shown in Figure 4.7. The contours were then smoothed and averaged. The same example after smoothing and averaging is shown in Figure 4.8. Superimposing the contours of a plain-pharyngealized minimal pair, allows for visual comparison of the vocal configuration during both speech sounds.

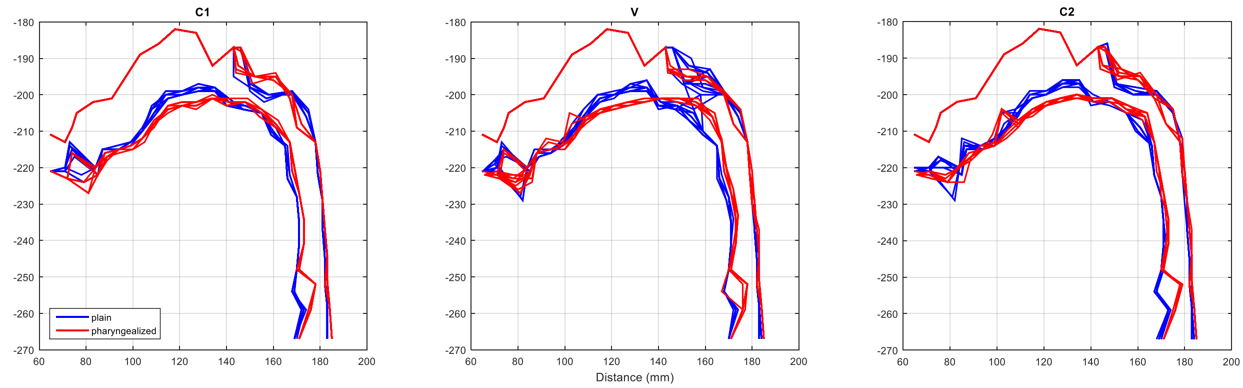


Figure 4.7: The pharyngeal and lingual contours automatically detected for the 20 repetitions of the target words /sa:b/ in blue (‘he left’) and /sˤa:b/ in red (‘he hit’) from SP5.

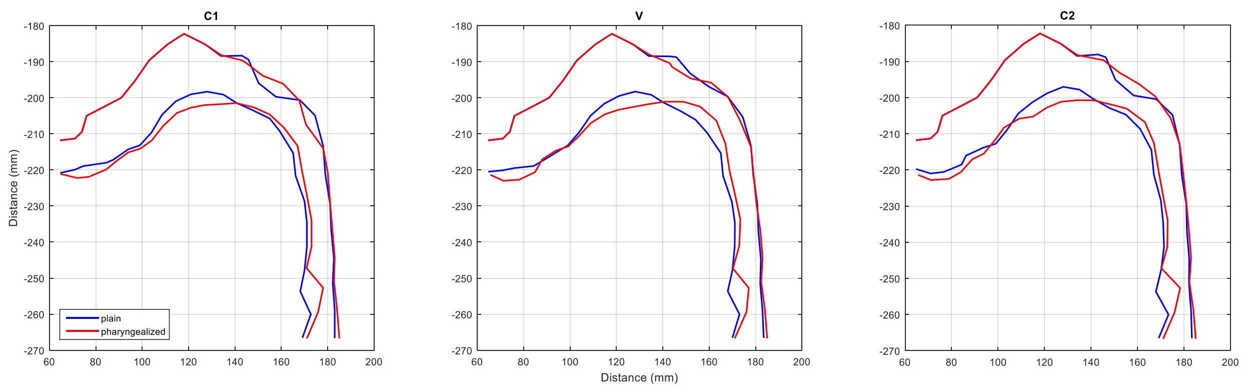


Figure 4.8: The smoothed pharyngeal and lingual contours averaged from the 20 repetitions of the target words /sa:b/ in blue (‘he left’) and /sˤa:b/ in red (‘he hit’) from SP5. Smoothing was performed using a Savitzky-Golay filter.

In this Figure 4.8 above, the vocal tract configuration is plotted for both the “pharyngealized word”, i.e. the word containing the pharyngealized speech sound, and the “plain word”, i.e. its plain contrastive counterpart. The two words are minimal pairs contrastive in the plain-pharyngealized consonant. In this example, the words that are plotted are /sa:b/ and /sˤa:b/. The first panel from the left is a plot of the vocal tract configuration corresponding to the midconsonantal /sˤ/ extracted from the pharyngealized word and the midconsonantal /s/ extracted from the plain word. In that panel, the red contours correspond to the vocal tract configuration of pharyngealized segment, while the blue contours correspond to the vocal tract configuration of the plain segment. Thus, it is possible to compare the vocal tract configurations during both members of the minimal pair. The middle panel is a similar plot of the /a:/ vowel. The vocal tract configuration corresponding to the middle of the /a:/ vowel extracted from the pharyngealized word is plotted in red, while that corresponding to the /a:/ vowel extracted from plain word is plotted in blue. The third panel on the right is a similar plot of the midconsonantal plot of the /b/ extracted from the pharyngealized word in red and a plot of the /b/ extracted from the plain word in blue. These plots are useful for the following:

1) With these plots, it is possible to observe the change of the vocal tract configuration with respect to time during the articulation of one word. Thus, this method allows us to observe pharyngealization spread and examine the magnitude of this spread and its direction.
2) It is also possible to visually compare the vocal tract configurations of the two words.

The averaging and smoothing in Figure 4.8 above is done in order to correct for any potential errors in the edge-detection or any noise in the image. The smoothing is done using a Savitzky-Golay filter. Using an unweighted linear least-squares regression and a second-degree polynomial model to compute coefficients, this filter produces a moving average for a given contour (Savitzky and Golay, 1964). For the averaged and smoothed contours in Figure 4.8, ±95% confidence intervals are calculated and plotted in Figure 4.9. At the non-overlapping confidence intervals of the contours, it can be asserted with 95% confidence that the differences in vocal tract constrictions are statistically significance. Figure 4.10 shows the same plots in Figure 4.9, but with shaded confidence intervals.

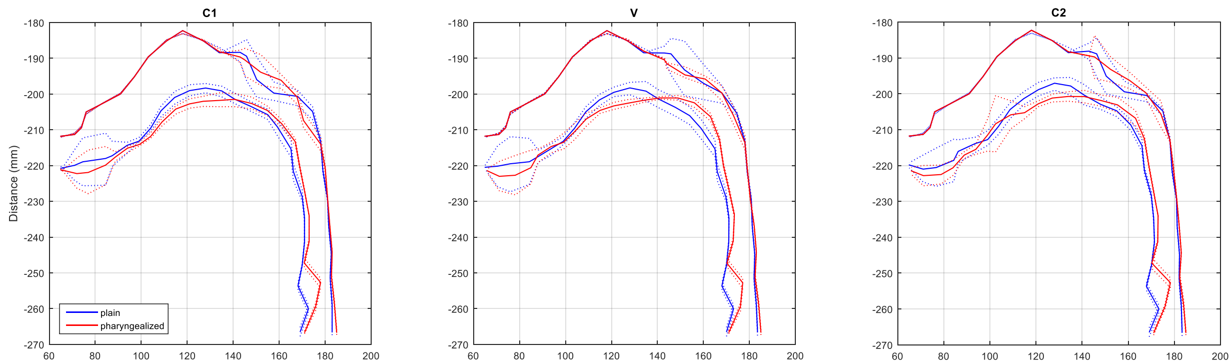


Figure 4.9: Averaged and smoothed pharyngeal and lingual contours with ±95% confidence intervals. Contours are extracted from the three speech sounds in target words /sa:b/ in blue (‘he left’) and /s^{ʕ}a:b/ in red (‘he hit’) from SP5.

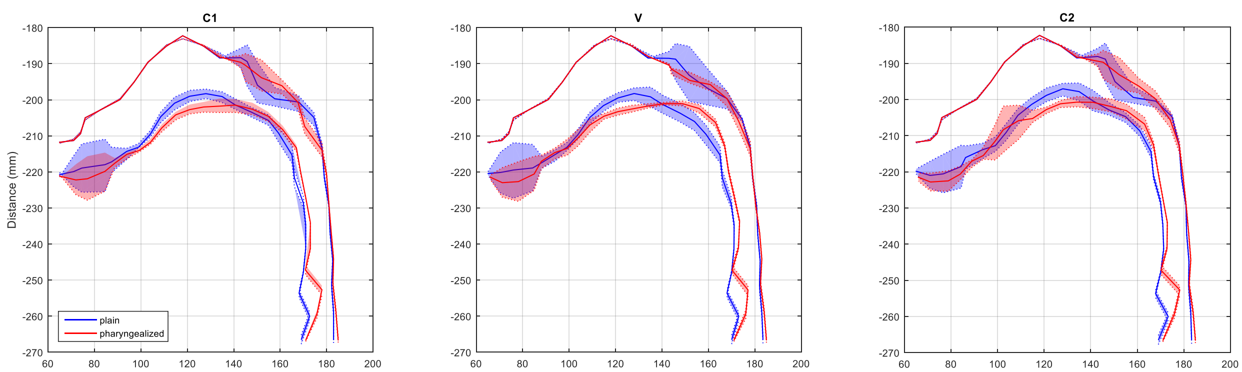


Figure 4.10: Same plots in Figure 4.9 with shaded confidence intervals. Averaged and smoothed pharyngeal and lingual contours with ±95% shaded confidence intervals. Contours are extracted from the three speech sounds in target words /sa:b/ in blue (‘he left’) and /s^{ʕ}a:b/ in red (‘he hit’) from SP5.

In order to quantify the difference between vocal tract configurations, two-dimensional vocal tract areas are defined and computed. Two measures are proposed: the oral cavity/area and the pharyngeal area.

1) The two-dimensional pharyngeal area (2D pharyngeal area) is defined as the two-dimensional area between the glottis and the end of the soft palate. This includes the pharynx.
2) The two-dimensional oral cavity (2D oral area) is defined as the two-dimensional area between the lips and the end of the soft palate. This includes the oral cavity and the velopharyngeal region.

Figure 4.11 below illustrates these two measures. In the MRI frame on the left, the gridline roughly corresponding to the end of the soft palate is demarcated in yellow. This line is thus orthogonal to the midline of the vocal tract. In the plot on the right, the vocal tract contours are extracted, and the two areas are shown. The 2D oral area is highlighted in magenta and the 2D pharyngeal area is highlighted in green. The dividing between the two areas corresponds to the yellow gridline in the image on the left.

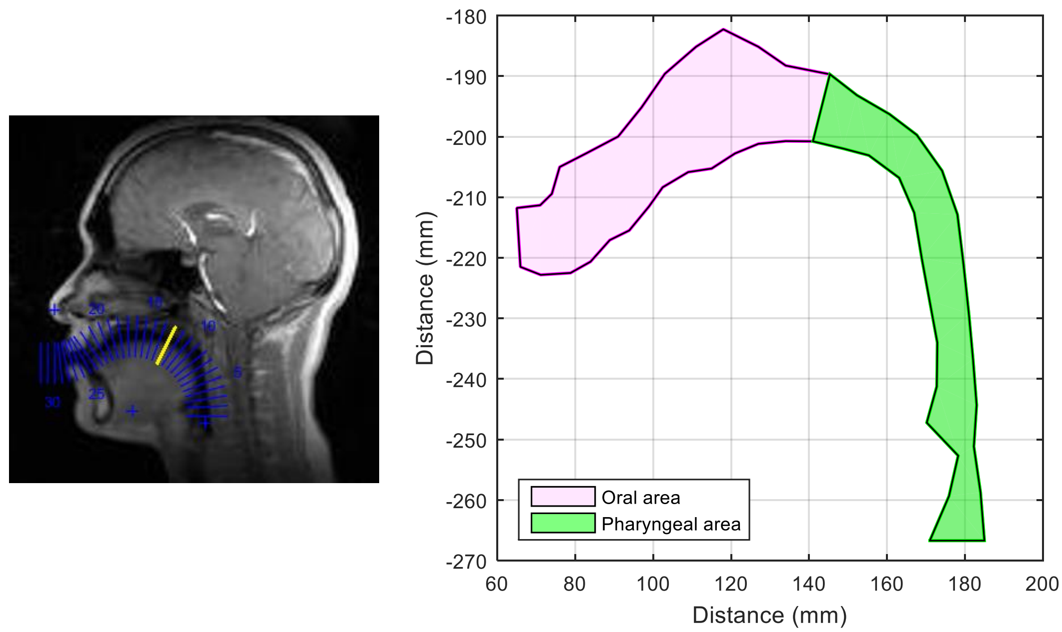


Figure 4.11: a. (left): The gridline in yellow roughly corresponding to the end of the soft palate. b. (right): An illustration of the 2D oral area in magenta and the 2D pharyngeal area in green. The dividing line between the two areas corresponds to the yellow gridline in a.

The 2D pharyngeal area allows for quantifying the pharyngeal constrictions. This measure captures the 2D change in the configuration of the pharynx, both in the upper regions and lower regions, because it is observed that the constriction resulting from pharyngealization, rather than being localized at a specific point, has the effect of narrowing an extensive part of the pharynx. Similarly, the 2D oral area allows for quantifying the oral cavity. Pharyngealization can cause enlargement of the oral cavity as a result of the depression of the tongue's palatine dorsum, or as a result of the concavity of the tongue body. Thus, this measure captures and quantifies both phenomenon. Both 2D area measure are used heuristically only; they do not have the same value as the area function, which could be used to synthesize the vocal tract acoustics.

4.5 Acoustic data analysis

The acoustic data analysis is conducted on the "clean" acoustic acquired in the sound-attenuating booth in the Phonetics and Phonology Lab. Each speaker produced seven repetitions of the test materials described in section 4.3. This acoustic data was also segmented in Praat (Boersma & Weenink, 2013). The analysis is conducted on the vowels in the target words, thus only the V segment was identified in the data. In this "clean" data, the start and end of the vowel is marked from the start of the second and third formant frequencies until the end of these formants in the spectrogram. Figure 4.12 shows an example of the segmentation from a target word produced by SP4. The target word is /ba:s^ʕ/. The figure shows the segmentation of the vowel /a:/.

The duration and formant frequencies are measured for all vowels using FormantPro, a Praat script developed by Yi Xu (2007-2015)[5]. In addition to vowel durations, with this application the mean F1 and F2 values were extracted for each vowel. Mean F1 and F2 are defined as the average formant value throughout the duration of a vowel. This application also measures twenty equidistant values of the formant frequencies throughout the entire duration of the vowel. Thus, these are time-normalized formant measures. Time normalization allows for visual examination of the point of maximum and minimum value. Furthermore, with these equidistant time-normalized measures, SSANOVA curves can be plotted to graphically compare the behavior of the formant frequencies.

[5] Downloaded from: http://www.homepages.ucl.ac.uk/~uclyyix/FormantPro/.

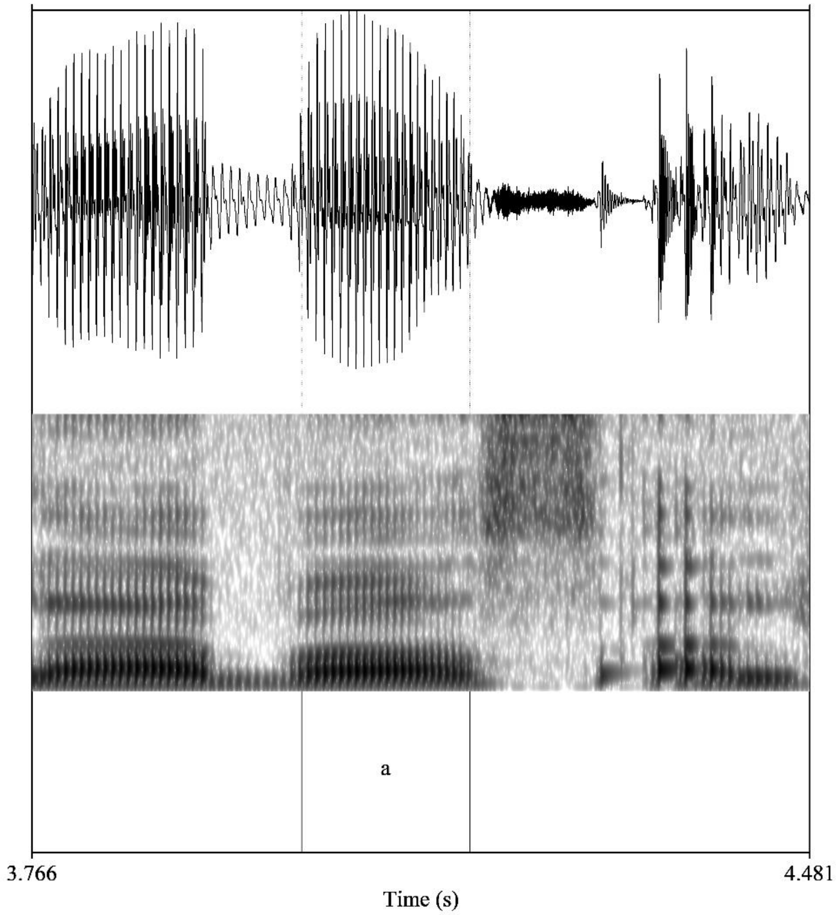


Figure 4.12: Segmentation of the vowel /a:/ within the target word /ba:sˤ/ (‘bus’) as produced by SP4.

Chapter 5: Results

5.1 Results from articulatory data

Analyzing the lingual and pharyngeal contours for all four speakers reveal the following general observations:

1) The pharyngealized consonant is produced with a more constricted pharynx than its plain counterpart. This is the general trend, regardless of the vowel environment in which the plain-pharyngealized contrast occurs and regardless of the vowel length. This is also the general trend, regardless of whether the plain-pharyngealized contrast occurs at the end of the word (or in the coda position within a syllable), or at the beginning of the word (or in the onset position within a syllable). Furthermore, the constriction of the pharynx is not restricted to one specific point in the pharynx; instead, it extends throughout the pharynx. Additionally, a lowered tongue body is sometimes observed in the pharyngealized consonant when compared to its plain counterpart. This observation is evident visually from tongue contours plots. Quantitatively, as described in section 4.4 the constricted pharynx and the lowered tongue body (enlarged oral cavity) are captured with two measures: the 2D pharyngeal and oral areas respectively.
2) Within the same word containing the pharyngealized consonant, the other speech segments are produced with a generally more constricted pharynx and a lowered tongue body, compared with their counterparts in the word containing the plain consonant. This is generally the case, regardless of the vowel quality and the vowel length, and regardless of where the plain-pharyngealized contrast occurs. This is evident from tongue contour plots and 2D area box plots. This is indicative of the pharyngealization spread in both directions.

3) Speech segments preceding the pharyngealized consonants are generally more constricted than those following the pharyngealized consonant. This suggests that anticipatory (leftward) spread is greater in magnitude than perseveratory (rightward) spread.

4) Among two minimal pairs containing the same pharyngealized consonant but differing in vowel length, the 2D pharyngeal areas are generally smaller in the speech segments of the word containing the longer vowel. This is evident in the vocal tract contour plots, and suggests that the pharynx is more constricted, and thus that the effect of pharyngealization is stronger when there is a longer vowel.

5) To examine and compare the effect of pharyngealization as a function of the quality of the vowel, we look at the difference in the 2D areas between the pharyngealized and plain members. It is found that the magnitude of this difference is generally greatest when the vowel is /a/ and is generally the least when the vowel is /u/. This suggests that the effect induced by pharyngealization is generally greatest in an /a/ context, followed by an /i/ context, and it is the least in an /u/ context.

In the following are examples from some of the results demonstrating each of these points. All the results from all speakers are listed in the Appendix.

Figure 5.1 shows examples of the articulatory configuration during /s/ and /s^{ʕ}/ as produced by SP5. In the plot on the left, the two sounds are extracted from the target words /sa:b/ (‘he left’) and /s^{ʕ}a:b/ (‘he hit’) respectively. In the plot on the right, the two sounds are extracted from the target words /ba:s/ (‘he kissed’) and /ba:s^{ʕ}/ (‘bus’). Both plots visually illustrate the three observations described above in point 1) as follows:

- A more constricted pharynx is observed in the pharyngealized member (in red) when compared against the plain member (in blue).
- The constriction extends along the pharyngeal region and is not localized to specific point or articulation.
- The tongue body is lower in the pharyngealized member when compared against the plain member.
- These observations occur when the plain-pharyngealized contrast is at the beginning of the word (in the onset position), and when the plain-pharyngealized contrast is at the end of the word (in coda position).

Point 1) above also mentions vowel length and vowel quality. These factors will be discussed in detail later in this chapter.

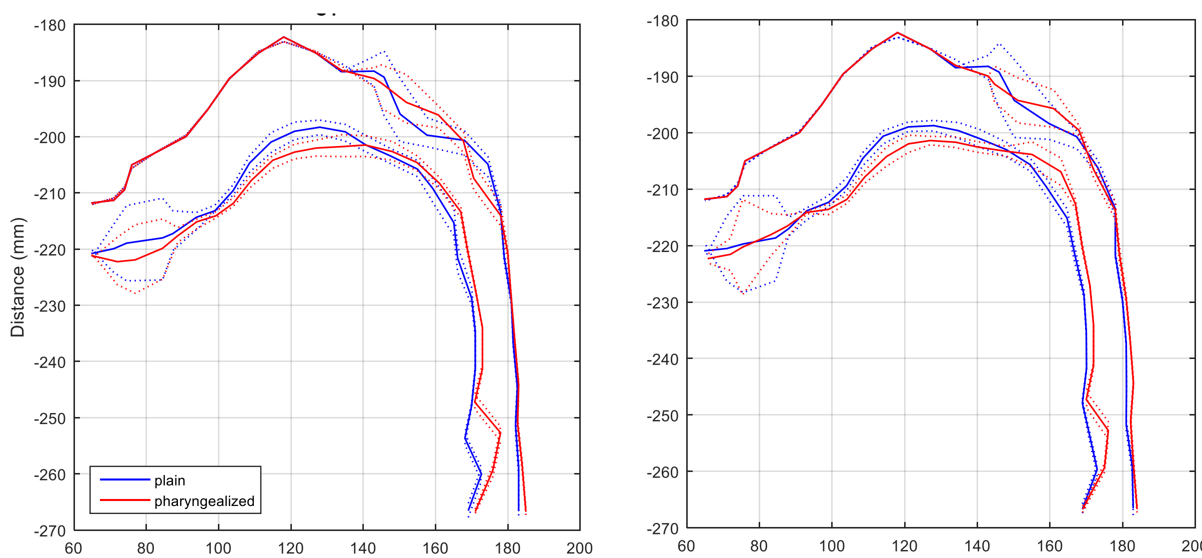


Figure 5.1: a. (left) Vocal tract contours of pharyngealized /sˤ/ and plain /s/ extracted from /sˤa:b/ ('he hit') and /sa:b/ ('he left') as produced by SP5. b. (right) Vocal tract contours of pharyngealized /sˤ/ and plain /s/ extracted from /ba:sˤ/ ('bus') and /ba:s/ ('he kissed') as produced by SP5.

Figure 5.2 shows box plots of the 2D pharyngeal and oral areas during plain /s/ and pharyngealized /sˤ/ in /sa:b/ (‘he left’) and /sˤa:b/ (‘he hit’) respectively as produced by SP5. The plot on the left shows the 2D pharyngeal areas. It is clear that the average 2D pharyngeal area is smaller in the pharyngealized member than in the plain counterpart. The plot on the right shows the 2D oral areas. Here, the average 2D oral area is larger in the pharyngealized member than in the plain counterpart.

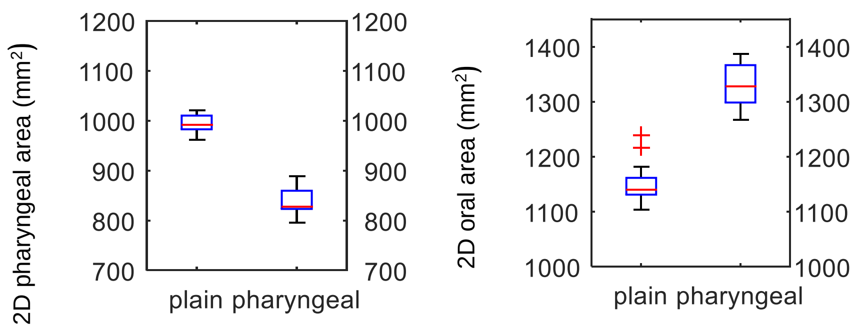


Figure 5.2: a. (left) 2D pharyngeal areas in (mm^2) during plain /s/ and pharyngealized /sˤ/ extracted from /sa:b/ (‘he left’) and /sˤa:b/ (‘he hit’) as produced by SP5. b. (right) 2D oral areas in (mm^2) during plain /s/ and pharyngealized /sˤ/ extracted from /sa:b/ (‘he left’) and /sˤa:b/ (‘he hit’) as produced by SP5

Figure 5.3 shows the same two plots of the 2D pharyngeal and oral areas for the same two speech sounds (plain /s/ and pharyngealized /sˤ/) but occurring at the end of the word in /ba:s/ (‘he kissed’) and /ba:sˤ/ (‘bus’) respectively. The plots are from speaker SP5, as well. The same patterns described above are observed here: a smaller 2D pharyngeal area in the pharyngealized member when compared against the plain counterpart, and a larger 2D oral area in the pharyngealized member when compared against the plain member.

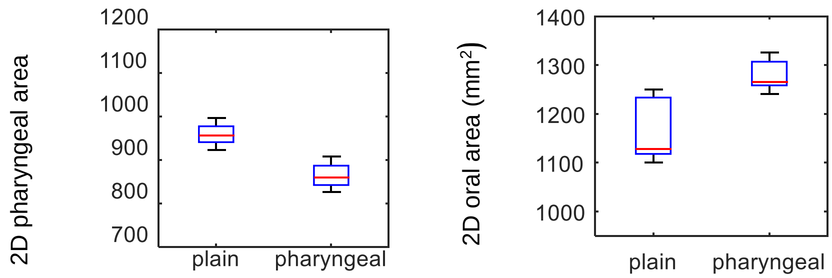


Figure 5.3: a. (left) 2D pharyngeal areas in (mm^2) during plain /s/ and pharyngealized /sˁ/ extracted from /ba:s/ (‘he kissed’) and /ba:sˁ/ (‘bus’) as produced by SP5. b. (right) 2D oral areas in (mm^2) during plain /s/ and pharyngealized /sˁ/ extracted from /ba:s/ (‘he kissed’) and /ba:sˁ/ (‘bus’) as produced by SP5.

The second result described above is illustrated in Figure 5.4 and Figure 5.5 below. Figure 5.4 shows vocal tract contours during SP5’s production of /sa:b/ and /sˁa:b/. The figure shows a generally more constricted pharynx in all the panels for the segments extracted from the pharyngealized /sˁa:b/. The figure also shows a lowered tongue in these segments. This thus indicates a rightward spread of pharyngealization.

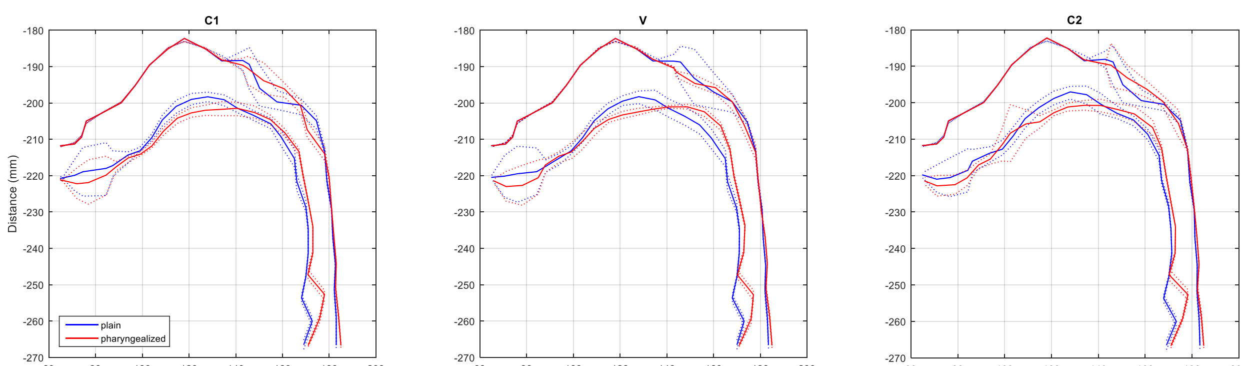


Figure 5.4: An illustration of rightward pharyngealization spread from SP5. Blue contours represent vocal tract configurations in segments from /sa:b/. Red contours represent vocal tract configuration in segments from /sˁa:b/.

Figure 5.5, in contrast, illustrates leftward spread of pharyngealization. The three panels show the articulatory configuration of the three segments extracted from /ba:s/ in blue, and /ba:sˤ/ in red. Throughout the three panels, a more constricted pharynx and a lowered tongue is evident in the pharyngealized members.

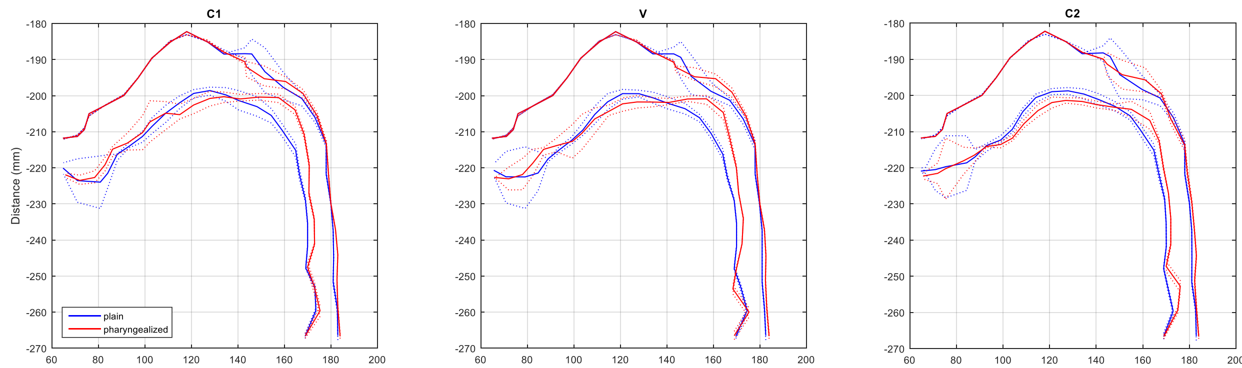


Figure 5.5: An illustration of rightward pharyngealization spread from SP5. Blue contours represent vocal tract configurations in segments from /ba:s/. Red contours represent vocal tract configuration in segments from /ba:sˤ/.

Box plots in Figure 5.6 and Figure 5.7 show the 2D pharyngeal and oral areas, respectively, measured in the three segments of /sa:b/ and /sˤa:b/ shown in the panels of Figure 5.4 above. In Figure 5.6, the 2D pharyngeal areas in the pharyngealized member are smaller than in the plain member. This is the case in all three segments. Similarly, in Figure 5.7, the oral 2D areas in the pharyngealized member are larger than in the plain member in all three segments.

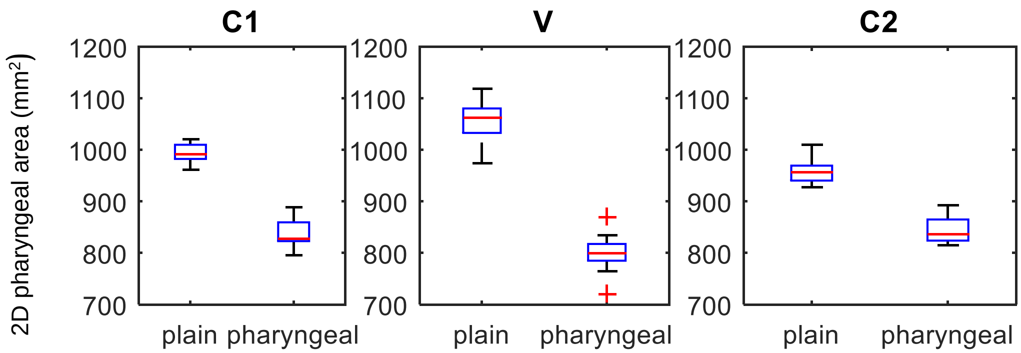


Figure 5.6: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /sa:b/ and /sˤa:b/ segments as produced by SP5

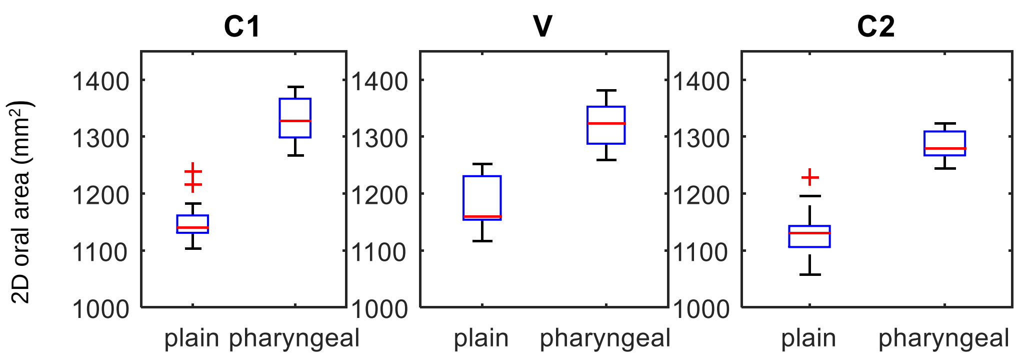


Figure 5.7: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /sa:b/ and /sˤa:b/ segments as produced by SP5

Similar box plots for the 2D areas of the segments in /ba:s/ and /ba:sˤ/ shown in the panels of Figure 5.5 above are plotted in Figure 5.8 and Figure 5.9 below. The same general trend is observed in Figure 5.8. The 2D pharyngeal areas are smaller in the pharyngealized members in the three segments. Figure 5.9 plots the 2D oral areas and shows larger oral areas in the pharyngealized segments in the V and the C2 panel, but not the C1 panel (representing the plain and pharyngealized /b/ segments).

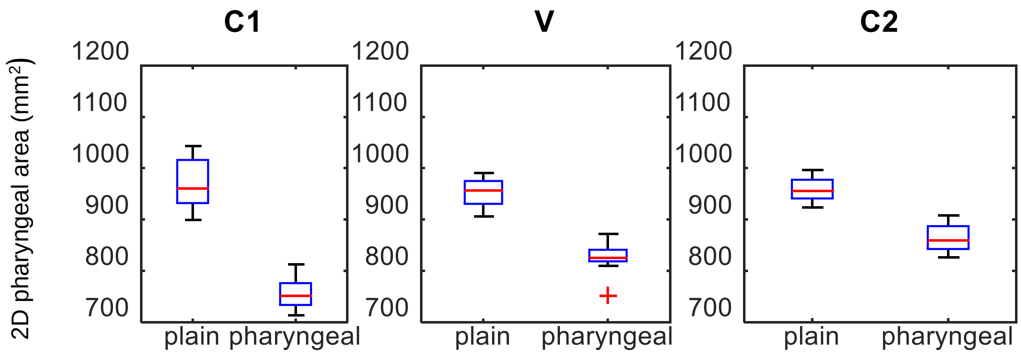


Figure 5.8: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /ba:s/ and /ba:sˤ/ segments as produced by SP5

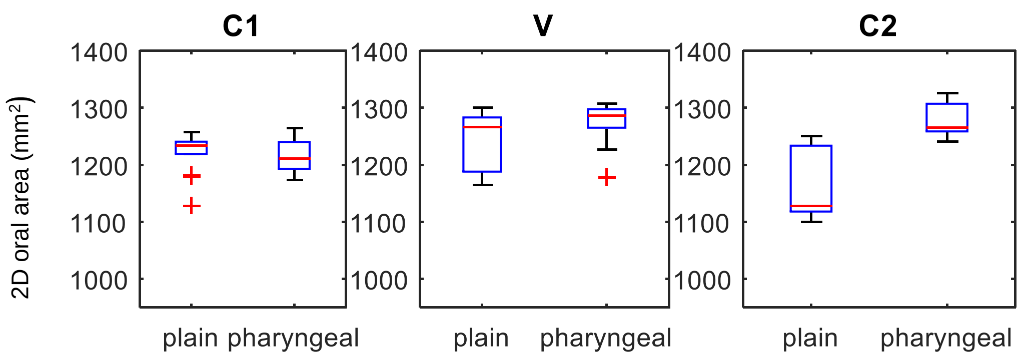


Figure 5.9: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /ba:s/ and /ba:sˤ/ segments as produced by SP5

Referring back to Figure 5.5 which illustrates the vocal tract contours for /ba:s/ and /ba:sˤ/, and looking at the leftmost panel corresponding to the /b/ segment, it is clear that the tongue body is indeed lower in the pharyngealized member. The oral 2D area, as described in section 4.4, is computed by measuring the area from the grid line corresponding to the lips up until the gridline corresponding to the end of the palate. The blue contour for the plain member appears slightly below the red contour for the pharyngealized member close to the lip region, and perhaps this is why the average 2D oral area is larger for the plain member than for the pharyngealized member.

This situation also occurs with other speakers and in other target words, as can be seen in the data in the Appendix (See Figure A.118 - Figure A.149 in the Appendix). Thus, a comparison of the 2D oral areas between the pharyngealized and plain members alone does not accurately capture the lowered tongue body in the pharyngealized member. It is thus important to evaluate the two 2D area measures together with the contours and not independently.

The more constricted pharynx is a trend that is generally observed regardless of vowel quality across the four speakers. The lowered tongue body however, for some speakers, is observed in some vowels, but not in others. Figure 5.10 - Figure 5.13 below show examples in which both the constricted pharynx and lowered tongue body occur in different vowel environments. The figures come from the four participants in this study. Figure 5.10 shows the vocal tract configuration during /si:n/ (the letter ‘s’ in Arabic) and /sˤi:n/ (‘China’) as produced by SP5. Figure 5.11 shows the configurations during /bi:d/ (‘exterminate’) and /bi:dˤ/ (‘white’) as produced by SP1. Figure 5.12 shows the configurations during /tu:b/ (‘repent’) and /tˤu:b/ (‘stones’) as produced by SP4. Finally, Figure 5.13 shows the configurations during /bu:z/ (‘muzzle’) and /bu:zˤ/ (‘rot’) as produced by SP2.

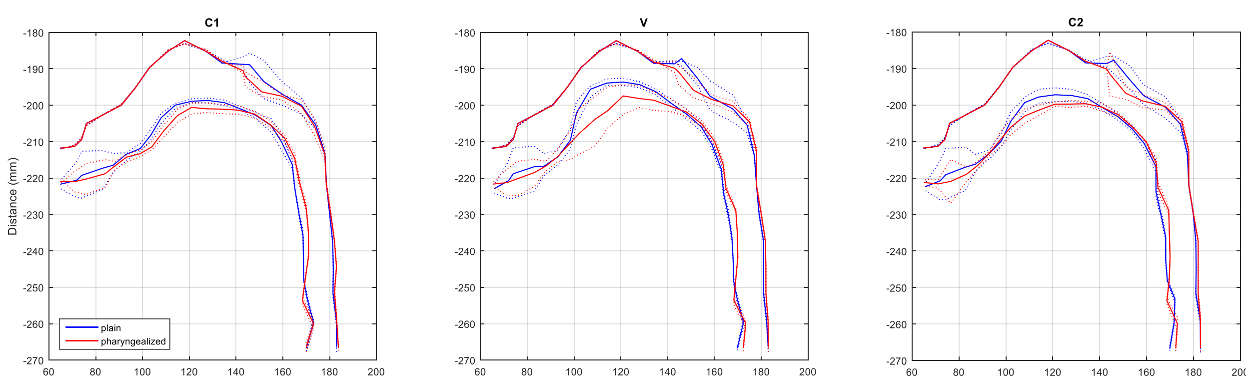


Figure 5.10: The vocal tract configurations during /si:n/ (the letter ‘s’ in Arabic) in red and /sˤi:n/ (‘China’) in blue as produced by SP5

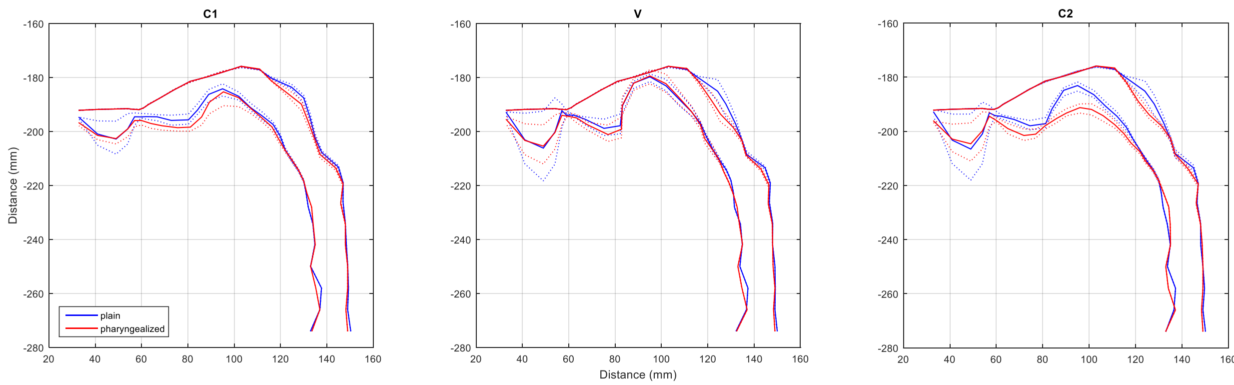


Figure 5.11: The vocal tract configurations during /bi:d/ (‘exterminate’) in blue and /bi:d$^{\varsigma}$/ (‘white’) in red as produced by SP1

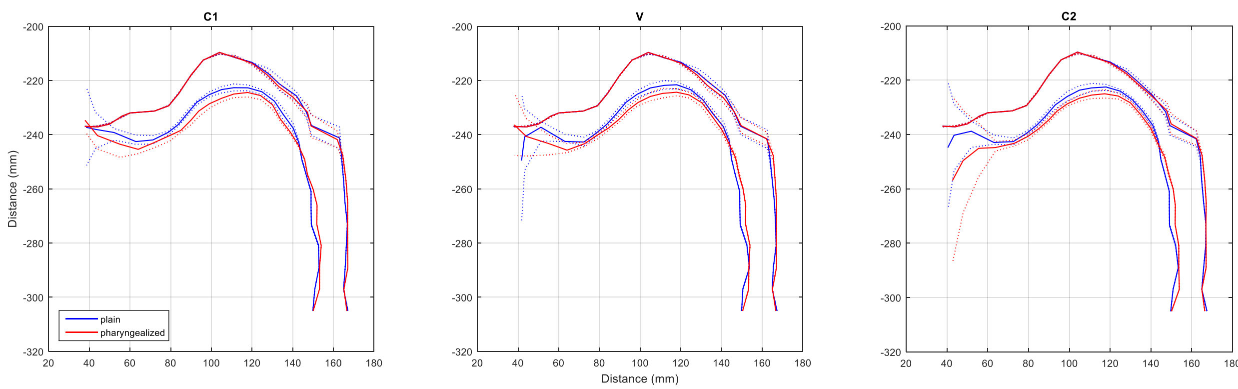


Figure 5.12: The vocal tract configurations during /tu:b/ (‘repent’) in blue and /t$^{\varsigma}$u:b/ (‘stones’) in red as produced by SP4

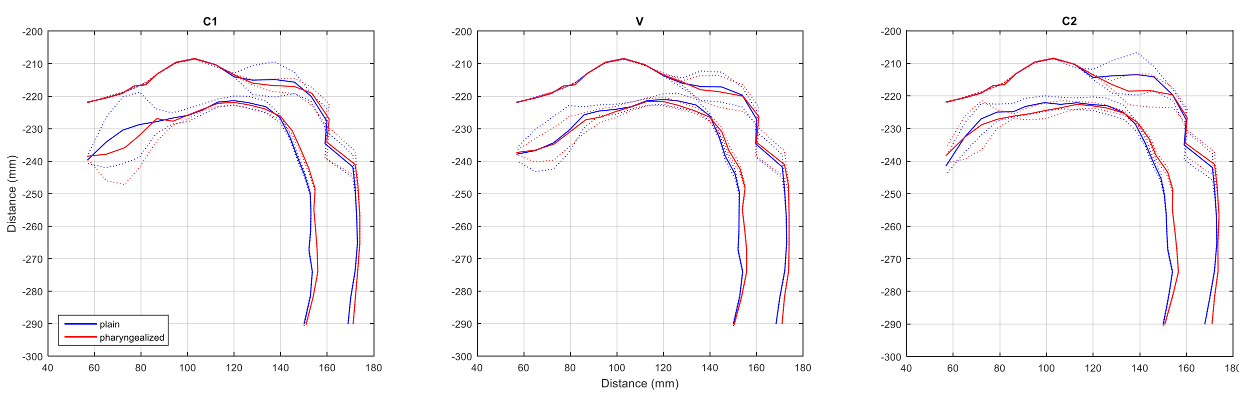


Figure 5.13: The vocal tract configurations during /bu:z/ (‘muzzle’) in blue and /bu:z$^{\varsigma}$/ (‘rot’) in red as produced by SP2

The box plots depicting the 2D oral and pharyngeal areas for Figure 5.10 - Figure 5.13 above are shown below in Figure 5.14 - Figure 5.17.

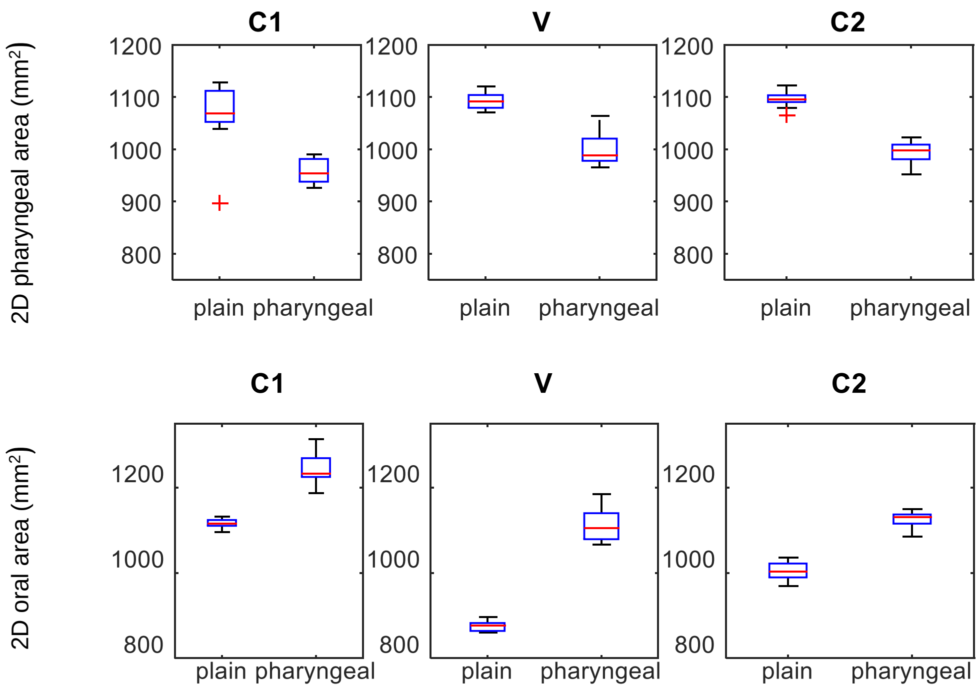


Figure 5.14: 2D pharyngeal areas (top) and 2D oral areas (bottom) in (mm^2) for the C1, V, and C2 segments in /si:n/ (the letter ‘s’ in Arabic) and /sˤi:n/ (‘China’) as produced by SP5

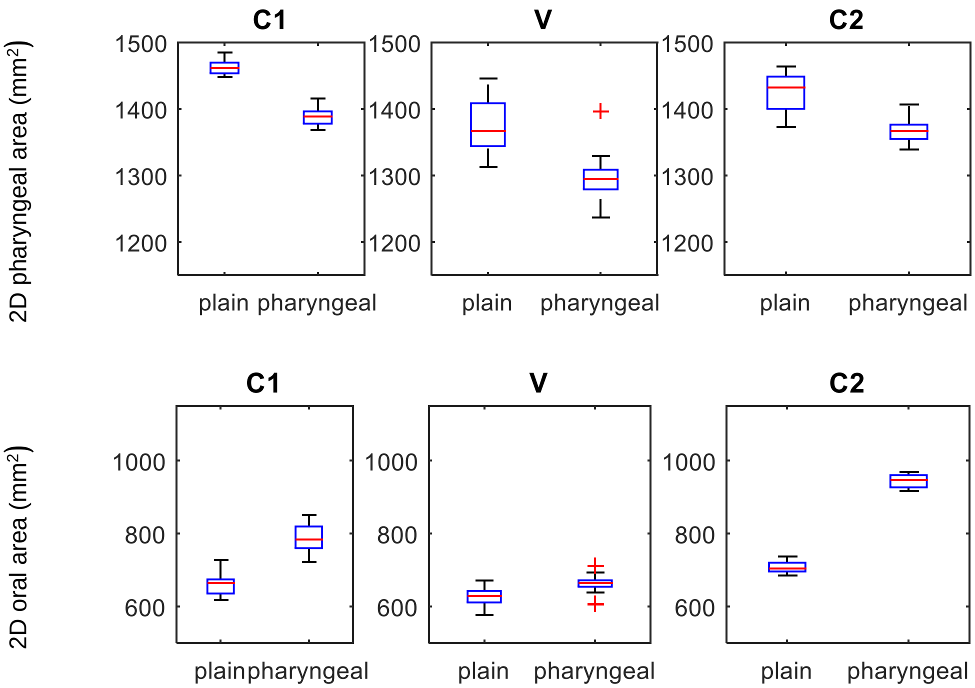


Figure 5.15: 2D pharyngeal areas (top) and 2D oral areas (bottom) in (mm^2) for the C1, V, and C2 segments in /bi:d/ ('exterminate') and /bi:dˤ/ ('white') as produced by SP1

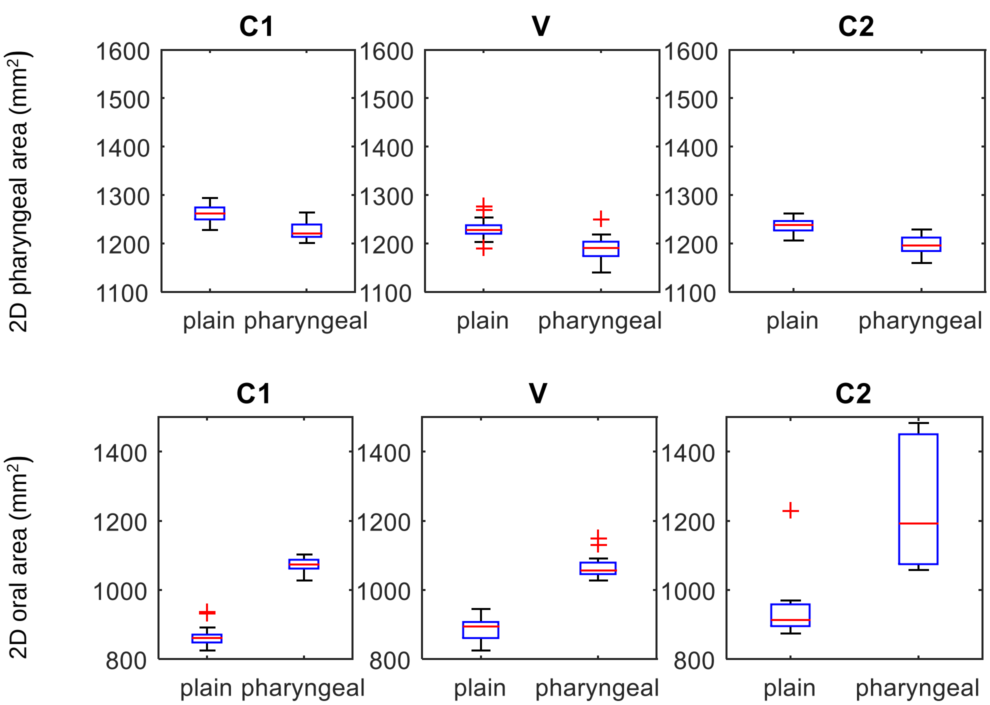


Figure 5.16: 2D pharyngeal areas (top) and 2D oral areas (bottom) in (mm^2) for the C1, V, and C2 segments in /tu:b/ ('repent') and /tˤu:b/ ('stones') as produced by SP4

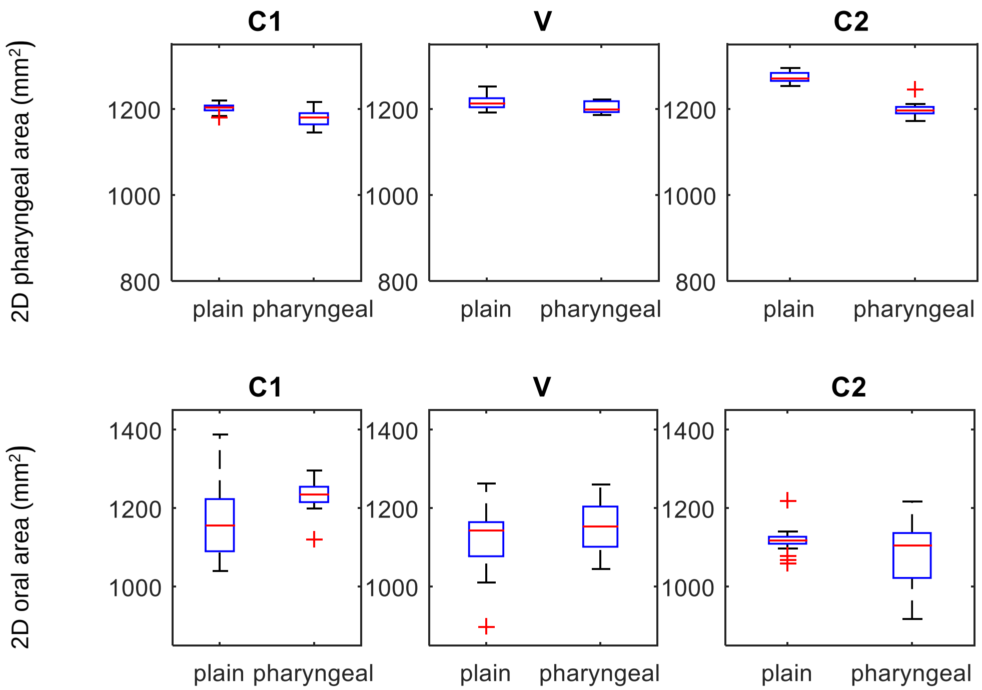


Figure 5.17: 2D pharyngeal areas (top) and 2D oral areas (bottom) in (mm^2) for the C1, V, and C2 segments in /bu:z/ ('muzzle') and /bu:zˤ/ ('rot') as produced by SP2

The third observation discussed above proposes that segments preceding the pharyngealized consonant will be more pharyngealized than segments following a pharyngealized consonant. That is, the leftward (anticipatory) spread of pharyngealization is stronger than the rightward (perseveratory) spread. Within this study, this claim can be verified by comparing two sets of target words: /sˤa:b/-/ba:sˤ/ ('he hit' and 'bus') and /sˤab/- /basˤ/ ('he poured' and 'he looked'). The two words in each of these sets are symmetrical. Thus, /sˤa:b/ is the mirror image of /ba:sˤ/. In the former, the pharyngealization is triggered by the initial /sˤ/ and spreads rightward to the final /b/. In the latter, the pharyngealization is triggered by the final /sˤ/ and spreads leftward to the initial /b/. Therefore, comparing the effect of pharyngealization spread on the /b/ segment in /sˤa:b/ with that on the /b/ segment in /ba:sˤ/ can reveal whether rightward or leftward pharyngealization spread is stronger. The same logic applies to /sˤab/ and /basˤ/ which are also mirror images of each other. Within the remaining target words, no other sets are symmetrical and thus cannot be compared in this way.

The plots in Figure 5.18 - Figure 5.21 below show the vocal tract contours corresponding to the /b/ segment in /sˤa:b/-/ba:sˤ/ in the panels on the right and the /b/ segments in /sˤab/- /basˤ/ in the panels on the right for all four speakers.

/sˤa:**b**/-/**b**a:sˤ/	/sˤa**b**/-/**b**asˤ/

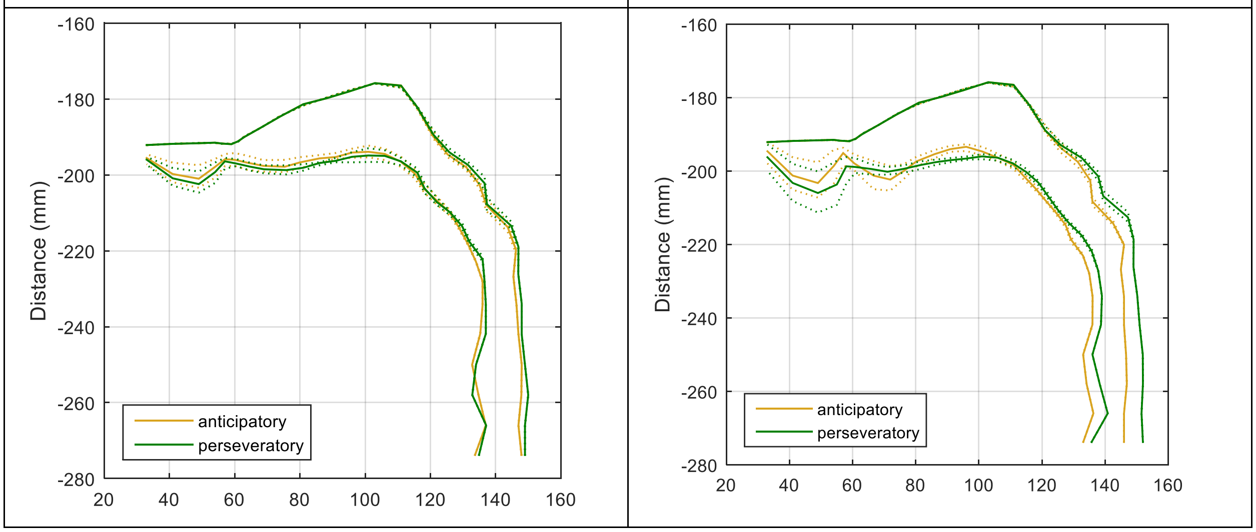


Figure 5.18: Vocal tract contours of /b/ segments in /sˤa:b/-/ba:sˤ/ (left) and /sˤab/- /basˤ/ (right) for speaker SP1.

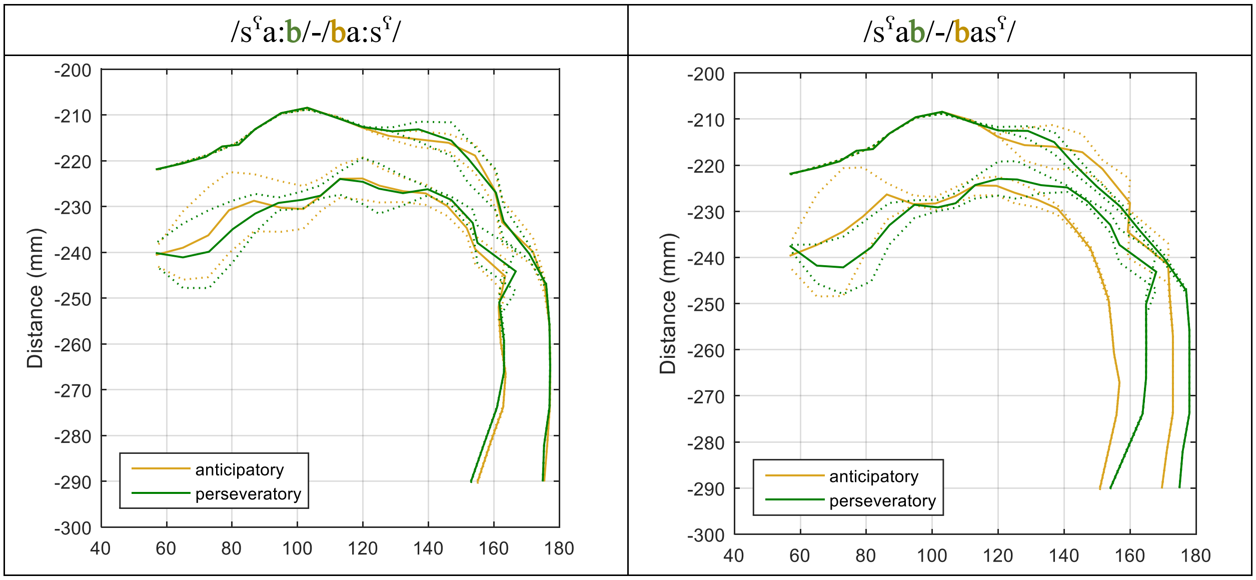


Figure 5.19: Vocal tract contours of /b/ segments in /sˤa:b/-/ba:sˤ/ (left) and /sˤab/- /basˤ/ (right) for speaker SP2.

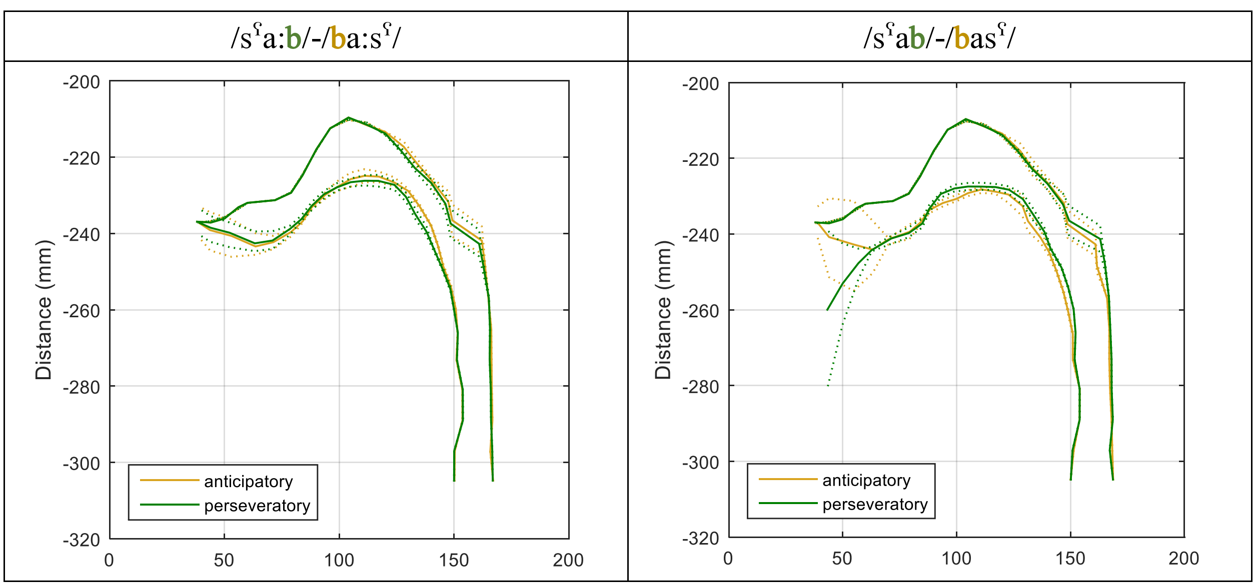


Figure 5.20: Vocal tract contours of /b/ segments in /sˤa:b/-/ba:sˤ/ (left) and /sˤab/- /basˤ/ (right) for speaker SP4.

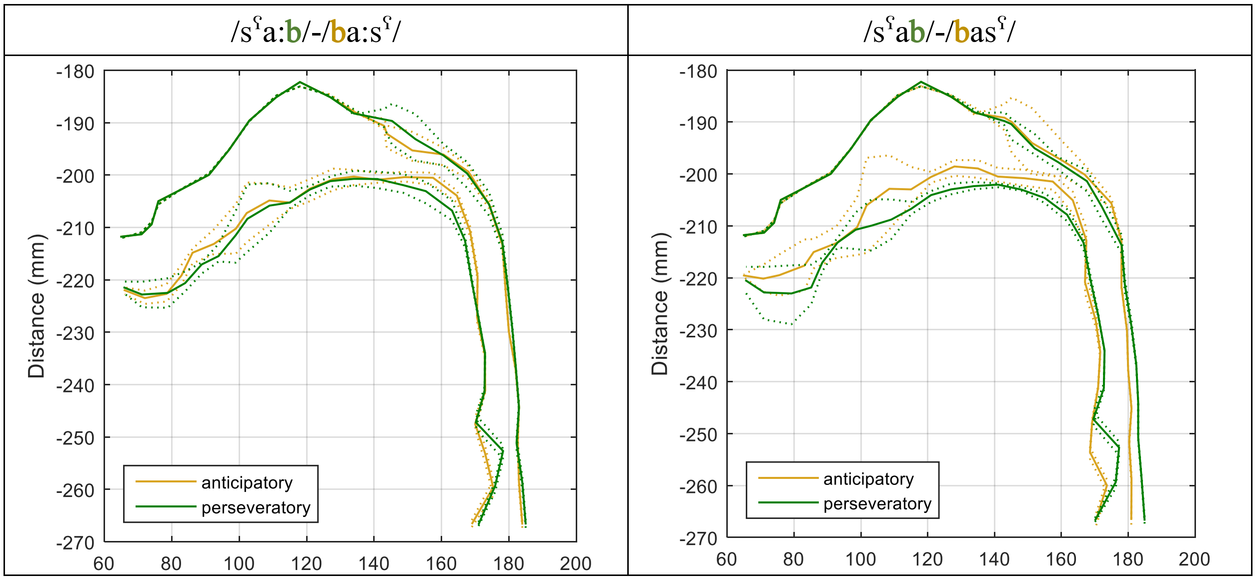


Figure 5.21: Vocal tract contours of /b/ segments in /sˤa:b/-/ba:sˤ/ (left) and /sˤab/- /basˤ/ (right) for speaker SP5.

In the plots for SP5, especially, in Figure 5.21 above, it can be argued that the vocal tract contours of the /b/ in /ba:sˤ/ in yellow (i.e., the /b/ modified by anticipatory pharyngealization spread) exhibit a more constricted pharynx, especially in the velopharyngeal region when compared against the vocal tract contours of the /b/ in /sˤa:b/ in green (i.e. modified by perseveratory pharyngealization spread). This may be interpreted as indicative of a stronger effect of anticipatory spread. To quantitatively compare the effect of anticipatory and perseveratory pharyngealization spread, Figure 5.22 -Figure 5.25 below show the 2D pharyngeal areas in the relevant /b/ segments across the four speakers. To examine statistical significance, analysis of variance (ANOVA) was conducted on the 2D pharyngeal areas with vowel length (`vowel_length`) and direction of spread (`direction`) as factors. The results of the ANOVA model are presented below each figure in Table 5.1 - Table 5.4.

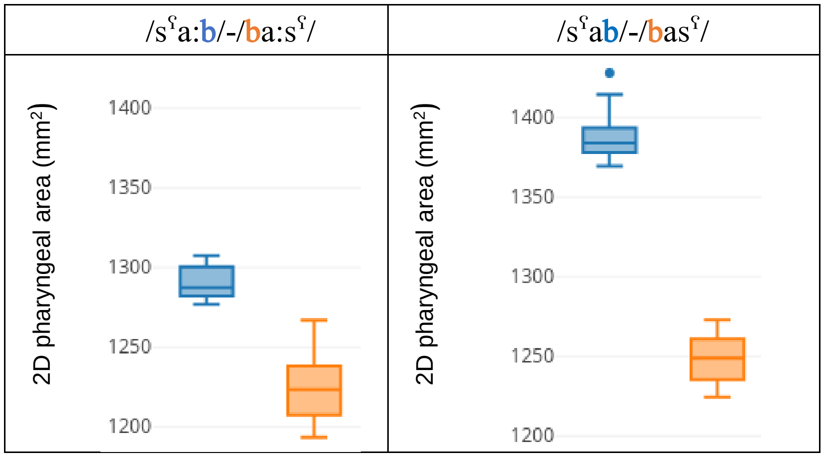


Figure 5.22: 2D pharyngeal areas (in mm^2) of the /b/ segments in /sˤa:b/-/ba:sˤ/ (left) and /sˤab/-/basˤ/ (right) for SP1.

Table 5.1: Analysis of variance (ANOVA) for 2D pharyngeal areas data in Figure 5.22 of SP1.

```
             Df Sum Sq Mean Sq F value Pr(>F)    
vowel_length  1  74024   74024   124.0 <2e-16 ***
direction     1 213469  213469   357.6 <2e-16 ***
Residuals    77  45971     597                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

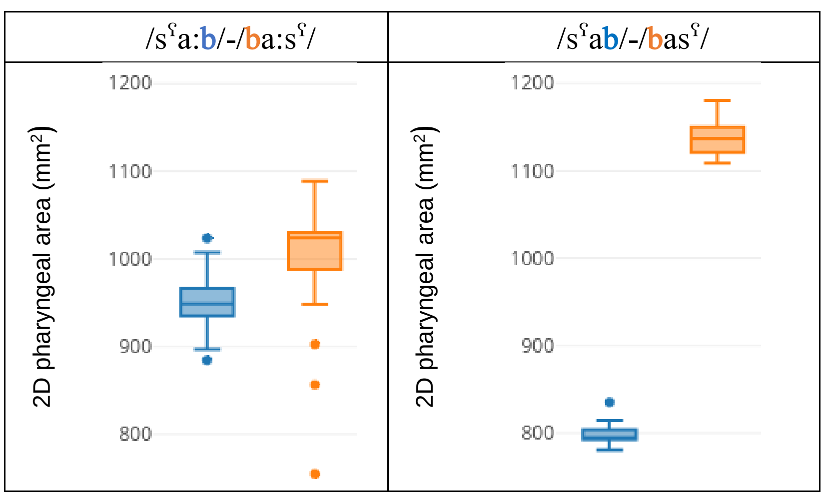


Figure 5.23: 2D pharyngeal areas (in mm^2) of the /b/ segments in /sˤa:b/-/ba:sˤ/ (left) and /sˤab/-/basˤ/ (right) for SP2.

Table 5.2: Analysis of variance (ANOVA) for 2D pharyngeal areas data in Figure 5.23 of SP2.

```
             Df Sum Sq Mean Sq F value  Pr(>F)    
vowel_length  1    242     242   0.032   0.858    
direction     1 752914  752914 100.498 1.3e-15 ***
Residuals    77 576870    7492                    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

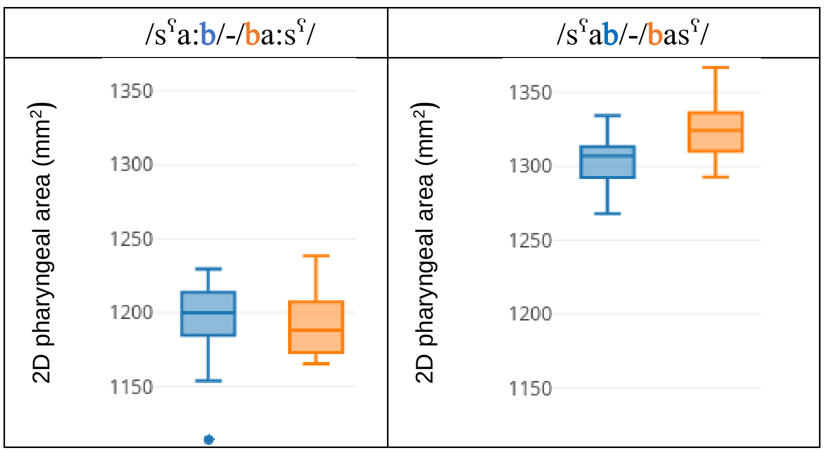


Figure 5.24: 2D pharyngeal areas (in mm^2) of the /b/ segments in /sˤa:b/-/ba:sˤ/ (left) and /sˤab/-/basˤ/ (right) for SP4.

Table 5.3: Analysis of variance (ANOVA) for 2D pharyngeal areas data in Figure 5.24 of SP4.

```
             Df Sum Sq Mean Sq F value Pr(>F)    
vowel_length  1 286682  286682 565.512 <2e-16 ***
direction     1   1496    1496   2.952 0.0898 .  
Residuals    77  39035     507                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

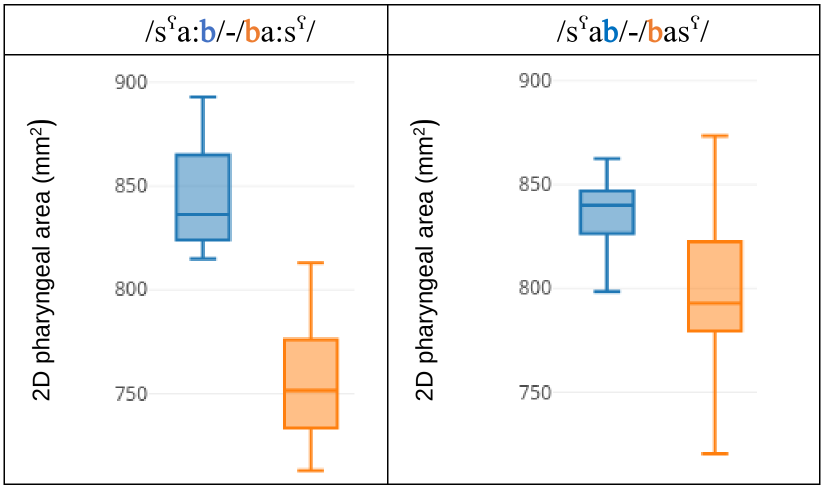


Figure 5.25: 2D pharyngeal areas (in mm^2) of the /b/ segments in /sˤa:b/-/ba:sˤ/ (left) and /sˤab/-/basˤ/ (right) for SP5.

Table 5.4: Analysis of variance (ANOVA) for 2D pharyngeal areas data in Figure 5.25 of SP5.

```
             Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_length  1  12650   12650   12.43 0.000714 ***
direction     1  72421   72421   71.18 1.46e-12 ***
Residuals    77  78339    1017                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Results in Figure 5.22 - Figure 5.25 above provide quantitative support for the claim that anticipatory pharyngealization spread is stronger than perseveratory pharyngealization spread in two of the four speakers (SP1 and SP5) across both short and long vowels. Thus, we see that the 2D pharyngeal areas are smaller during the /b/ in /ba:sˤ/ and /basˤ/ when compared against the /b/ in /sˤa:b/ and /sˤab/ respectively. The smaller 2D pharyngealized areas suggest a more constricted pharynx, which in turn, suggests stronger pharyngealization.

The fourth observation above addresses the influence of pharyngealization on longer versus shorter vowels. The vocal tract contour plots in Figure 5.26 - Figure 5.28 below superimpose two target words with pharyngealized consonants: one having a short vowel, and the other having a long vowel. These plots show that the vocal tract is more constricted throughout the duration of the word with the longer vowel, regardless of vowel quality. This is the case for most of the speakers, and in most of the target words. Figure 5.26 - Figure 5.28 show some samples. The remaining plots are listed in the Appendix (See Figure A.95 - Figure A.117 in the Appendix).

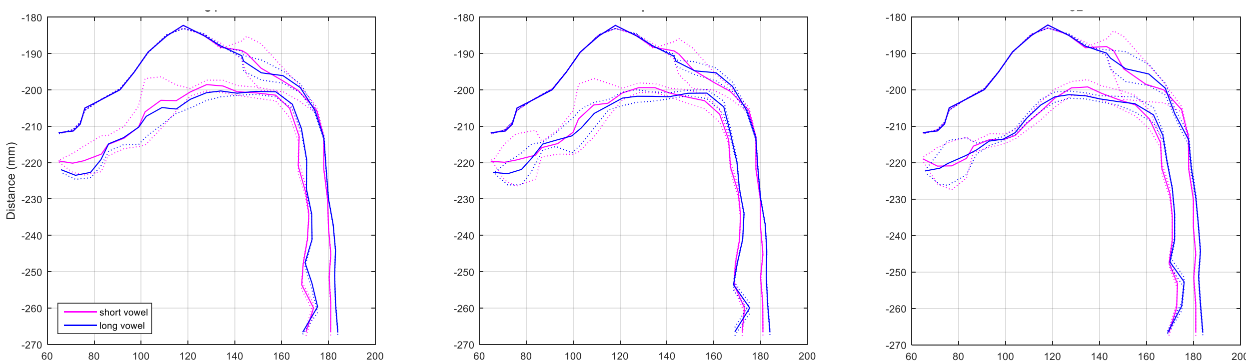


Figure 5.26: Vocal tract contours during /ba:s/ (‘bus’) in blue and /bas/ (‘he looked’) in magenta as produced by SP5.

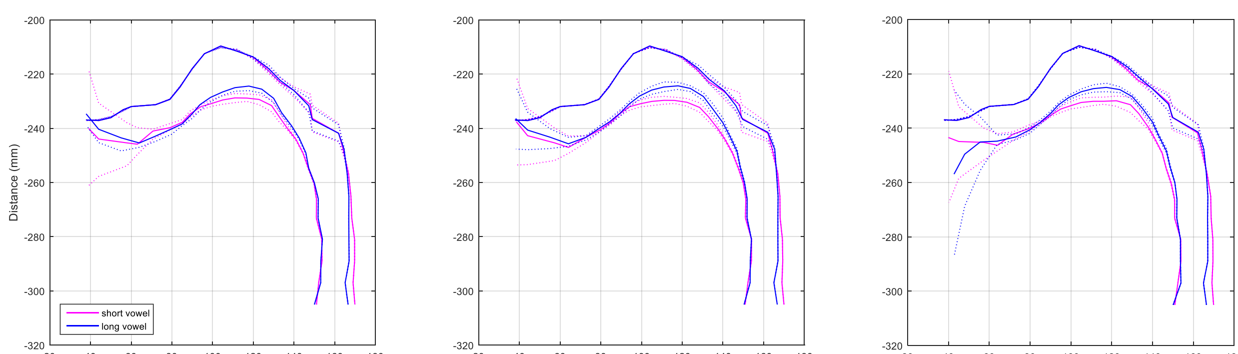


Figure 5.27: Vocal tract contours during /tu:b/ (‘stones’) in blue and /tub/ (‘show up unexpectedly’) in magenta as produced by SP4.

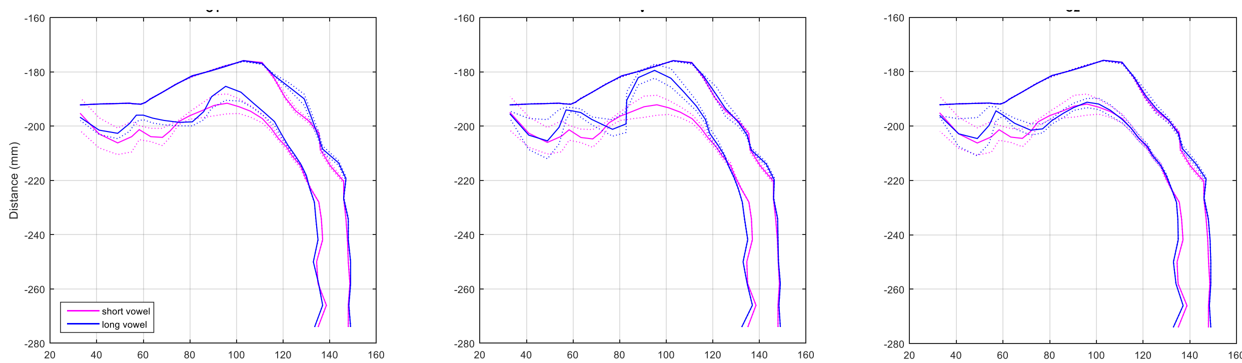


Figure 5.28: Vocal tract contours during /bi:d/ ('white') in blue and /fa:yid/ ('leftover') in magenta as produced by SP1.

The boxplots in Figure 5.29 - Figure 5.32 show the 2D pharyngeal areas during the short and long vowels of the target words for the four speakers. The box plots in Figure 5.33 - Figure 5.36 show the 2D oral areas during the short and long vowels. In most cases, the 2D pharyngeal areas are smaller and the 2D oral areas are larger in the long vowel (in orange), indicating a more constricted pharynx and a more enlarged oral cavity respectively, and hence more pharyngealization. To examine statistical significance, analysis of variance (ANOVA) was conducted on the 2D pharyngeal areas and 2D oral areas with vowel length (`vowel_length`), vowel quality (`vowel_qual`) and direction of spread (`spread_direction`) as factors. The results of the ANOVA model are presented below each figure in Table 5.5 - Table 5.8 and Table 5.9 - Table 5.12 respectively.

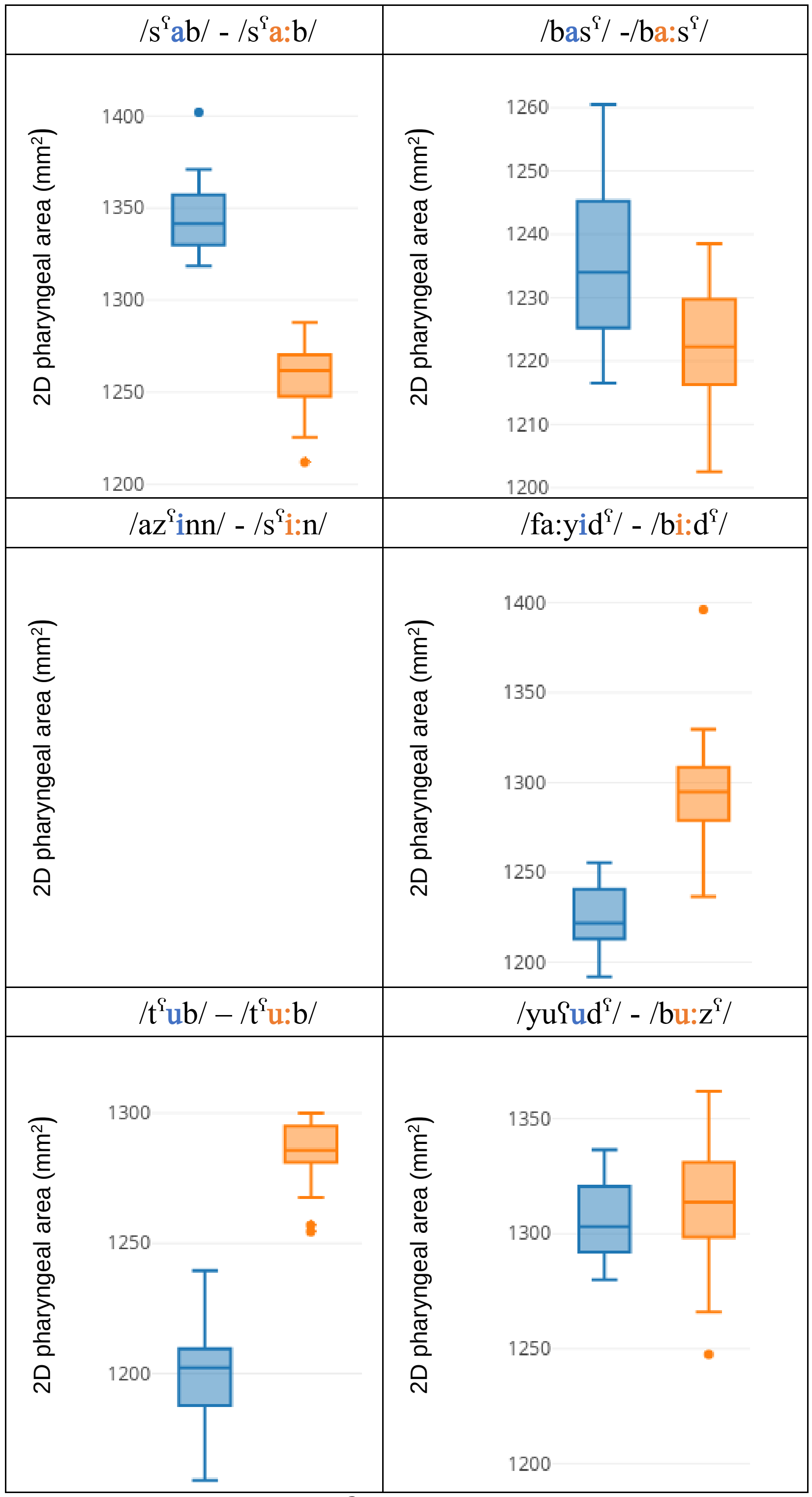


Figure 5.29: 2D pharyngeal areas (in mm^2) of the pharyngealized short vowels (in blue) and pharyngealized long vowels (in orange) for SP1.

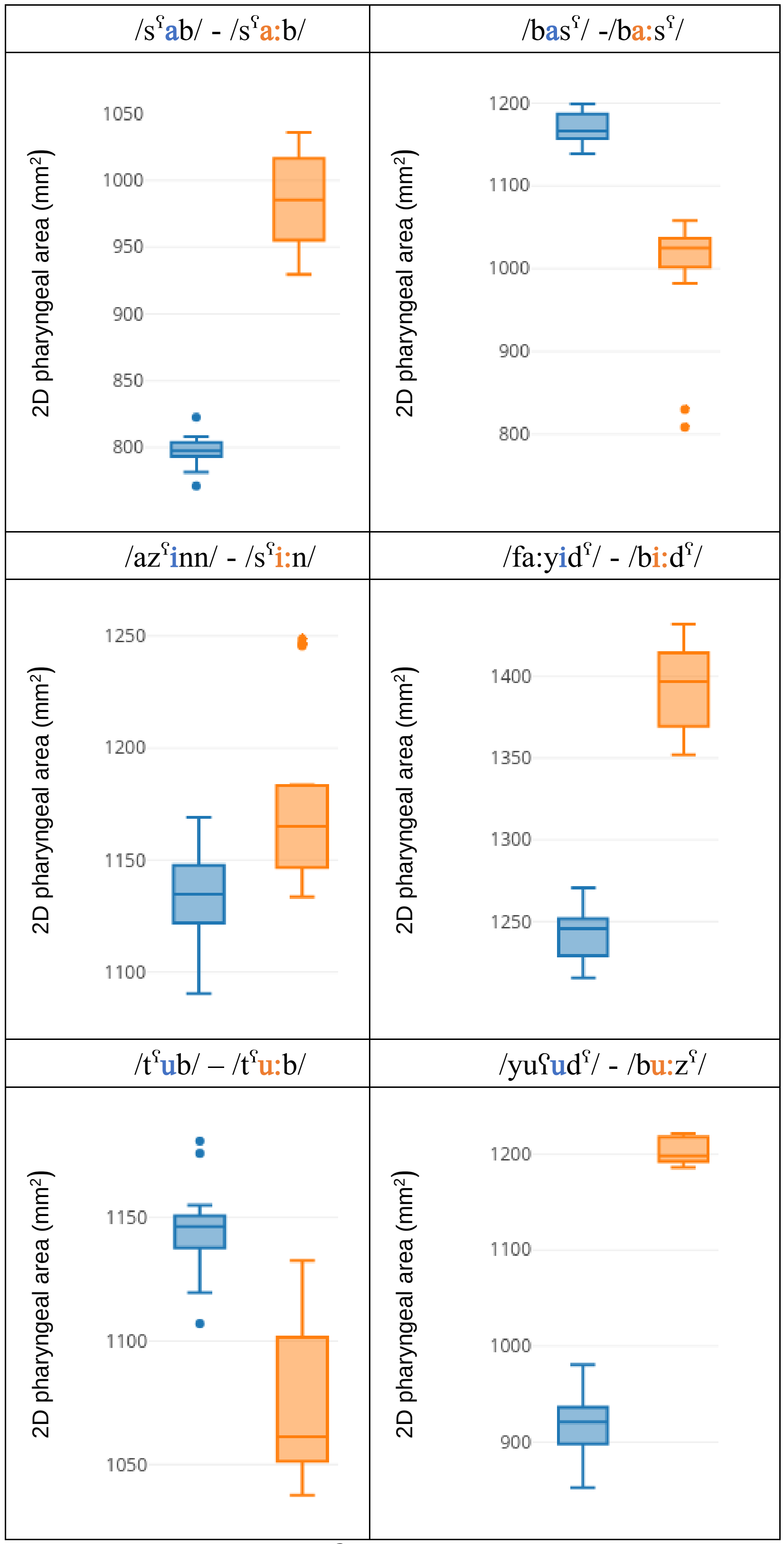


Figure 5.30: 2D pharyngeal areas (in mm^2) of the pharyngealized short vowels (in blue) and pharyngealized long vowels (in orange) for SP2.

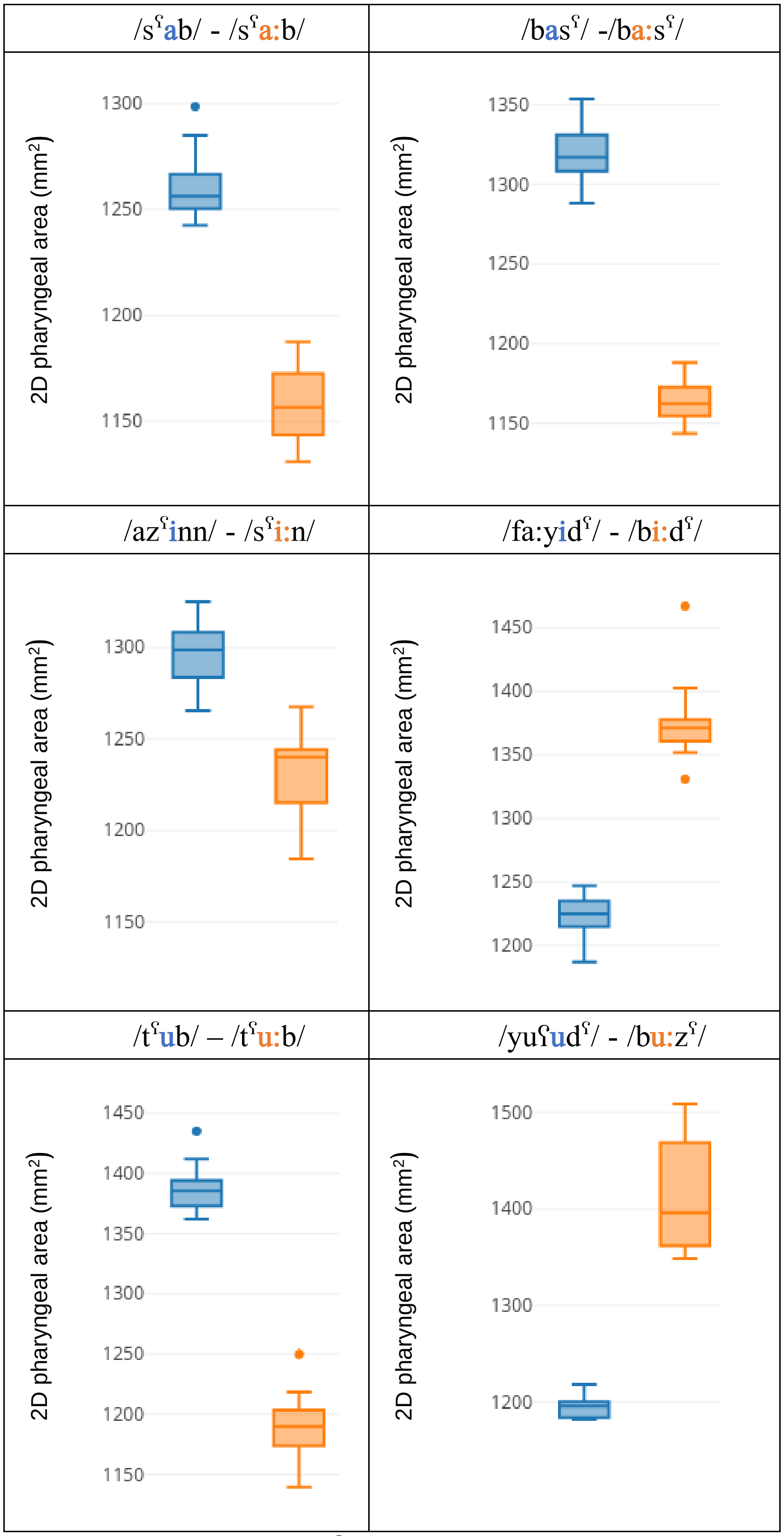


Figure 5.31: 2D pharyngeal areas (in mm^2) of the pharyngealized short vowels (in blue) and pharyngealized long vowels (in orange) for SP4.

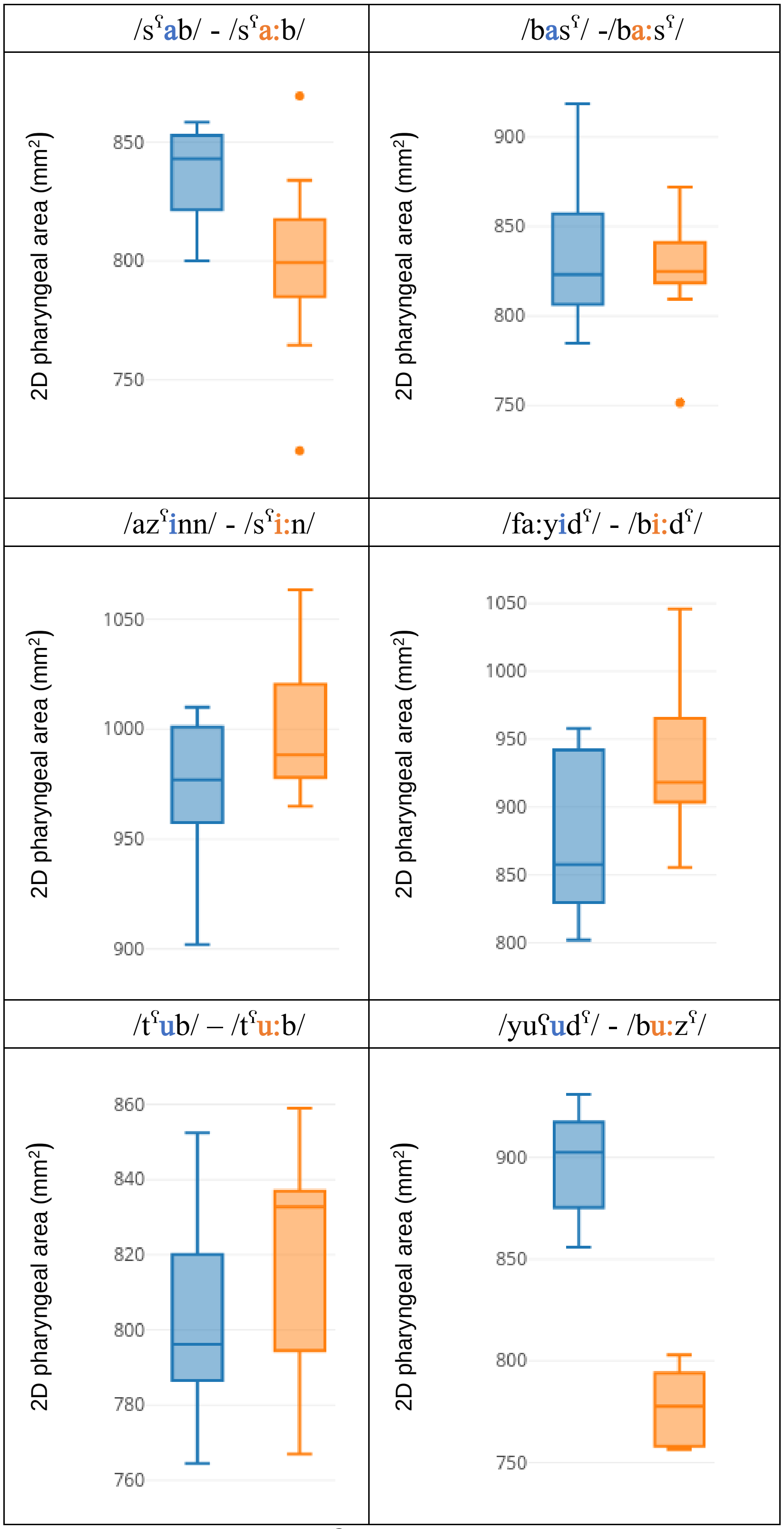


Figure 5.32: 2D pharyngeal areas (in mm^2) of the pharyngealized short vowels (in blue) and pharyngealized long vowels (in orange) for SP5.

Table 5.5: Analysis of variance (ANOVA) for 2D pharyngeal areas data in Figure 5.29 of SP1.

```
                   Df  Sum Sq Mean Sq F value Pr(>F)    
vowel_length        1    5498    5498   1.601 0.2064    
vowel_qual          2   45841   22920   6.675 0.0014 ** 
type                1  400633  400633 116.669 <2e-16 ***
spread_direction    1   10281   10281   2.994 0.0843 .  
Residuals         434 1490328    3434                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
40 observations deleted due to missingness
```

Table 5.6: Analysis of variance (ANOVA) for 2D pharyngeal areas data in Figure 5.30 of SP2.

```
                   Df  Sum Sq Mean Sq F value Pr(>F)    
vowel_length        1 1150129 1150129  86.506 <2e-16 ***
vowel_qual          2 2979443 1489722 112.048 <2e-16 ***
type                1 1415927 1415927 106.498 <2e-16 ***
spread_direction    1    1181    1181   0.089  0.766    
Residuals         474 6302002   13295                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.7: Analysis of variance (ANOVA) for 2D pharyngeal areas data in Figure 5.31 of SP3.

```
                   Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length        1   19911   19911   2.537  0.11188    
vowel_qual          2  269648  134824  17.178 6.28e-08 ***
type                1  656713  656713  83.671  < 2e-16 ***
spread_direction    1   55459   55459   7.066  0.00812 ** 
Residuals         474 3720324    7849                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.8: Analysis of variance (ANOVA) for 2D pharyngeal areas data in Figure 5.32 of SP5.

```
                   Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length        1   33790   33790   5.865    0.016 *  
vowel_qual          2 1128494  564247  97.931  < 2e-16 ***
type                1  338296  338296  58.715 2.05e-13 ***
spread_direction    1   97632   97632  16.945 4.87e-05 ***
Residuals         330 1901356    5762                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

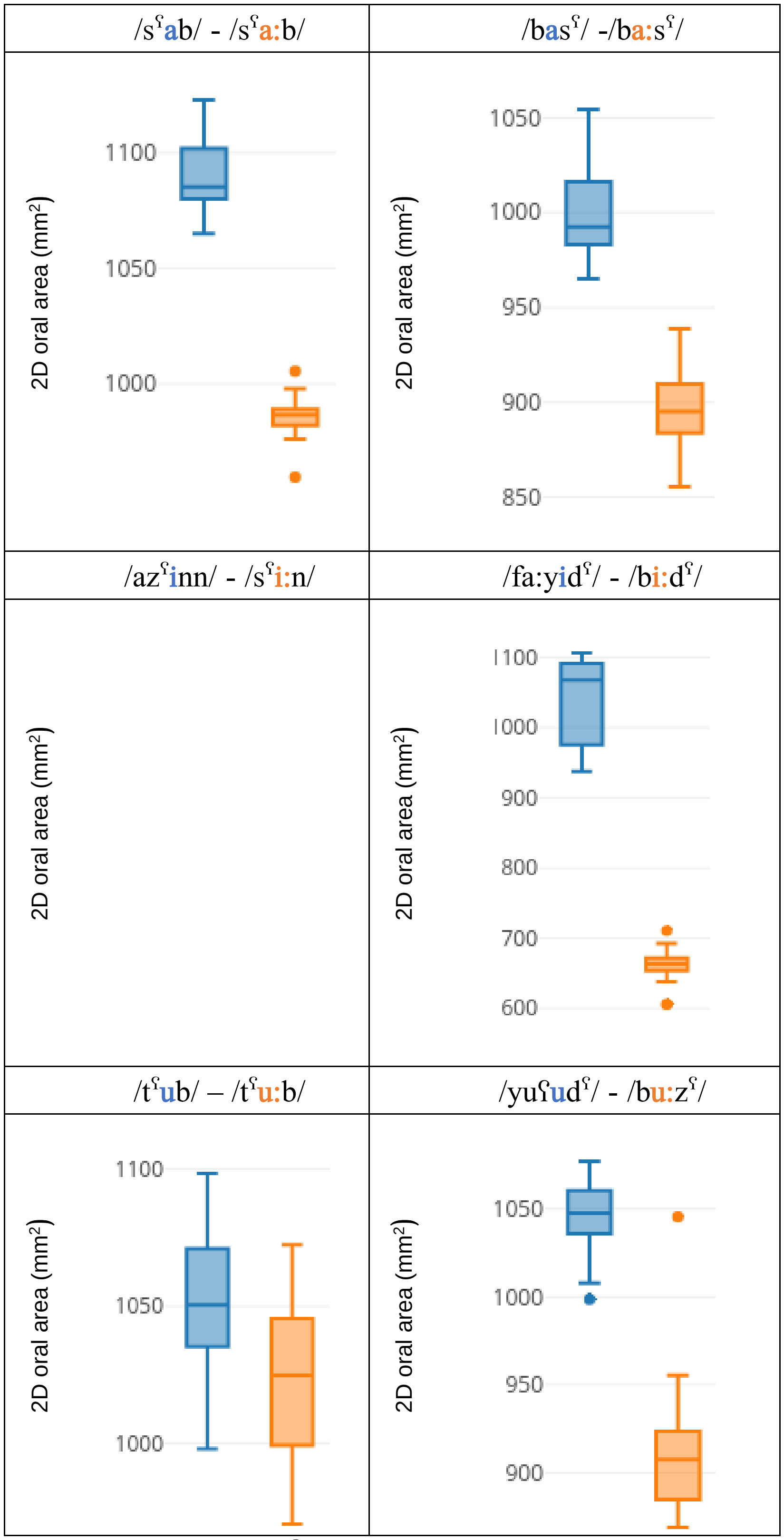


Figure 5.33: 2D oral areas (in mm^2) of the pharyngealized short vowels (in blue) and pharyngealized long vowels (in orange) for SP1.

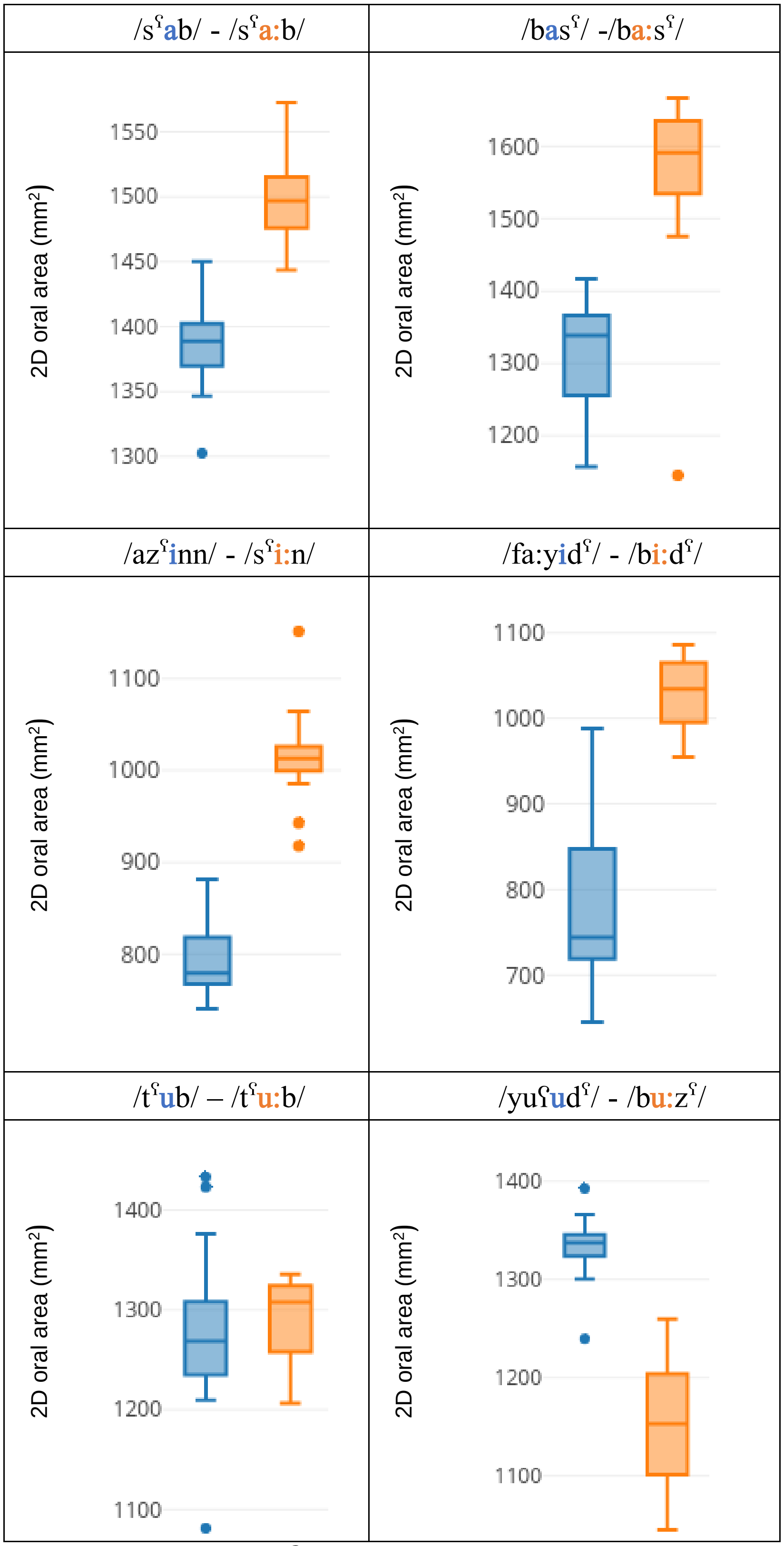


Figure 5.34: 2D oral areas (in mm^2) of the pharyngealized short vowels (in blue) and pharyngealized long vowels (in orange) for SP2.

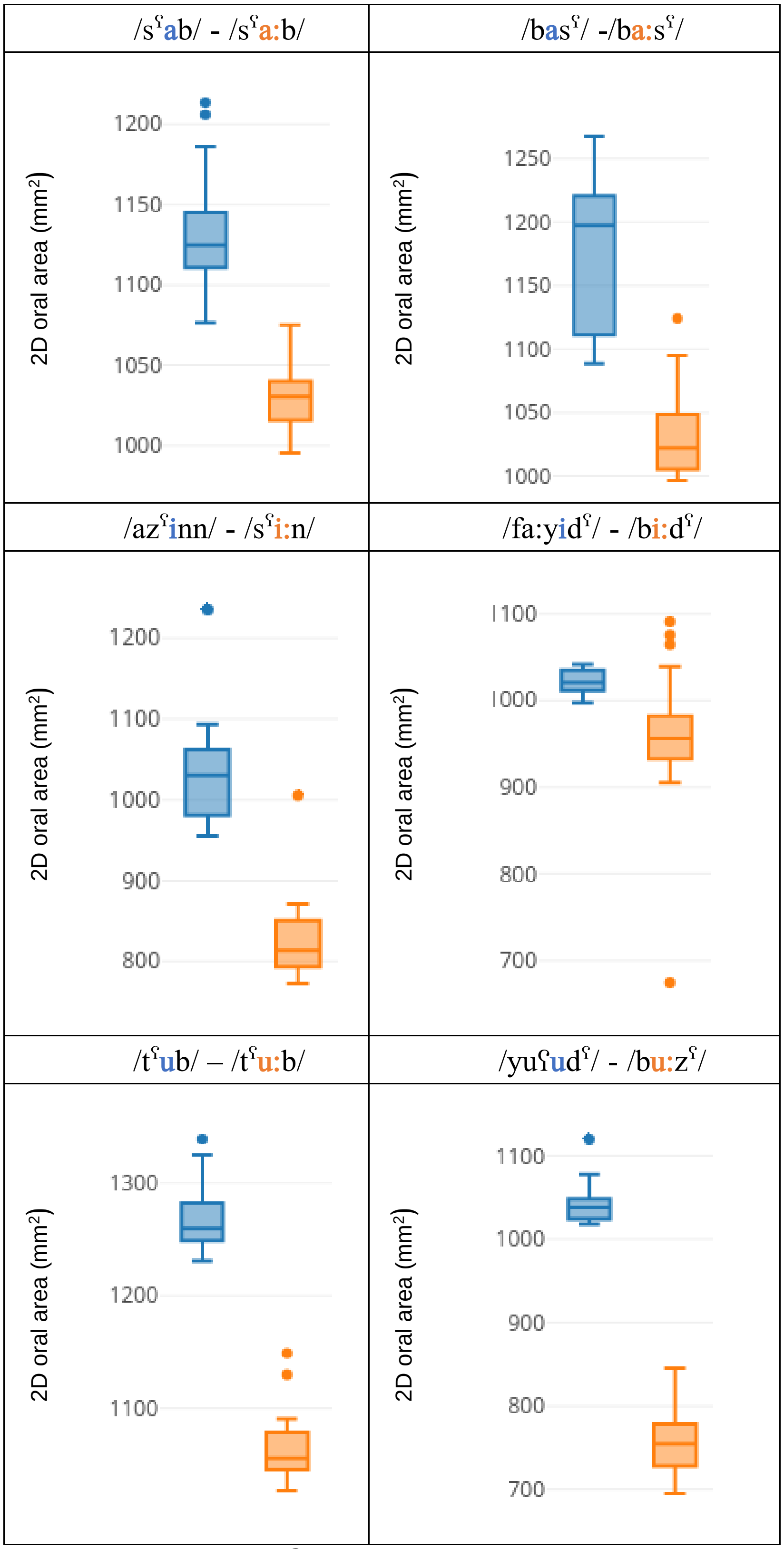


Figure 5.35: 2D oral areas (in mm^2) of the pharyngealized short vowels (in blue) and pharyngealized long vowels (in orange) for SP4.

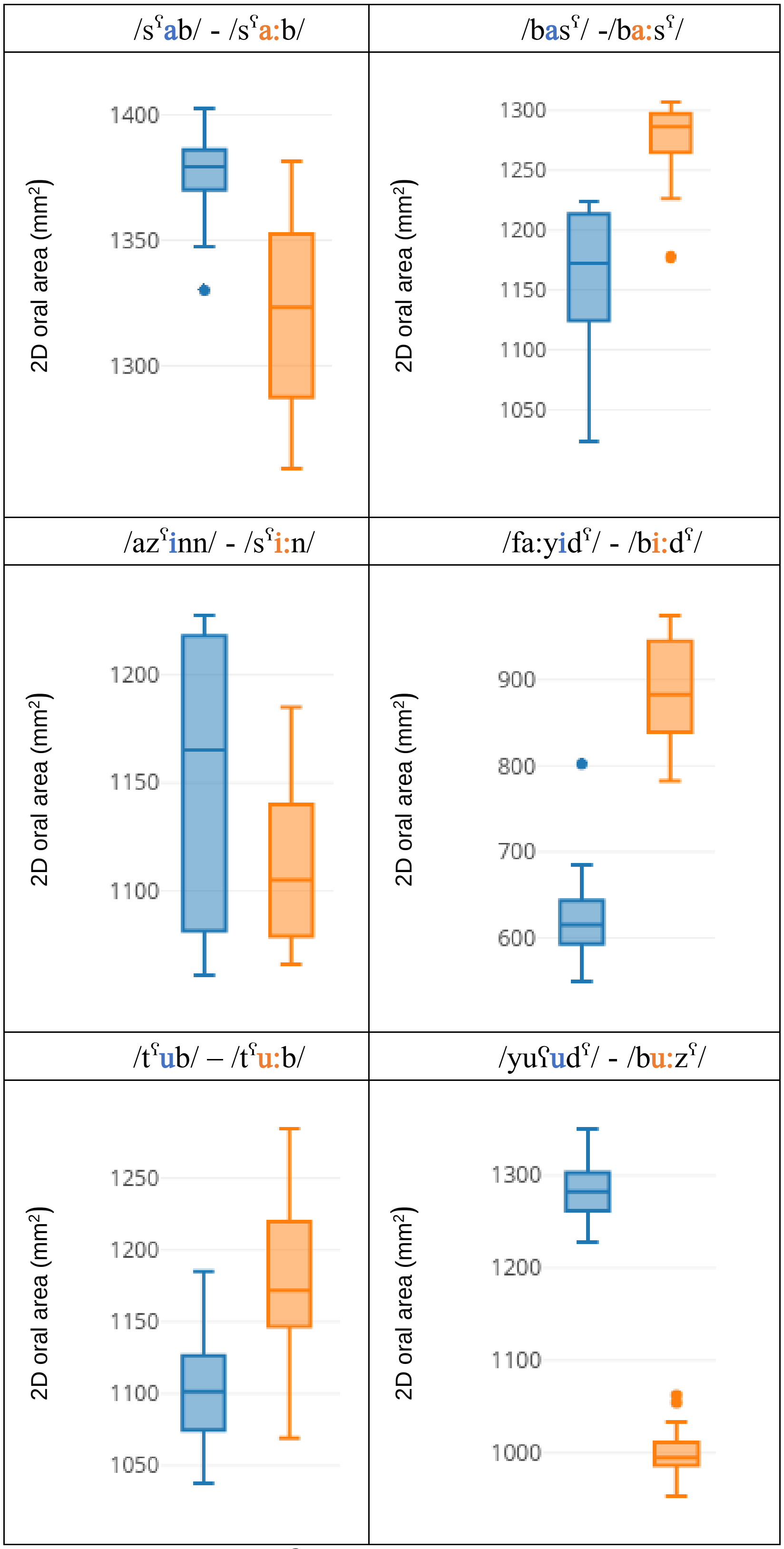


Figure 5.36: 2D oral areas (in mm^2) of the pharyngealized short vowels (in blue) and pharyngealized long vowels (in orange) for SP5.

Table 5.9: Analysis of variance (ANOVA) for 2D oral areas data in Figure 5.33 of SP1.

```
                  Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length       1 3610401 3610401 527.201  < 2e-16 ***
vowel_qual         2 4513280 2256640 329.521  < 2e-16 ***
type               1  256642  256642  37.476 2.07e-09 ***
spread_direction   1   11459   11459   1.673    0.197    
Residuals        434 2972138    6848                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
40 observations deleted due to missingness
```

Table 5.10: Analysis of variance (ANOVA) for 2D oral areas data in Figure 5.34 of SP2.

```
                  Df   Sum Sq Mean Sq F value   Pr(>F)    
vowel_length       1   412046  412046   26.68 3.55e-07 ***
vowel_qual         2 15997008 7998504  517.87  < 2e-16 ***
type               1   881982  881982   57.10 2.15e-13 ***
spread_direction   1    25791   25791    1.67    0.197    
Residuals        474  7320949   15445                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.11: Analysis of variance (ANOVA) for 2D oral areas data in Figure 5.35 of SP3.

```
                  Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length       1 2514090 2514090  225.05  < 2e-16 ***
vowel_qual         2 1878182  939091   84.06  < 2e-16 ***
type               1   26470   26470    2.37    0.124    
spread_direction   1  282779  282779   25.31 6.93e-07 ***
Residuals        474 5295094   11171                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.12: Analysis of variance (ANOVA) for 2D oral areas data in Figure 5.36 of SP5.

```
                  Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length       1   10598   10598   0.792   0.3741    
vowel_qual         2 5092414 2546207 190.296  < 2e-16 ***
type               1   36855   36855   2.754   0.0979 .  
spread_direction   1  731827  731827  54.695 1.17e-12 ***
Residuals        330 4415482   13380                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
144 observations deleted due to missingness
```

The fifth and final observation has to do with the extent of the influence of pharyngealization as a function of the vowel quality. In order to examine this, the difference between the 2D pharyngeal areas in the vowels of a minimal pair of target words, contrastive in the plain-pharyngealized consonants is calculated. A greater difference is indicative of a greater effect of pharyngealization. For example, let us assume the pharynx has a 2D pharyngeal area of x in the plain vowel and a 2D pharyngeal area of y in the pharyngealized vowel. A small difference between x and y indicates that the area of the pharynx did not greatly change due to the pharyngealization. In contrast, a greater difference between x and y indicates that the pharyngealization caused greater change in the pharyngeal area. It can then be deduced that the effect of pharyngealization in the second case is stronger than in the first. Figure 5.37 - Figure 5.52 below shows plots of the 2D pharyngeal areas in the various vowels of all the target words for all speakers. Figure 5.37 - Figure 5.40 show plots of the 2D pharyngeal areas during long vowels following the plain-pharyngealized contrast. Figure 5.41 - Figure 5.44 show 2D pharyngeal areas during short vowels following the plain-pharyngealized contrast. Figure 5.45 - Figure 5.48 show 2D pharyngeal areas during long vowels preceding the plain-pharyngealized contrast. Figure 5.49 - Figure 5.52 show 2D pharyngeal areas during short vowels preceding the plain-pharyngealized contrast.

Visually, in the plot for SP1 in Figure 5.37, for example, the difference in the 2D pharyngeal areas for the /a:/ in /sˤa:b/ (in blue) and the /a:/ in /sa:b/ (in orange) is much greater than the difference between the /i:/ in /sˤi:n/ (in green) and the /i:/ in /si:n/ (in red). This indicates that the effect of the pharyngealization is greater through an /a:/ than through an /i:/. Similarly, the 2D pharyngeal areas of the /u:/ in /tu:b/ are plotted in brown, and those of the /u:/ in /tˤu:b/ are plotted in purple. Visually, it can be seen that the difference between these two areas is the smallest. Thus, it can be deduced that the effect of pharyngealization in a /u:/ is less than its effect in an /i:/, which is less than its effect in an /a:/. This general trend is observed in most of the data of the four speakers.

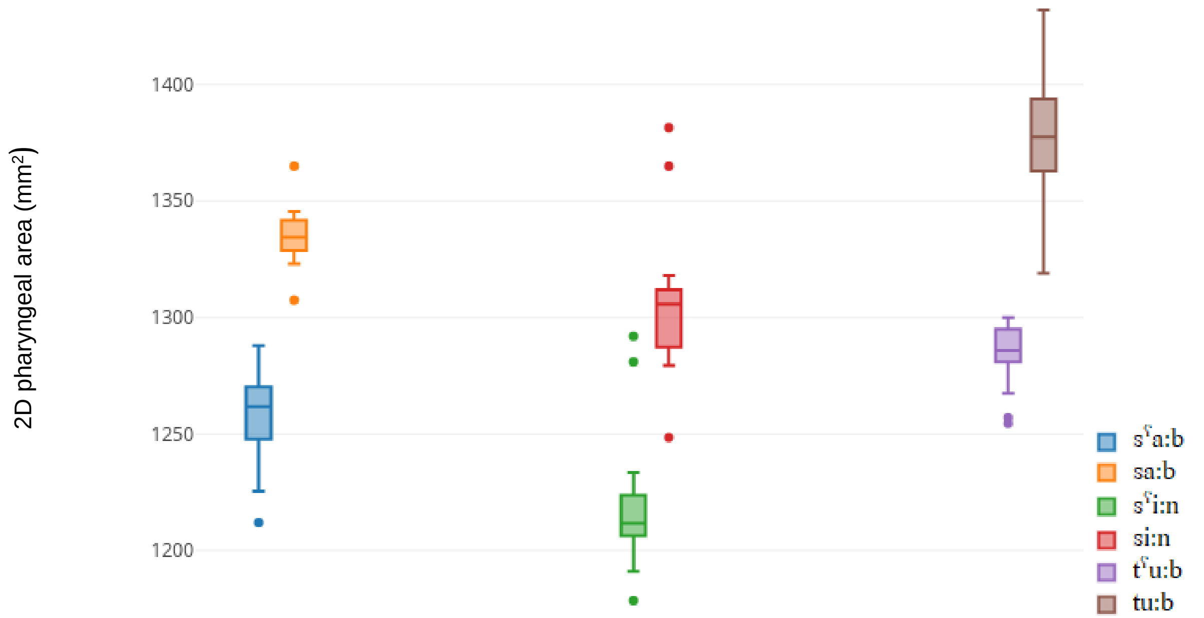


Figure 5.37: 2D pharyngeal areas (in mm^2) during long vowels following the plain-pharyngealized contrast for SP1.

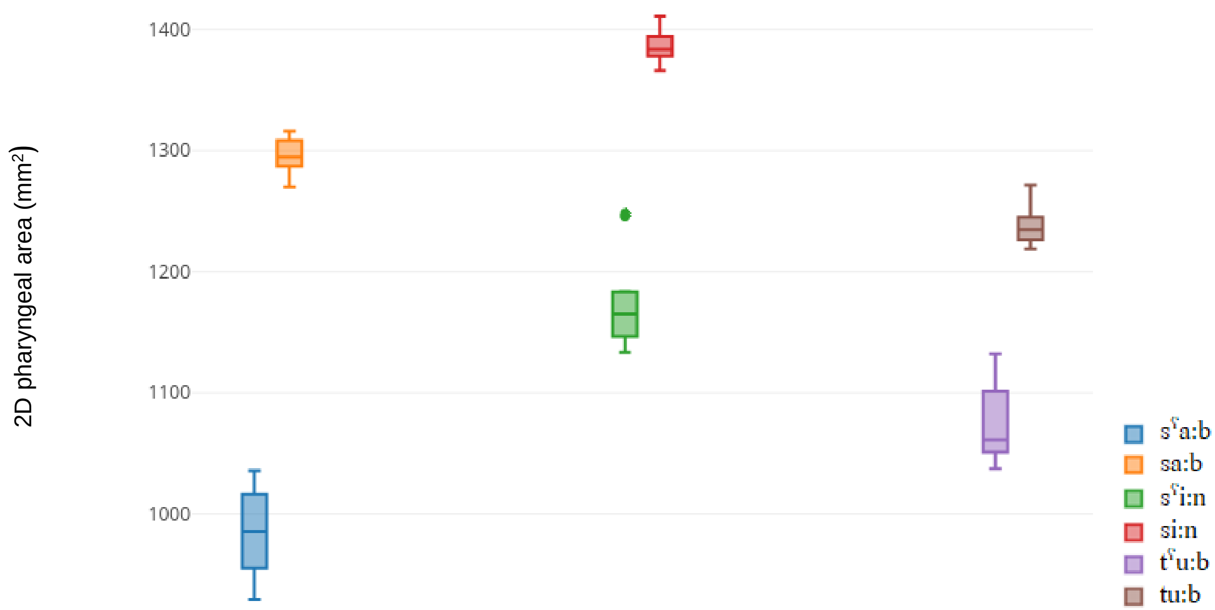


Figure 5.38: 2D pharyngeal areas (in mm^2) during long vowels following the plain-pharyngealized contrast for SP2.

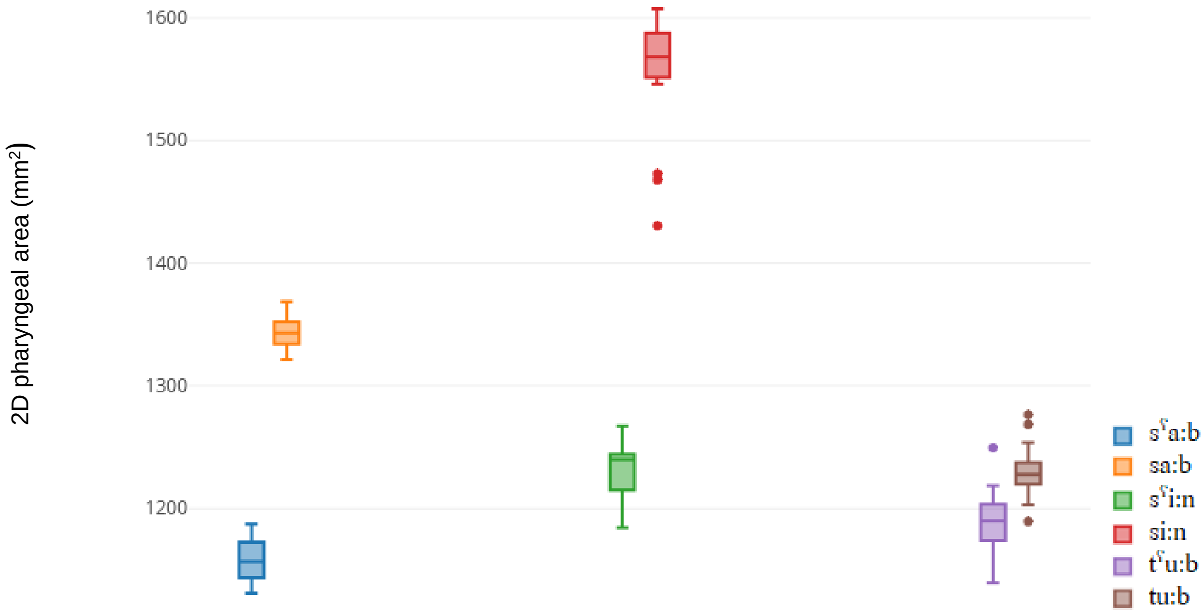


Figure 5.39: 2D pharyngeal areas (in mm^2) during long vowels following the plain-pharyngealized contrast for SP4.

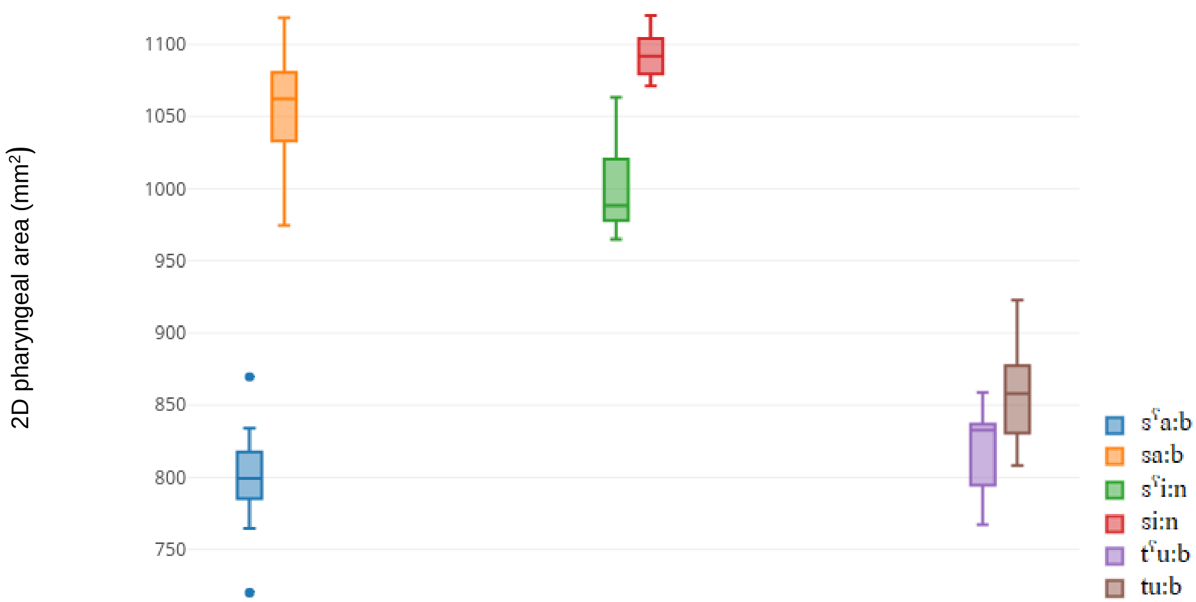


Figure 5.40: 2D pharyngeal areas (in mm^2) during long vowels following the plain-pharyngealized contrast for SP5.

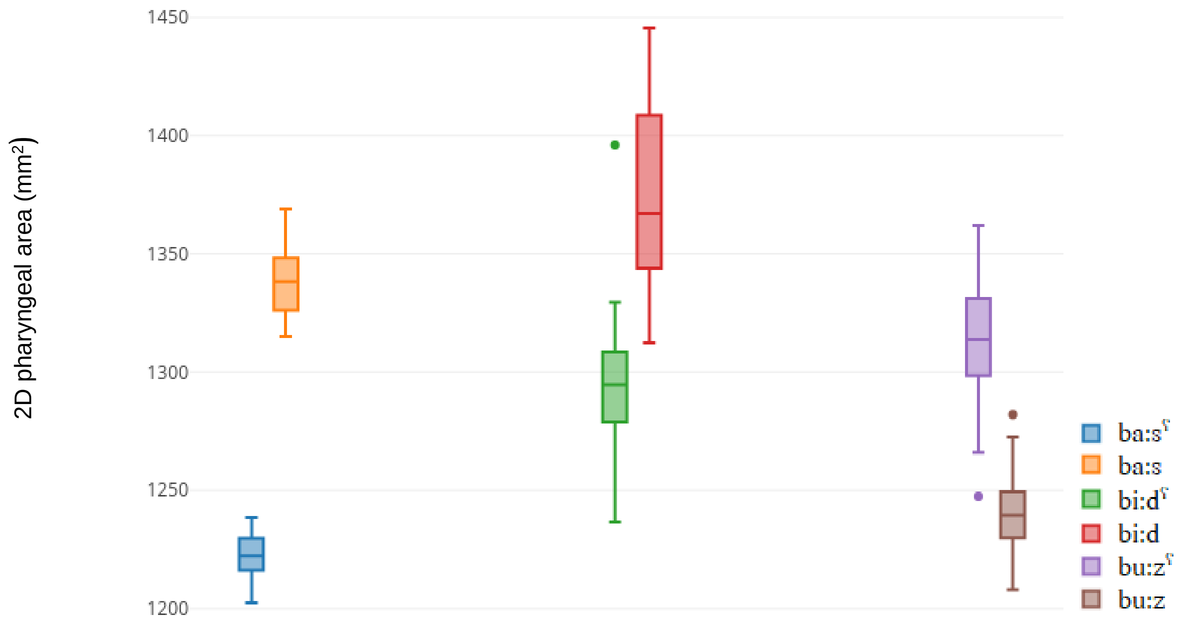


Figure 5.41: 2D pharyngeal areas (in mm^2) during long vowels preceding the plain-pharyngealized contrast for SP1.

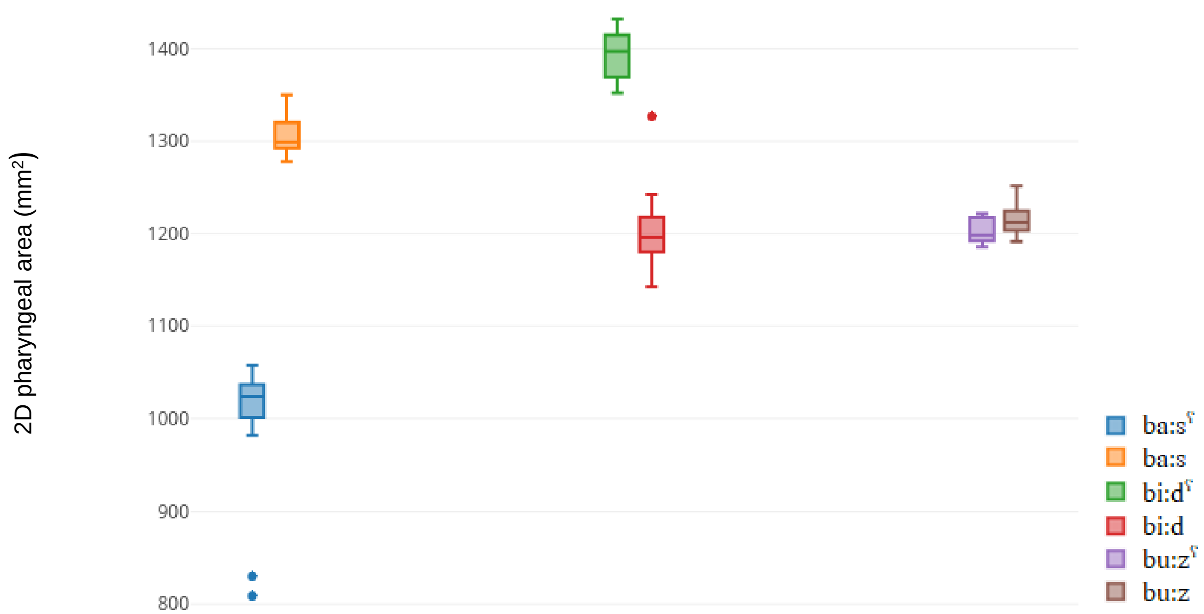


Figure 5.42: 2D pharyngeal areas (in mm^2) during long vowels preceding the plain-pharyngealized contrast for SP2.

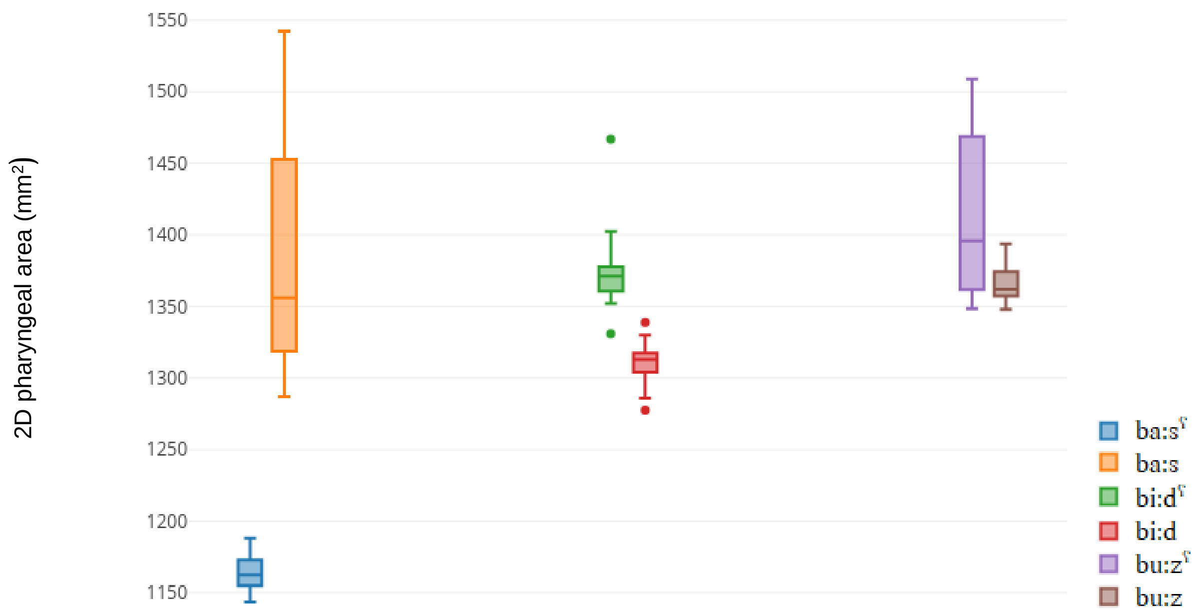


Figure 5.43: 2D pharyngeal areas (in mm^2) during long vowels preceding the plain-pharyngealized contrast for SP4.

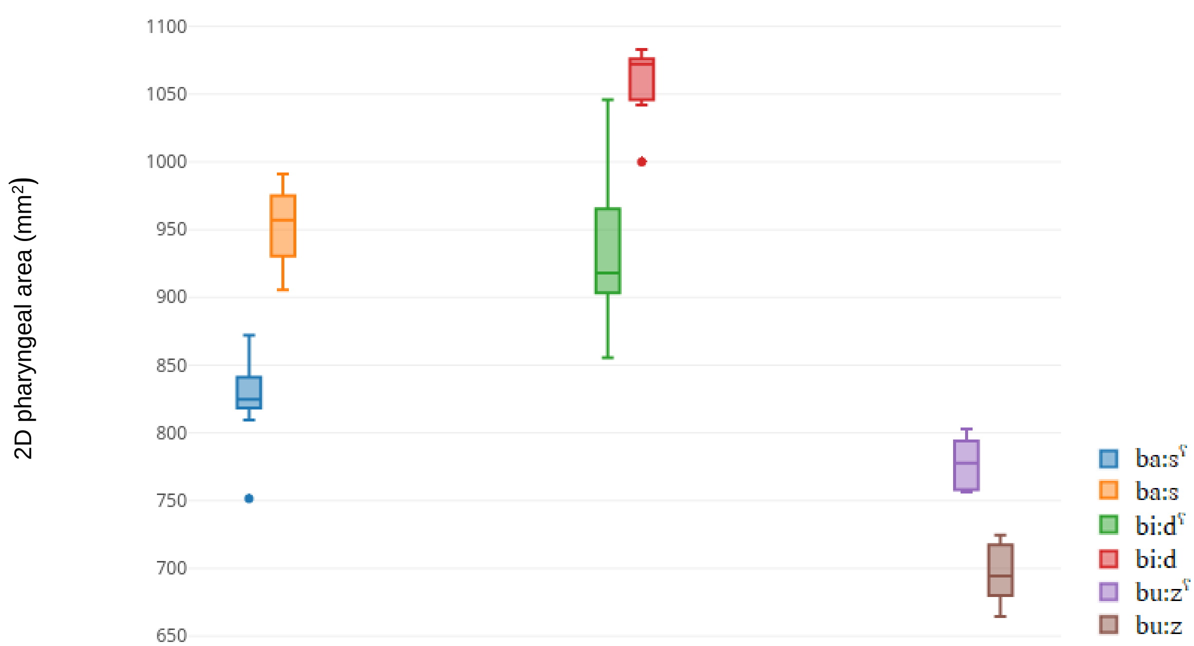


Figure 5.44: 2D pharyngeal areas (in mm^2) during long vowels preceding the plain-pharyngealized contrast for SP5.

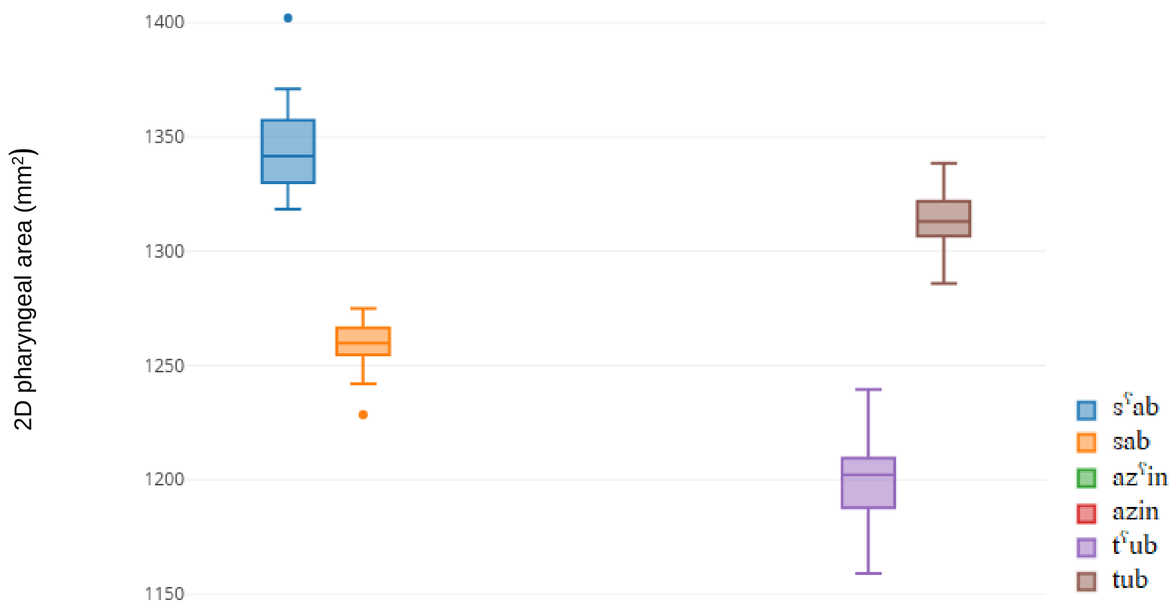


Figure 5.45: 2D pharyngeal areas (in mm^2) during short vowels following the plain-pharyngealized contrast for SP1.

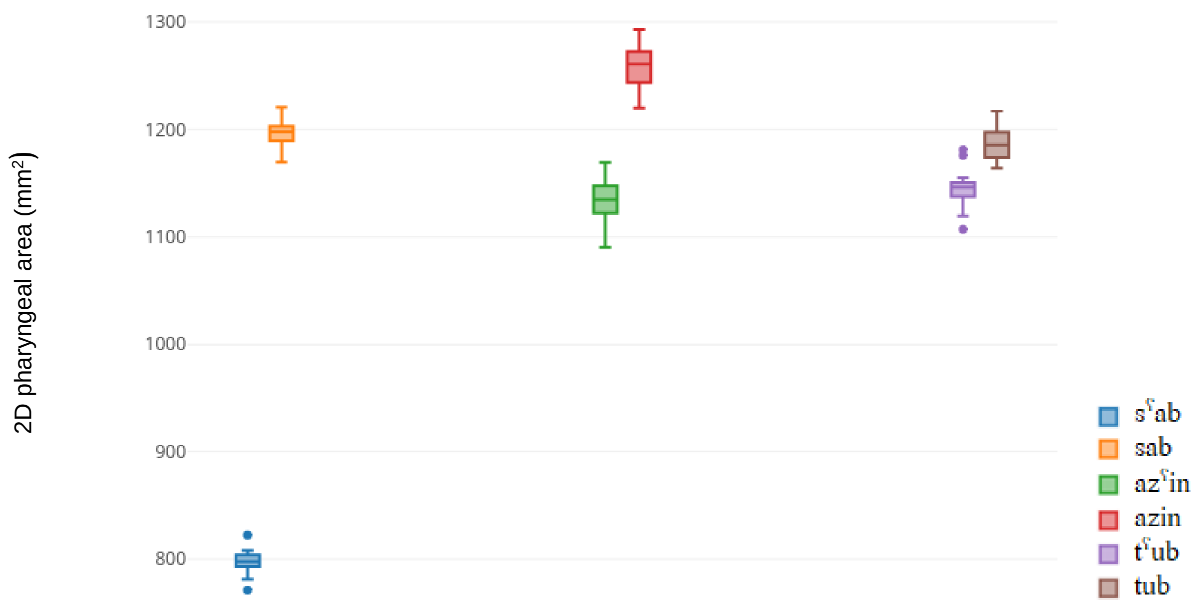


Figure 5.46: 2D pharyngeal areas (in mm^2) during short vowels following the plain-pharyngealized contrast for SP2.

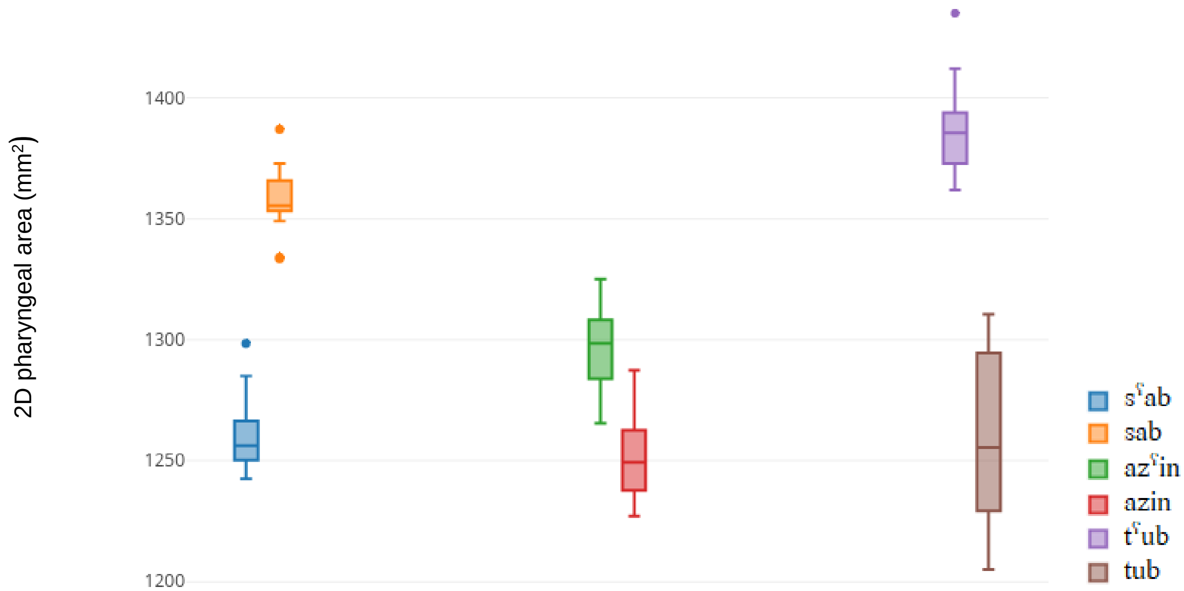


Figure 5.47: 2D pharyngeal areas (in mm^2) during short vowels following the plain-pharyngealized contrast for SP4.

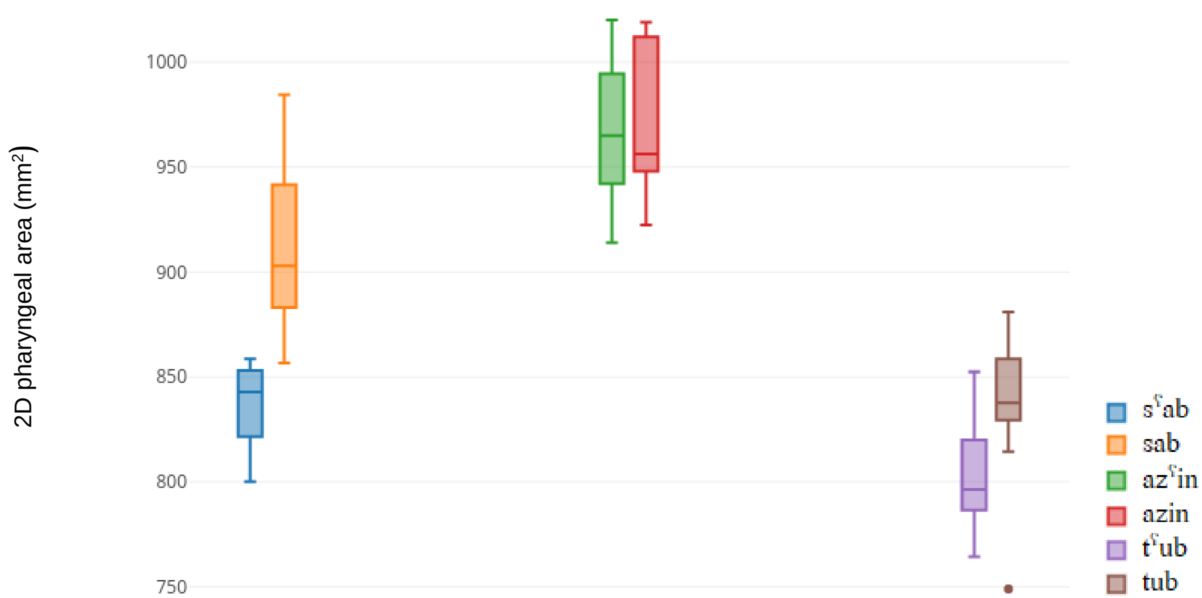


Figure 5.48: 2D pharyngeal areas (in mm^2) during short vowels following the plain-pharyngealized contrast for SP5.

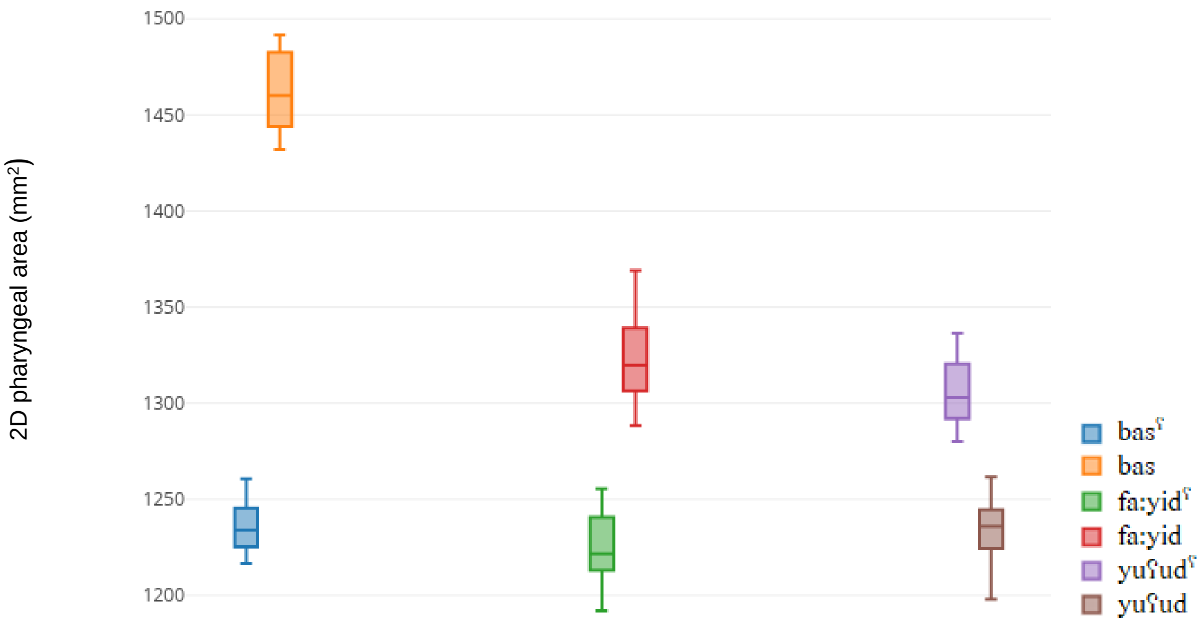


Figure 5.49: 2D pharyngeal areas (in mm^2) during short vowels preceding the plain-pharyngealized contrast for SP1.

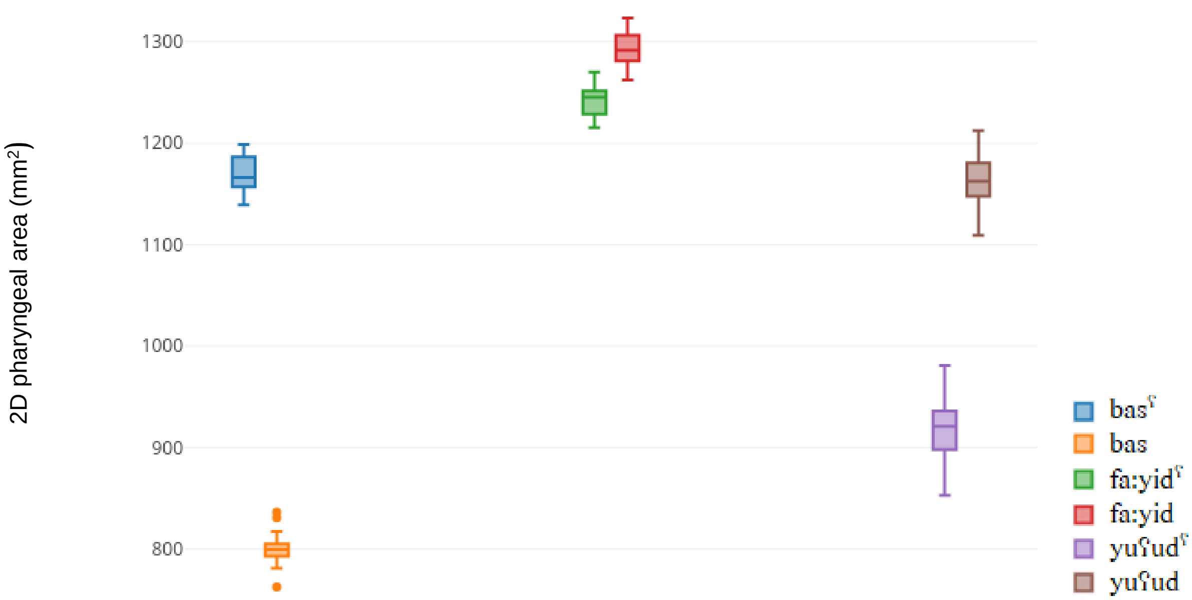


Figure 5.50: 2D pharyngeal areas (in mm^2) during short vowels preceding the plain-pharyngealized contrast for SP2.

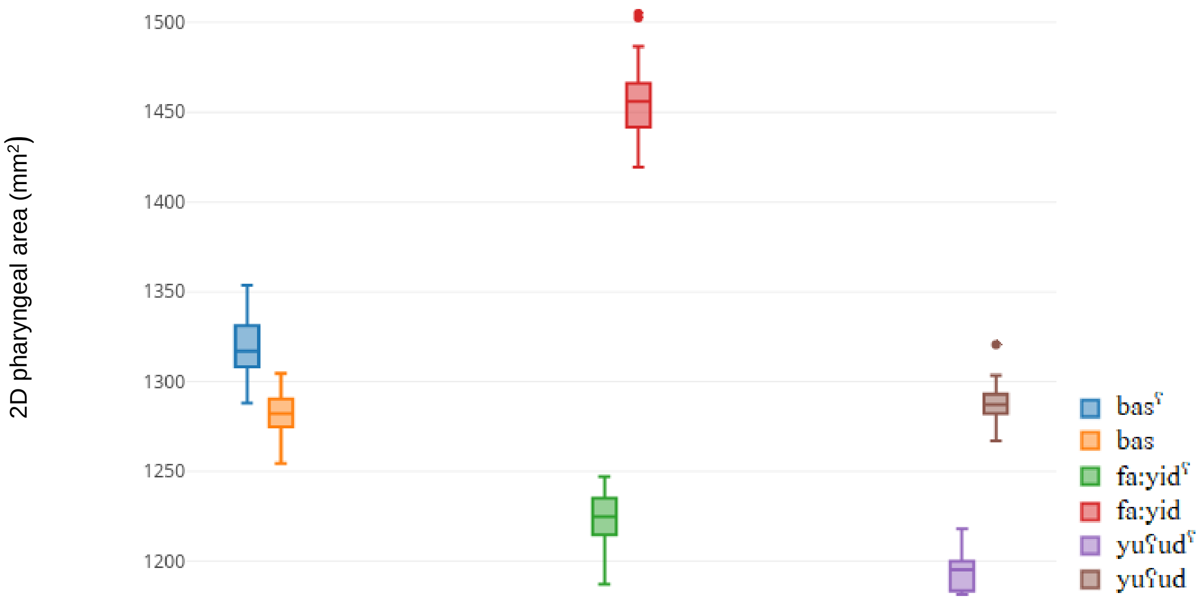


Figure 5.51: 2D pharyngeal areas (in mm^2) during short vowels preceding the plain-pharyngealized contrast for SP4.

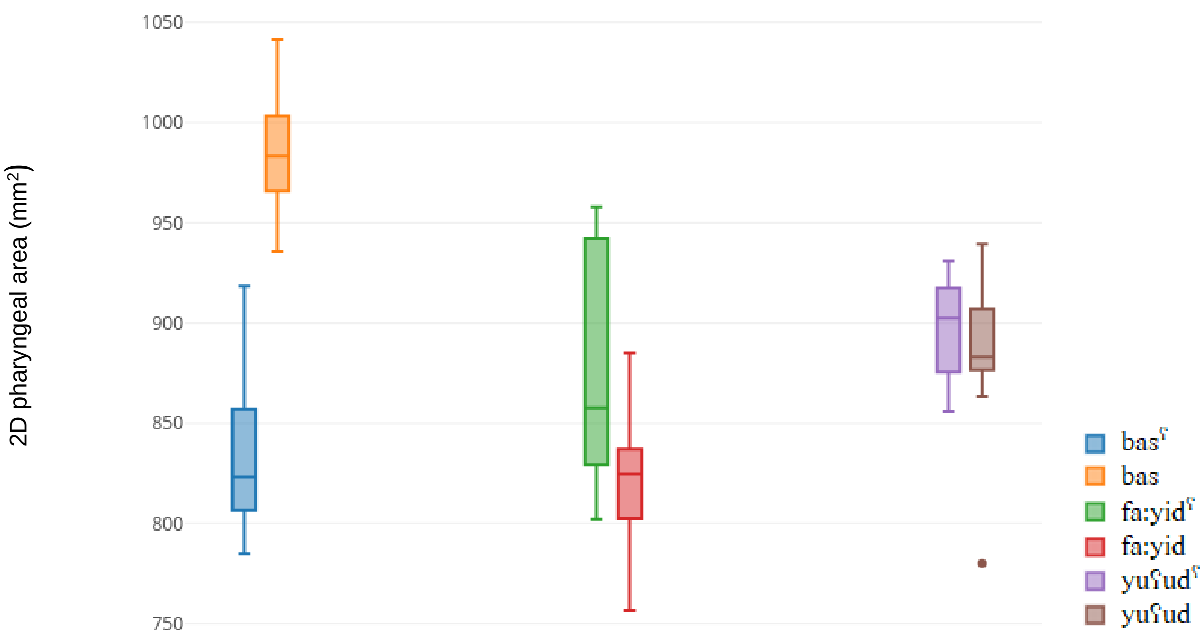


Figure 5.52: 2D pharyngeal areas (in mm^2) during short vowels preceding the plain-pharyngealized contrast for SP5.

The numerical averages of the 2D pharyngeal areas are listed in Table 5.13 - Table 5.16, as well as the absolute difference in the 2D pharyngeal areas between the pharyngealized and the plain pairs. This absolute difference is plotted in Figure 5.53 - Figure 5.56.

Table 5.13: Average 2D pharyngeal areas (in mm^2) during long vowels following the plain-pharyngealized contrast and the absolute difference between each pair for all speakers

		sˤa:b	sa:b	sˤi:n	si:n	tˤu:b	tu:b
SP1	Area	1259.575	1334.775	1218.625	1305.3	1284.8	1379.75
	Diff	75.2		86.675		94.95	
SP2	Area	984.6	1296.45	1175.85	1386	1074.6	1236.225
	Diff	311.85		210.15		161.625	
SP4	Area	1159.025	1342.525	1232.875	1557.475	1187.3	1231.05
	Diff	183.5		324.6		43.75	
SP5	Area	799.0357	1056.286	997.9643	1091.964	823.6786	857.6071
	Diff	257.25		94		33.92857	

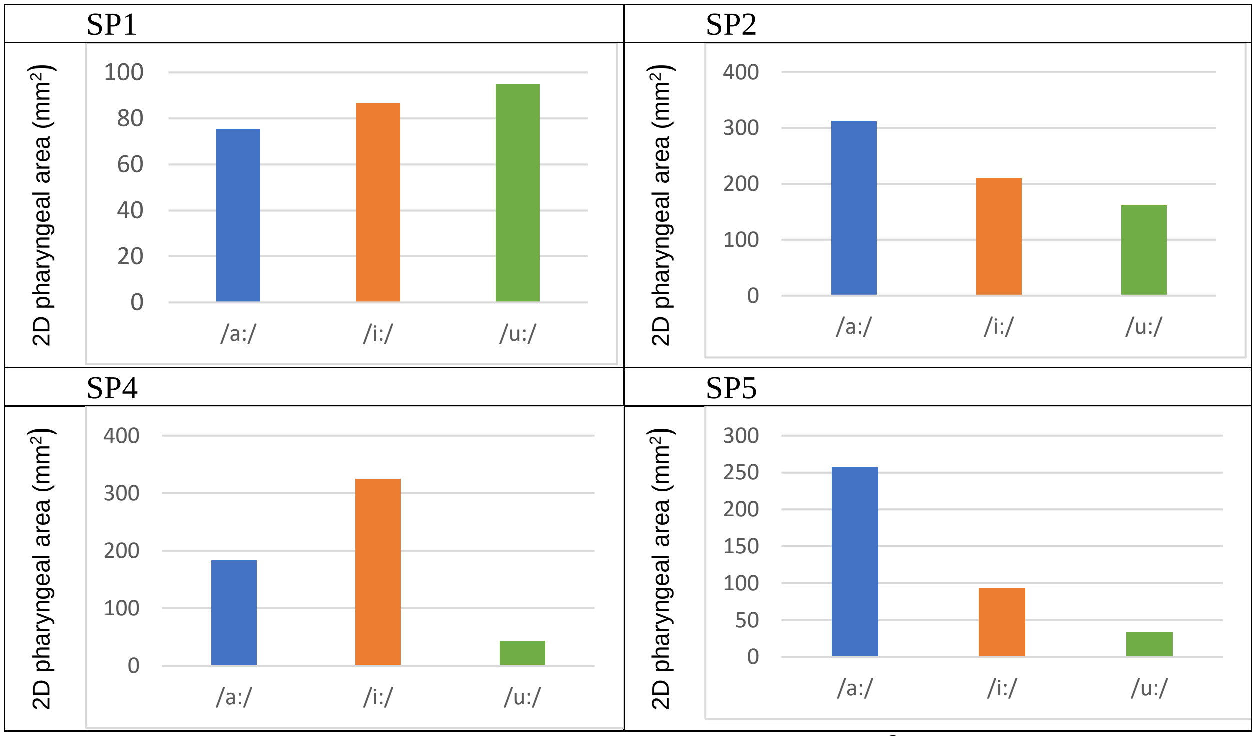


Figure 5.53: The absolute difference in 2D pharyngeal areas (in mm^2) in long vowels following plain-pharyngealized consonants for all speakers

Figure 5.53 - Figure 5.56 graphically show that for most of the data, the general trend is that the difference in 2D pharyngeal areas induced by pharyngealization is largest in an /a:/ vowel, followed by /i:/, and then /u:/.

Table 5.14: Average 2D pharyngeal areas (in mm^2) during long vowels preceding the plain-pharyngealized contrast and the absolute difference between each pair for all speakers

		ba:sˤ	ba:s	bi:dˤ	bi:d	bu:zˤ	bu:z
SP1	Area	1221.925	1338.3	1296.525	1376.8	1313.775	1240.8
	Diff	116.375		80.275		72.975	
SP2	Area	1003.475	1306.175	1393.45	1201.8	1203.225	1215.95
	Diff	302.7		191.65		12.725	
SP4	Area	1163.475	1391.05	1372.975	1311.2	1411.8	1366
	Diff	227.575		61.775		45.8	
SP5	Area	825.8214	949.9643	930.4643	1061.643	777.3571	696.2143
	Diff	124.1429		131.1786		81.14286	

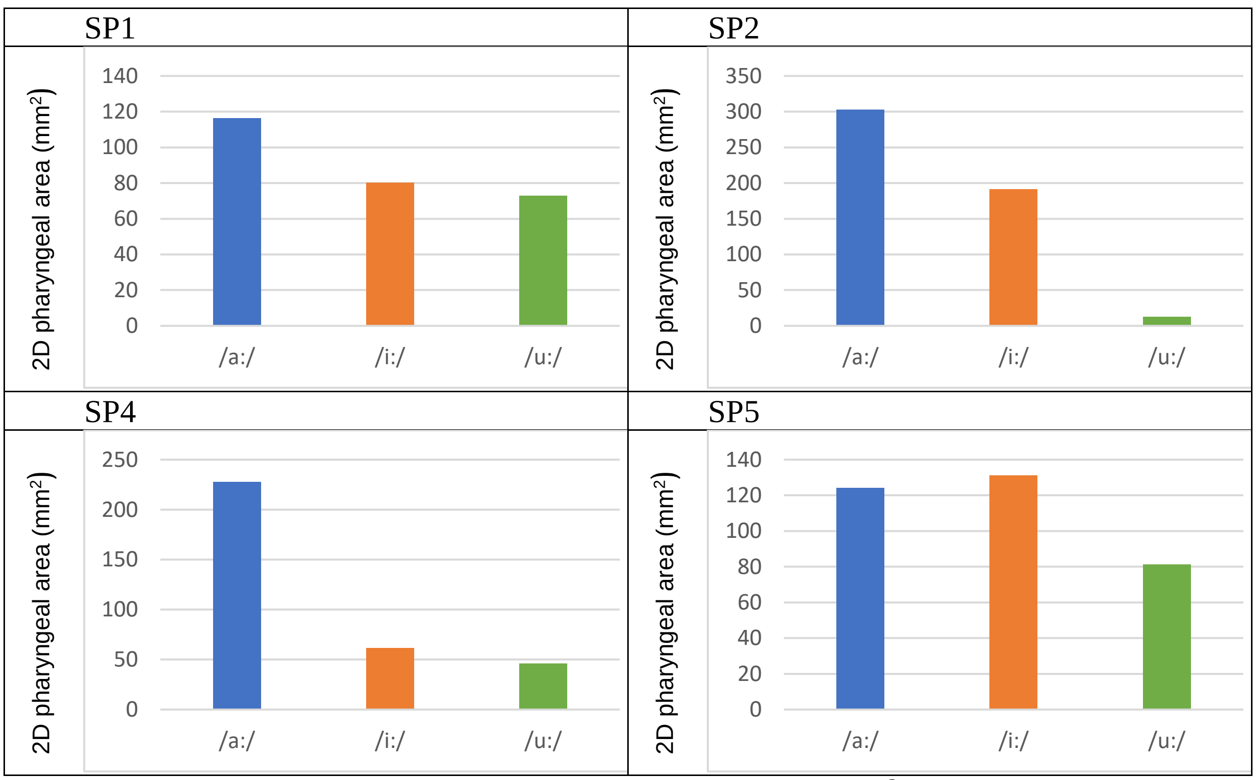


Figure 5.54: The absolute difference in 2D pharyngeal areas (in mm^2) in long vowels preceding plain-pharyngealized consonants for all speakers

Table 5.15: Average 2D pharyngeal areas (in mm^2) during short vowels following the plain-pharyngealized contrast and the absolute difference between each pair for all speakers

		sˤabb	sabb	azˤinn	azinn	tˤubb	tubʔa
SP1	Area	1345.625	1259	No data		1198.95	1313.925
	Diff	86.625				114.975	
SP2	Area	798.1	1196.2	1133.825	1258.875	1144.35	1186.5
	Diff	398.1		125.05		42.15	
SP4	Area	1260.175	1357.8	1295.775	1251.025	1386.475	1258.975
	Diff	97.625		44.75		127.5	
SP5	Area	835.6786	913.6071	966.4643	967.9286	803.0714	838.9286
	Diff	77.92857		1.464286		35.85714	

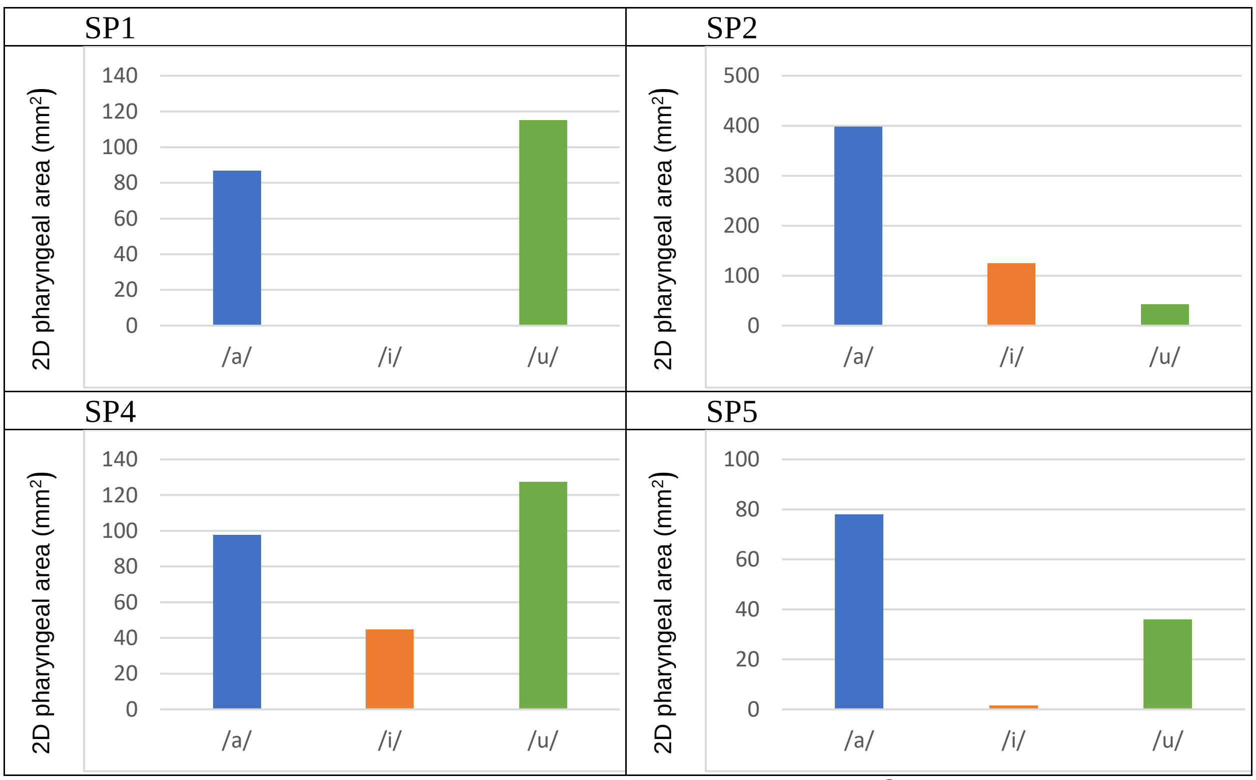


Figure 5.55: The absolute difference in 2D pharyngeal areas (in mm^2) in short vowels following plain-pharyngealized consonants for all speakers. No /i/ data is available for SP1.

Table 5.16: Average 2D pharyngeal areas (in mm^2) during short vowels preceding the plain-pharyngealized contrast and the absolute difference between each pair for all speakers

		basˤsˤ	bass	fa:yidˤ	fa:yid	yuʕudˤdˤ	yuʕud
SP1	Area	1235.65	1462.775	1224.55	1323.45	1305.95	1234.925
	Diff	227.125		98.9		71.025	
SP2	Area	1169.05	799.975	1241	1293.55	917.125	1164.45
	Diff	369.075		52.55		247.325	
SP4	Area	1319.5	1282.125	1221.975	1456.4	1194.25	1287.7
	Diff	37.375		234.425		93.45	
SP5	Area	833.1429	988.4286	875.3214	821.8571	898.8929	884
	Diff	155.2857		53.46429		14.89286	

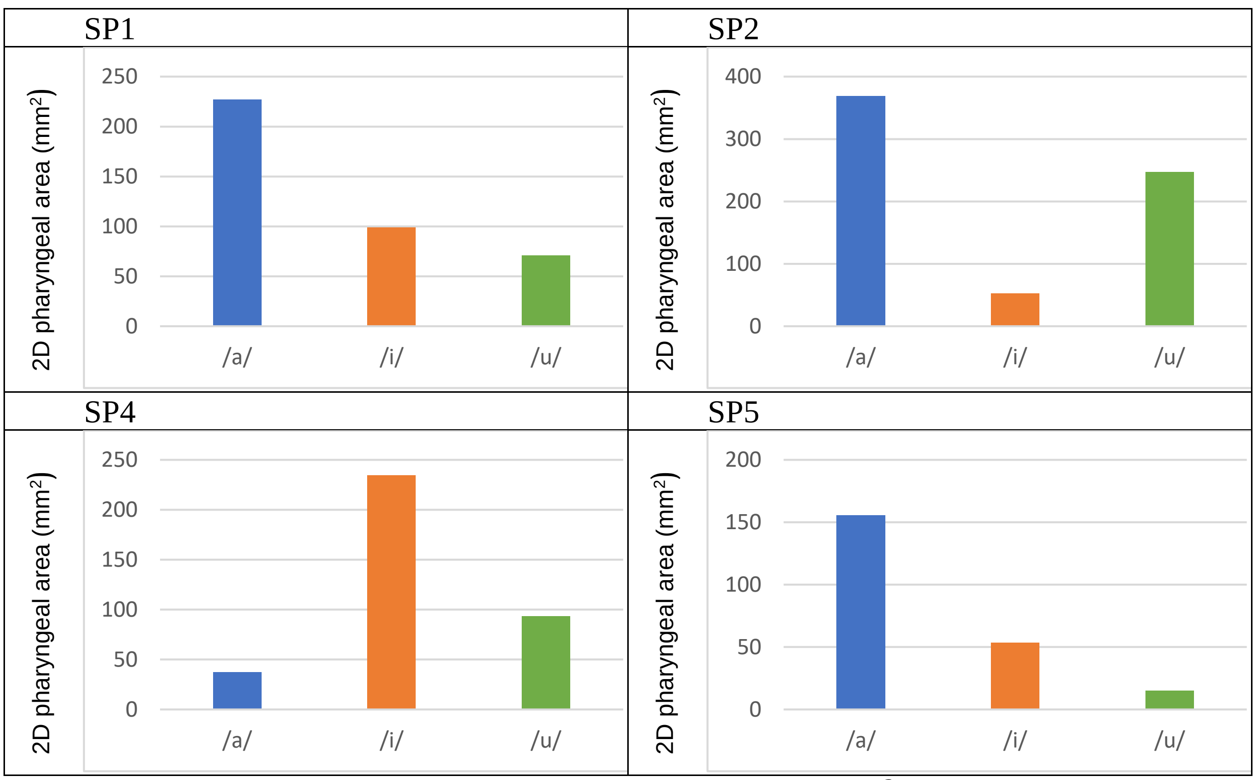


Figure 5.56: The absolute difference in 2D pharyngeal areas (in mm^2) in short vowels preceding plain-pharyngealized consonants for all speakers.

5.2 Results from acoustic data

Analyzing the acoustic data consisting of the vowel durations and formant frequencies for all four speakers reveal the following general observations:

1) The duration of the vowel extracted from the word with the pharyngealized consonant is generally longer than its counterpart extracted from the word with the plain consonant. This is generally the case regardless of vowel quality, and regardless of whether the plain-pharyngealized contrast occurs before or after the vowel.
2) The major acoustic consequence of a pharyngealized consonant is the lowering of F2. Thus, F2 in the vowel extracted from the word with the pharyngealized member is lower than F2 in the vowel extracted from the word with the plain counterpart. This is the case, regardless of vowel quality and vowel length. It is also the case whether the plain-pharyngealized contrast occurs before or after the vowel.
3) It is also observed that F1 in the pharyngealized vowel is sometimes higher than F1 in the plain counterpart.
4) The difference in the formant frequency modifications due to pharyngealization is generally the greatest in /a/, followed by /i/. The least formant frequency modification due to pharyngealization occurs in /u/. This is the case regardless of vowel length, and regardless of whether the pharyngealized consonant occurs before or after the vowel.
5) The difference in formant frequency modifications is greater in short vowels than in long vowels, regardless of vowel quality.
6) The difference in formant frequency modifications is generally greater in vowels preceding the pharyngealized consonants than in vowels following them.

In what follows are results demonstrating the previous observations from the four speakers.

Figure 5.57 - Figure 5.68 below show vowel durations for each speaker. These figures combine pharyngealized and plain vowels. A general trend is observed is that the average duration of pharyngealized vowel is longer than the average duration of its plain counterpart. This is the case for both long and short vowels, in all vowel qualities, and regardless of whether the plain-pharyngealized contrast occurs before or after the vowel. Nevertheless, an analysis of variance (ANOVA) of the vowel durations reveals that this difference does not attain statistical significance in most of the cases. The ANOVA model was computed for each speaker with vowel quality, spread direction, and consonant type (i.e. plain or pharyngealized) as factors. Results of the ANOVA analyses are presented in Table 5.17 - Table 5.24 below.

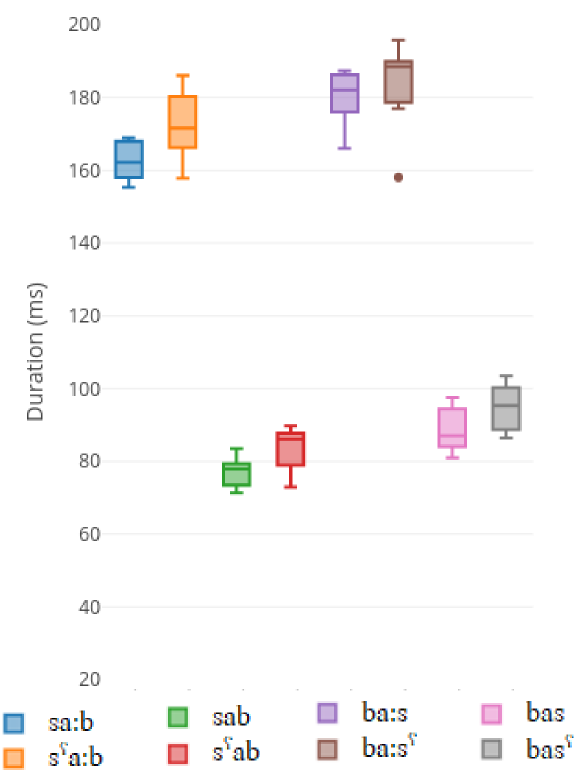


Figure 5.57: Long and short /a/ vowel durations in all target words for SP1.

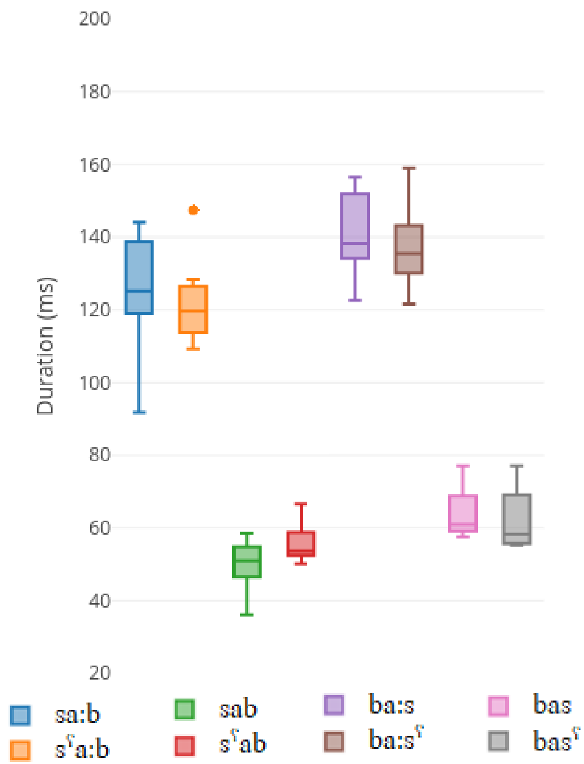


Figure 5.58: Long and short /a/ vowel durations in all target words for SP2.

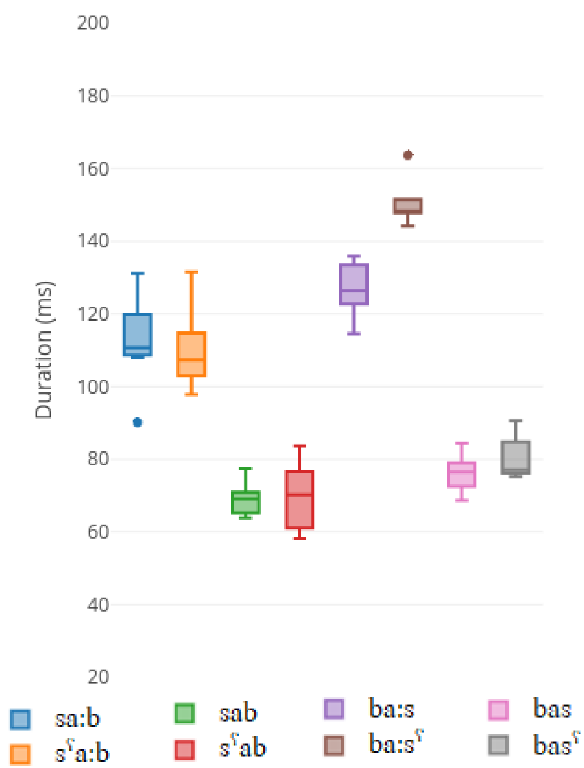


Figure 5.59: Long and short /a/ vowel durations in all target words for SP4.

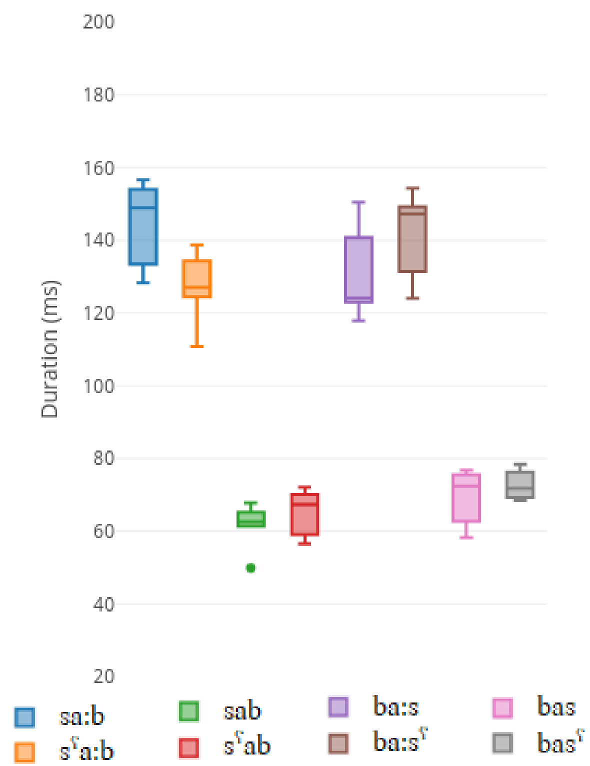


Figure 5.60: Long and short /a/ vowel durations in all target words for SP5.

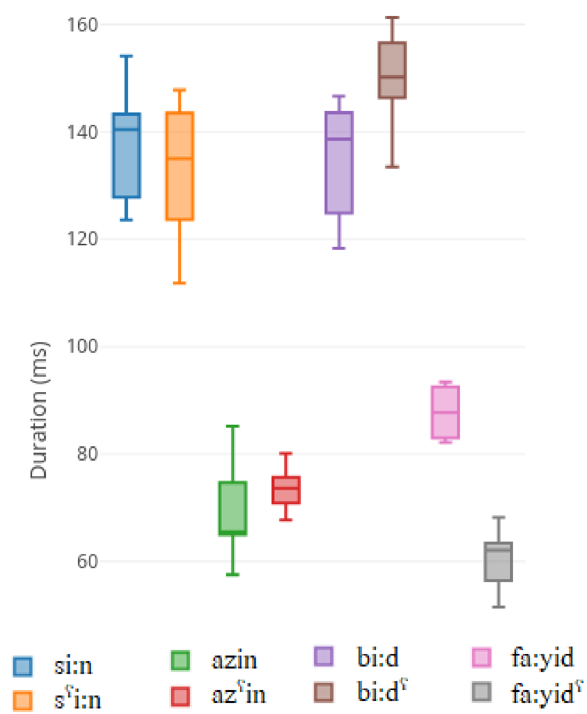


Figure 5.61: Long and short /i/ vowel durations in all target words for SP1.

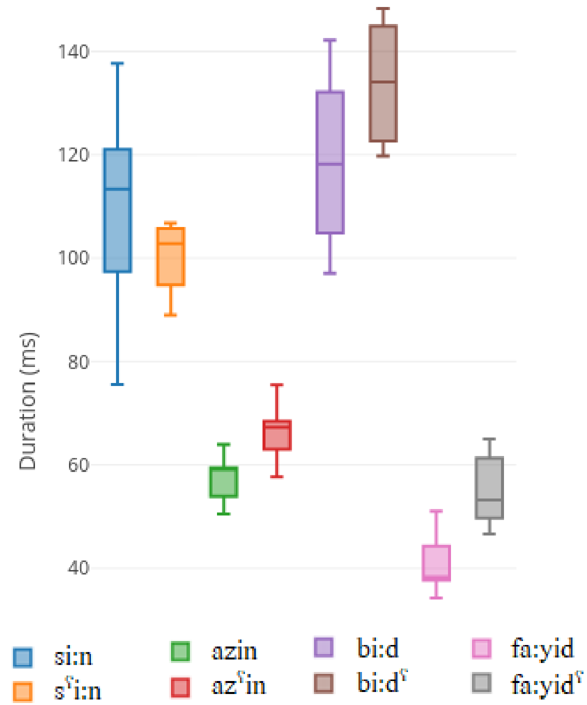


Figure 5.62: Long and short /i/ vowel durations in all target words for SP2.

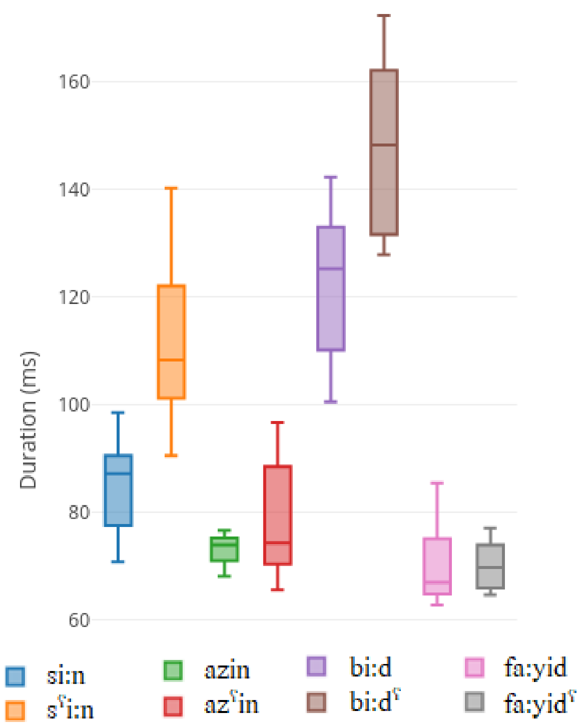


Figure 5.63: Long and short /i/ vowel durations in all target words for SP4.

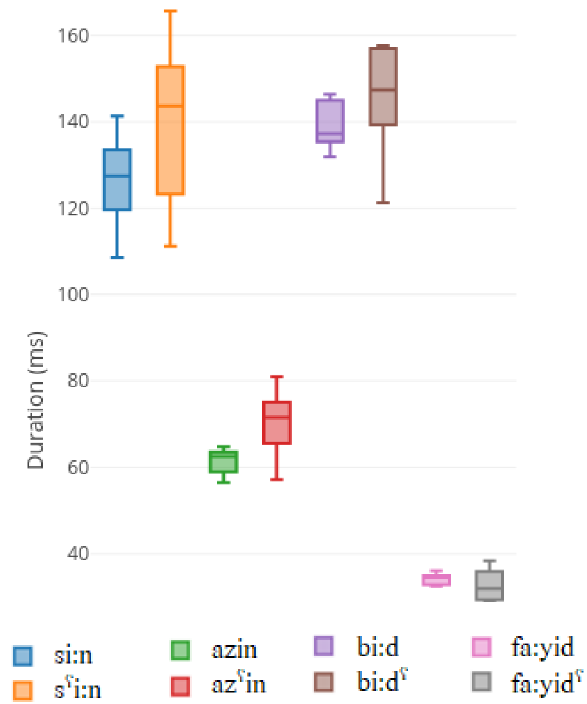


Figure 5.64: Long and short /i/ vowel durations in all target words for SP5.

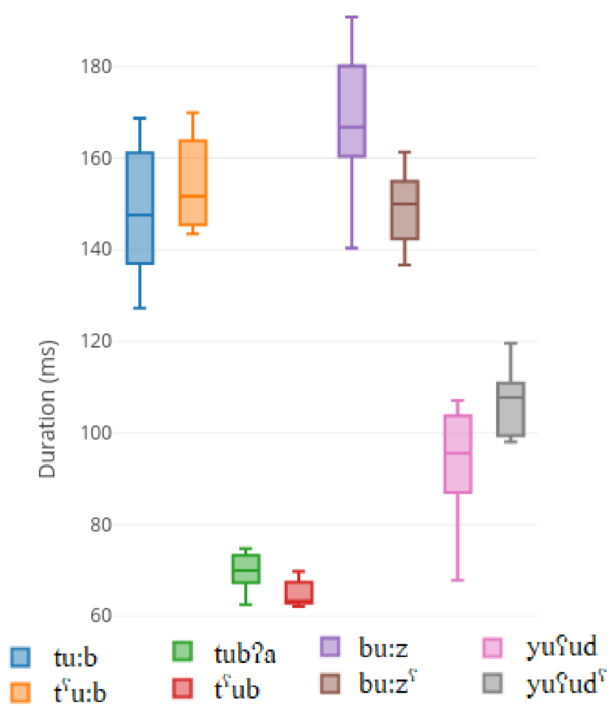


Figure 5.65: Long and short /u/ vowel durations in all target words for SP1.

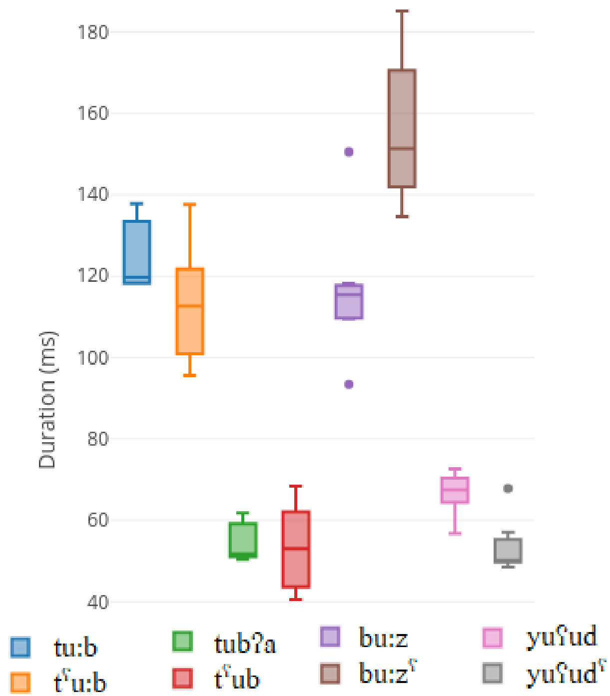


Figure 5.66: Long and short /u/ vowel durations in all target words for SP2.

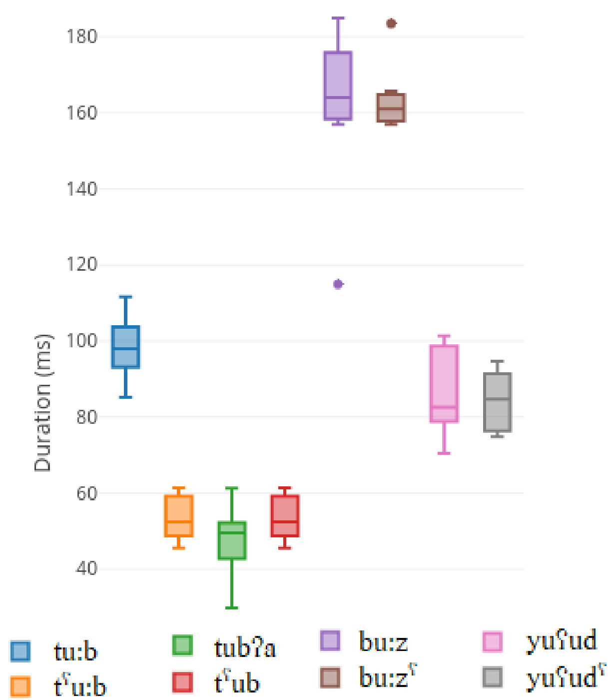


Figure 5.67: Long and short /u/ vowel durations in all target words for SP4.

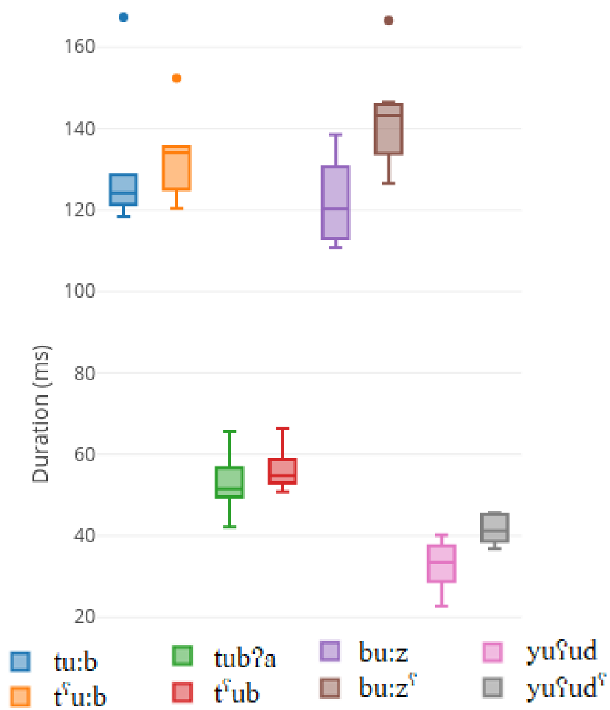


Figure 5.68: Long and short /u/ vowel durations in all target words for SP5.

Table 5.17: Analysis of variance (ANOVA) for long vowel duration of SP1.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)
vowel_qual        2  17779    8890  59.413  < 2e-16 ***
type              1     76      76   0.506 0.478882
spread_direction  1   1786    1786  11.935 0.000889 ***
Residuals        79  11820     150
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.18: Analysis of variance (ANOVA) for short vowel duration of SP1.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)
vowel_qual        2   2755    1378   10.54 8.77e-05 ***
type              1      4       4    0.03    0.864
spread_direction  1   5117    5117   39.14 1.90e-08 ***
Residuals        79  10328     131
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.19: Analysis of variance (ANOVA) for long vowel duration of SP2.

```
                  Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_qual         2   3822    1911   6.759  0.00195 ** 
type               1    461     461   1.630  0.20542    
spread_direction   1   6879    6879  24.328 4.41e-06 ***
Residuals         79  22336     283                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.20: Analysis of variance (ANOVA) for short vowel duration of SP2.

```
                  Df Sum Sq Mean Sq F value Pr(>F)
vowel_qual         2    162   80.76   0.861  0.426
type               1    111  110.73   1.181  0.280
spread_direction   1     12   12.44   0.133  0.717
Residuals         79   7406   93.75               
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.21: Analysis of variance (ANOVA) for long vowel duration of SP4.

```
                  Df Sum Sq Mean Sq F value Pr(>F)    
vowel_qual         2    981     491   0.994  0.375    
type               1    474     474   0.961  0.330    
spread_direction   1  53289   53289 107.985 <2e-16 ***
Residuals         79  38986     493                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.22: Analysis of variance (ANOVA) for short vowel duration of SP4.

```
                  Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_qual         2    564     282   2.071    0.133    
type               1    118     118   0.868    0.354    
spread_direction   1   3367    3367  24.722 3.77e-06 ***
Residuals         79  10758     136                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.23: Analysis of variance (ANOVA) for long vowel duration of SP5.

```
                 Df Sum Sq Mean Sq F value Pr(>F)
vowel_qual        2    515   257.7   1.403 0.2520
type              1    767   767.2   4.176 0.0443 *
spread_direction  1    269   269.5   1.467 0.2295
Residuals        79  14514   183.7
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.24: Analysis of variance (ANOVA) for short vowel duration of SP5.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)
vowel_qual        2   7313    3657  35.814 8.49e-12 ***
type              1    402     402   3.941   0.0506 .
spread_direction  1   4144    4144  40.584 1.16e-08 ***
Residuals        79   8066     102
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

The second point above discusses the major acoustic consequence of pharyngealization, which is the modification of the formant frequencies. The general trend that is reported in the literature and observed in the results here is the lowering of F2. Other reports also mention the raising of F1. The results below especially corroborate the former modification (lowering of F2). This is generally observed in all vowels, regardless of quality and length. The raising of F1, however, is observed in some data. These results are plotted from mean formant values in Figure 5.69 - Figure 5.92. Figure 5.69 - Figure 5.72, Figure 5.73 - Figure 5.76, and Figure 5.77 - Figure 5.80 show plots of F1 during /a/ vowels for all speakers, during /i/ vowels for all speakers, and during /u/ vowels for all speakers respectively. Figure 5.81 - Figure 5.84, Figure 5.85 - Figure 5.88, and Figure 5.89 - Figure 5.92 show plots of F2 during /a/ vowels for all speakers, during /i/ vowels for all speakers, and during /u/ vowels for all speakers respectively. More comprehensive measurements of the formant frequencies throughout the duration of the vowel are discussed and presented later in this chapter.

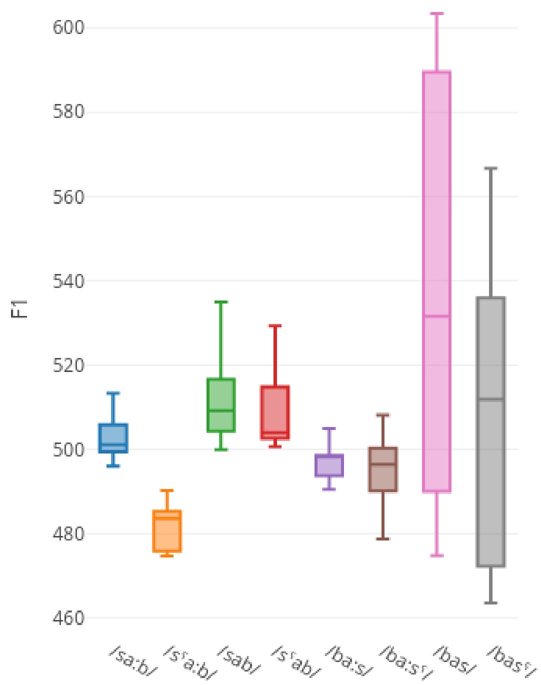


Figure 5.69: Mean F1 values in /a/ vowels for SP1

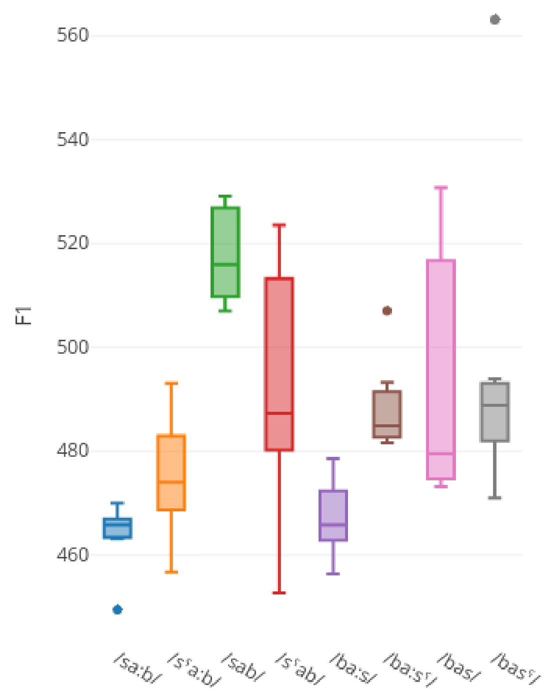


Figure 5.70: Mean F1 values in /a/ vowels for SP2

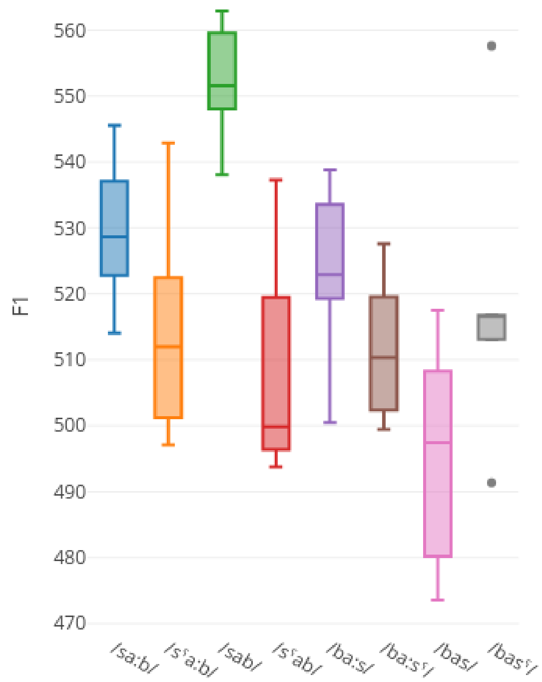


Figure 5.71: Mean F1 values in /a/ vowels for SP4

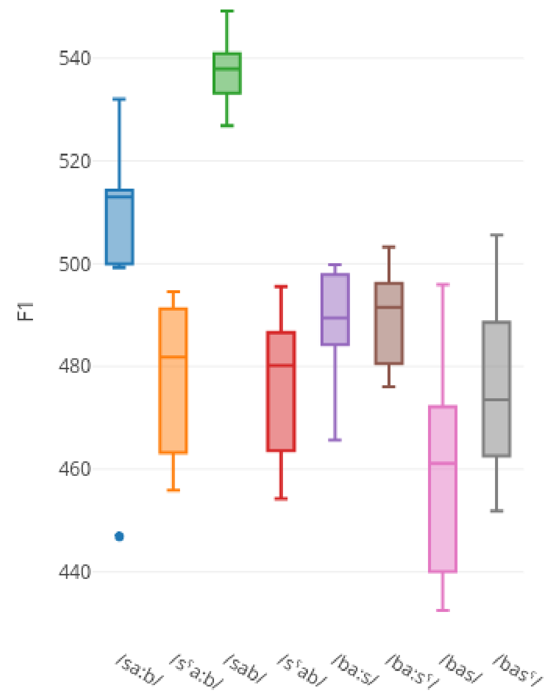


Figure 5.72: Mean F1 values in /a/ vowels for SP5

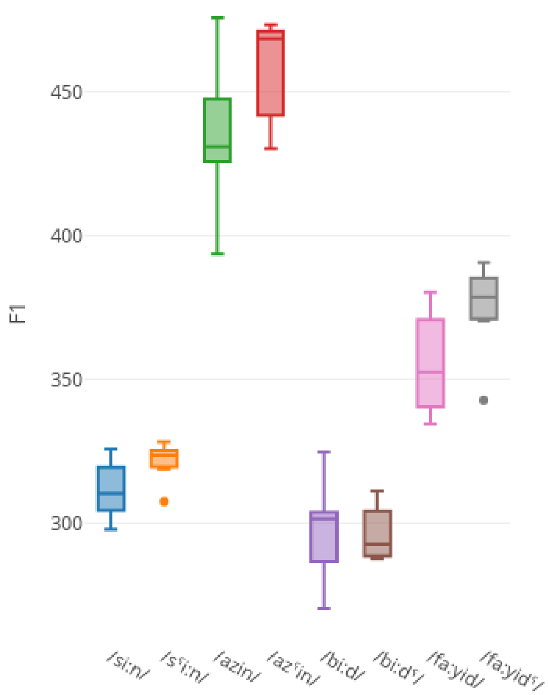


Figure 5.73: Mean F1 values in /i/ vowels for SP1

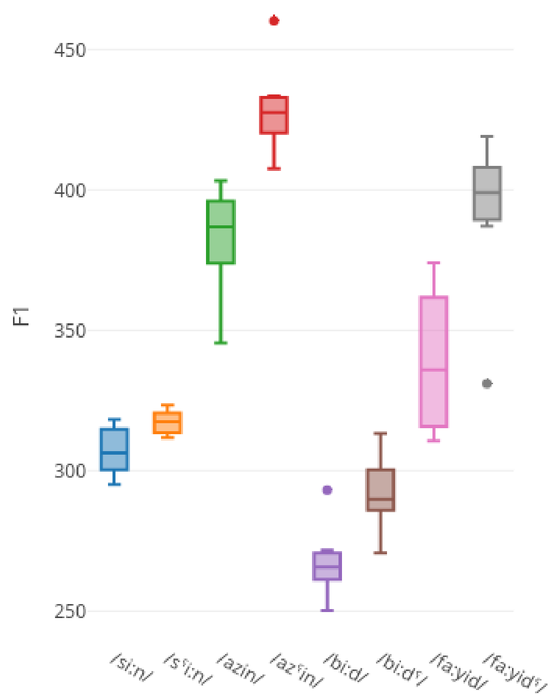


Figure 5.74: Mean F1 values in /i/ vowels for SP2

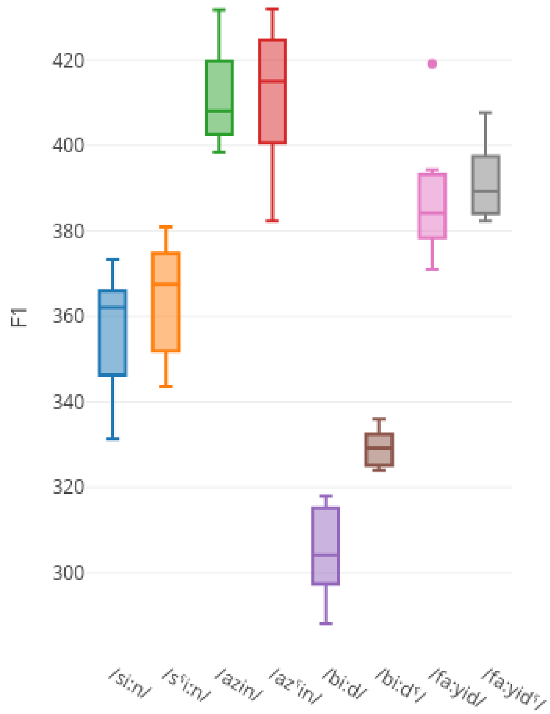


Figure 5.75: Mean F1 values in /i/ vowels for SP4

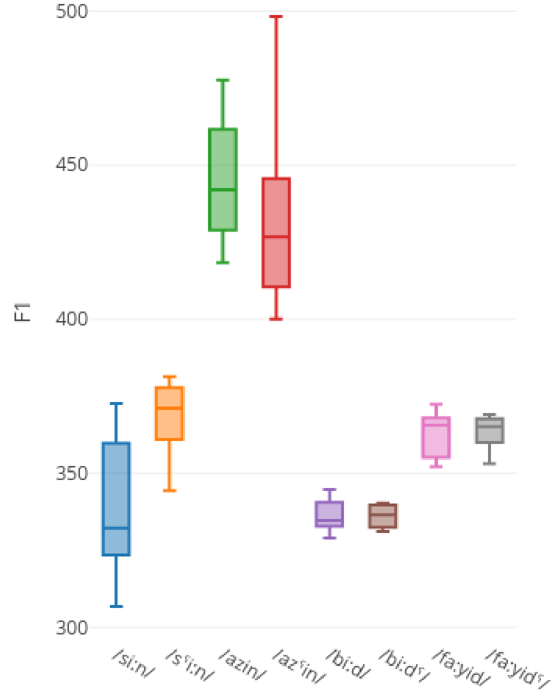


Figure 5.76: Mean F1 values in /i/ vowels for SP5

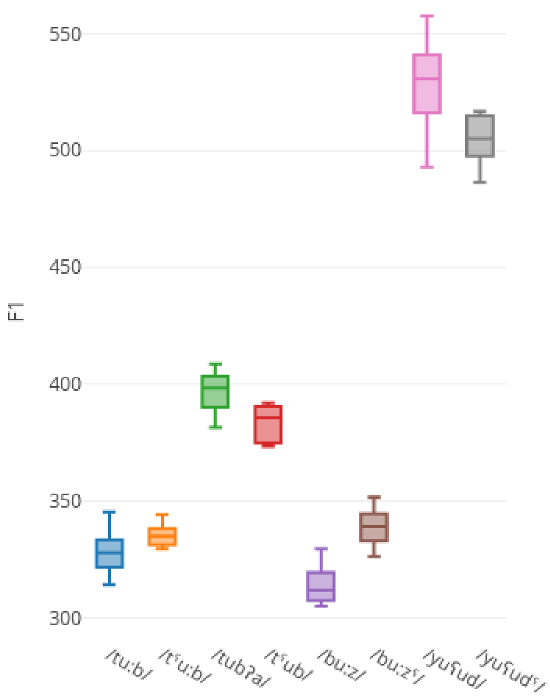


Figure 5.77: Mean F1 values in /u/ vowels for SP1

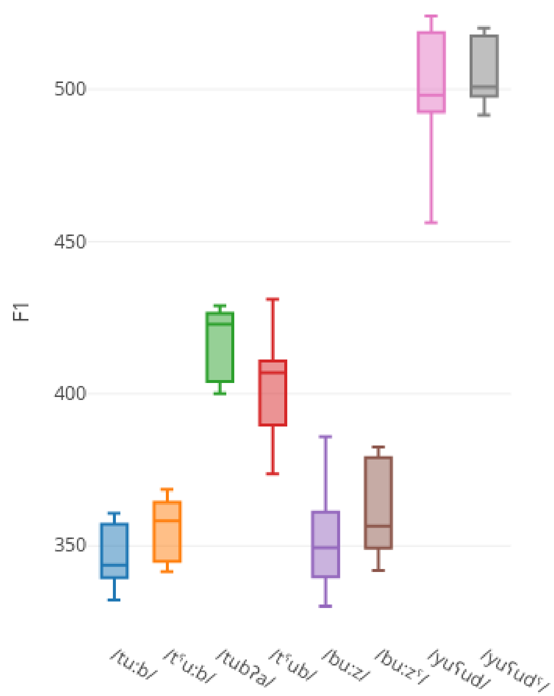


Figure 5.78: Mean F1 values in /u/ vowels for SP2

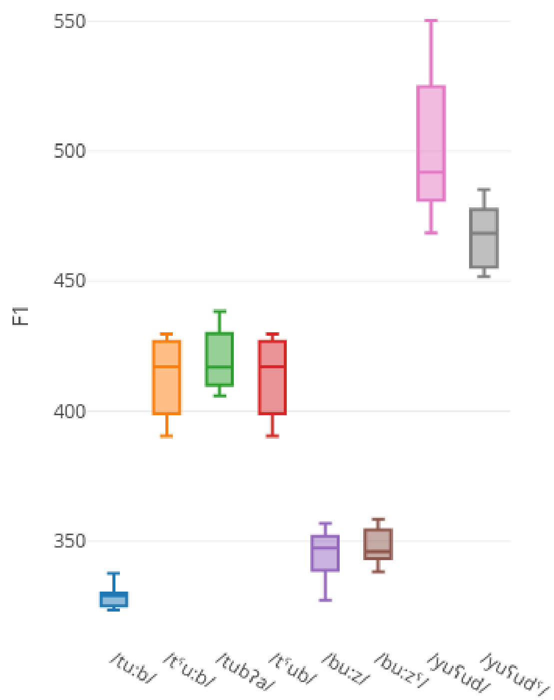


Figure 5.79: Mean F1 values in /u/ vowels for SP4

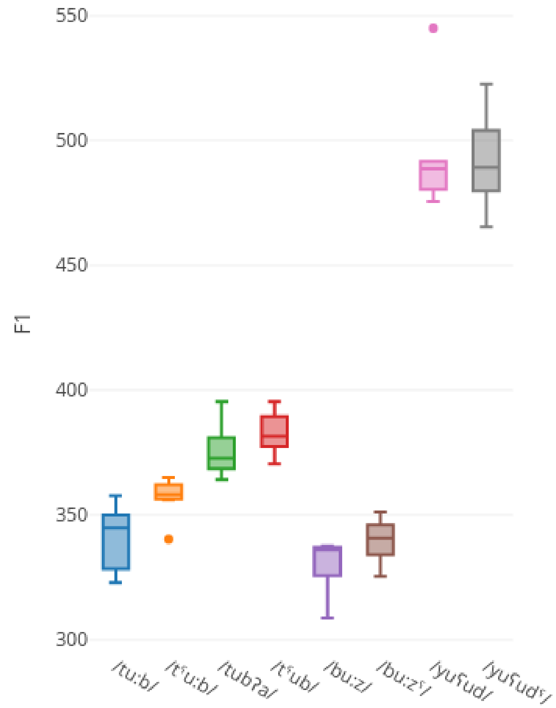


Figure 5.80: Mean F1 values in /u/ vowels for SP5

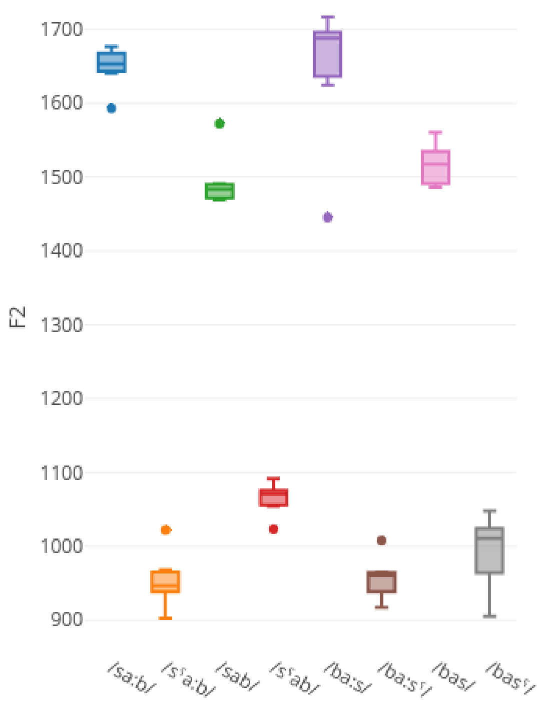


Figure 5.81: Mean F2 values in /a/ vowels for SP1

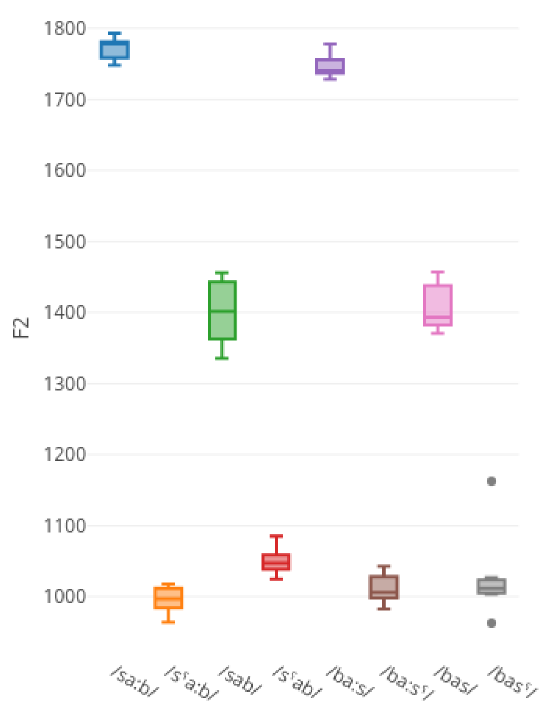


Figure 5.82: Mean F2 values in /a/ vowels for SP2

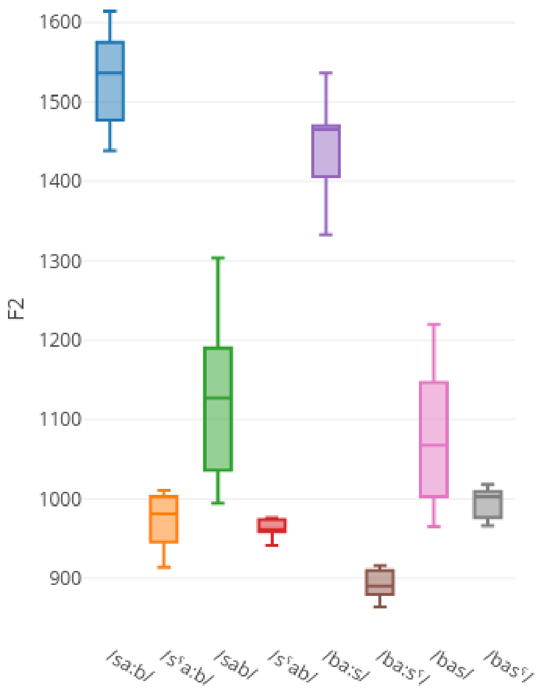


Figure 5.83: Mean F2 values in /a/ vowels for SP4

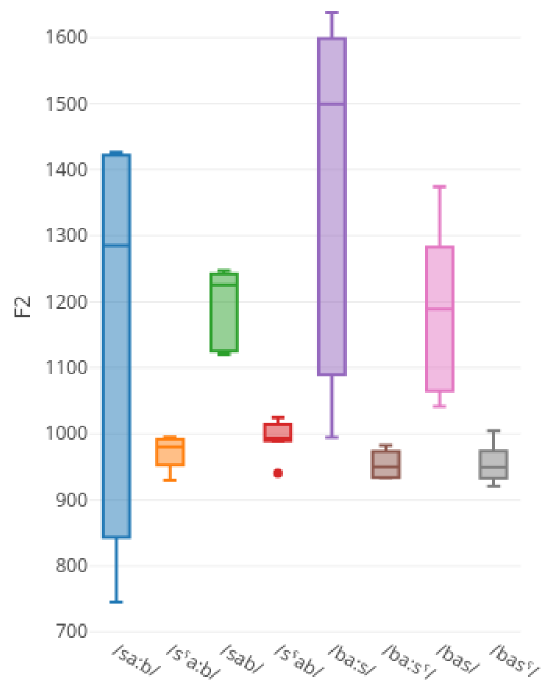


Figure 5.84: Mean F2 values in /a/ vowels for SP5

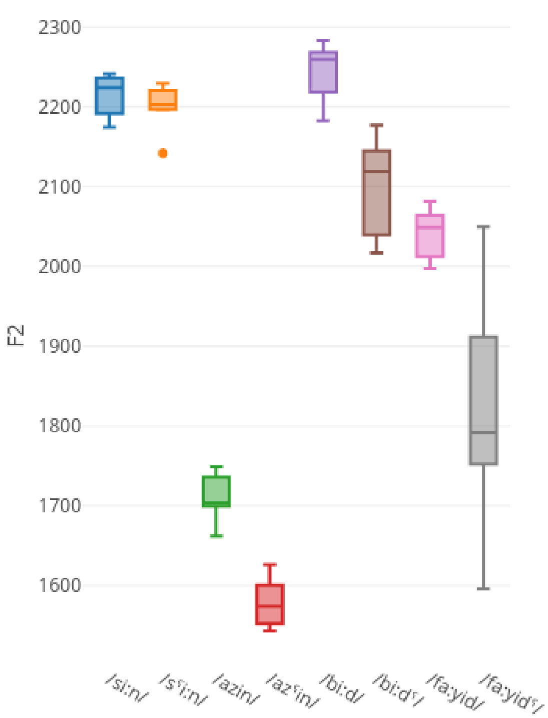


Figure 5.85: Mean F2 values in /i/ vowels for SP1

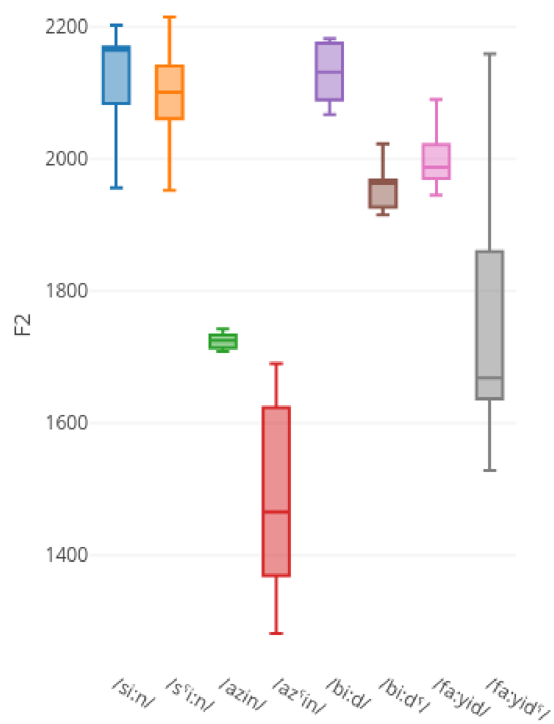


Figure 5.86: Mean F2 values in /i/ vowels for SP2

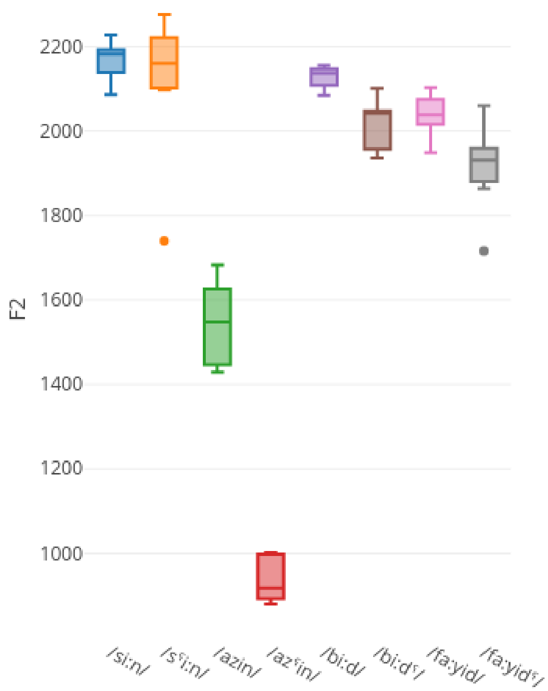


Figure 5.87: Mean F2 values in /i/ vowels for SP4

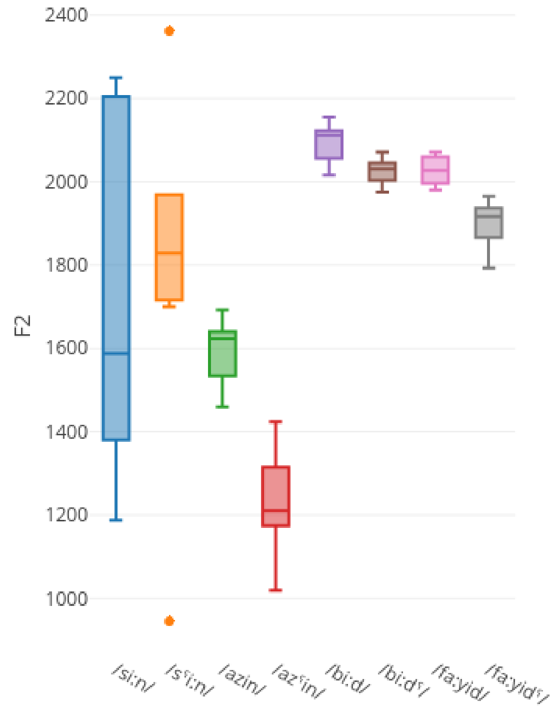


Figure 5.88: Mean F2 values in /i/ vowels for SP5

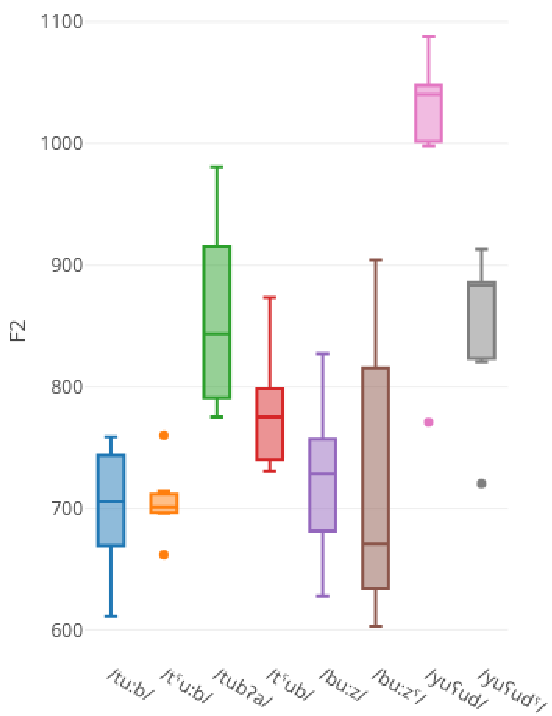


Figure 5.89: Mean F2 values in /u/ vowels for SP1

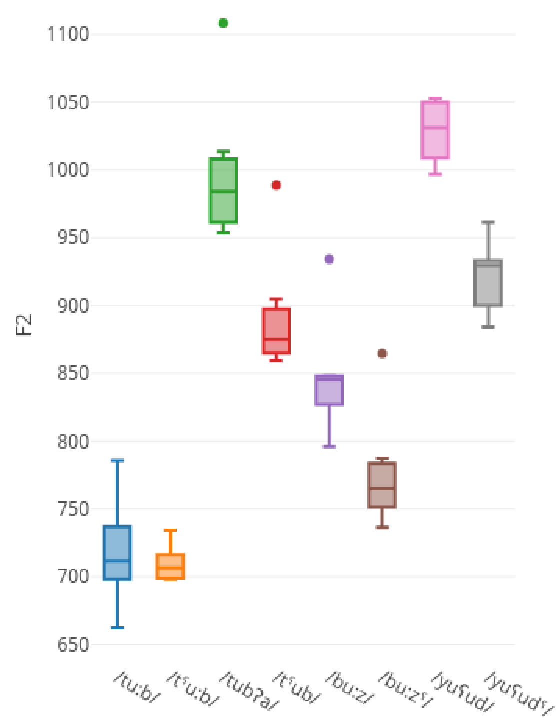


Figure 5.90: Mean F2 values in /u/ vowels for SP2

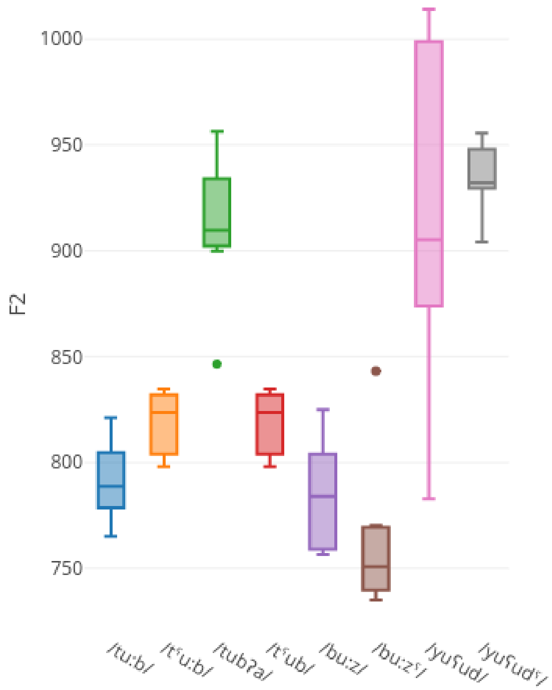


Figure 5.91: Mean F2 values in /u/ vowels for SP4

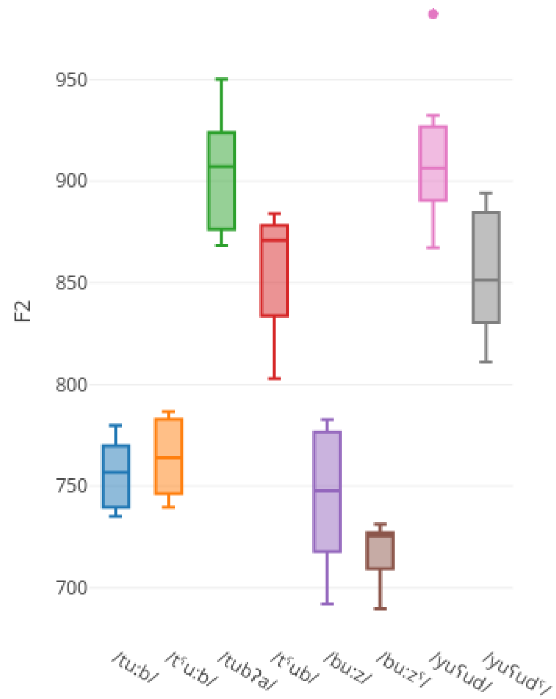


Figure 5.92: Mean F2 values in /u/ vowels for SP5

To measure statistical significance of differences in in formant frequencies, analysis of variance models were computed, with vowel length (`vowel_length`), spread direction (`spread_direction`), and consonant type (`type`) (i.e. plain or pharyngealized) as factors. Table 5.24 - Table 5.48 present results from this ANOVA tests.

Table 5.25: Analysis of variance (ANOVA) for F1 in /a/ in Figure 5.69 of SP1.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)
vowel_length      1   7349    7349  12.822 0.000753 ***
type              1   2732    2732   4.767 0.033543 *
spread_direction  1    936     936   1.633 0.206975
Residuals        52  29804     573
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.26: Analysis of variance (ANOVA) for F1 in /a/ in Figure 5.70 of SP2.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1   9373    9373  23.106 1.35e-05 ***
type              1    100     100   0.246    0.622    
spread_direction  1     16      16   0.040    0.842    
Residuals        52  21095     406                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.27: Analysis of variance (ANOVA) for F1 in /a/ in Figure 5.71 of SP4.

```
                 Df Sum Sq Mean Sq F value  Pr(>F)   
vowel_length      1     21    21.3   0.058 0.81031   
type              1   2214  2214.0   6.039 0.01737 * 
spread_direction  1   2661  2661.0   7.258 0.00948 **
Residuals        52  19065   366.6                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.28: Analysis of variance (ANOVA) for F1 in /a/ in Figure 5.72 of SP5.

```
                 Df Sum Sq Mean Sq F value  Pr(>F)   
vowel_length      1     94      94   0.157 0.69338   
type              1   4027    4027   6.768 0.01206 * 
spread_direction  1   6042    6042  10.155 0.00243 **
Residuals        52  30938     595                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.29: Analysis of variance (ANOVA) for F1 in /i/ in Figure 5.73 of SP1.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1 137468  137468 265.831  < 2e-16 ***
type              1   2362    2362   4.567   0.0373 *  
spread_direction  1  35798   35798  69.226 3.98e-11 ***
Residuals        52  26890     517                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.30: Analysis of variance (ANOVA) for F1 in /i/ in Figure 5.74 of SP2.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1 112888  112888  296.28  < 2e-16 ***
type              1  15513   15513   40.72 4.80e-08 ***
spread_direction  1  18350   18350   48.16 6.18e-09 ***
Residuals        52  19813     381                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.31: Analysis of variance (ANOVA) for F1 in /i/ in Figure 5.75 of SP4.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1  53570   53570 257.450  < 2e-16 ***
type              1   1097    1097   5.274   0.0257 *  
spread_direction  1  14728   14728  70.779 2.85e-11 ***
Residuals        52  10820     208                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.32: Analysis of variance (ANOVA) for F1 in /i/ in Figure 5.76 of SP5.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1  43931   43931   77.02 7.72e-12 ***
type              1    234     234    0.41    0.525    
spread_direction  1  31415   31415   55.08 1.05e-09 ***
Residuals        52  29659     570                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.33: Analysis of variance (ANOVA) for F1 in /u/ in Figure 5.77 of SP1.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1 215035  215035 155.511  < 2e-16 ***
type              1     25      25   0.018    0.894    
spread_direction  1  51824   51824  37.479 1.23e-07 ***
Residuals        52  71904    1383                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.34: Analysis of variance (ANOVA) for F1 in /u/ in Figure 5.78 of SP2.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1 145004  145004 187.103  < 2e-16 ***
type              1     87      87   0.112     0.74    
spread_direction  1  35197   35197  45.415 1.29e-08 ***
Residuals        52  40300     775                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.35: Analysis of variance (ANOVA) for F1 in /u/ in Figure 5.79 of SP4.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1 117652  117652  89.497 6.81e-13 ***
type              1   1801    1801   1.370   0.2471    
spread_direction  1   6880    6880   5.233   0.0263 *  
Residuals        52  68359    1315                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.36: Analysis of variance (ANOVA) for F1 in /u/ in Figure 5.80 of SP5.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1 124815  124815  97.132 1.71e-13 ***
type              1    888     888   0.691     0.41    
spread_direction  1  35271   35271  27.448 2.97e-06 ***
Residuals        52  66821    1285                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.37: Analysis of variance (ANOVA) for F2 in /a/ in Figure 5.81 of SP1.

```
                 Df  Sum Sq Mean Sq F value Pr(>F)    
vowel_length      1   17272   17272   3.156 0.0815 .  
type              1 4771966 4771966 871.860 <2e-16 ***
spread_direction  1    1806    1806   0.330 0.5682    
Residuals        52  284613    5473                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.38: Analysis of variance (ANOVA) for F2 in /a/ in Figure 5.82 of SP2.

```
                 Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1  361070  361070   31.49 7.84e-07 ***
type              1 4393970 4393970  383.26  < 2e-16 ***
spread_direction  1     462     462    0.04    0.842    
Residuals        52  596171   11465                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.39: Analysis of variance (ANOVA) for F2 in /a/ in Figure 5.83 of SP4.

```
                 Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1  401421  401421  24.194 9.14e-06 ***
type              1 1600399 1600399  96.459 1.93e-13 ***
spread_direction  1   29006   29006   1.748    0.192    
Residuals        52  862761   16592                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.40: Analysis of variance (ANOVA) for F2 in /a/ in Figure 5.84 of SP5.

```
                 Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1    9860    9860   0.373    0.544    
type              1  879211  879211  33.261 4.48e-07 ***
spread_direction  1   21396   21396   0.809    0.372    
Residuals        52 1374550   26434                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.41: Analysis of variance (ANOVA) for F2 in /i/ in Figure 5.85 of SP1.

```
                 Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1 2254845 2254845  187.29  < 2e-16 ***
type              1  228513  228513   18.98 6.24e-05 ***
spread_direction  1  222950  222950   18.52 7.45e-05 ***
Residuals        52  626041   12039                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.42: Analysis of variance (ANOVA) for F2 in /i/ in Figure 5.86 of SP2.

```
                 Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1 1579578 1579578  79.580 4.60e-12 ***
type              1  413766  413766  20.846 3.08e-05 ***
spread_direction  1  152227  152227   7.669  0.00777 ** 
Residuals        52 1032151   19849                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.43: Analysis of variance (ANOVA) for F2 in /i/ in Figure 5.87 of SP4.

```
                 Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1 3452552 3452552   53.77 1.46e-09 ***
type              1  696550  696550   10.85  0.00178 ** 
spread_direction  1 1544863 1544863   24.06 9.59e-06 ***
Residuals        52 3339039   64212                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.44: Analysis of variance (ANOVA) for F2 in /i/ in Figure 5.88 of SP5.

```
                 Df  Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1  710532  710532  12.040  0.00106 ** 
type              1  232063  232063   3.932  0.05266 .  
spread_direction  1 2488349 2488349  42.164 3.18e-08 ***
Residuals        52 3068803   59015                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.45: Analysis of variance (ANOVA) for F2 in /u/ in Figure 5.89 of SP1.

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
vowel_length      1 358909  358909  52.459 2.03e-09 ***
type              1  45814   45814   6.696  0.01250 *  
spread_direction  1  51973   51973   7.596  0.00805 ** 
Residuals        52 355769    6842                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5.46: Analysis of variance (ANOVA) for F2 in /u/ in Figure 5.90 of SP2.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
vowel_length	1	543376	543376	265.06	< 2e-16	***
type	1	76329	76329	37.23	1.33e-07	***
spread_direction	1	58275	58275	28.43	2.14e-06	***
Residuals	52	106602	2050			

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 5.47: Analysis of variance (ANOVA) for F2 in /u/ in Figure 5.91 of SP4.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
vowel_length	1	159257	159257	64.197	1.22e-10	***
type	1	3982	3982	1.605	0.211	
spread_direction	1	3370	3370	1.359	0.249	
Residuals	52	129000	2481			

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 5.48: Analysis of variance (ANOVA) for F2 in /u/ in Figure 5.92 of SP5.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
vowel_length	1	258979	258979	270.426	< 2e-16	***
type	1	13503	13503	14.100	0.000439	***
spread_direction	1	2116	2116	2.209	0.143226	
Residuals	52	49799	958			

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

F1 versus F2-F1 are also plotted for each speaker in Figure 5.93 - Figure 5.96. They corroborate the general trend described above: a lowering of F2 and in some cases a raising of F1.

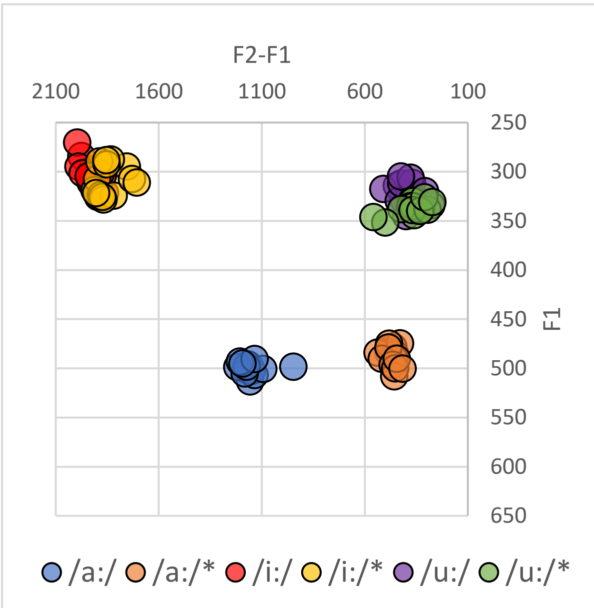
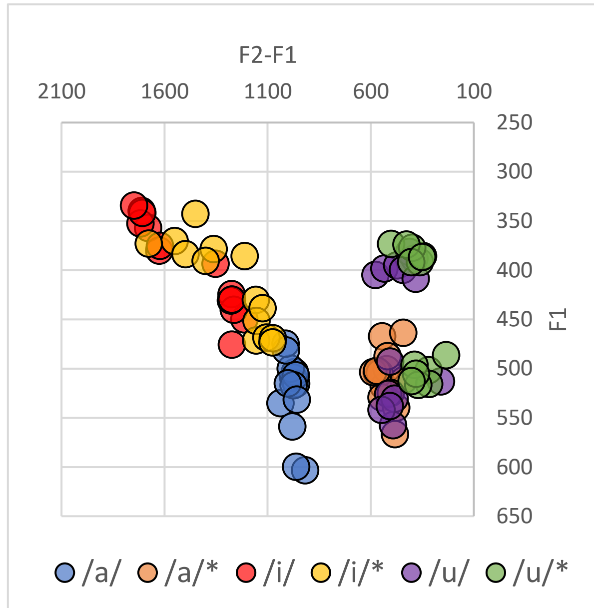
Long vowels	Short vowels
	

Figure 5.93: F1 vs. F2-F1 plots of long and short vowels for SP1.

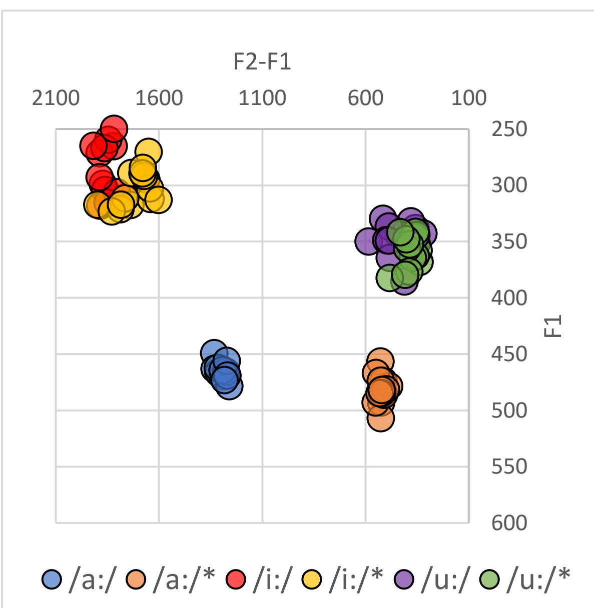
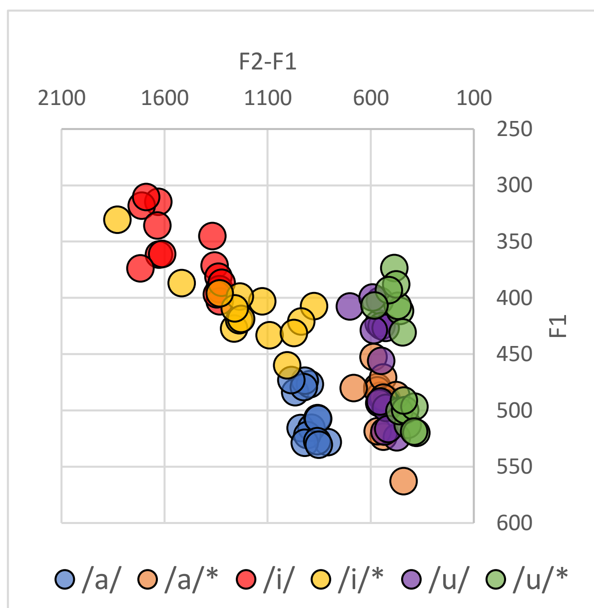
Long vowels	Short vowels
	

Figure 5.94: F1 vs. F2-F1 plots of long and short vowels for SP2.

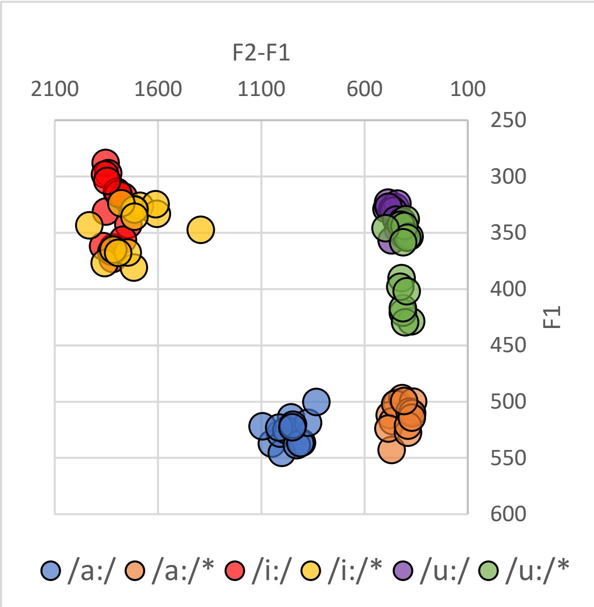
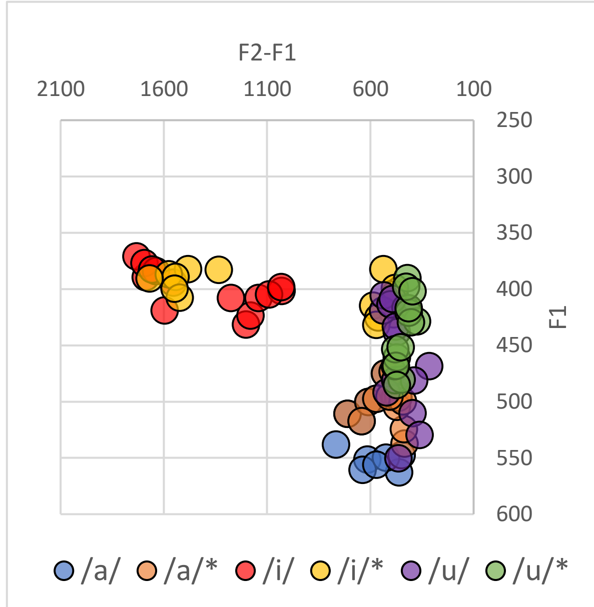
Long vowels	Short vowels
	

Figure 5.95: F1 vs. F2-F1 plots of long and short vowels for SP4.

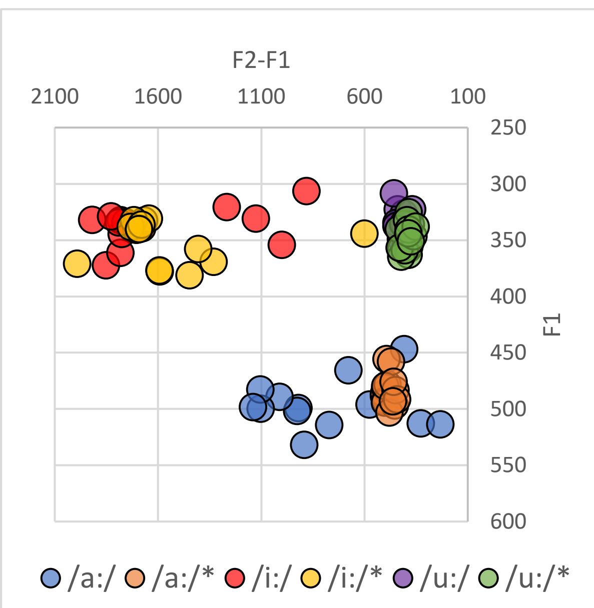
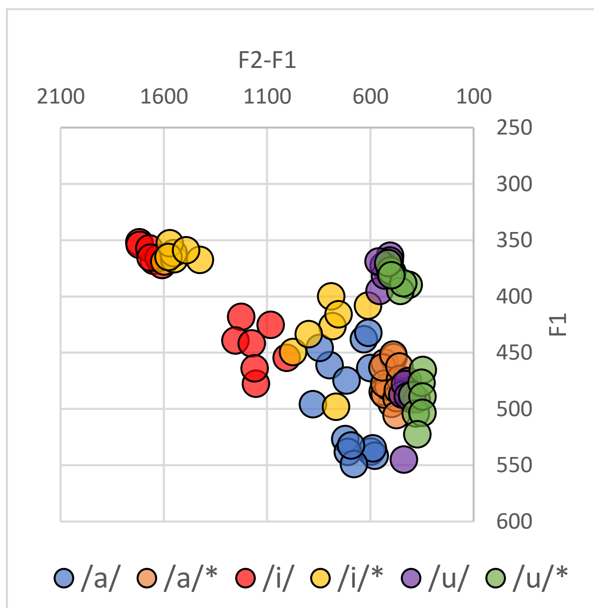
Long vowels	Short vowels
	

Figure 5.96: F1 vs. F2-F1 plots of long and short vowels for SP5.

To observe the dynamic performance of the formant frequencies throughout the duration of the vowel, SSANOVA curves are computed. SSANOVA curves for /a/, /i/, and /u/ vowels are plotted in Figure 5.97 - Figure 5.100, Figure 5.101 - Figure 5.104, and Figure 5.105 - Figure 5.108 respectively. From non-overlapping confidence intervals of SSANOVA curves, we can assert with 95% confidence that the differences in formant frequencies are statistically significant.

Additional SSANOVA plots are presented in Figure 5.109 - Figure 5.112 comparing the modifications in formant frequencies throughout the duration of the vowel induced by a pharyngealized consonant preceding a vowel against the modifications induced by a pharyngealized consonant following the vowel.

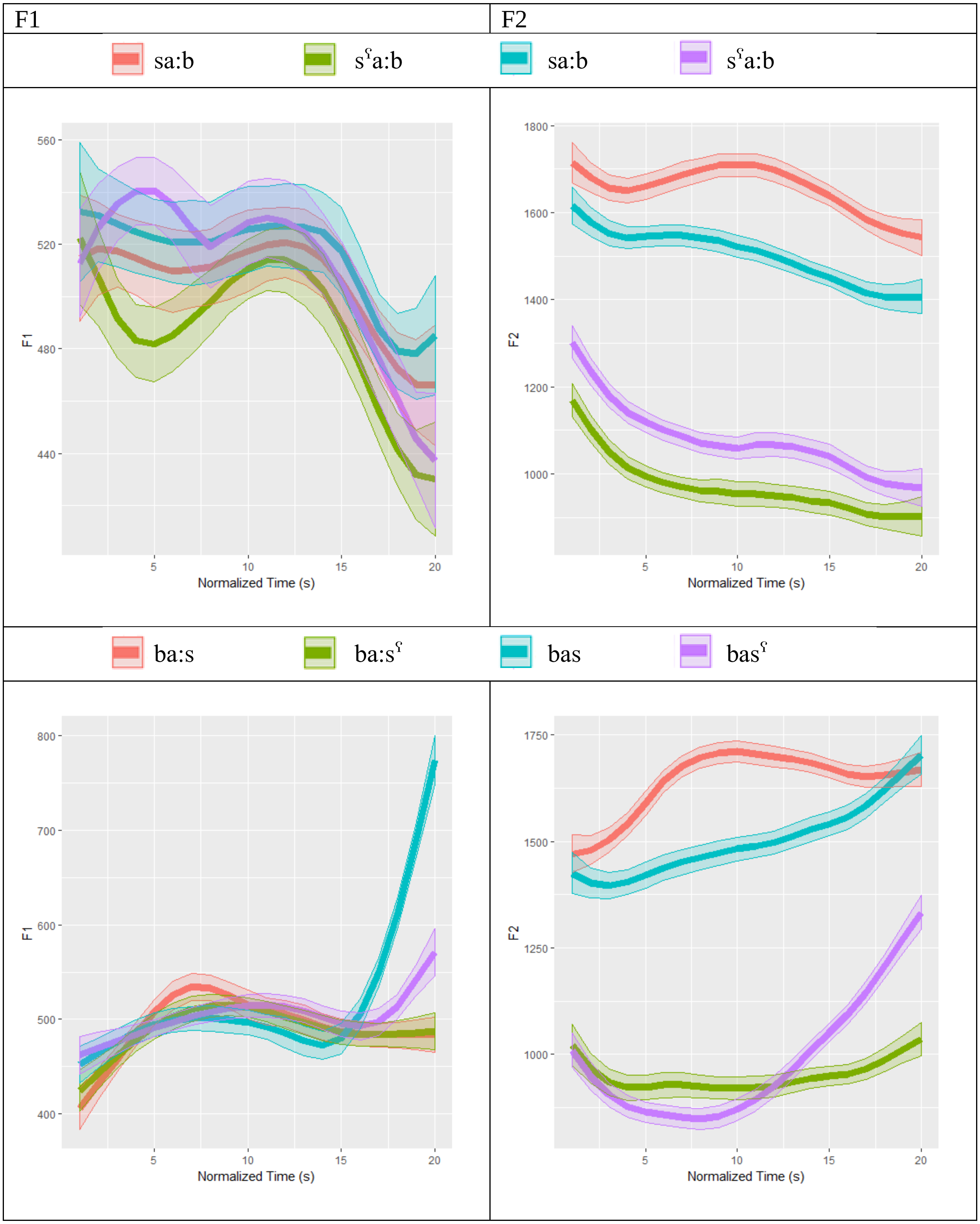


Figure 5.97: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /a/ vowels produced by SP1.

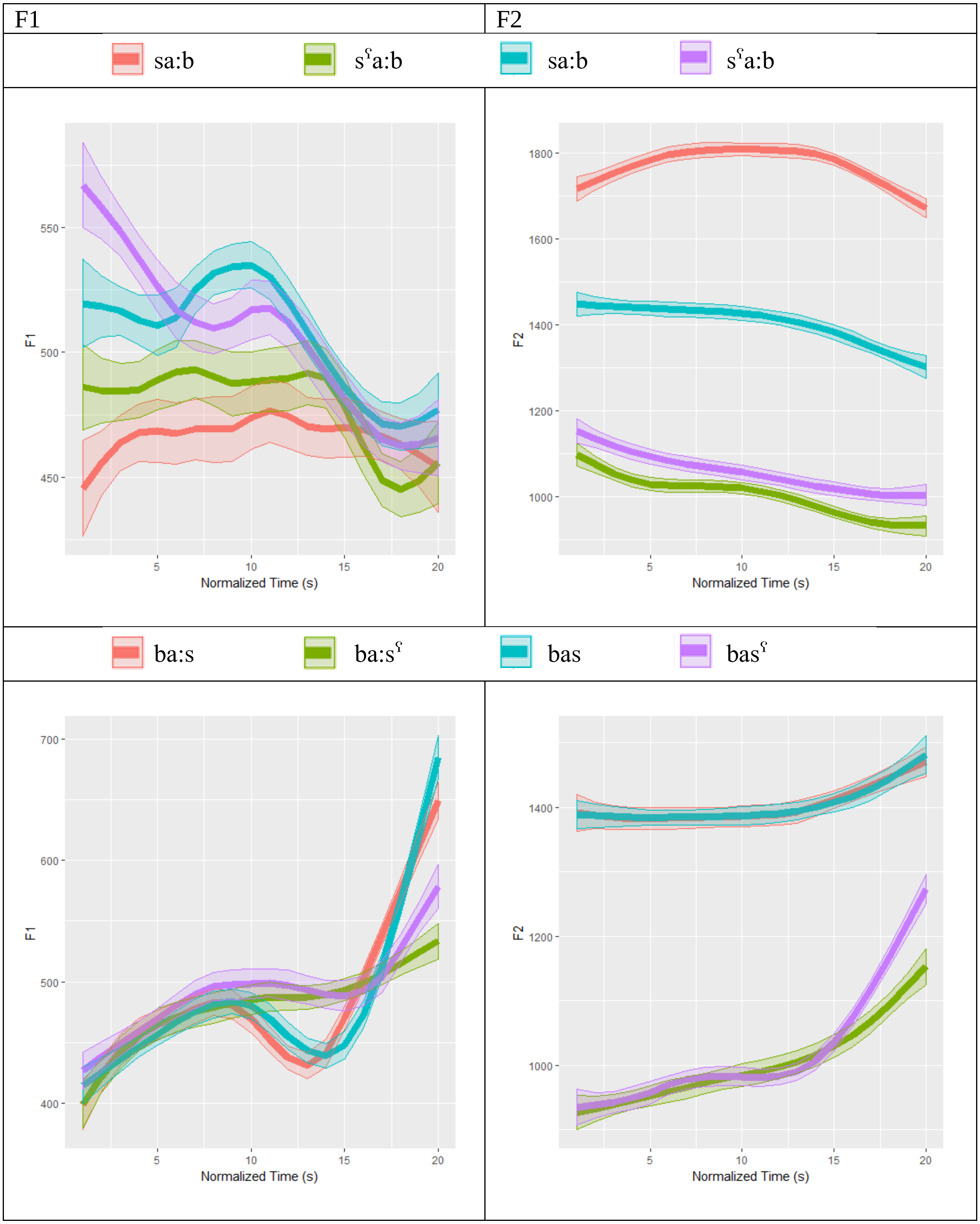


Figure 5.98: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /a/ vowels produced by SP2.

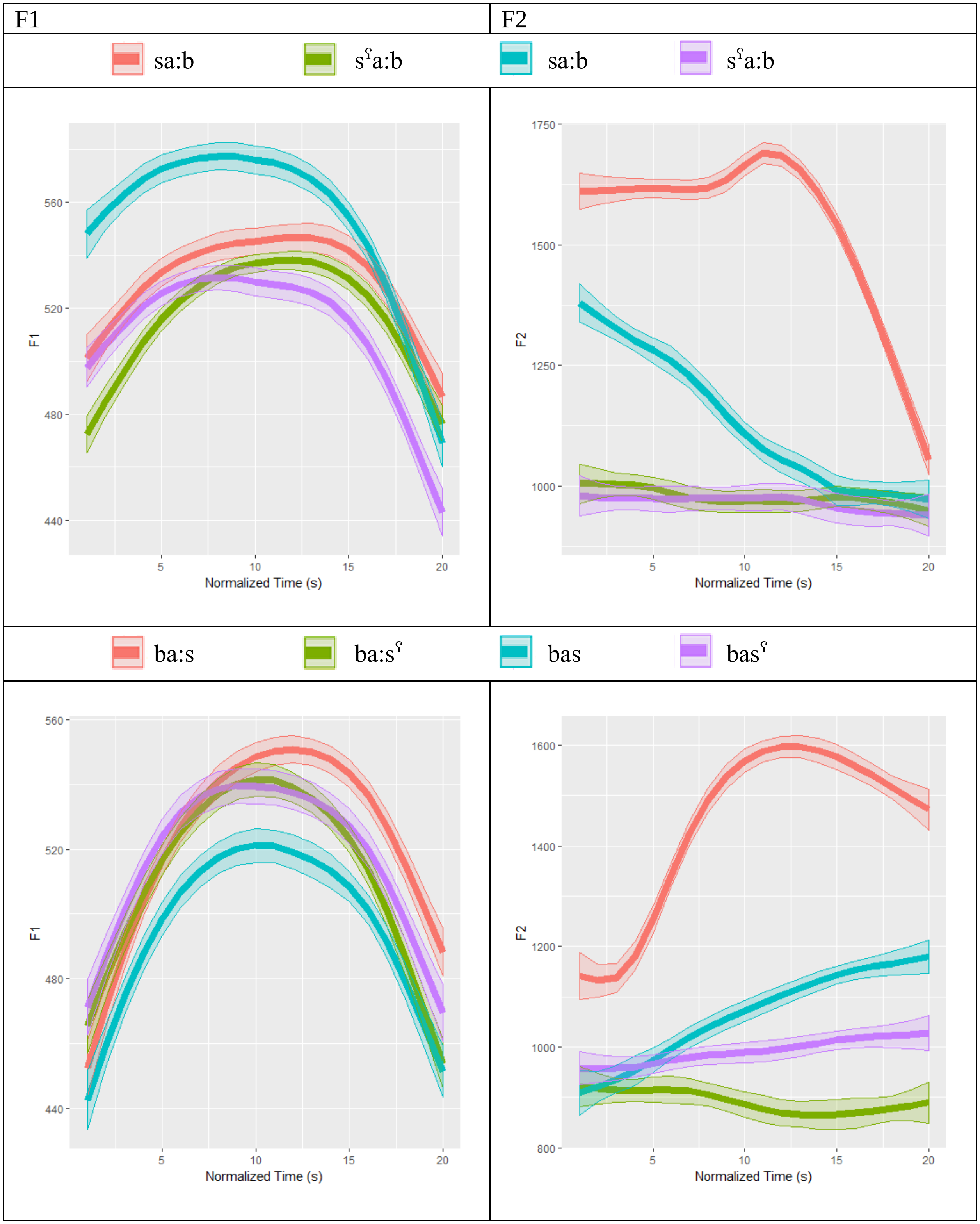


Figure 5.99: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /a/ vowels produced by SP4.

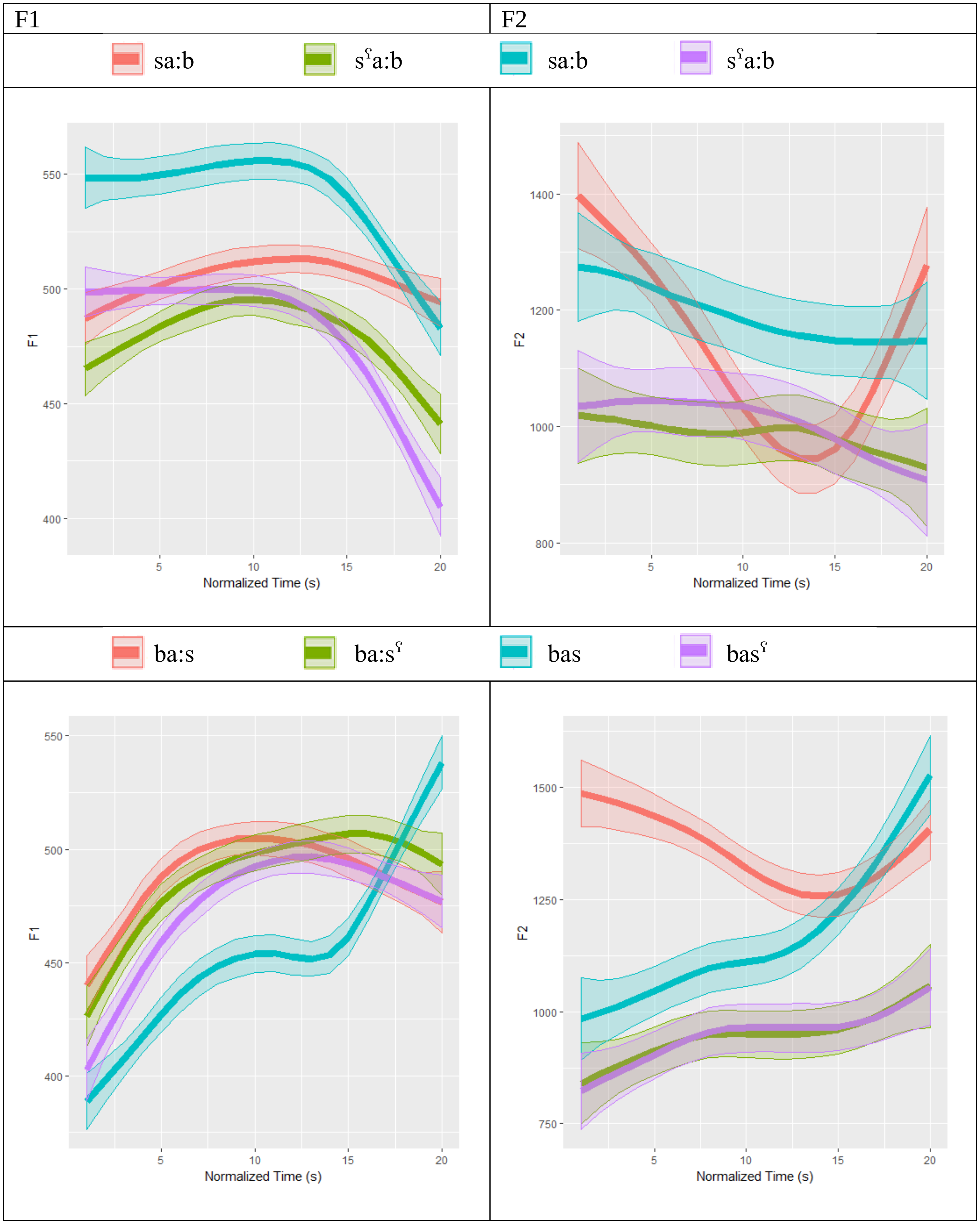


Figure 5.100: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /a/ vowels produced by SP5.

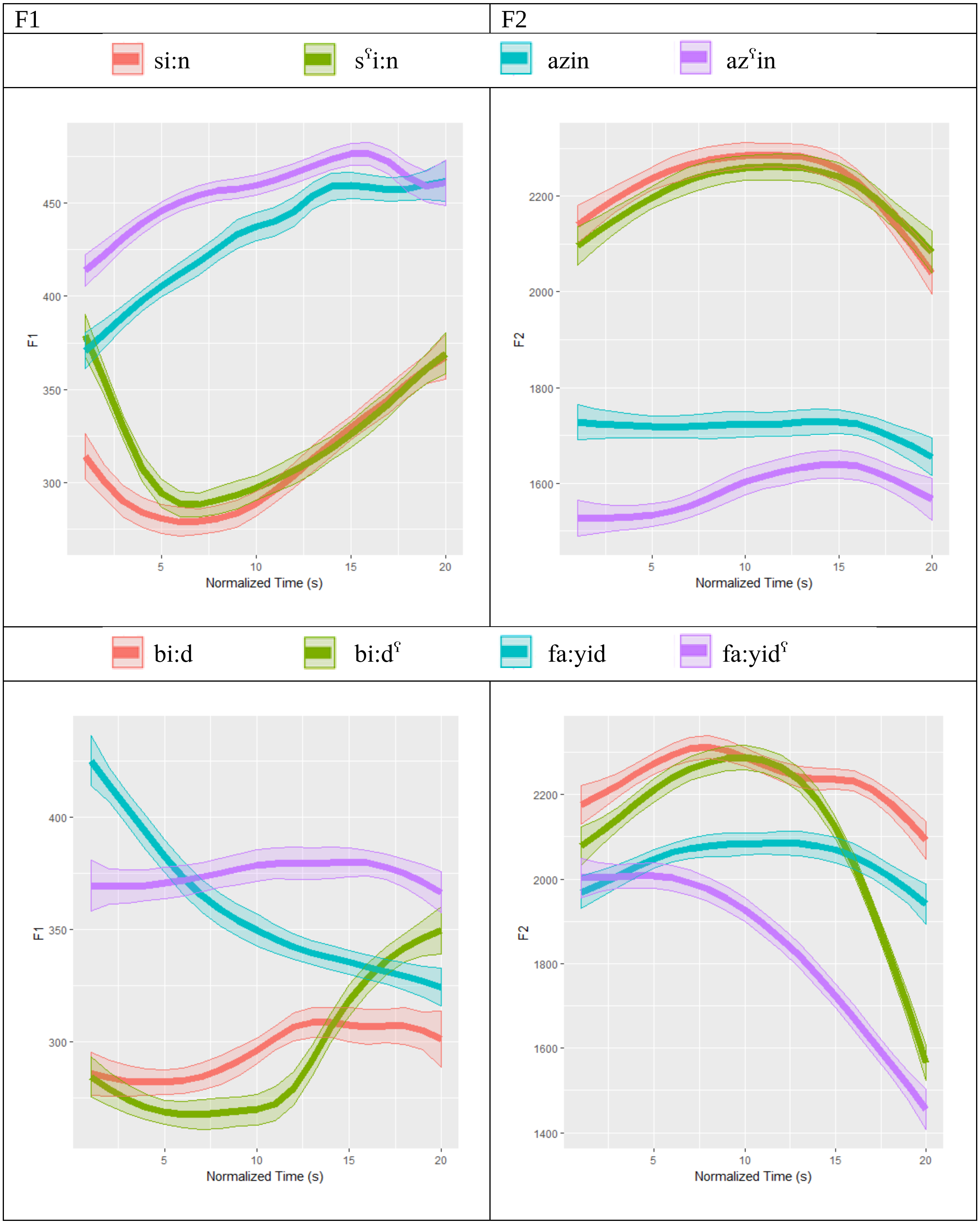


Figure 5.101: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /i/ vowels produced by SP1.

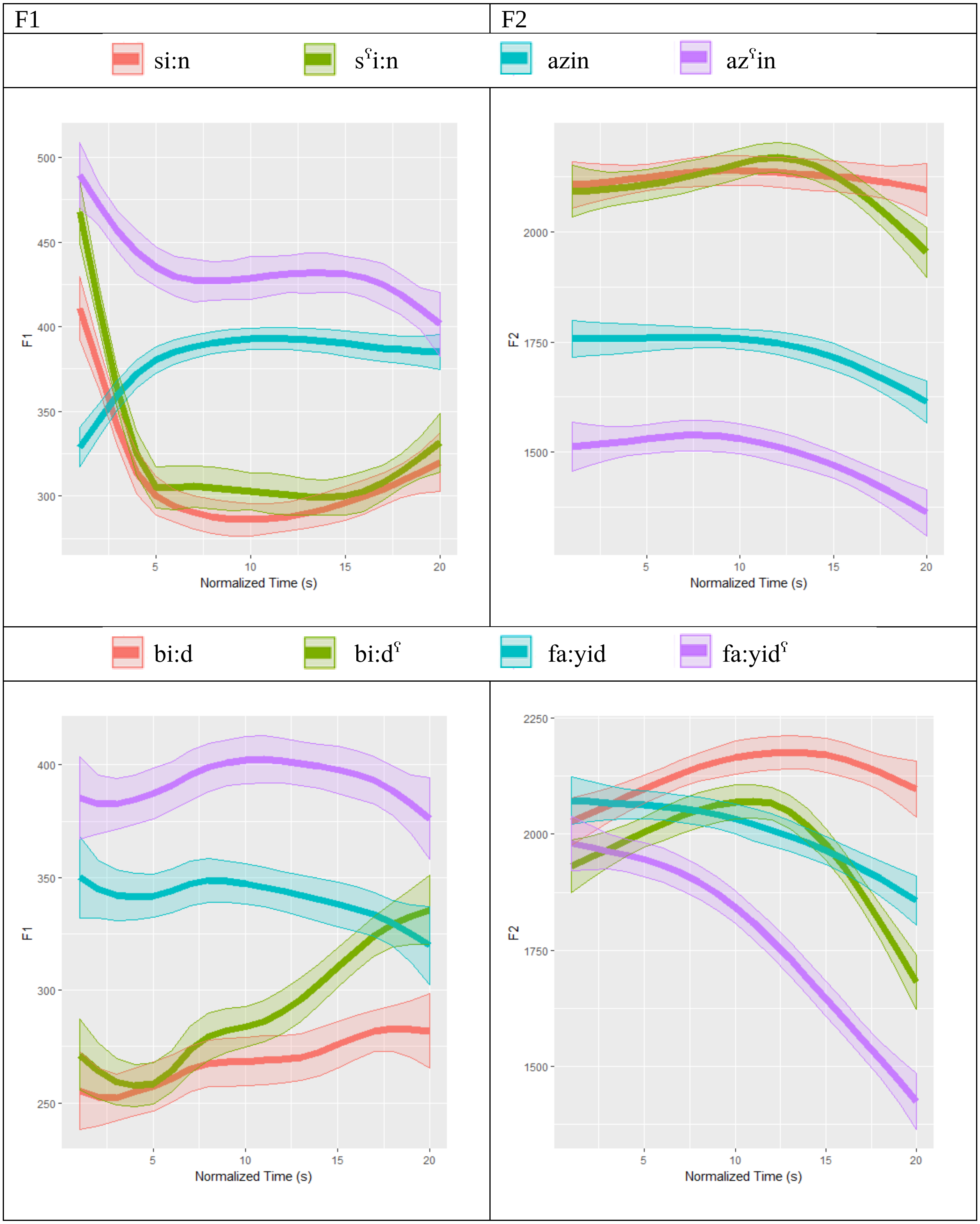


Figure 5.102: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /i/ vowels produced by SP2.

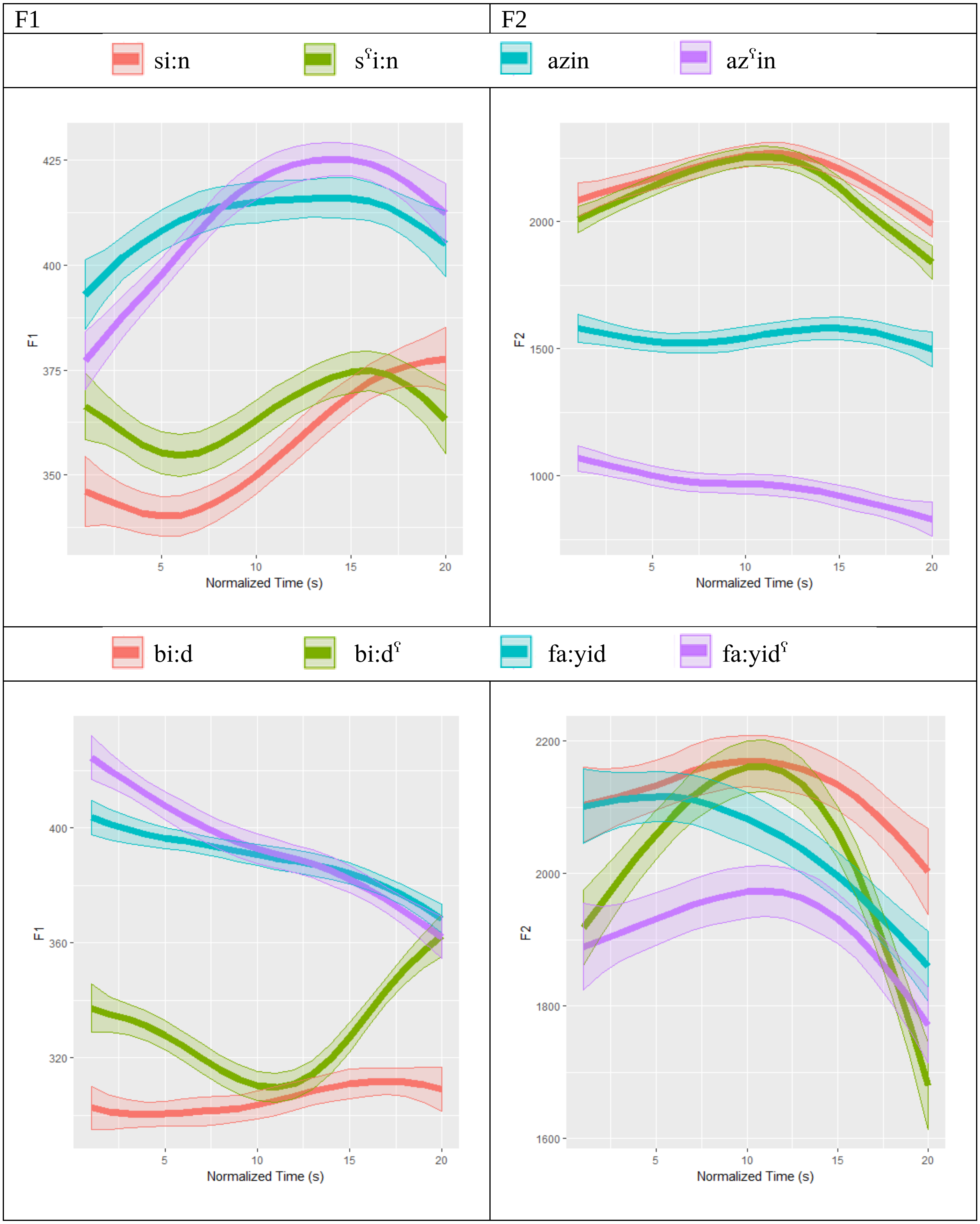


Figure 5.103: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /i/ vowels produced by SP4.

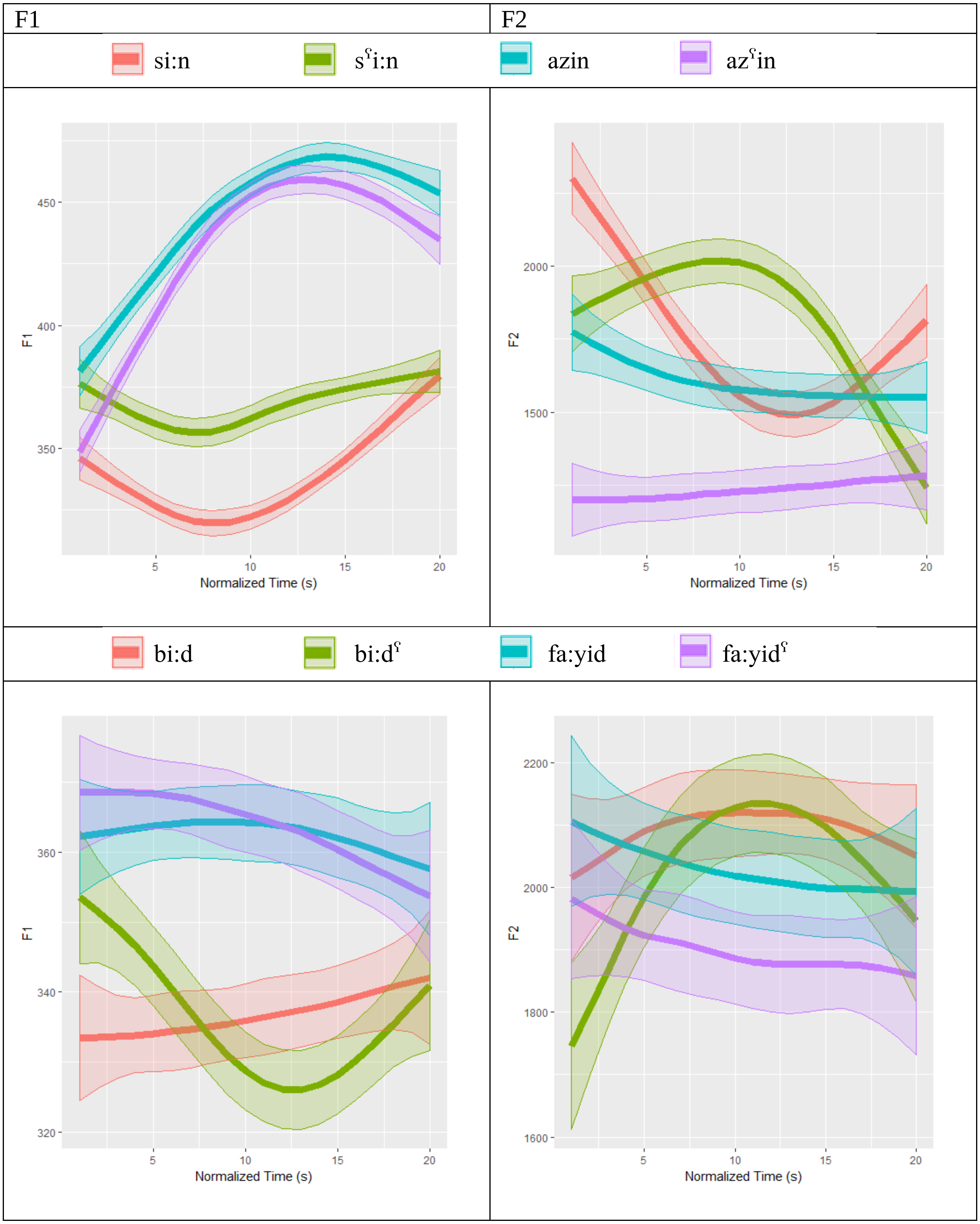


Figure 5.104: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /i/ vowels produced by SP5.

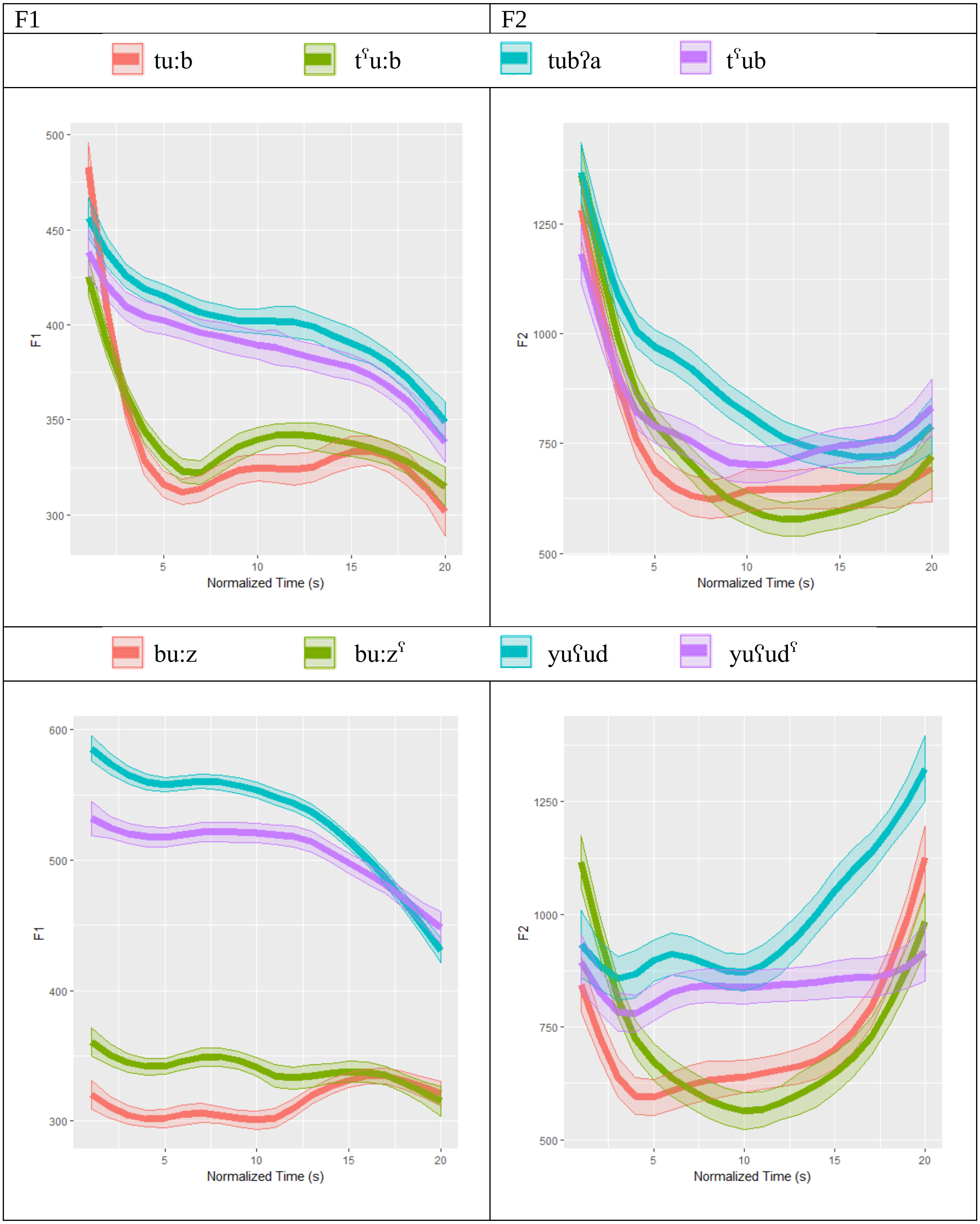


Figure 5.105: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /u/ vowels produced by SP1.

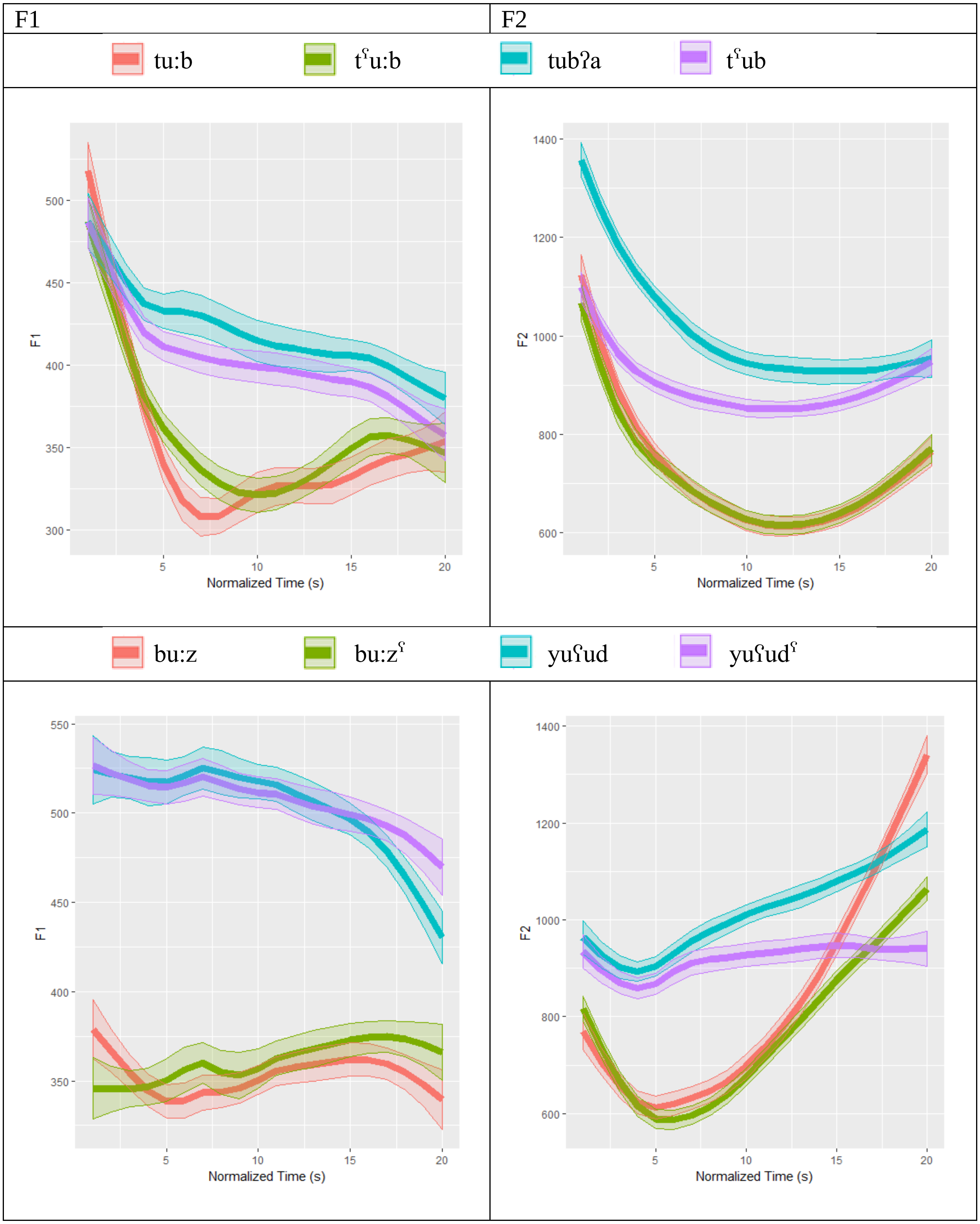


Figure 5.106: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /u/ vowels produced by SP2.

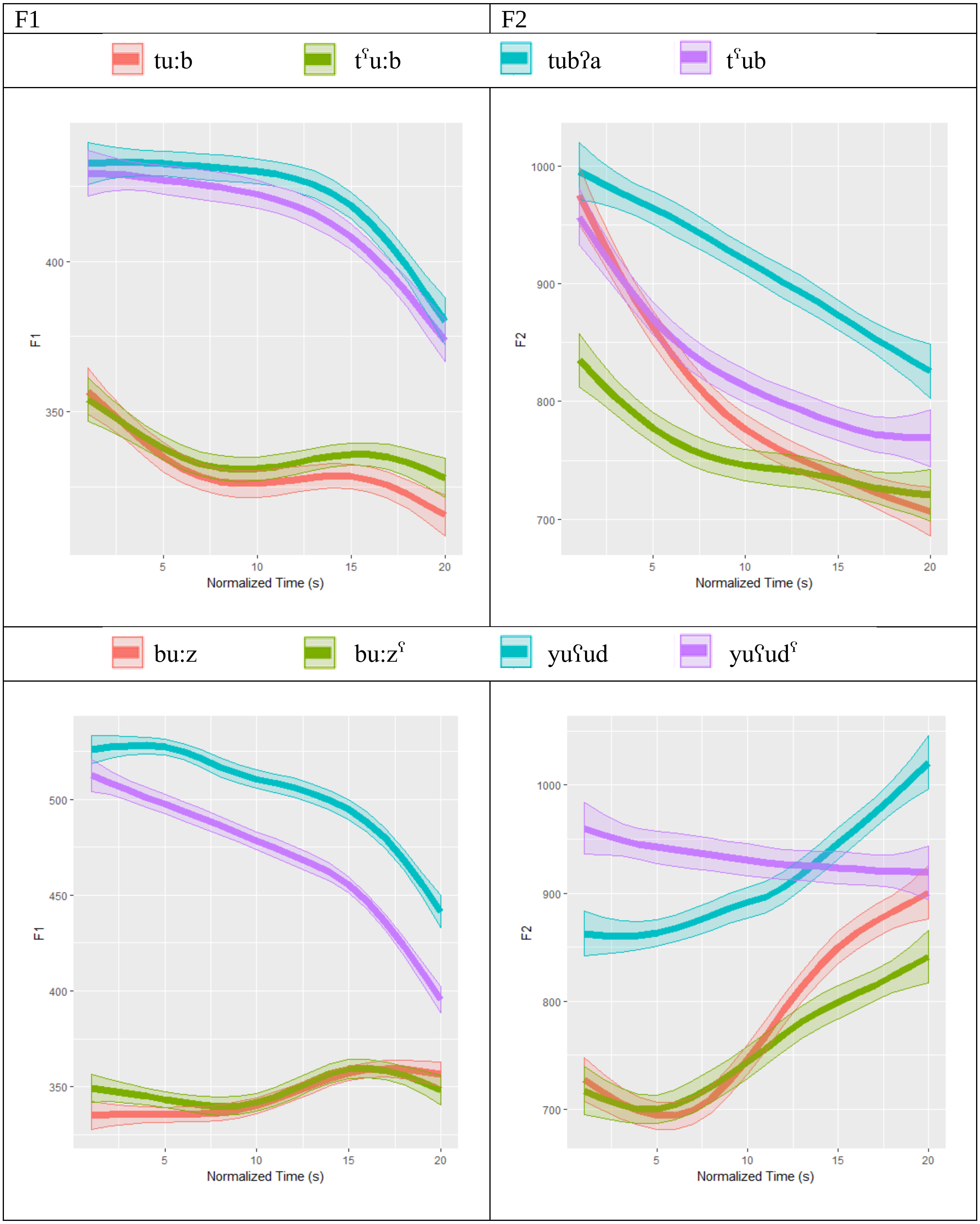


Figure 5.107: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /u/ vowels produced by SP4.

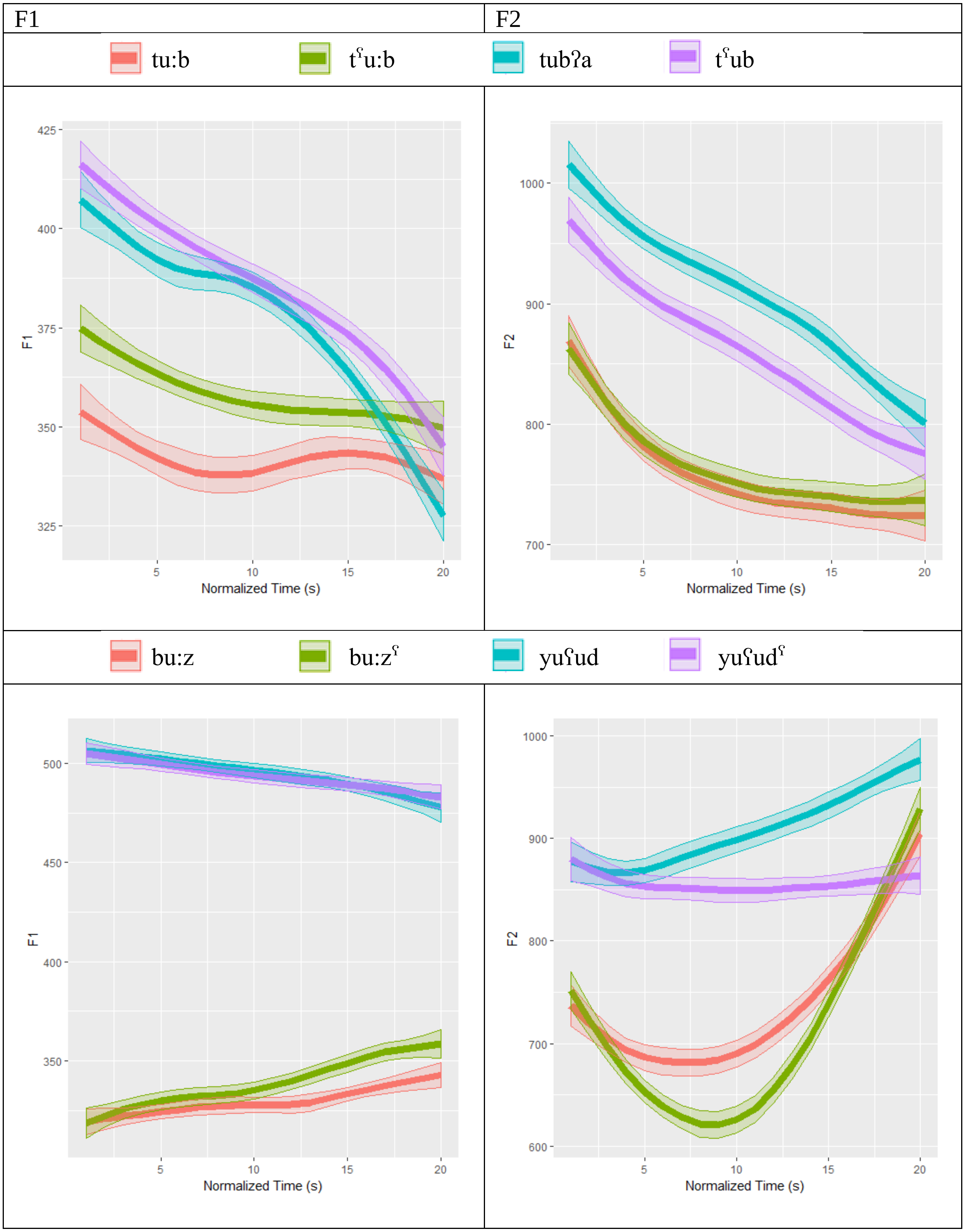


Figure 5.108: SSANOVA curves of F1 (left) and F2 (right) changes in normalized time for /u/ vowels produced by SP5.

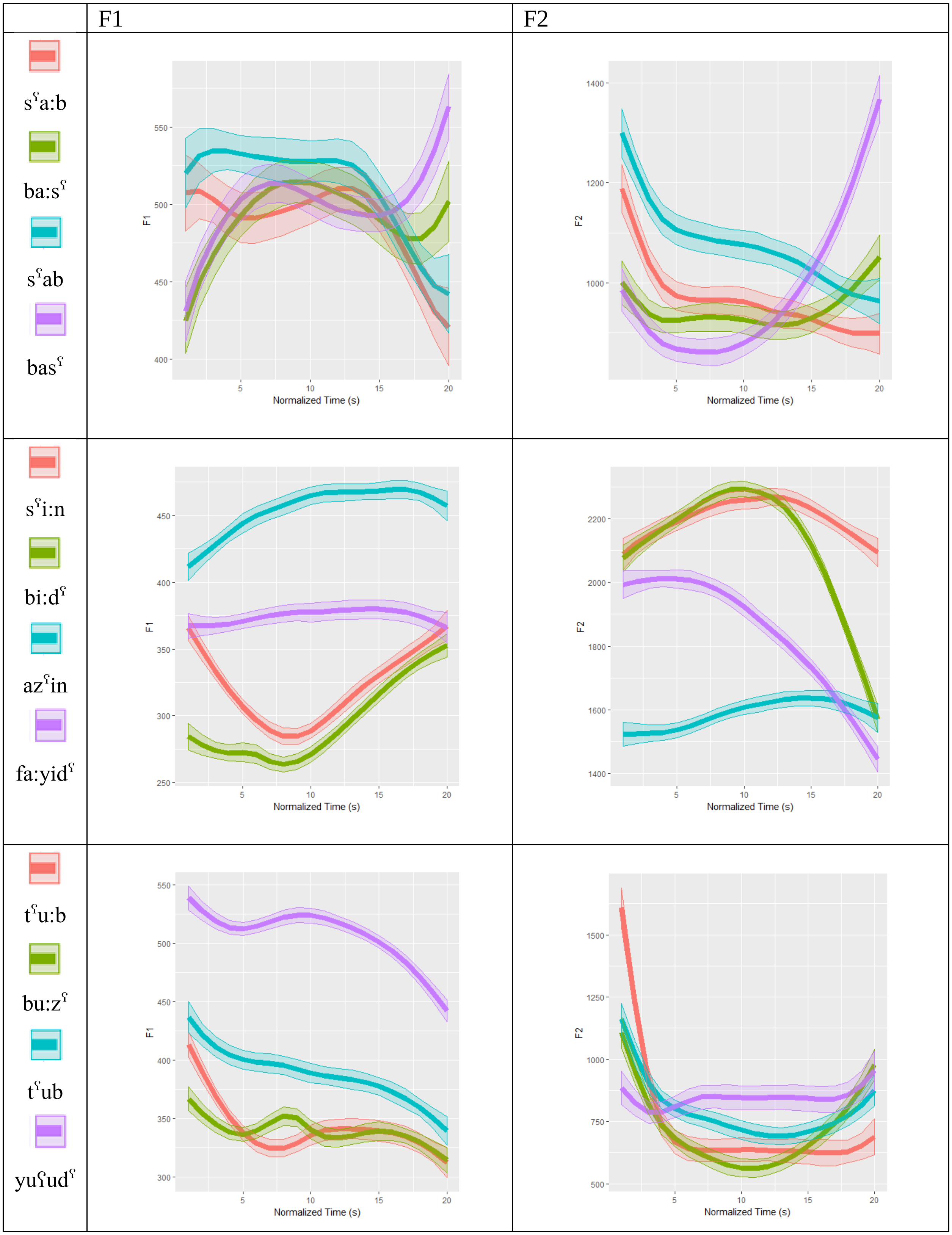


Figure 5.109: SSANOVA curves illustrating F1 and F2 modifications induced by anticipatory versus perseveratory pharyngealization for all vowels produced by SP1.

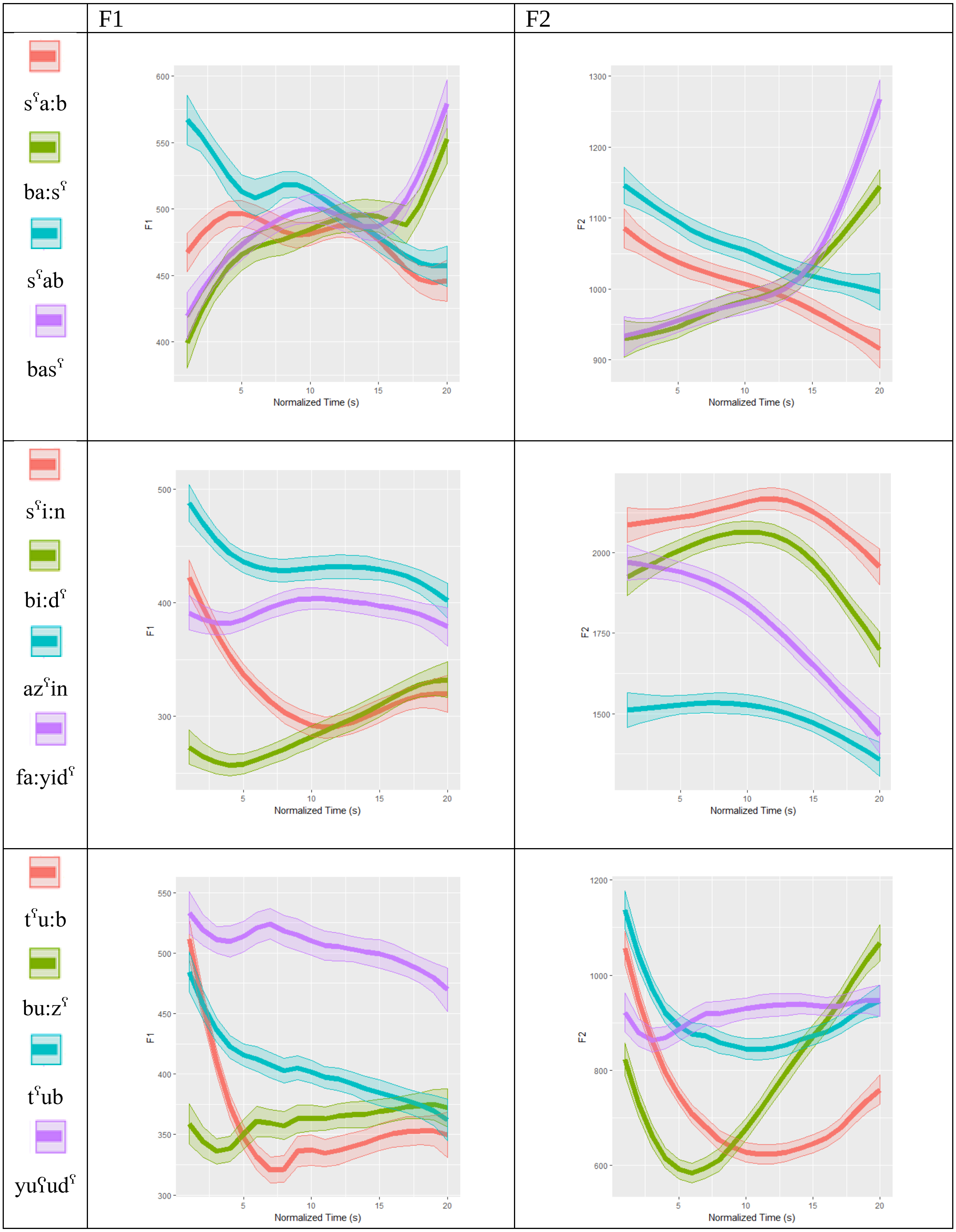


Figure 5.110: SSANOVA curves illustrating F1 and F2 modifications induced by anticipatory versus perseveratory pharyngealization for all vowels produced by SP2.

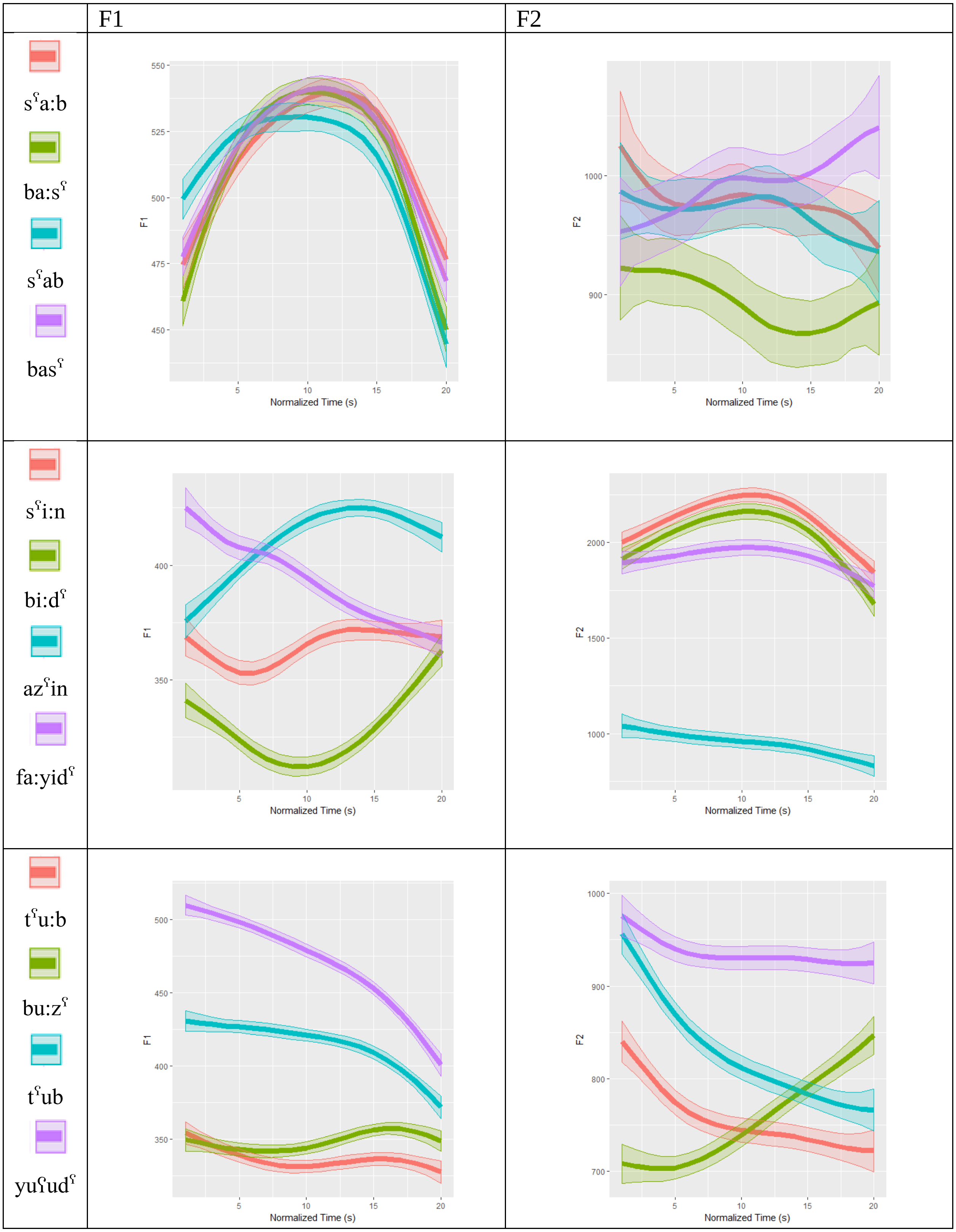


Figure 5.111: SSANOVA curves illustrating F1 and F2 modifications induced by anticipatory versus perseveratory pharyngealization for all vowels produced by SP4.

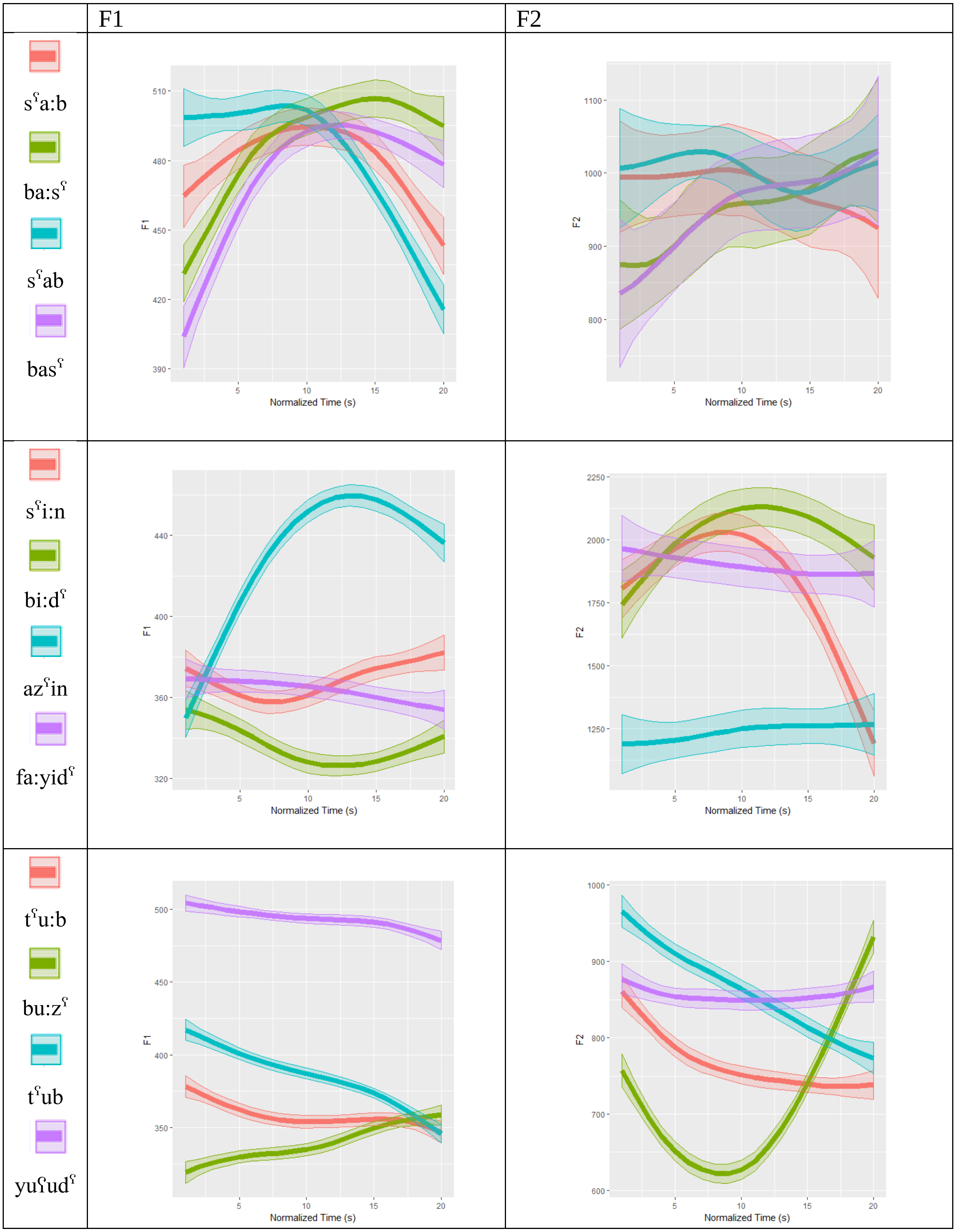


Figure 5.112: SSANOVA curves illustrating F1 and F2 modifications induced by anticipatory versus perseveratory pharyngealization for all vowels produced by SP5.

Chapter 6: Discussion

6.1 Discussion of results from the analysis of articulatory data

The lingual and pharyngeal contours of the pharyngealized members show an articulatory configuration that generally consists of a decrease in the pharyngeal cavity and an increase in the oral cavity. This is consistent with articulatory descriptions of pharyngealized consonants presented in Ghazeli (1977) and Watson (2002). Ghazeli's (1977) description identifies three principle articulatory correlates for pharyngealized consonants:

1) The primary alveolar constriction produced by the approximation of tongue tip and blade to the dental-alveolar region. This is visible especially in some plots, such as in Figure 6.1 below, in which the approximation of the tongue tip to the alveolar ridge to form the alveolar constriction for /s/ and /sˤ/ in the first panel on the left is evident. In some Figures, this primary constriction is not as clear. This may be due to a weakness in the edge detection method such that it failed to detect the tip of the tongue and rather drew a contour connecting the tongue blade directly to the lip opening. An example of this is in Figure 6.2 below. In the rightmost panel corresponding to /d/ and /dˤ/, one would expect a similar approximation of the tongue tip to the alveolar ridge to form an alveolar constriction, but such a constriction is not visible.
2) The secondary back constriction consisting of a "rearward movement of the back of the tongue towards the back wall of the pharynx" (Ghazeli, 1977:72). This is visible in lingual and pharyngeal contour plots, such as in Figure 6.3. In other examples such as in Figure 6.4, an elevation the back of the tongue to form a uvular or a velar constriction in the velopharyngeal region is observed.

3) A depression of the tongue’s palatine dorsum resulting from the retraction of the back of the tongue to form the constriction in (2) above. This configuration has also been described in the literature as tongue concavity (Lehn, 1963), which results in a larger oral cavity. In the present data, this is clear in some data such as in Figure 6.5, but not as evident in other data such as in Figure 6.6.

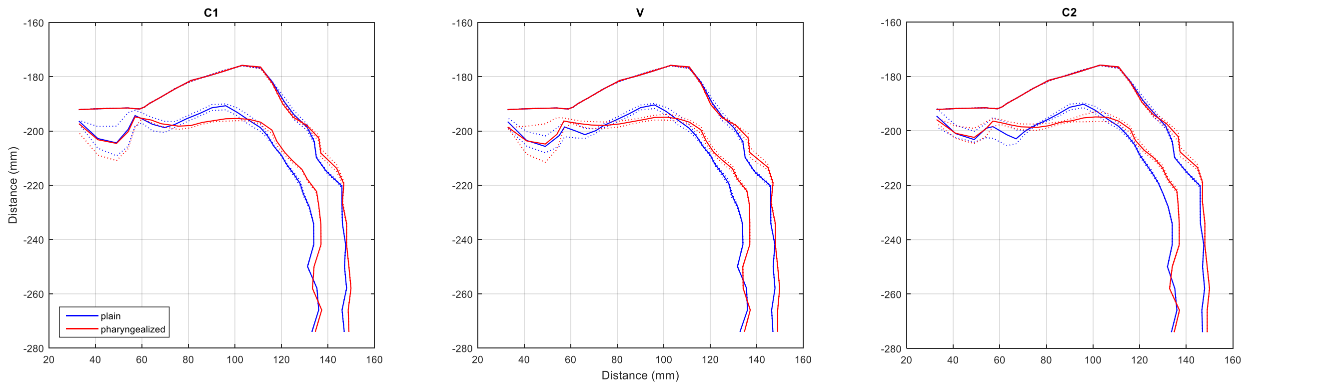


Figure 6.1: Vocal tract contours during /sˤa:b/ and /sa:b/ as produced by SP1.

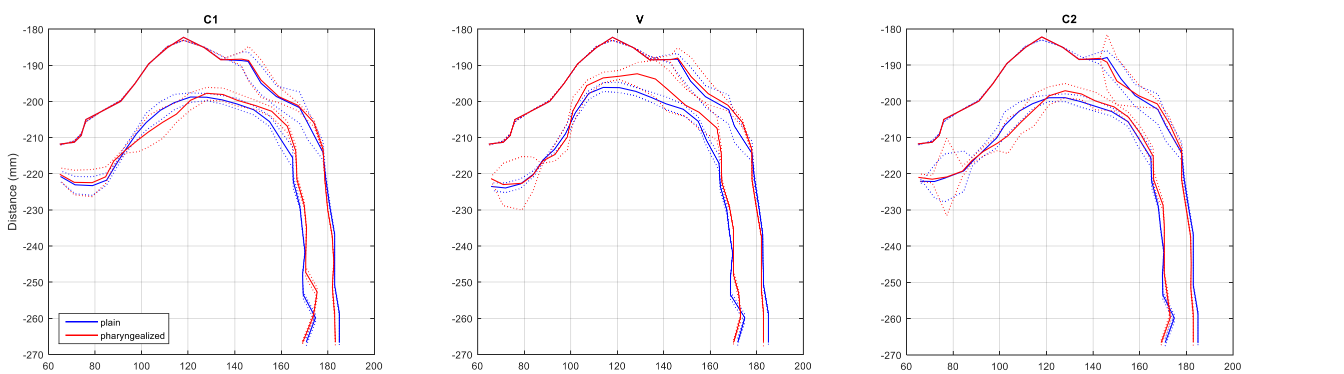


Figure 6.2: Vocal tract contours during /bi:dˤ/ and /bi:d/ as produced by SP5.

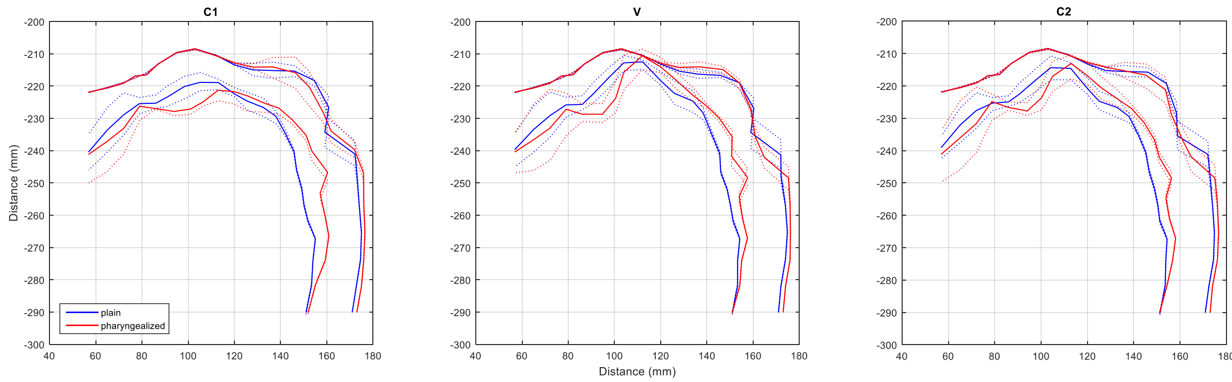


Figure 6.3: Vocal tract contours during /sˤi:n/ and /si:n/ as produced by SP4.

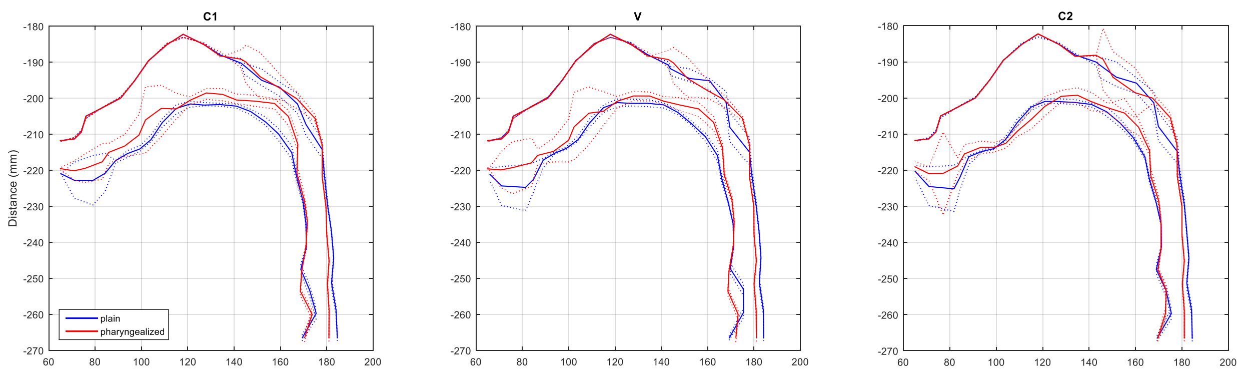


Figure 6.4: Vocal tract contours during /basˤ/ and /bas/ as produced by SP5.

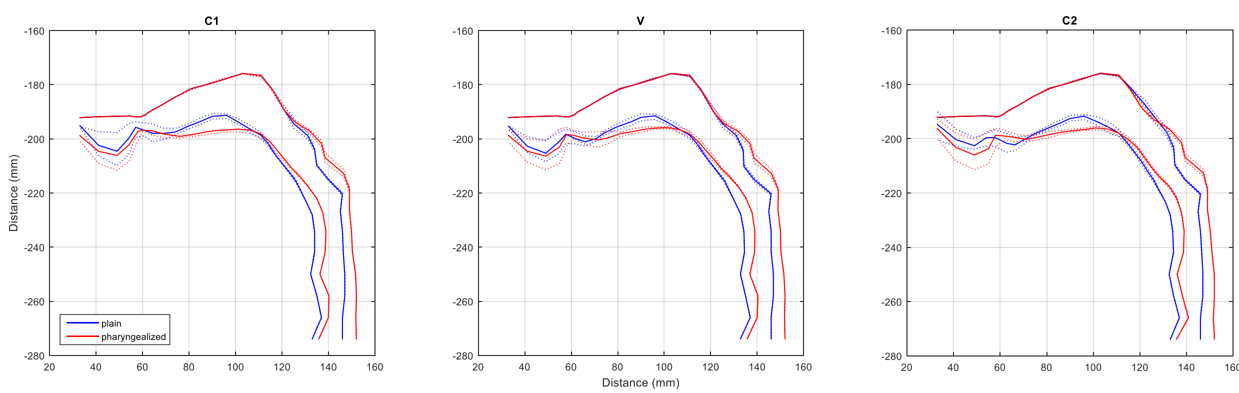


Figure 6.5: Vocal tract contours during /sˤab/ and /sab/ as produced by SP1.

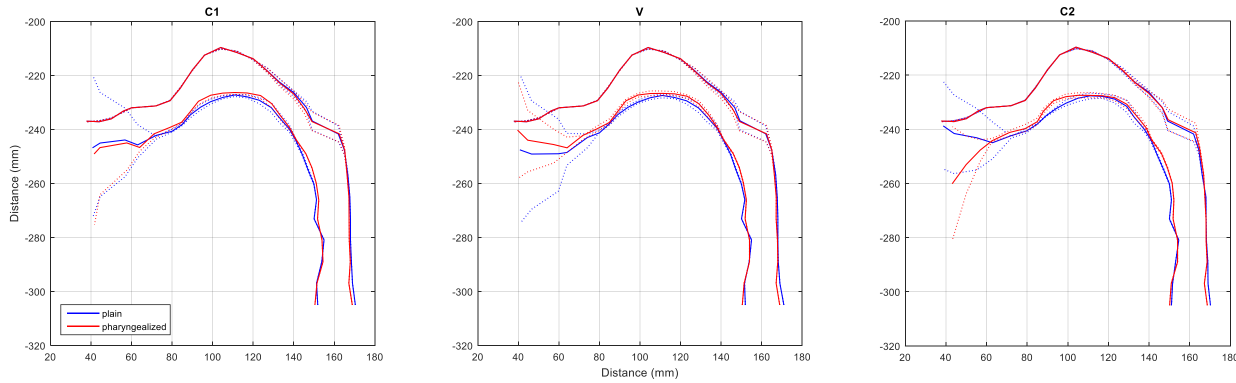


Figure 6.6: Vocal tract contours during /sˤab/ and /sab/ as produced by SP2.

In addition to these three correlates, other gestures are reported in the literature as associated with pharyngealization. These include: a retracted primary constriction, lip protrusion (labialization), and sulculization (Lehn, 1963). It was not possible to examine these gestures in this study. The sulculization, for example, would not be observed in a midsagittal view, rather would have to be viewed in a coronal plane. Furthermore, the edge detection method implemented in this study did not detect the lips in such a way as to allow for examining the lip protrusion.

Articulatory results show that the pharyngeal constriction is not formed at one specific point in the pharynx, rather, extends over a broad region, resulting in a generally more constricted pharynx. This is in line with observations in McCarthy (1994). He observes that back sounds are defined not by major articulators, but by place of articulation. Thus, whereas the speech sounds produced in the anterior part of the vocal tract are defined by the active articulators (labials, coronals, dorsals), the speech sounds involving a constriction in the back of the vocal tract are defined by place of articulation. The region of the vocal tract in which the labials, coronals, and dorsals are produced is approximately equal in length to the region reserved for back speech sounds. This leads to an asymmetry in that “finer distinctions of place are made in the front of the vocal tract than in the back” (McCarthy, 1994:199). McCarthy argues that this is linked to the weaker sensory acuity in the posterior region of the vocal tract, when compared with the anterior region – the distribution of the sensory neurons is not uniform throughout the vocal tract. He quotes Grossman (1964): “This review of the reported oral sensory nerve elements reveals a progressive decrease in the frequency of sensory endings from the front to the rear of the mouth in humans … These findings are compatible with the author’s initial experimental evidence which indicates that tactile discriminations are most acute in the anterior mucosal surfaces of the mouth. It is probably not coincidental that many important speech articulatory phenomena occur in the same oral regions” (Grossman, 1964:132, quoted in McCarthy, 1994: 200). In their MRI study on pharyngeal and pharyngealized Arabic speech sounds, Shosted et. al. (2011) divide up the region extending from the velum to the larynx into five areas: laryngeal, hypopharyngeal, epiglottal, oropharyngeal, and nasopharyngeal. Using Principle Component Analysis (PCA) to interpret the variation in the pharyngeal width during the pharyngeal and pharyngealized speech sounds, they conclude that only two regions are sufficient for discriminating both types: an upper pharynx, comprising the oropharyngeal and nasopharyngeal regions, and a lower region comprising the remaining laryngeal, hypopharyngeal, and epiglottal regions. The former, is the region implicated in the production of pharyngealized speech sounds of interest in this study. Thus, results from that study too, indicate that the large pharyngeal region is relatively poorly differentiated and that the place of articulation in that region is spread out over a wide region. This perhaps explains why the back constriction in the pharyngealized consonants in the data in this study is not restricted to a specific point in the pharynx. Furthermore, it explains why the constriction extends over a wide range, and not a single point of contact.

The uvular constriction observed in some of the data is in line with what has been reported in the literature (Watson, 2002).

In addition to the back constriction, in much of the data for the pharyngealized consonants, the depression in the palatine dorsum described in (3) above is observed. This depression is observed to form a concave shape in some data, as reported in the literature (Watson, 2002).

That this depression occurs in some data, but not in others is in line with Khattab's observation that:

> There is no consistent single articulatory exponent of [pharyngealization]. Rather, speakers have a range of articulatory strategies at their disposal, including how high in the pharynx to create a constriction. Which strategy a speaker uses will depend on several factors that may include not only native dialect and phonological context, but also gender and possibly other social variables (Khattab et. al., 2006:140).

The results also clearly show pharyngealization spread, both to the right and to the left of the pharyngealized consonant, indicated by the constricted pharynx in the plots of the lingual and pharyngeal contours. The spread of pharyngealization is not restricted to vowels adjacent to the pharyngealized consonant, rather extends further beyond the adjacent vowels to affect the consonants. Watson (2002) suggests that this behavior distinguishes the behavior of pharyngealized consonants from pharyngeals. Unlike pharyngealized consonants, pharyngeals do not have a primary coronal articulation, rather only one articulation in the pharynx. According to

Watson, both sound types trigger pharyngealization spread in Egyptian Arabic, but the latter type triggers spread that is limited to the adjacent vowels, while the former triggers longer distance spread and targets both vowels and consonants (Watson, 2002: 271). Watson argues that "the more contingent the phonetic realization of the non-primary feature on the primary feature, the further the non-primary feature will spread and the less specific the targets of the spread will be". Thus, in the case of pharyngeal consonants, the primary pharyngeal constriction is not restrained by any other stricture in the vocal tract, which produces shorter distance pharyngealization spread to adjacent vowels. In contrast, in the case of the doubly-articulated pharyngealized consonants, the constriction formed by the back of the tongue is highly influenced by the primary coronal one, and thus greater constraints are imposed on the tongue to achieve both the oral and pharyngeal articulations. The primary constriction "adds tension to the tongue dorsum and restricts pharyngeal constriction to the upper pharynx", while the back pharyngeal constriction "retracts the tongue blade from the top of the incisors towards the alveolar ridge" (Watson, 2002: 197). Thus the long-distance pharyngealization spread is explained to be a consequence of the longer relaxation time required for such a constrained tongue to return to its neutral state: "the stronger the relationship between a primary and a non-primary feature, the longer the muscle relaxation time, the longer the dorsum and vocal tract take to return to a neutral position, and hence the further pharyngealization will spread within the word" (Watson, 2002:273). As Yeou (1997) argues, this constrained articulatory configuration makes pharyngealized sounds more resistant to coarticulatory effects from adjacent vowels. Pharyngealized sounds, therefore, induce greater coarticulatory effects on surrounding segments (i.e. the pharyngealization spread). This is why pharyngealized consonants are generally considered the locus of pharyngealization (Jongman, 2009) modifying surrounding segments, rather than the opposite: i.e. it is generally not understood that pharyngealized consonants are doubly-articulated due to coarticulatory influence of surrounding vowels, for example.

In a similar discussion, Heselwood and Al-Tamimi (2011) argue for grouping Arabic pharyngeals together with Arabic pharyngealized consonants in the same set. They argue that pharyngeals are, essentially, pharyngealized laryngeals. For them, the pharyngeal constriction is not a primary, rather a secondary constriction. They point to larynx elevation and simultaneous gestures below the pharynx involving the aryepiglottic folds, ventricular bands and the arytenoid cartilage as a primary articulation in the case of /ʕ/. In the case of /ħ/, they suggest that the primary articulation can be “the narrow space between the arytenoids and the base of the retracted epiglottis, and between the aryepiglottic folds and the upper part of the epiglottis at the laryngeal aditus” (Heselwood & Al-Tamimi, 2011:124). Thus, in their view, pharyngeals have a primary constriction below the secondary pharyngeal constriction. In contrast, pharyngealized coronals have a primary constriction above the secondary pharyngeal constriction. This explains the differences in the exact place of the pharyngeal constriction in both types: the secondary constriction is moderated by the primary constriction and as such closer to it: when the primary constriction is coronal, the secondary pharyngeal constriction is higher up in the pharynx; when the primary constriction is in the larynx, the secondary pharyngeal is deeper down in the pharynx.

Measures of the pharyngeal 2D areas suggest that leftward pharyngealization spread (i.e. anticipatory spread) is stronger than rightward spread. From the articulatory data, this is deduced from the more constricted pharynx on the left of the pharyngealized consonant when compared against the pharyngeal contours to the right of the pharyngealized consonant. That is, the pharyngeal 2D areas are smaller to the left of the pharyngealized consonant. Thus, the contours in Figure 5.21 for SP5, for example, show a more constricted pharynx (in yellow) in the case of the anticipatory pharyngealization spread. Similarly, the boxplots in Figure 5.22 show that the pharyngeal area in the initial /b/ in /bas^{ʕ}/ is more constricted than the pharyngeal area in the final /b/ in /s^{ʕ}ab/. The former /b/ is influenced by anticipatory pharyngealization spread from the final /s^{ʕ}/ in /bas^{ʕ}/, while the latter is influenced by perseveratory pharyngealization spread from the initial /s^{ʕ}/ in /s^{ʕ}ab/. This is the case for two of the four speakers. This provides evidence for more prominent anticipatory pharyngealization spread in those speakers.

This result can be explained as a result of the asymmetry in timing between the occurrence of the primary oral constriction and the secondary pharyngeal constriction described by Watson (2002): "[I]n pharyngealization, the pharynx narrows prior to the hold phase of the primary articulation. Pharyngealization is thus anchored more on the onset of the primary articulation, resulting in the typical anticipatory nature of pharyngealization spread." By measuring durations of the vowels preceding pharyngealized consonants and comparing them with durations of the same vowels preceding the plain counterparts, Hassan (1981) also reached the conclusion that the secondary pharyngeal constriction occurs before the primary oral one. He found that the vowels preceding the pharyngealized consonant are longer than those preceding the plain one, and he interpreted this as an indication that the tongue assumes the secondary position first, before assuming the primary oral one. This allows the vowel to be sustained for a longer duration before the constriction of the primary articulation of the pharyngealized consonant is realized.

Davis (1995) also reports that, where bidirectional pharyngealization spread occurs, dominant rightward anticipatory spread is generally more common among most Arabic dialects, and that this explains why opaque phonemes that block spread, are generally opaque to rightward spread and not leftward (anticipatory) spread. Though he also speculates that more in-depth examination of opaque elements in various Arabic dialects may reveal some that block leftward spread as well. The Cairene dialect in this study contains no opaque elements (Youssef, 2014).

Yeou (1997) reported a greater lowering of F2 in short vowels following pharyngealized consonants, when compared with long vowels, suggesting that pharyngealization is stronger in shorter vowels more than longer ones. The acoustic data in the study, as will be shown later in this chapter, does not support this observation by Yeou (1997). Pharyngeal and oral 2D areas are plotted for each minimal pair having pharyngealized consonants and contrastive in the short/long vowel in Tables 4.3 and 4.4 respectively. Since the articulatory correlates of pharyngealization are a constricted pharynx and a greater oral cavity, a smaller pharyngeal 2D area and/or a larger oral 2D area is interpreted as more pharyngealization. Looking at both tables together, it can be seen that the member of the shorter vowel generally has either or both articulatory correlates, providing articulatory evidence the stronger effect of pharyngealization on the shorter vowels.

Furthermore, Yeou (1997) reports that the greatest modifications due to pharyngealization occur in the formant frequencies of /a/ followed by /i/ and /u/. Indeed, Watson (2002) shows that pharyngealization results in a centralized (and lowered) realization of /i/ and /u/, and a retracted (and lowered) realization of /a/. In Egyptian Cairene Arabic, /a/ in a non-pharyngealized context is realized as [ɐ]. In a pharyngealized context, it is realized as the lowered, back [ɑ]. In pharyngealized contexts, /i/ is centralized to [ɨ] and /u/ is centralized to [ʉ].

Box plots in Figure 5.37 - Figure 5.51 show the pharyngeal 2D areas during all vowel qualities in minimal pairs contrastive in a pharyngealized/plain consonant. Figure 5.37 - Figure 5.44 show results for long vowels, while Figure 5.45 - Figure 5.52 show results for short vowels.

In the long vowels, especially, it is visually clear that the least difference in the pharyngeal 2D areas in a minimal pair generally occurs in the /u:/ vowel, while the greatest difference generally occurs in the /a:/ vowel. This trend can also be observed, to a lesser extent, in the results for short vowels. This is an articulatory result that supports the Yeou's (1997) observations that the greatest acoustic modifications due to pharyngealization occur in an /a/, and that the least modifications occur in an /u/.

Table 5.13 - Table 5.16 list the average 2D pharyngeal areas for data in Figure 5.37 - Figure 5.52. They also list the difference between the areas for each minimal pair. Figure 5.53 - Figure 5.56 plot this difference, to graphically illustrate the trend of the difference in the 2D pharyngeal areas that result from pharyngealization. Across the speakers, the general trend is that the difference in an /a/ vowel in blue is generally the highest, while the difference in an /u/ vowel in green is generally the smallest. This indicates that the greatest modification due to pharyngealization generally occurs in /a/ vowel, followed by /i/, and then /u/.

6.2 Discussion of results from the analysis of acoustic data

Measurements of the duration of pharyngealized vowels and their plain counterparts reveal that the pharyngealized vowel is generally longer as shown in Figure 5.57 - Figure 5.68. The ANOVA analysis, however, shows that in most cases, this difference is not statistically significant. Nonetheless, longer durations in the case of vowels preceding the pharyngealized consonant has been explained above as a result of the secondary pharyngeal constriction occurring before the primary oral one, therefore allowing the vowel to be sustained longer before the primary constriction is realized. As for the vowels following the pharyngealized consonant, their longer duration could be in order to more strongly signal for the presence of the pharyngealized consonant. A perception study conducted by Jongman et. al. (2011) showed that listeners' perception of pharyngealized relies on acoustic cues in adjacent vowels (and non-target consonants) more than on acoustic cues from the pharyngealized consonant itself. Thus, the longer duration of the vowel following the pharyngealized consonant could give the listener a chance to "hear" the pharyngealized consonant more.

Analysis of the first and second formant frequency measures F1 and F2 of the vowels in the target words reveal that the most considerable acoustic consequence of the presence of a pharyngealized consonant is the lowering of F2. Thus, F2 in the pharyngealized consonants are significantly lower than F2 in plain counterpart. The boxplots in Figure 5.69 - Figure 5.92 show mean F1 and F2 values measured across the vowels in all the data. It is clear that F2 is generally lower in the pharyngealized member of each minimal pair contrastive in a plain/pharyngealized consonant. This is the case regardless of the vowel quality and length, and regardless of whether the vowel precedes or follows the plain/pharyngealized contrast. A significantly lower F2 in pharyngealized vowels can be explained within the framework of Perturbation Theory (Chiba & Kajiyama, 1941). The back velopharyngeal region corresponds to a node (a point of maximum pressure) in the standing wave of F1, and an anti-node (a point of maximum velocity) in the standing wave of F2. Perturbation Theory predicts that the resonance frequency will increase if a constriction occurs at a node, and will decrease if the constriction occurs at an anti-node. Thus, in line with these predications, it has been reported that vowels adjacent to pharyngealized consonants exhibit raised F1 and a lowered F2 (Jongman et. al., 2011; Khattab, 2006).

Thus, the articulatory interpretation of a lowered F2 can be an increase in the size of the oral cavity due to the depression of the palatine dorsum described above. Watson suggests that the enlargement of the oral cavity can occur at "either extremity of the tract", and that the "enlargement at one end of a tract tend[s] to be enhanced by enlargement at the opposite end" (Watson, 2002: 270). She further maintains that, in the case of pharyngealized consonants, the enlargement of the oral cavity at the pharynx may be enhanced by enlargement at the other end of the tract in the form of labialization (lip protrusion). This is analogous to the articulation of labial segments, in which enlargement at the lips is often enhanced by enlargement at the pharynx (Watson, 2002). Indeed, as mentioned above, labialization in the form of lip protrusion has been reported for pharyngealized consonants.

The increase in F1 is not as consistent in the results from this study, and an explanation for this can be offered from Watson's analysis (2002). The constriction in the pharynx yields a raised F1, but the labialization yields a lowered F1. For her, this is "further evidence that F2 lowering is more significant than F1 raising in the identification of [pharyngealization]" (Watson, 2002: 270).

In Figure 5.93 - Figure 5.96, F1 is plotted against F2-F1. This gives the general distribution observed in the IPA vowel chart. The long vowels generally occupy separate space on the periphery and distribute as expected within the vowel space, with plain /i:/ occupying the high front space, plain /u:/ occupying the high back space, and plain /a:/ realized as [ɐ] as reported by Watson (2002). The pharyngealized long vowels are shown to be slightly lowered and more centralized in the case of pharyngealized /i:/ and pharyngealized /u:/ when compared against their plain counterparts. Pharyngealized /a:/ is retracted and occupies the space for [ɑ]. As for the short vowels /i/ and /u/, these plots show that they are generally more their position in the vowel space indicate that they are generally produced as the lax vowels [ɪ] and [ʊ], which are, by definition, slightly lower. This is in line with the description of Egyptian vowels given by Cowan (1970). As for short /a/, results indicate that it too is produced as a lower, more centralized vowel. As with long vowels, pharyngealization has the effect of centralizing short /i/ and /u/ and retracting short /a/.

The acoustic data analysis described above was conducted with mean formant frequencies, i.e. the value of the formant frequency averaged over the entire duration of the vowel. In order to more closely examine the behavior of the formant frequencies throughout the duration of the duration of the vowel, SSANOVA plots are produced in Figure 5.97 - Figure 5.108.

These plots show that for all vowel qualities:

1) the greatest decrease in F2 is in the part of the vowel closest to the pharyngealized consonant, i.e. in the transitions to and from the pharyngealized consonant.
2) there is more decrease in F2 values of long vowels than in in F2 values for short vowels, providing acoustic evidence that pharyngealization is stronger in longer vowels than in shorter ones.

Results in the SSANOVA plots in Figure 5.109 - Figure 5.112 provide acoustic support for stronger modifications due to perseveratory pharyngealization spread as evidenced in lower F2 values in vowels preceding the pharyngealized consonant when compared against their counterparts the follow pharyngealized consonants. Thus, in the columns on the right, the curves in green are generally lower than the curves in red for long vowels, and the curves in purple are generally lower than the curves in cyan for short vowels. This general trend is observed in all vowel qualities and for all speakers.

Consistent with previous studies, the articulatory results above show a secondary back constriction in pharyngealized sounds, consisting of a constriction in the velopharyngeal region. The results also show a generally more constricted pharynx. Similarly, in a previous rtMRI study on ejectives in Tigrinya (the emphatics of a South Semitic language), one of the main articulatory correlates of ejectivity was a more constricted pharynx. This was achieved through a complex mechanism involving the raising of the larynx and the retraction of the tongue root and dorsum (Hermes, et. al., 2016). It is thus phonetically plausible that the pharyngealization in Arabic is a result of diachronic lenition of ejectivity, favoring the view that ejectivity preceded pharyngealization.

This view can further be supported with results from the acoustics here. The longer duration of vowels preceding pharyngealized consonants here seems to parallel results found in the study of vowel duration in Tigrinya (Shosted & Rose, 2011), in which it is reported that vowels preceding ejectives were generally longer than those preceding the pulmonic congener. Furthermore, the considerable modification that pharyngealization imposes on formant frequencies shown here suggest that pharyngealized consonants are more resistant to coarticulatory effects from adjacent vowels, as has been argued by Yeou (1997). This is due to the greater constraints imposed on the tongue body due to the simultaneous presence of the primary coronal and secondary back constriction. Hermes et. al. (2016) also suggest that Tigrinya ejectives are more resistant to coarticulation. These results can also be added to evidence of auditory similarity between pharyngealization and ejectivity reported by Fre Woldu (1984-1986) in his study of Sudanese Colloquial Arabic and Tigrinya.

Thus, articulatory and acoustic evidence, lend support to the possible diachronic change from ejective glottalized consonants to pharyngealized consonants. This is an interesting question that merits further study.

Chapter 7: Conclusions

The aim of this acoustic and rtMRI study was to examine the articulatory configuration of pharyngealized consonants of Cairene Arabic, as well as the phonetic correlates associated with the pharyngealization spread triggered by these consonants. Specifically, this study looked at pharyngealization spread through different vowel qualities (/a/, /i/, and /u/), and different vowel lengths (short and long). Furthermore, it also examined pharyngealization spread in both directions, left-to-right and right-to-left. The acoustic data consisted of first and second formant frequency measures. The articulatory data consisted of rtMRI images. Analysis of both the acoustic and articulatory data suggested stronger and weaker pharyngealization spread across vowels of different lengths and qualities. In the acoustic data, this was understood from the variation in the extent of formant frequency modification due to the presence of a pharyngealized consonant. In the articulatory data, this was understood from the smaller 2D pharyngeal area measurements, and the more constricted pharyngeal contours.

Results from the articulatory data show that speech segments preceding pharyngealized consonants are generally more constricted than those following it, suggesting that anticipatory (leftward) spread is stronger than perseveratory (rightward) spread in this dialect. Furthermore, among two minimal pairs containing the same pharyngealized consonant but differing in vowel length, 2D pharyngeal areas are generally more constricted in the speech segments of the word containing the longer vowel, suggesting that the effect of pharyngealization is stronger in longer vowels. Finally, measuring the magnitude of pharyngealization across different vowel environments suggests that the effect of pharyngealization is generally greatest in an /a/ context, followed by an /i/ context, and then an /u/ context.

Formant frequency measures and SSANOVA plots in the acoustic data support these results showing that modification of F2 is greater in longer vowels than in shorter ones, and is greater in an /a/ context, followed by an /i/ context, and then an /u/ context.

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Appendix: Articulatory Contours and 2D Areas

Speaker 1 – SP1

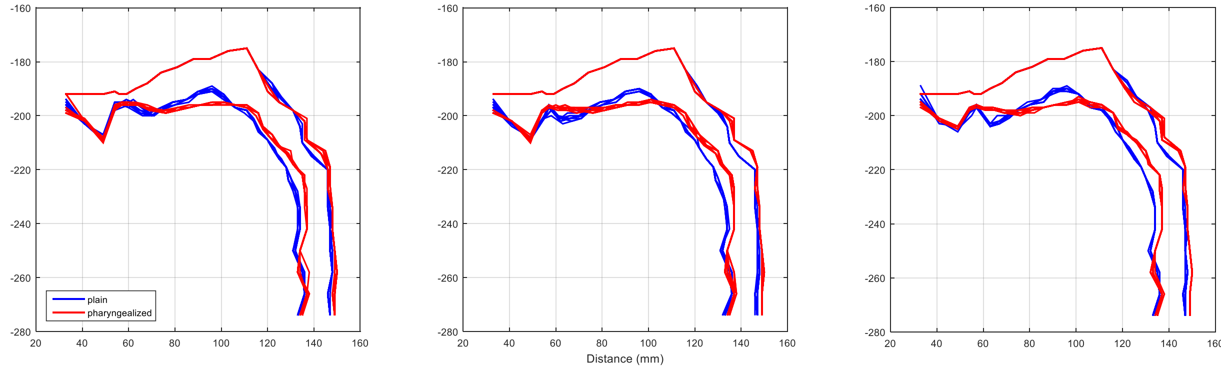

Figure A.1: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /sa:b/ in blue (‘he left’) and /sˤa:b/ in red (‘he hit’) from SP1.

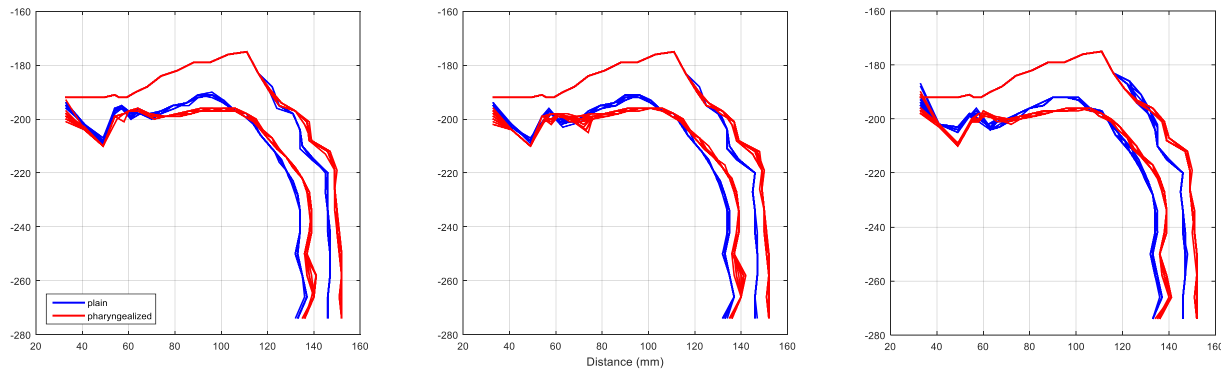

Figure A.2: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /sabb/ in blue (‘he insulted’) and /sˤabb/ in red (‘he poured’) from SP1.

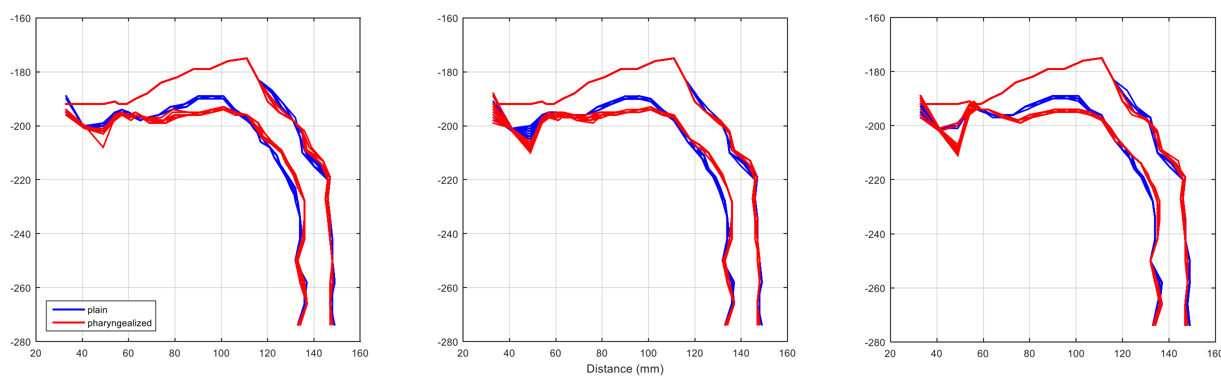

Figure A.3: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /ba:s/ in blue (‘he kissed’) and /ba:sˤ/ in red (‘bus’) from SP1.

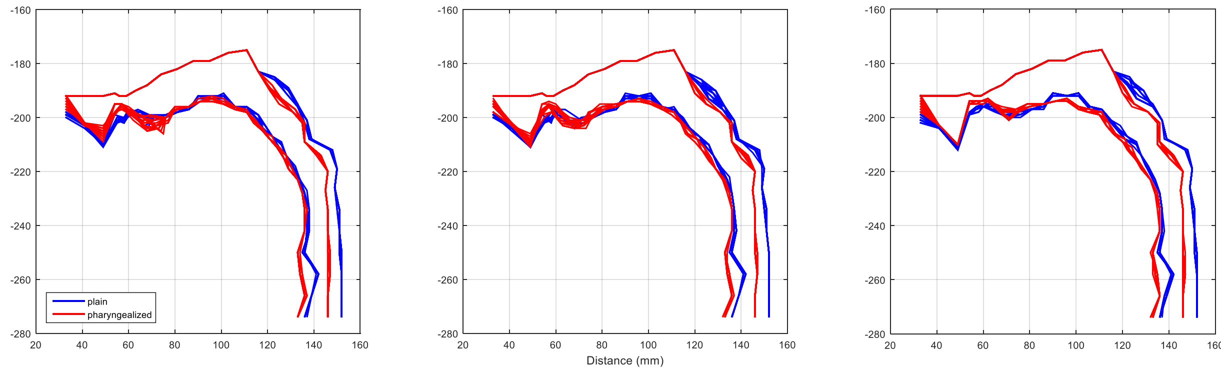

Figure A.4: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /bass/ in blue (‘enough!’) and /basˤsˤ/ in red (‘he looked’) from SP1.

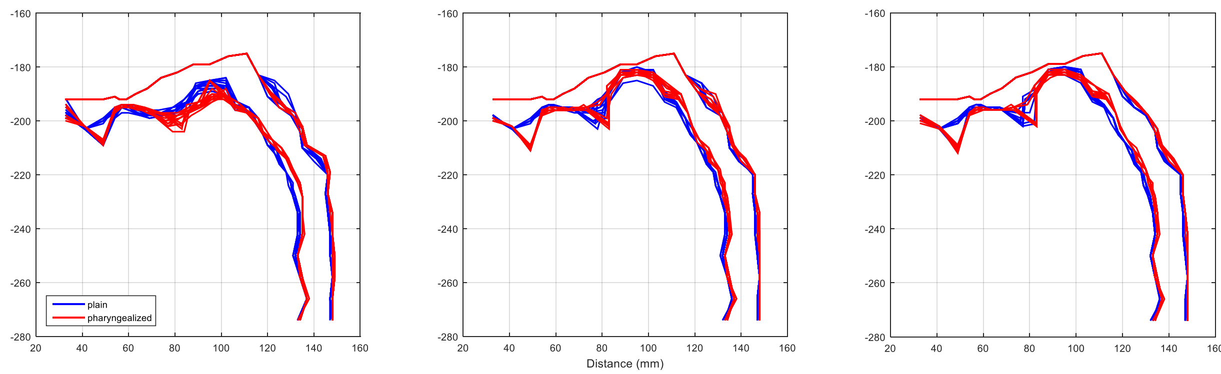

Figure A.5: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /si:n/ in blue (‘the Arabic letter /s/’) and /sˤi:n/ in red (‘China’) from SP1.

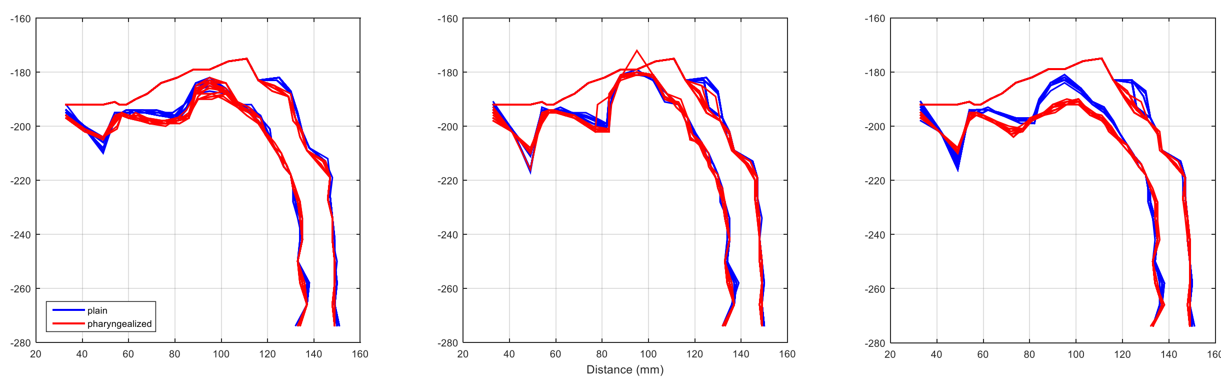

Figure A.6: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /bi:d/ in blue (‘exterminate’) and /bi:dˤ / in red (‘white’) from SP1.

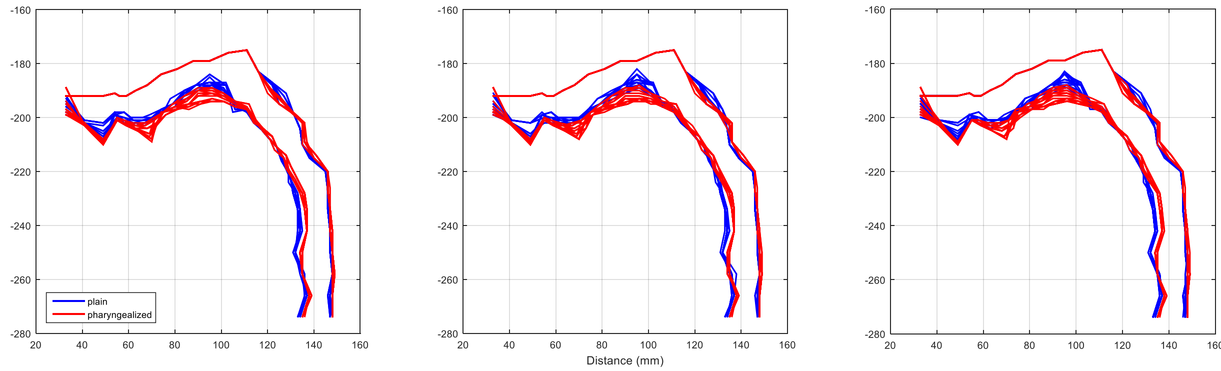

Figure A.7: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /fa:yid/ in blue (‘a town in Egypt’) and /fa:yi:dˁ / in red (‘remaining’) from SP1.

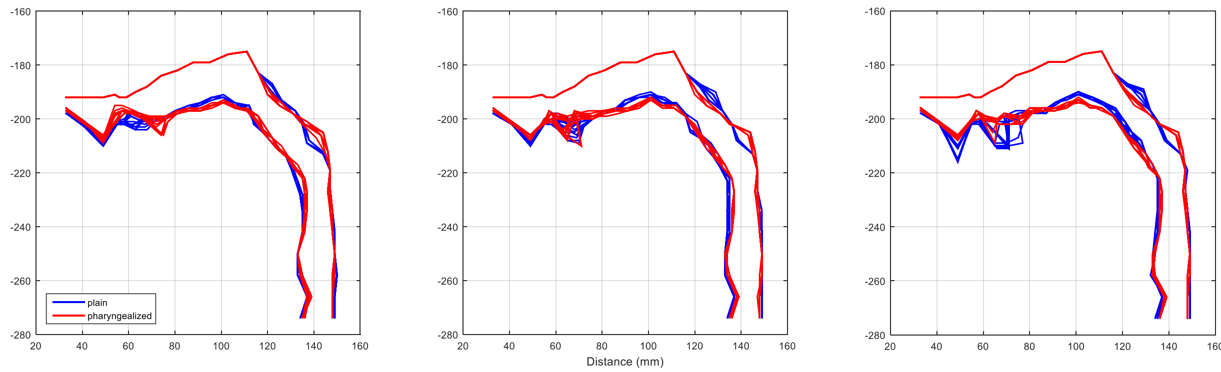

Figure A. 8: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /tu:b/ in blue (‘repent) and /tˁu:b/ in red (‘stones’) from SP1.

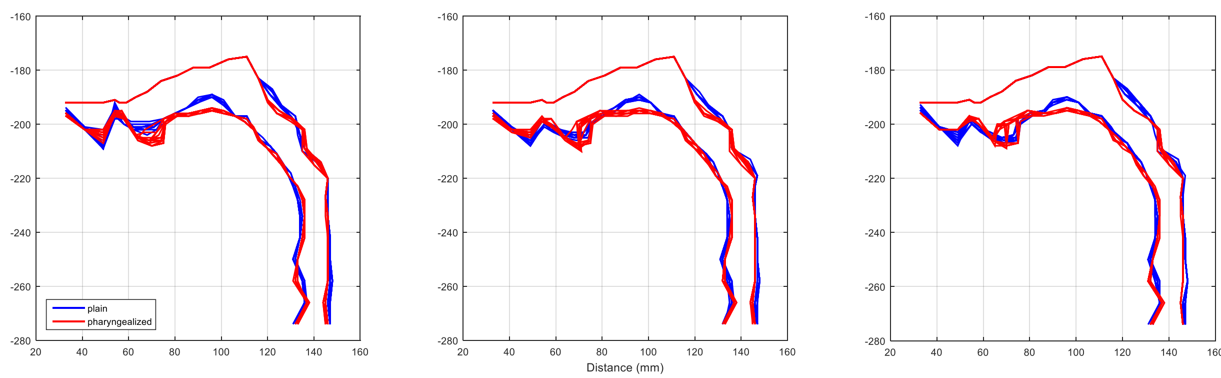

Figure A.9: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /tubʔa/ in blue (‘will become’) and /tˁubb/ in red (‘come unexpected’) from SP1.

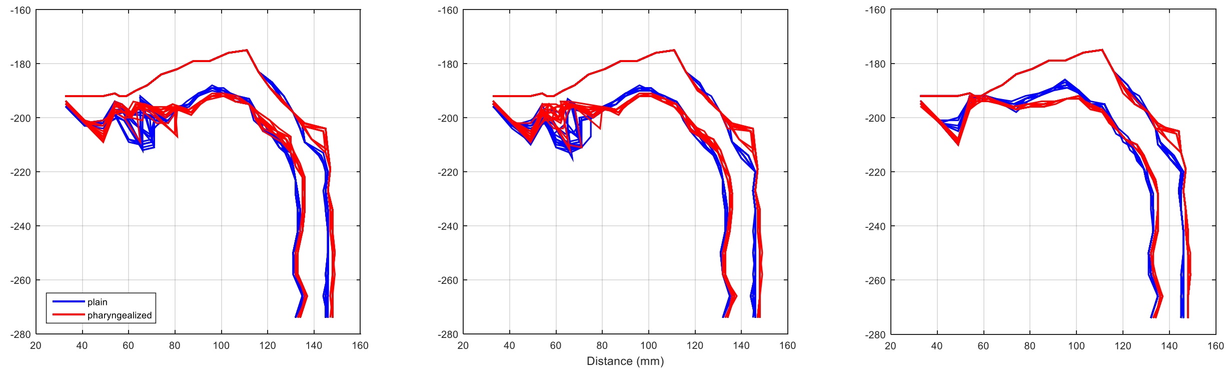

Figure A.10: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /bu:z/ in blue ('muzzle') and /bu:zˤ/ in red ('rot/damage') from SP1.

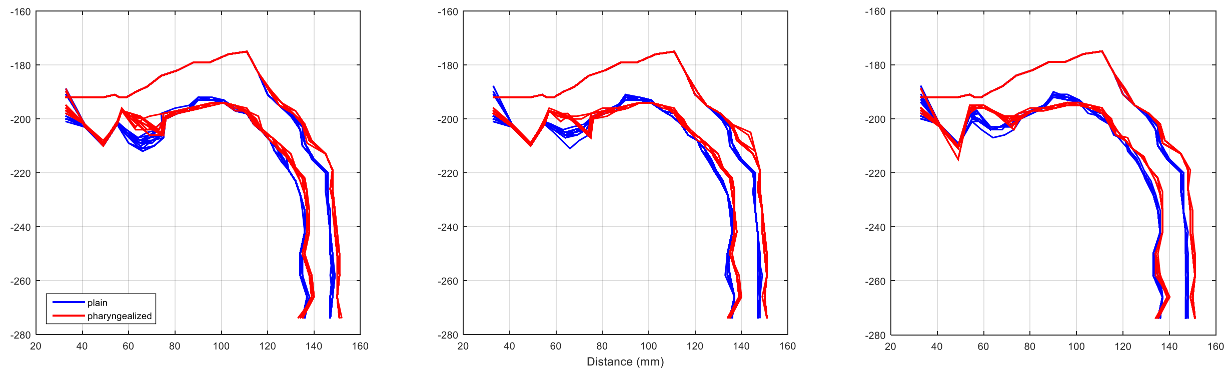

Figure A.11: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /yuʕud/ in blue ('he sits') and / yuʕudˤdˤ/ in red ('he bites') from SP1.

Speaker 2 – SP2

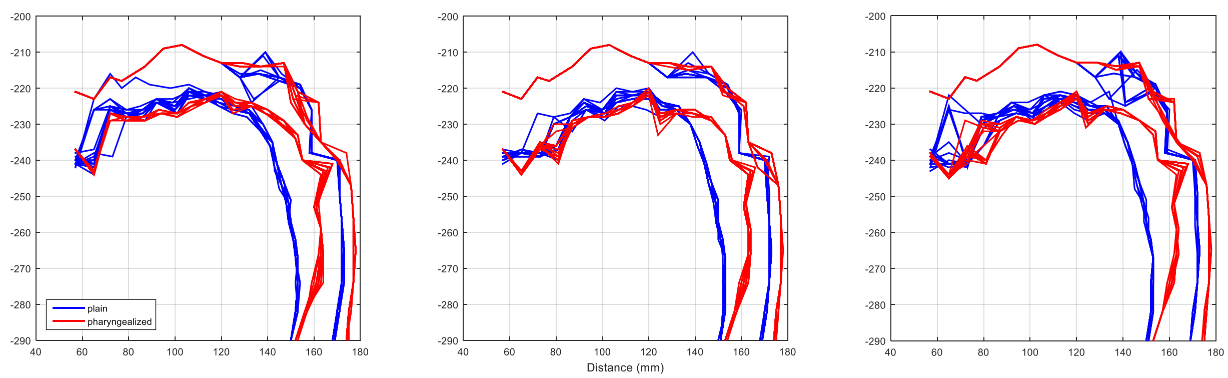

Figure A.12: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /sa:b/ in blue ('he left') and /sˤa:b/ in red ('he hit') from SP2.

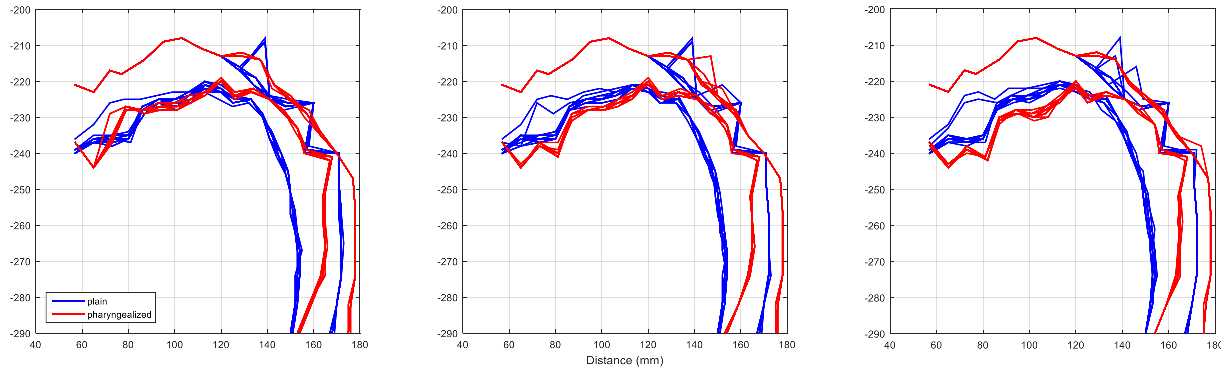

Figure A.13: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /sabb/ in blue (‘he insulted’) and /sˤabb/ in red (‘he poured’) from SP2.

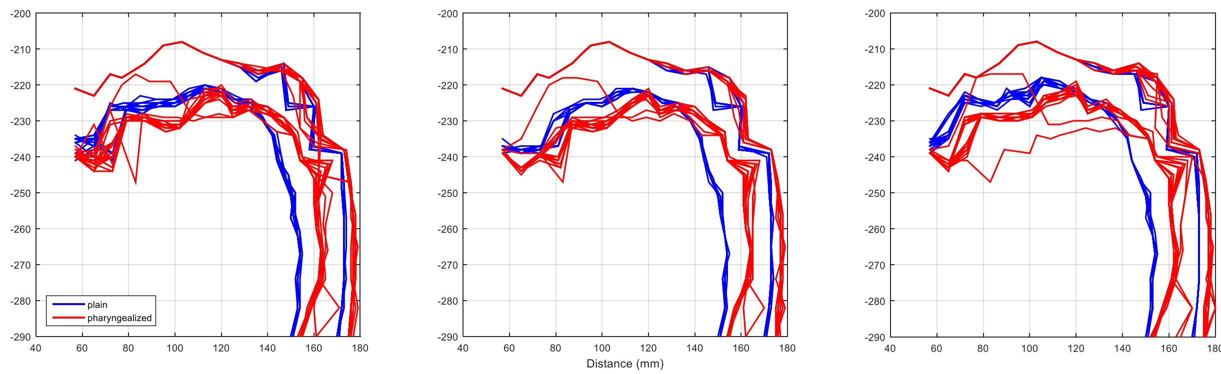

Figure A.14: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /ba:s/ in blue (‘he kissed’) and /ba:sˤ/ in red (‘bus’) from SP2.

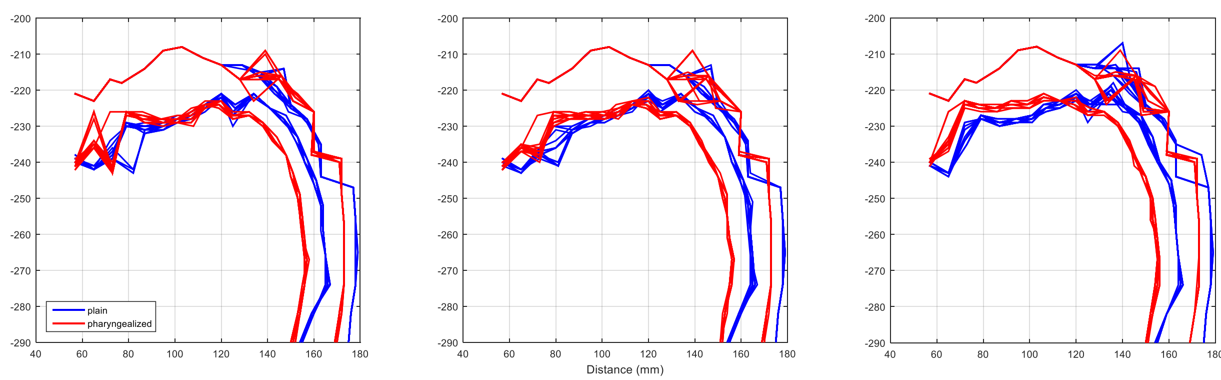

Figure A.15: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /bass/ in blue (‘enough!’) and /basˤsˤ/ in red (‘he looked’) from SP2.

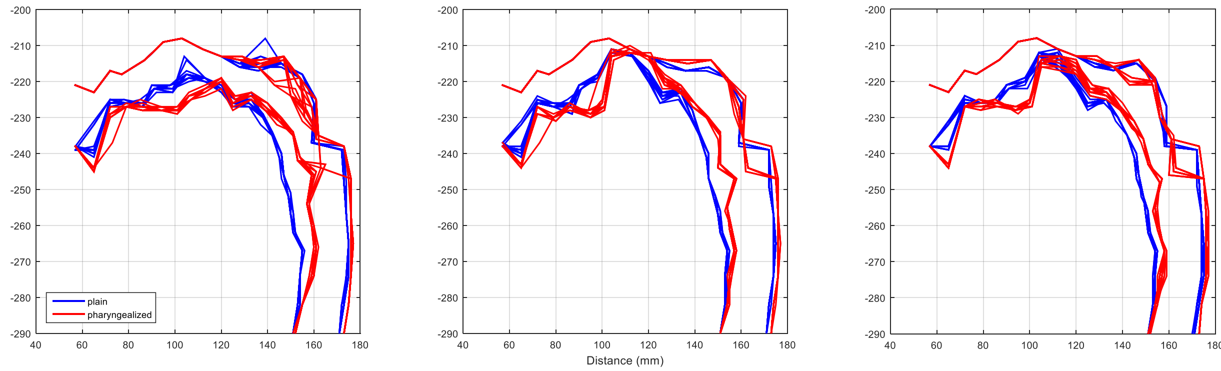

Figure A.16: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /si:n/ in blue (‘the Arabic letter /s/’) and /sˤi:n/ in red (‘China’) from SP2.

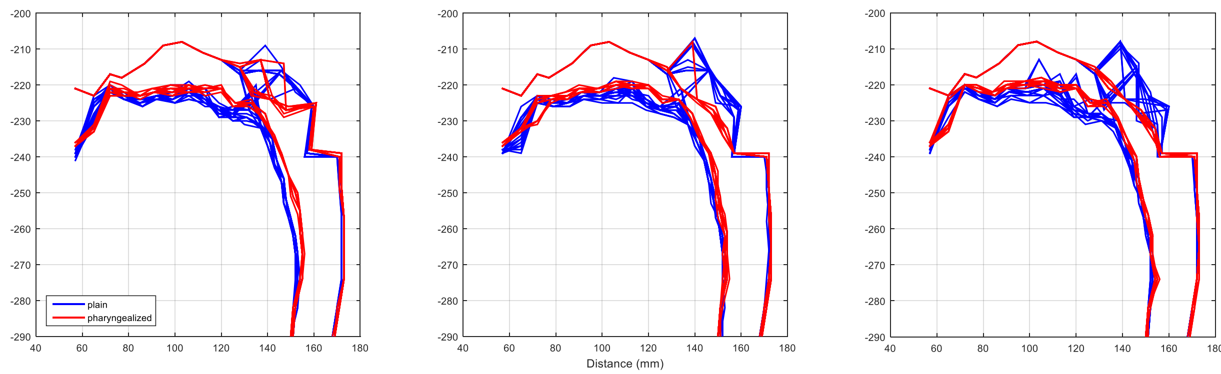

Figure A.17: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /azinn/ in blue (‘I whine’) and /azˤinn/ in red (‘I think’) from SP2.

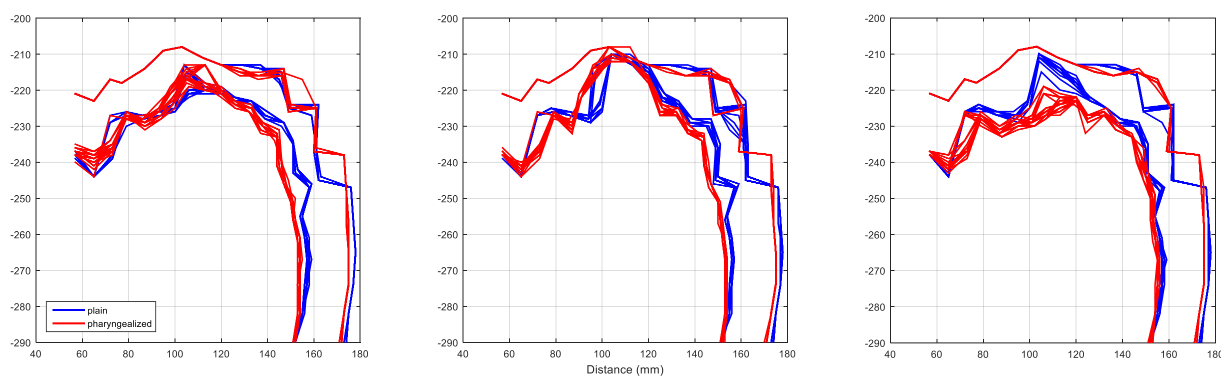

Figure A.18: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /bi:d/ in blue (‘exterminate’) and /bi:dˤ / in red (‘white’) from SP2.

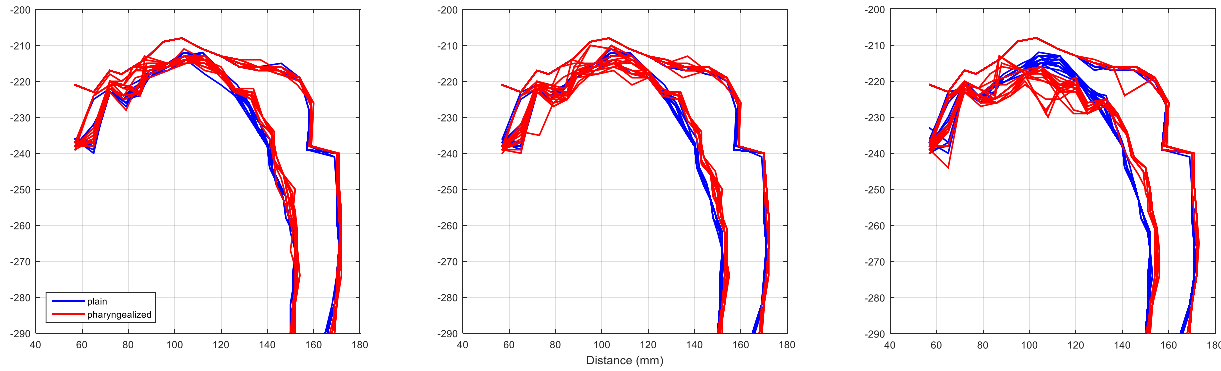

Figure A.19: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /fa:yid/ in blue (‘a town in Egypt’) and /fa:yi:d^{ʕ} / in red (‘remaining’) from SP2.

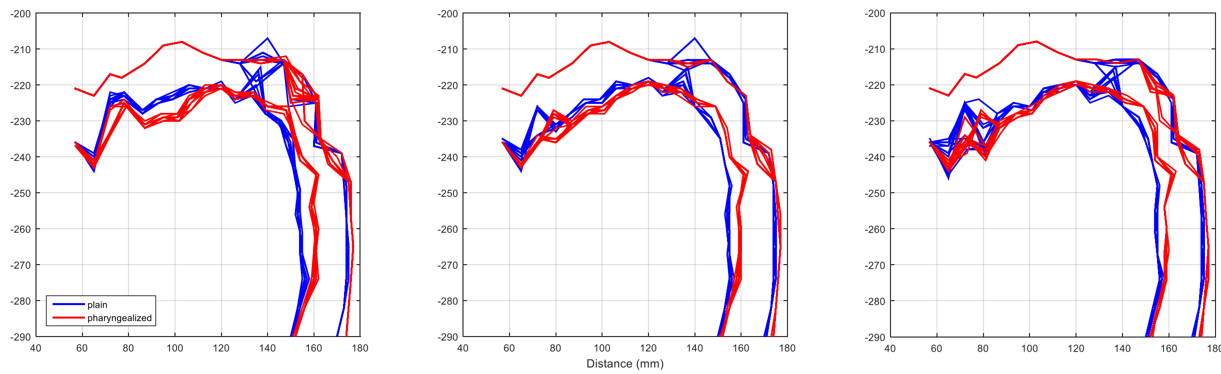

Figure A.20: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /tu:b/ in blue (‘repent) and /t^{ʕ}u:b/ in red (‘stones’) from SP2.

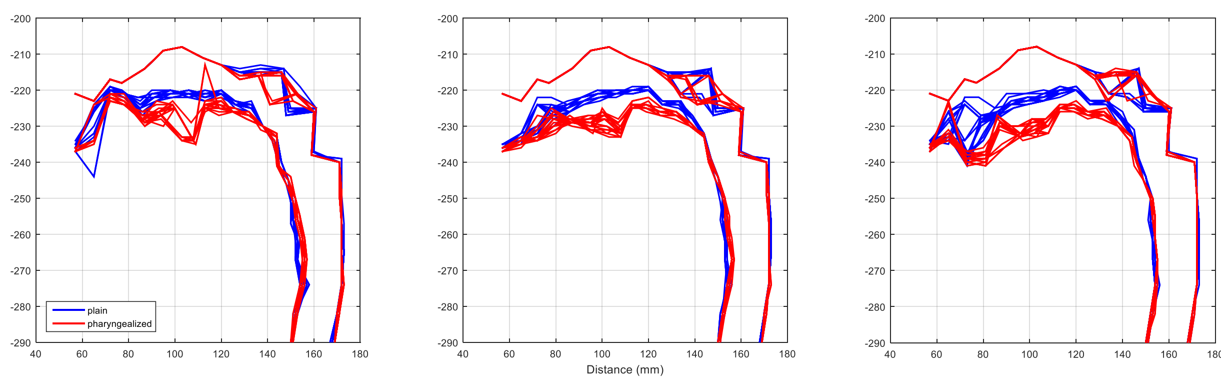

Figure A.21: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /tubʔa/ in blue (‘will become’) and /t^{ʕ}ubb/ in red (‘come unexpected’) from SP2.

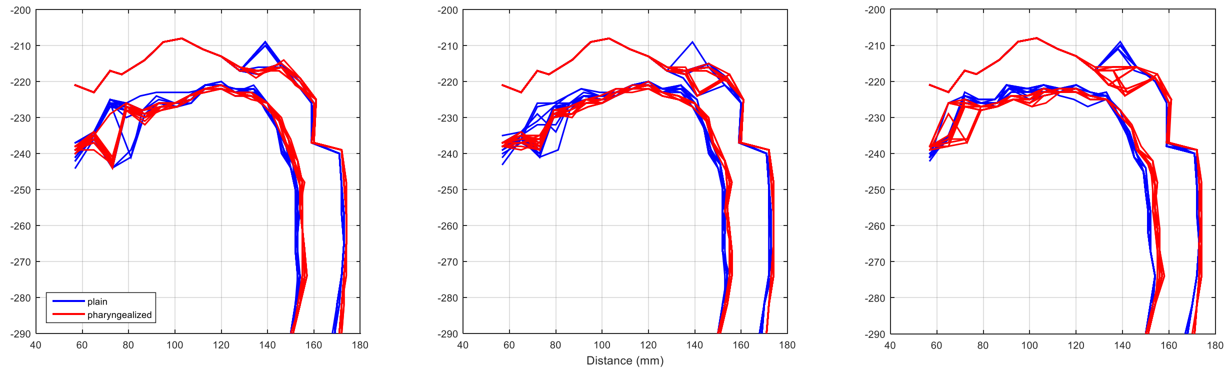

Figure A.22: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /bu:z/ in blue (‘muzzle’) and /bu:zˤ/ in red (‘rot/damage’) from SP2.

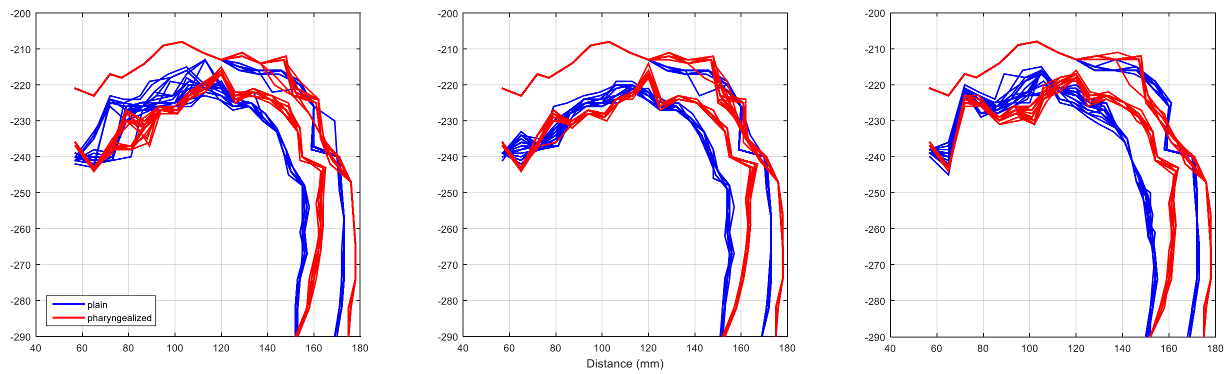

Figure A.23: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /yuʕud/ in blue (‘he sits’) and / yuʕudˤdˤ/ in red (‘he bites’) from SP2.

Speaker 4 – SP4

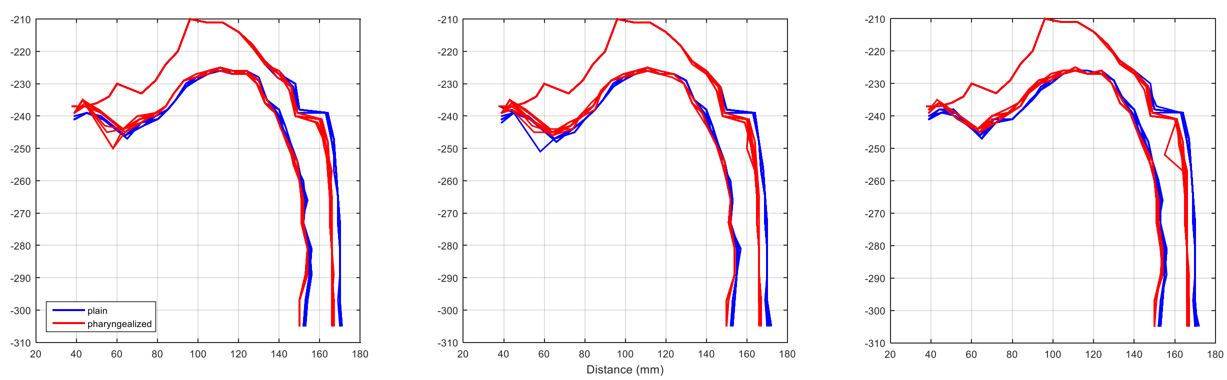

Figure A.24: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /sa:b/ in blue (‘he left’) and /sˤa:b/ in red (‘he hit’) from SP4.

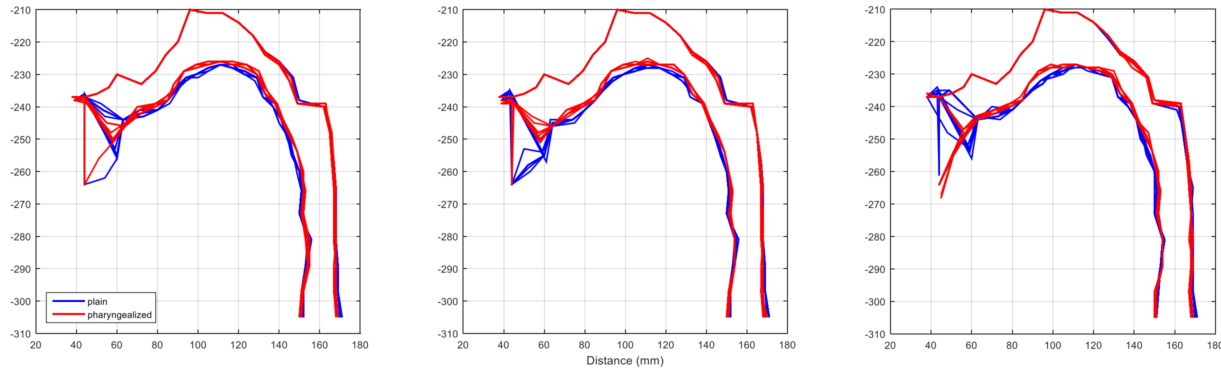

Figure A.25: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /sabb/ in blue (‘he insulted’) and /s$^{\text{ʕ}}$abb/ in red (‘he poured’) from SP4.

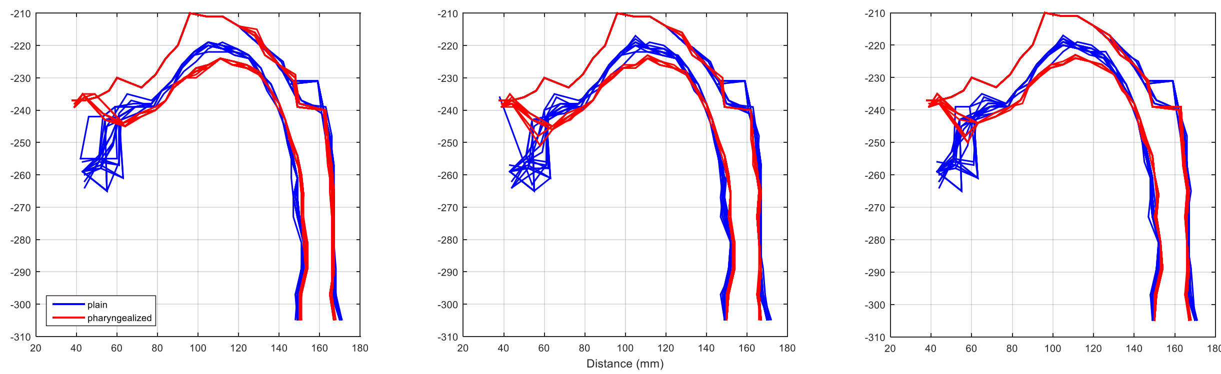

Figure A.26: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /ba:s/ in blue (‘he kissed’) and /ba:s$^{\text{ʕ}}$/ in red (‘bus’) from SP4.

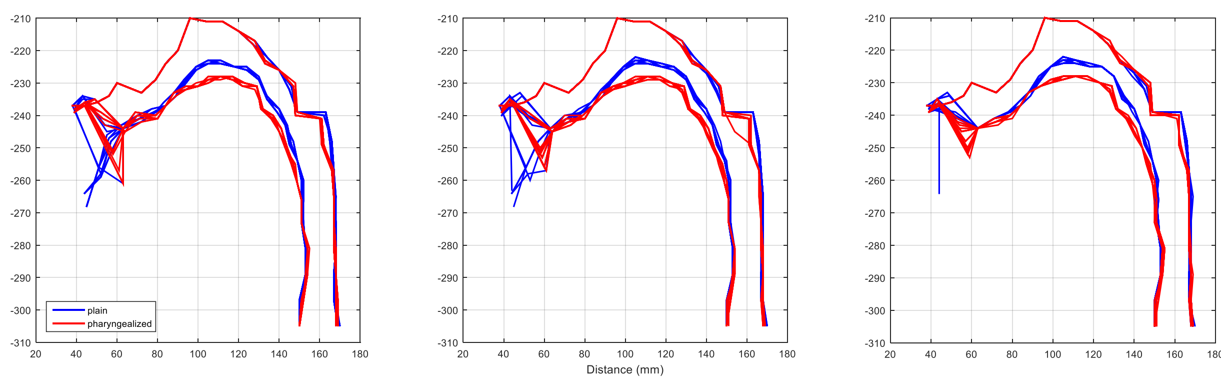

Figure A.27: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /bass/ in blue (‘enough!’) and /bas$^{\text{ʕ}}$s$^{\text{ʕ}}$/ in red (‘he looked’) from SP4.

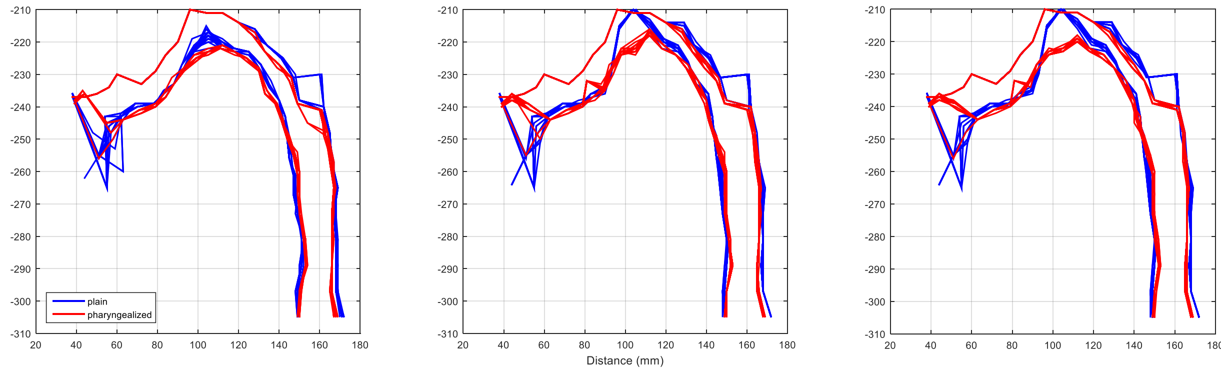

Figure A.28: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /si:n/ in blue (‘the Arabic letter /s/’) and /sˤi:n/ in red (‘China’) from SP4.

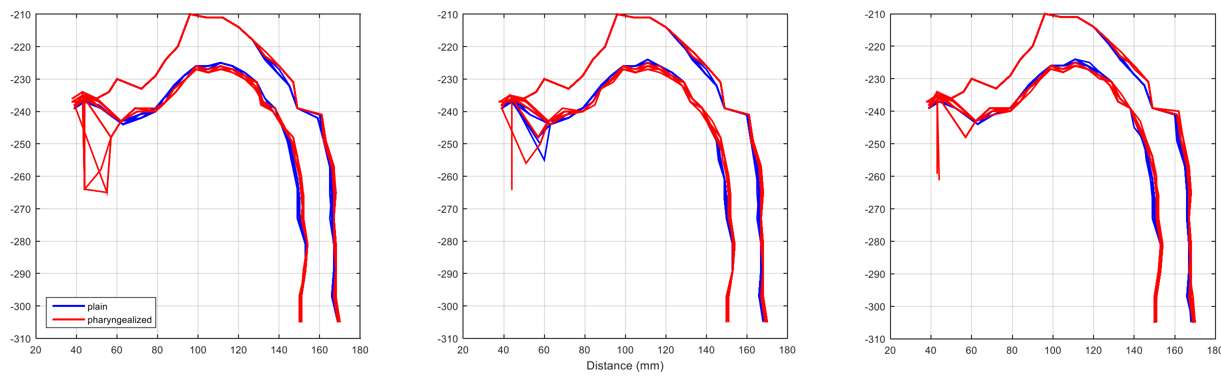

Figure A.29: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /azinn/ in blue (‘I whine’) and /azˤinn/ in red (‘I think’) from SP4.

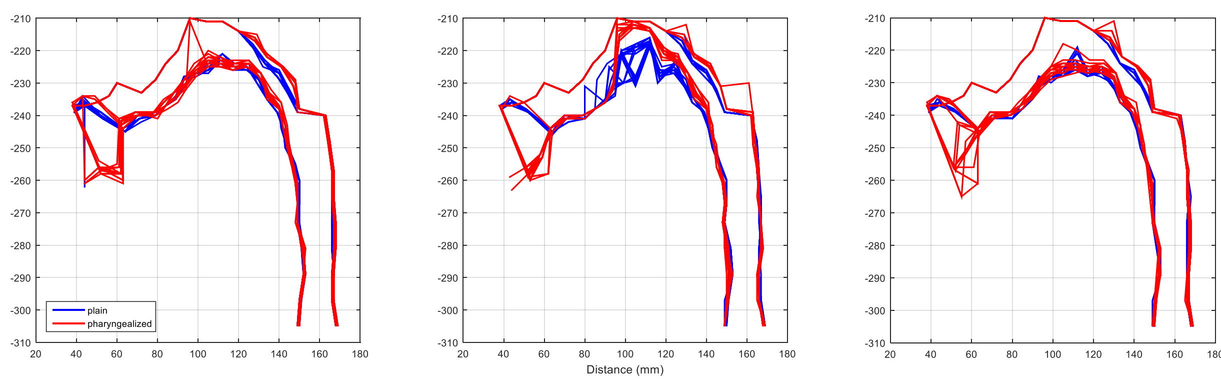

Figure A.30: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /bi:d/ in blue (‘exterminate’) and /bi:dˤ / in red (‘white’) from SP4.

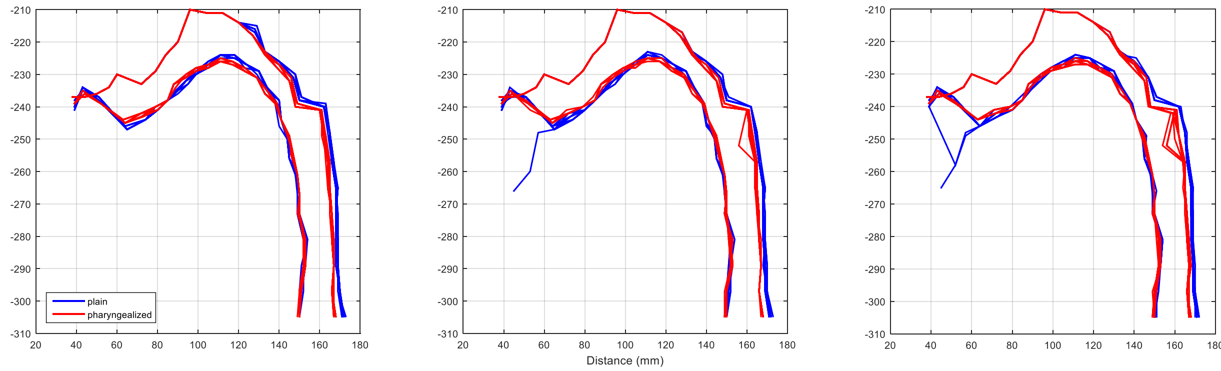

Figure A.31: The pharyngeal and lingual contours automatically detected for 20 repetitions of target words /fa:yid/ in blue (‘a town in Egypt’) and /fa:yi:dˤ / in red (‘remaining’) from SP4.

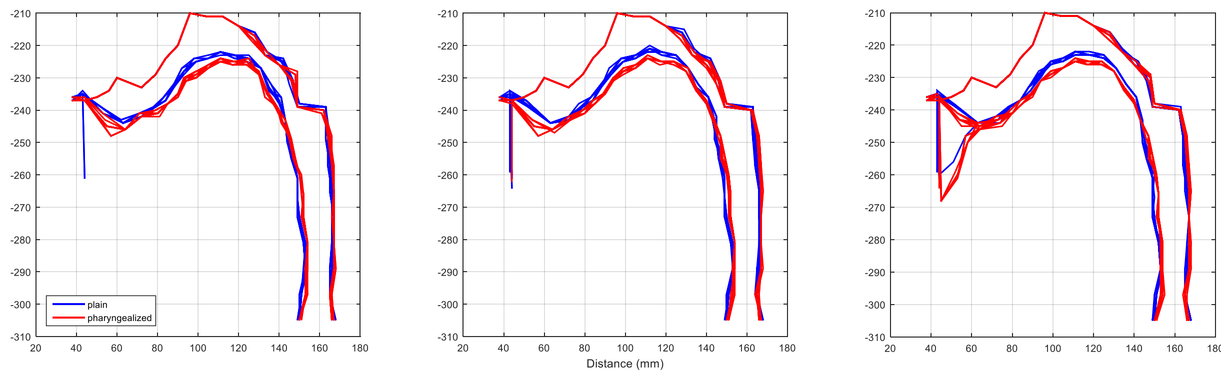

Figure A.32: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /tu:b/ in blue (‘repent) and /tˤu:b/ in red (‘stones’) from SP4.

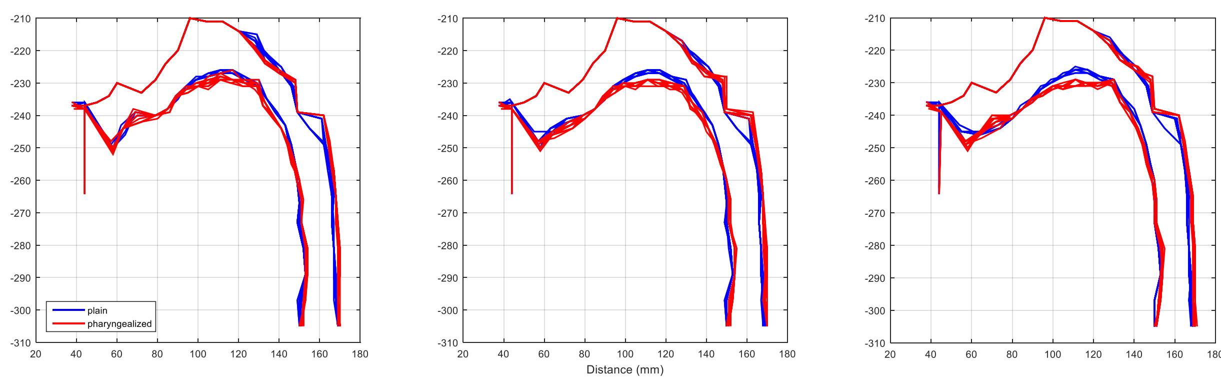

Figure A.33: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /tubʔa/ in blue (‘will become’) and /tˤubb/ in red (‘come unexpected’) from SP4.

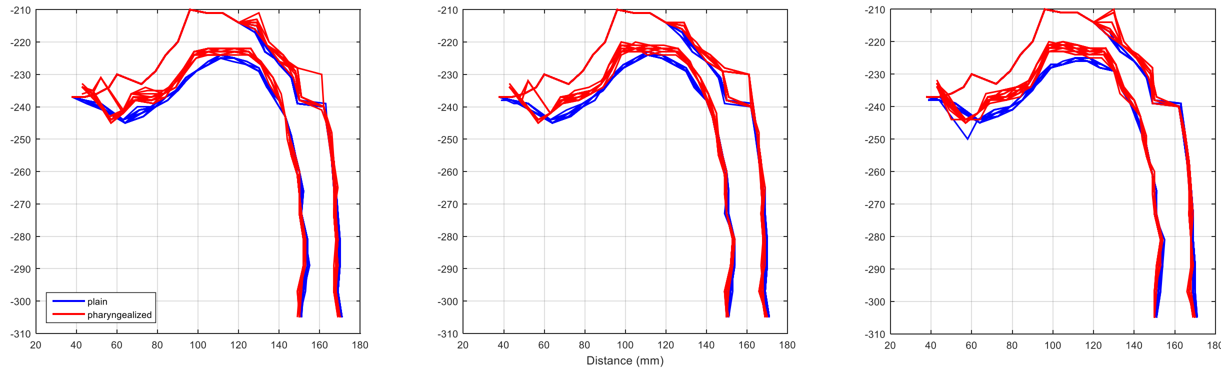

Figure A.34: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /bu:z/ in blue (‘muzzle’) and /bu:zˤ/ in red (‘rot/damage’) from SP4.

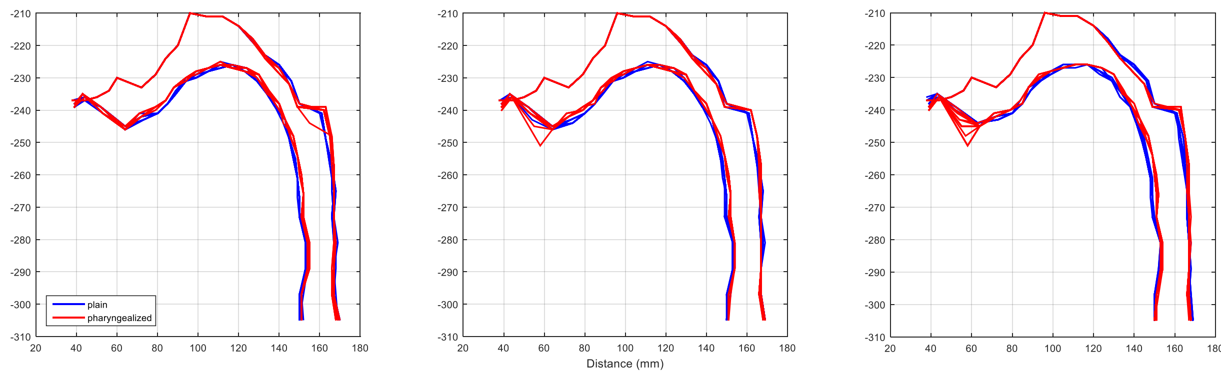

Figure A.35: The pharyngeal and lingual contours automatically detected for 20 repetitions of the target words /yuʕud/ in blue (‘he sits’) and / yuʕudˤdˤ/ in red (‘he bites’) from SP4.

Speaker 5 – SP5

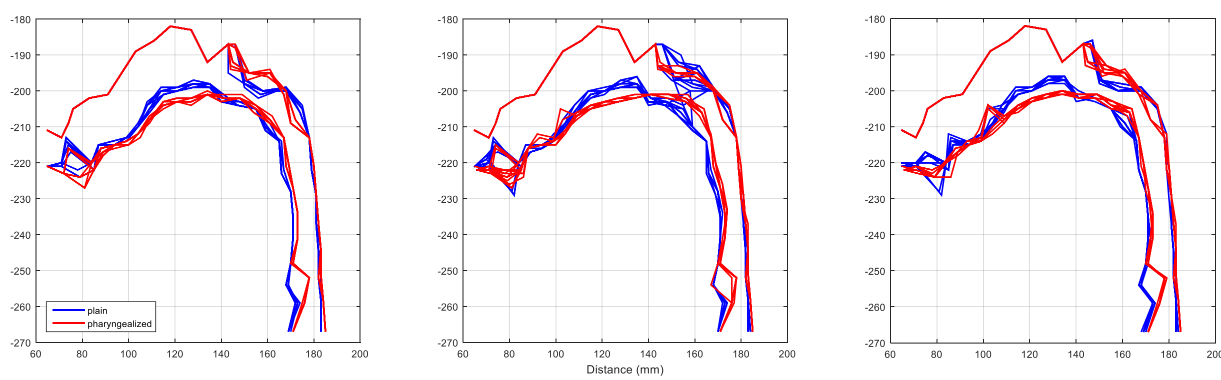

Figure A.36: The pharyngeal and lingual contours automatically detected for 14 repetitions of target words /sa:b/ in blue (‘he left’) and /sˤa:b/ in red (‘he hit’) from SP5.

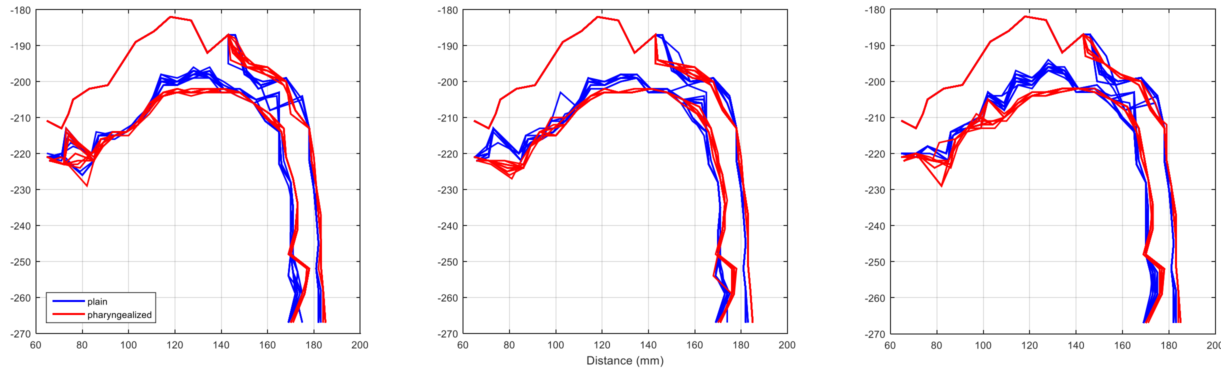

Figure A.37: The pharyngeal and lingual contours automatically detected for 14 repetitions of target words /sabb/ in blue (‘he insulted’) and /s^{ʕ}abb/ in red (‘he poured’) from SP5.

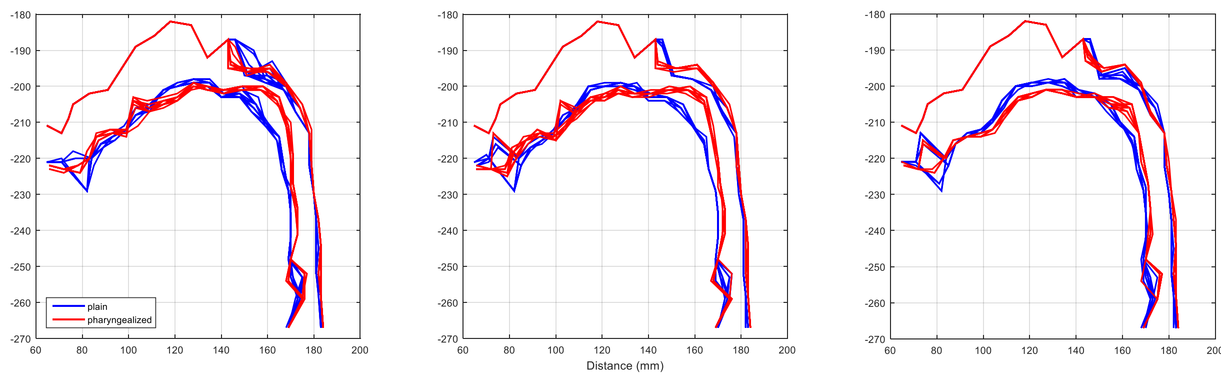

Figure A.38: The pharyngeal and lingual contours automatically detected for 14 repetitions of target words /ba:s/ in blue (‘he kissed’) and /ba:s^ʕ/ in red (‘bus’) from SP5.

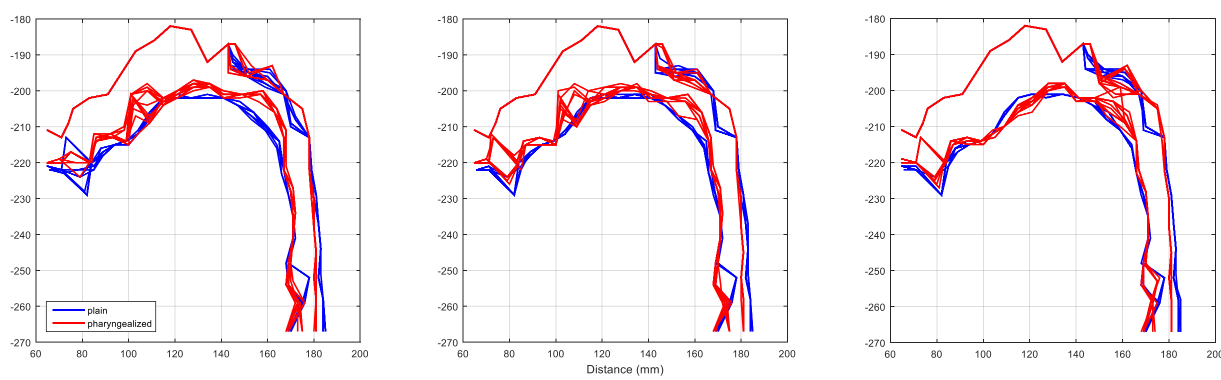

Figure A.39: The pharyngeal and lingual contours automatically detected for 14 repetitions of target words /bass/ in blue (‘enough!’) and /bas^{ʕ}s^ʕ/ in red (‘he looked’) from SP5.

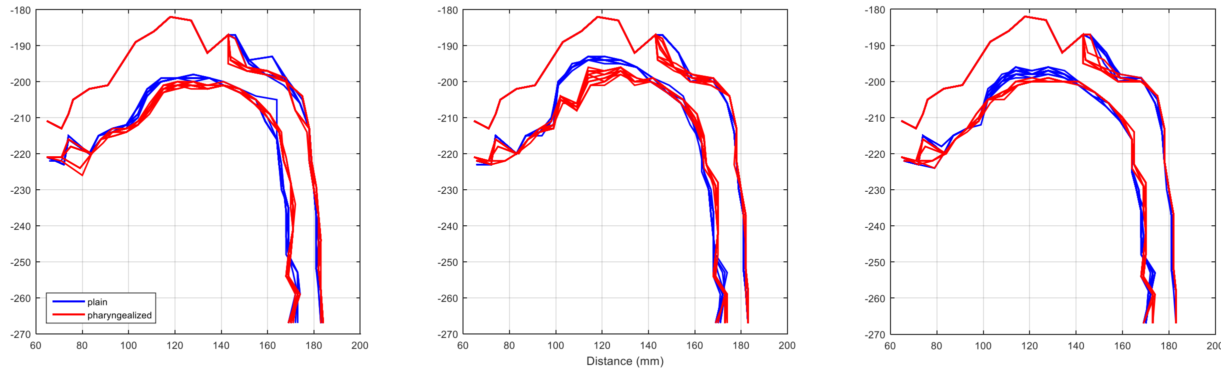

Figure A.40: The pharyngeal and lingual contours automatically detected for 14 repetitions of target words /si:n/ in blue ('the Arabic letter /s/') and /sˤi:n/ in red ('China') from SP5.

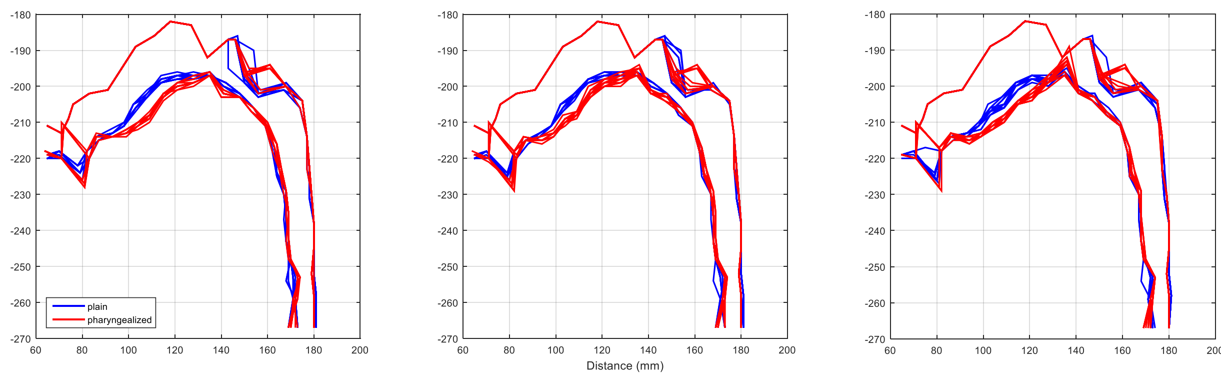

Figure A.41: The pharyngeal and lingual contours automatically detected for 14 repetitions of target words /azinn/ in blue ('I whine') and /azˤinn/ in red ('I think') from SP5.

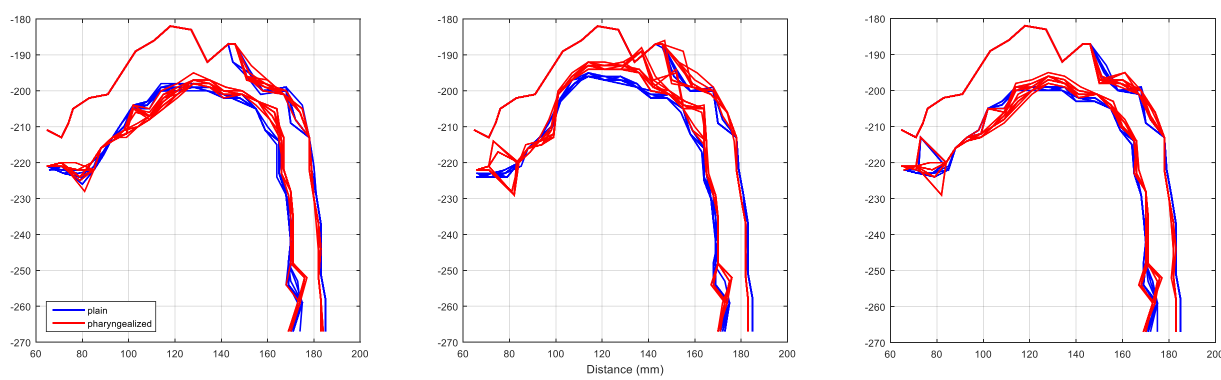

Figure A.42: The pharyngeal and lingual contours automatically detected for 14 repetitions of target words /bi:d/ in blue ('exterminate') and /bi:dˤ / in red ('white') from SP5.

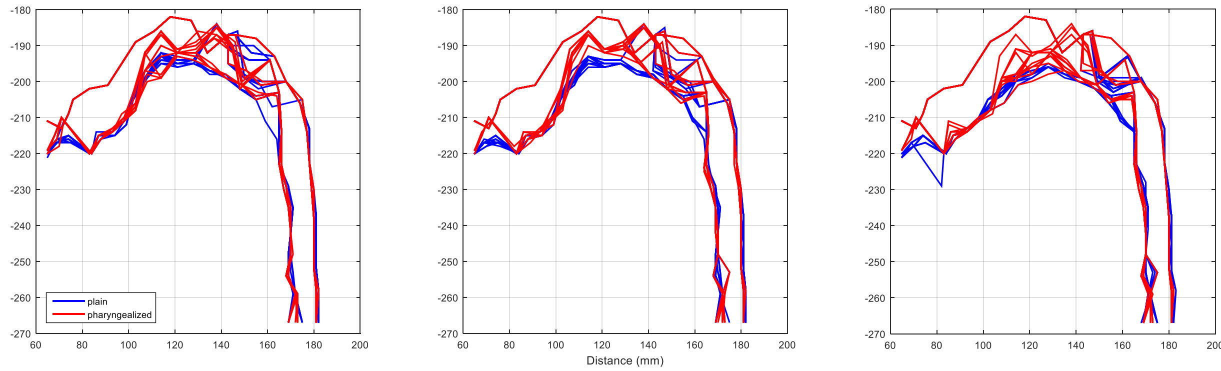

Figure A.43: The pharyngeal and lingual contours automatically detected for 14 repetitions of target words /fa:yid/ in blue (‘a town in Egypt’) and /fa:yi:dˤ / in red (‘remaining’) from SP5.

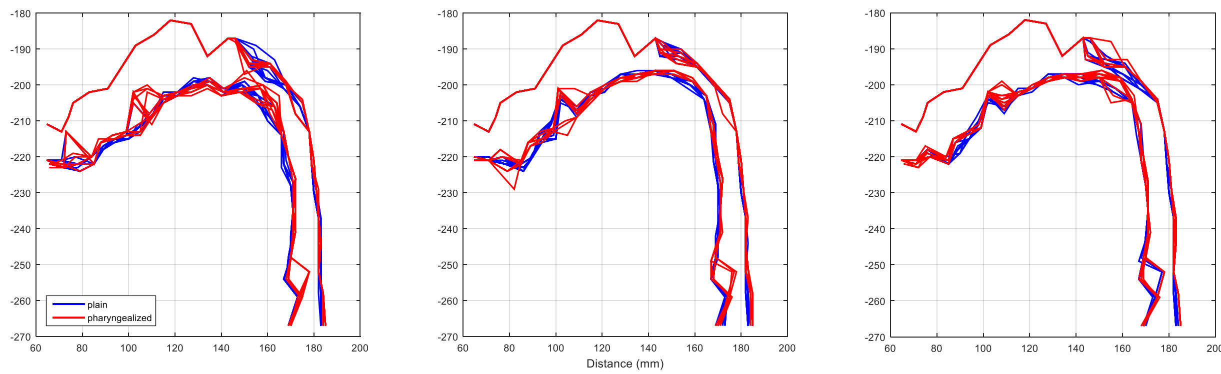

Figure A.44: The pharyngeal and lingual contours automatically detected for 14 repetitions of the target words /tu:b/ in blue (‘repent) and /tˤu:b/ in red (‘stones’) from SP5.

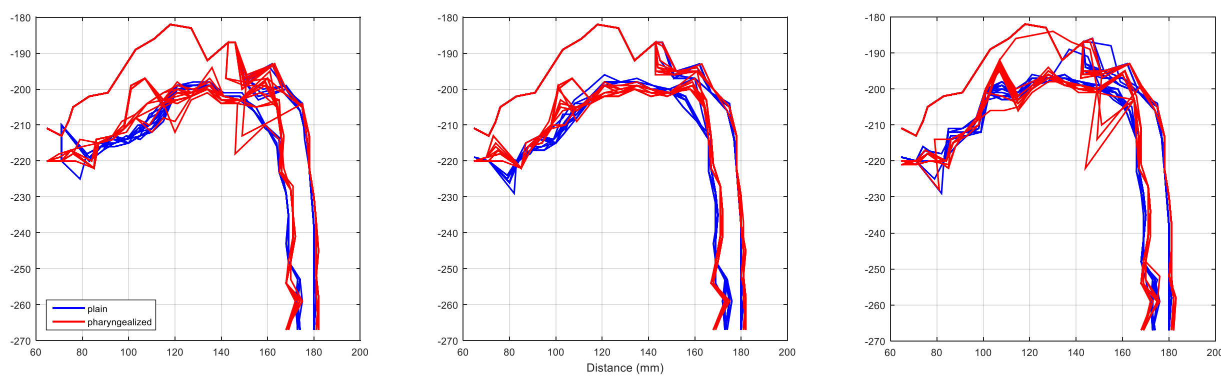

Figure A.45: The pharyngeal and lingual contours automatically detected for 14 repetitions of the target words /tubʔa/ in blue (‘will become’) and /tˤubb/ in red (‘come unexpected’) from SP5.

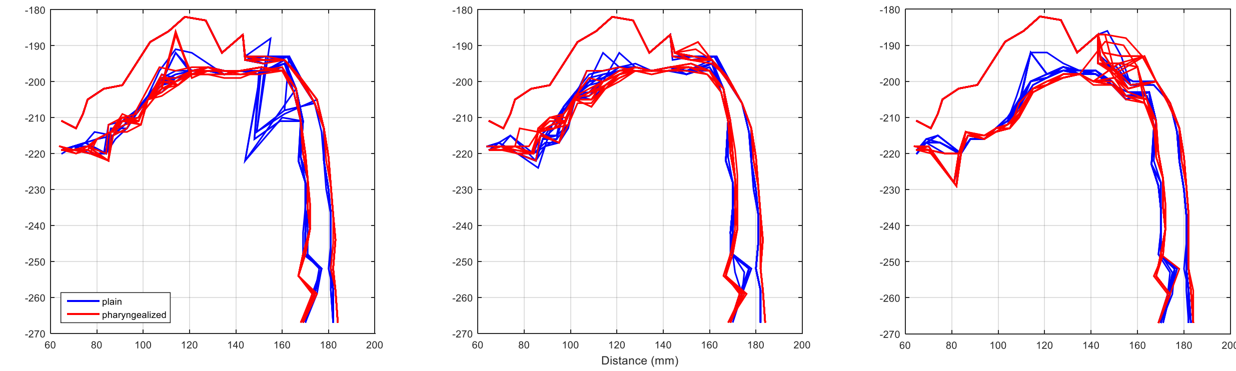

Figure A.46: The pharyngeal and lingual contours automatically detected for 14 repetitions of the target words /bu:z/ in blue (‘muzzle’) and /bu:zˤ/ in red (‘rot/damage’) from SP5.

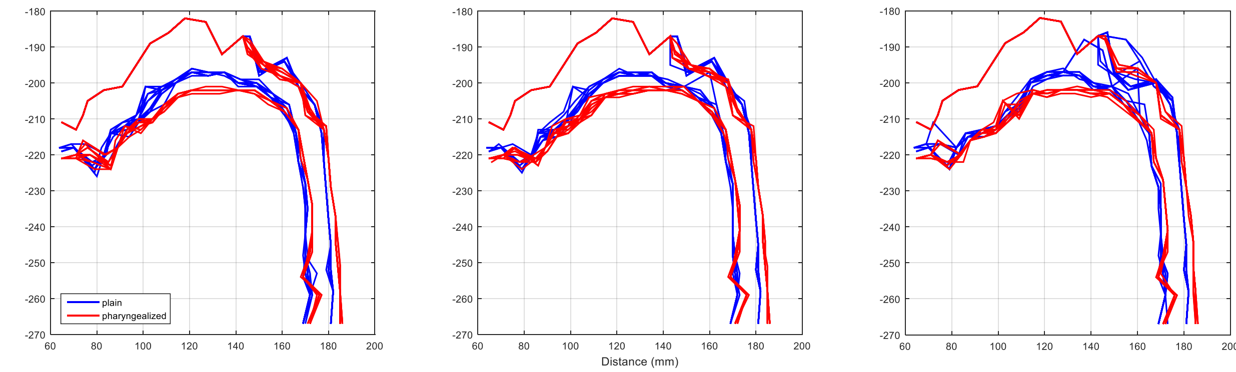

Figure A.47: The pharyngeal and lingual contours automatically detected for 14 repetitions of the target words /yuʕud/ in blue (‘he sits’) and / yuʕudˤdˤ/ in red (‘he bites’) from SP5.

Speaker 1 – SP1

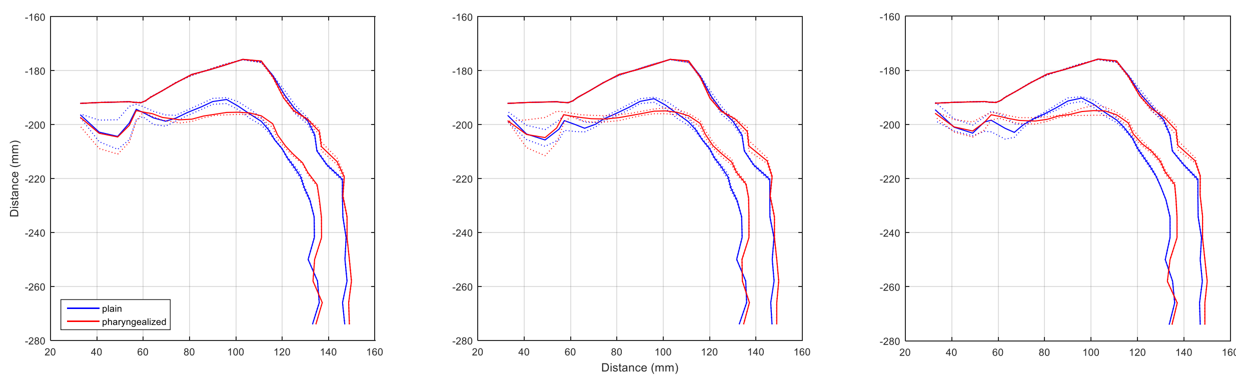

Figure A.48: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /sa:b/ in blue (‘he left’) and /sˤa:b/ in red (‘he hit’) from SP1.

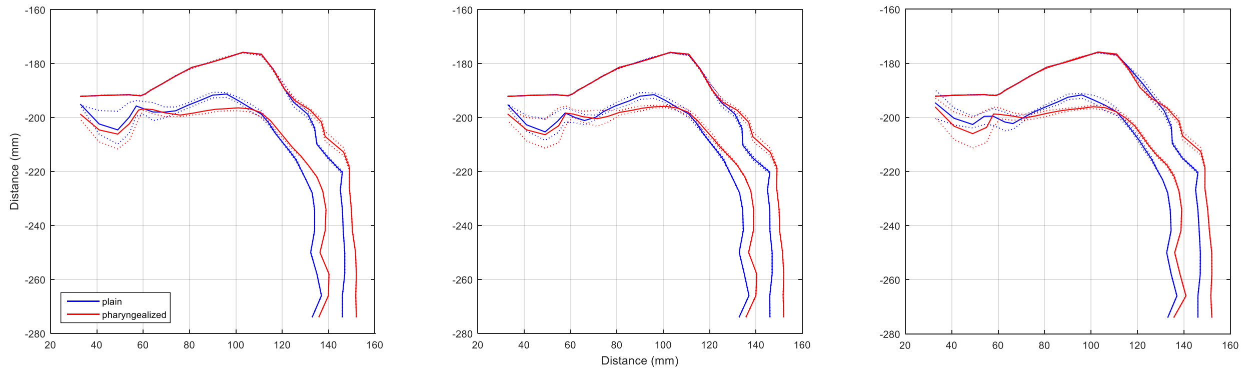

Figure A.49: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /sabb/ in blue (‘he insulted’) and /s^{ʕ}abb/ in red (‘he poured’) from SP1.

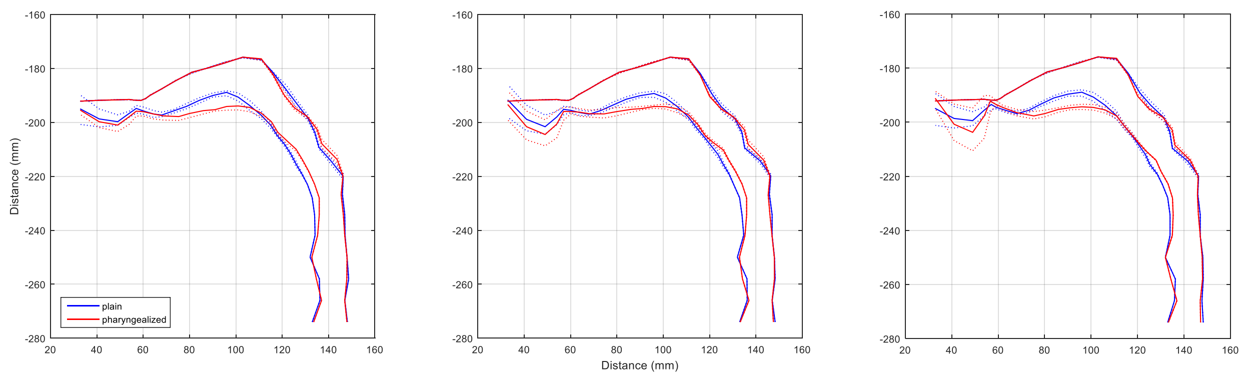

Figure A.50: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /ba:s/ in blue (‘he kissed’) and /ba:s^{ʕ}/ in red (‘bus’) from SP1.

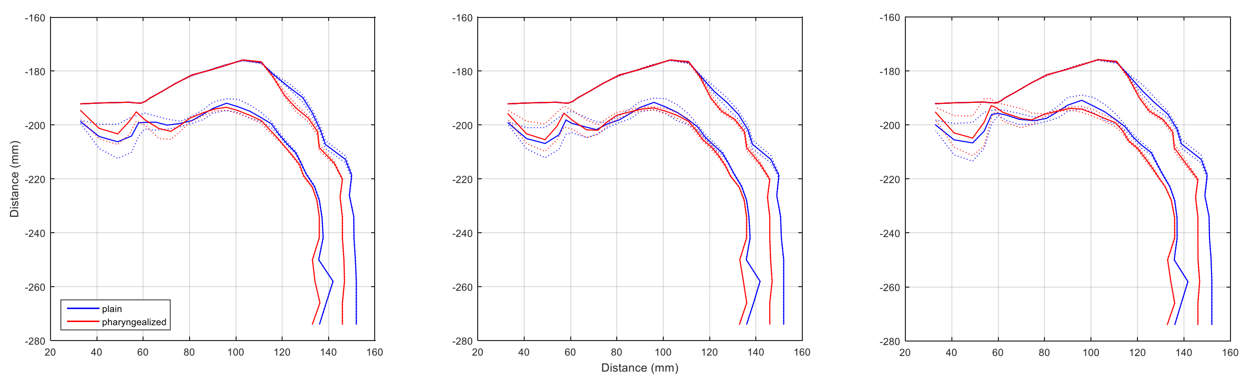

Figure A.51: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bass/ in blue (‘enough!’) and /bas^{ʕ}s^{ʕ}/ in red (‘he looked’) from SP1.

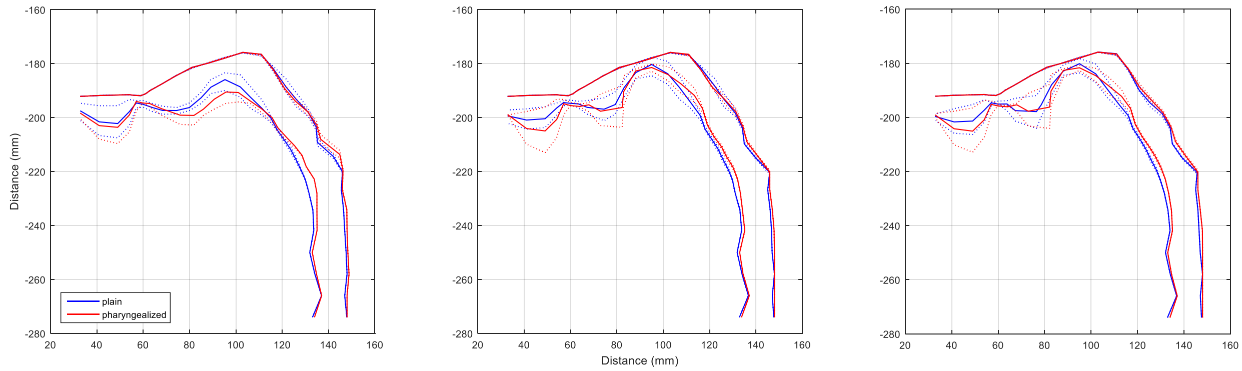

Figure A.52: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /si:n/ in blue (‘the Arabic letter /s/’) and /s^{ʕ}i:n/ in red (‘China’) from SP1.

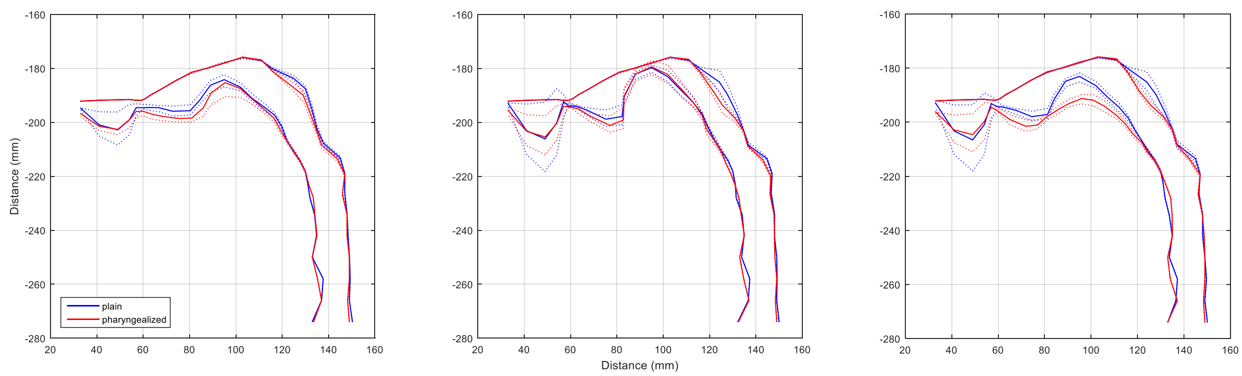

Figure A.53: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bi:d/ in blue (‘exterminate’) and /bi:d^ʕ / in red (‘white’) from SP1.

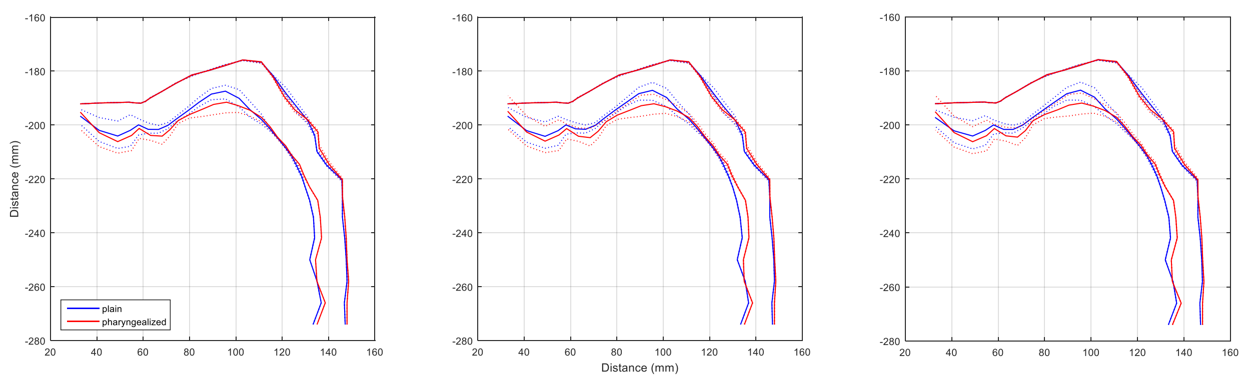

Figure A.54: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /fa:yid/ in blue (‘a town in Egypt’) and /fa:yi:d^ʕ / in red (‘remaining’) from SP1.

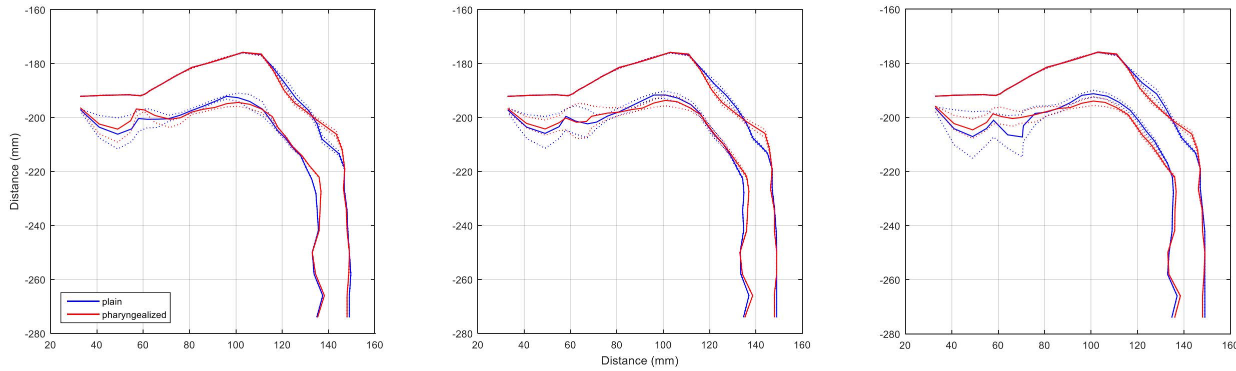

Figure A.55: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /tu:b/ in blue (‘repent) and /tˤu:b/ in red (‘stones’) from SP1.

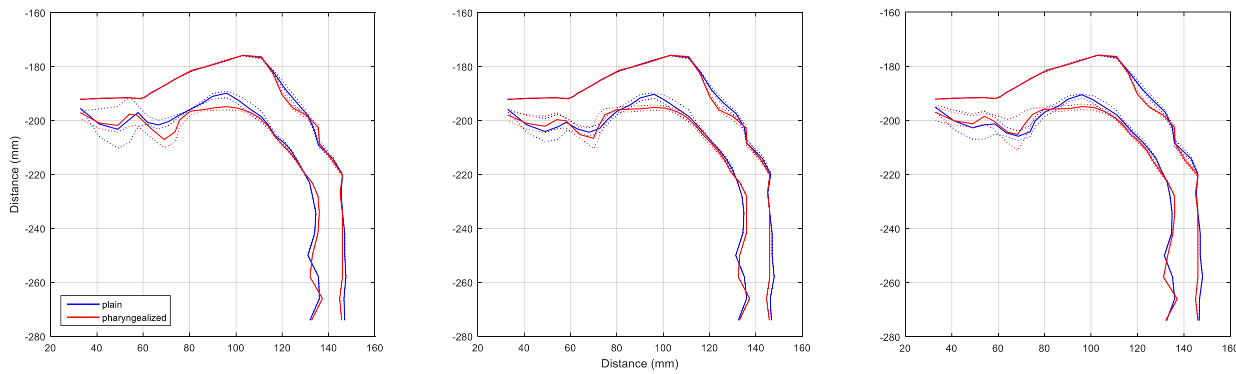

Figure A.56: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /tubʔa/ in blue (‘will become’) and /tˤubb/ in red (‘come unexpected’) from SP1.

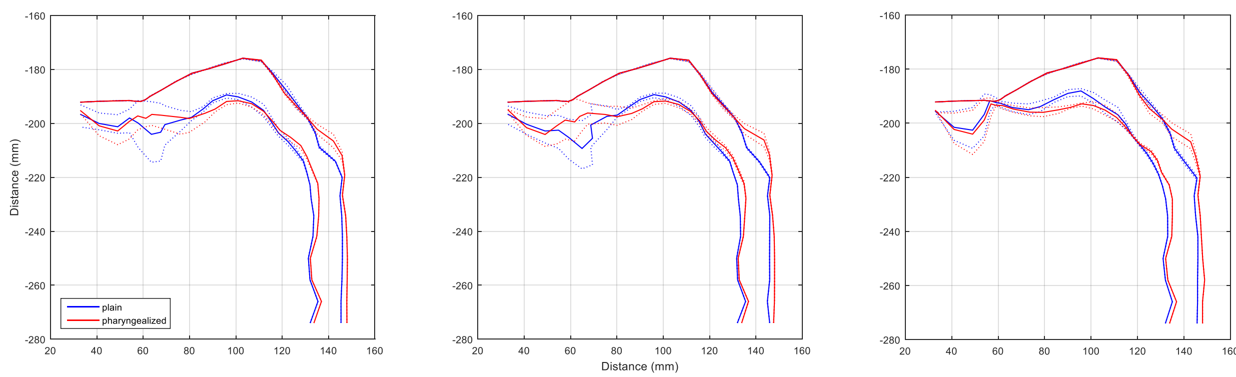

Figure A.57: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bu:z/ in blue (‘muzzle’) and /bu:zˤ/ in red (‘rot/damage’) from SP1.

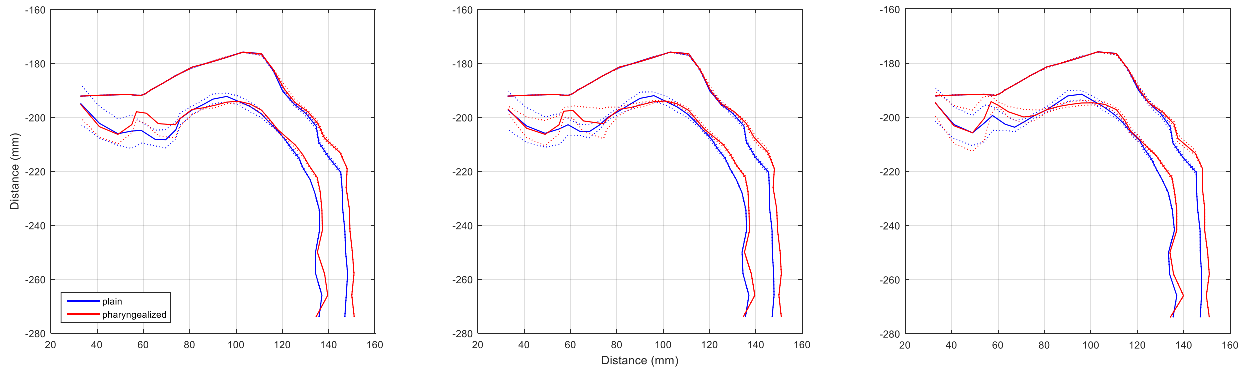

Figure A.58: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /yuʕud/ in blue (‘he sits’) and / yuʕud^{ʕ}d^{ʕ}/ in red (‘he bites’) from SP1.

Speaker 2 – SP2

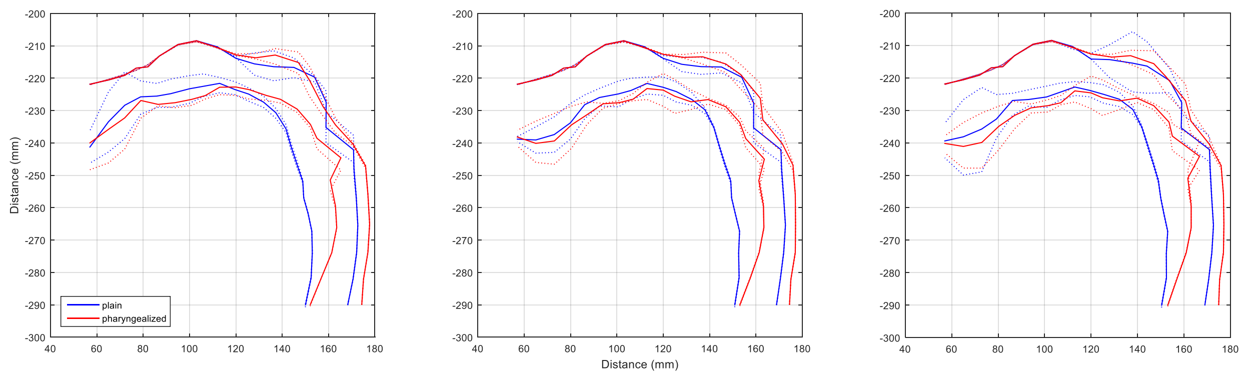

Figure A.59: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /sa:b/ in blue (‘he left’) and /s^{ʕ}a:b/ in red (‘he hit’) from SP2.

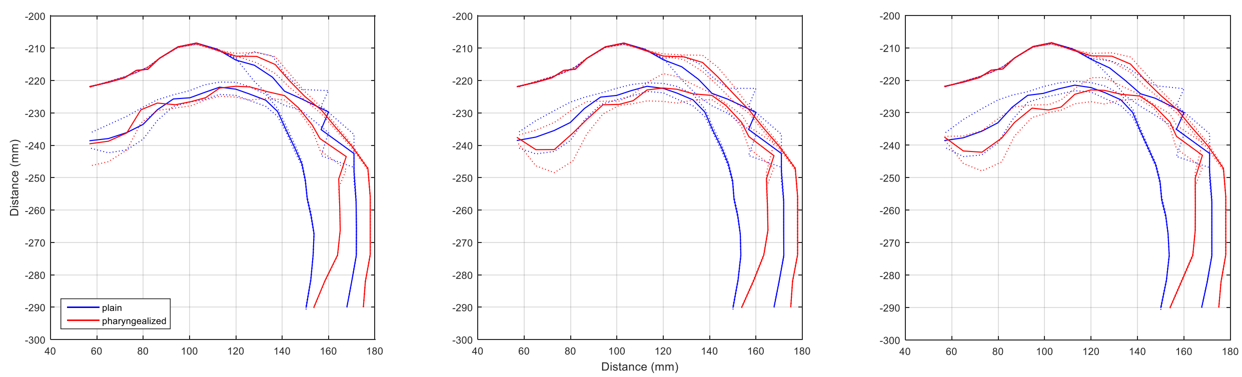

Figure A.60: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /sabb/ in blue (‘he insulted’) and /s^{ʕ}abb/ in red (‘he poured’) from SP2.

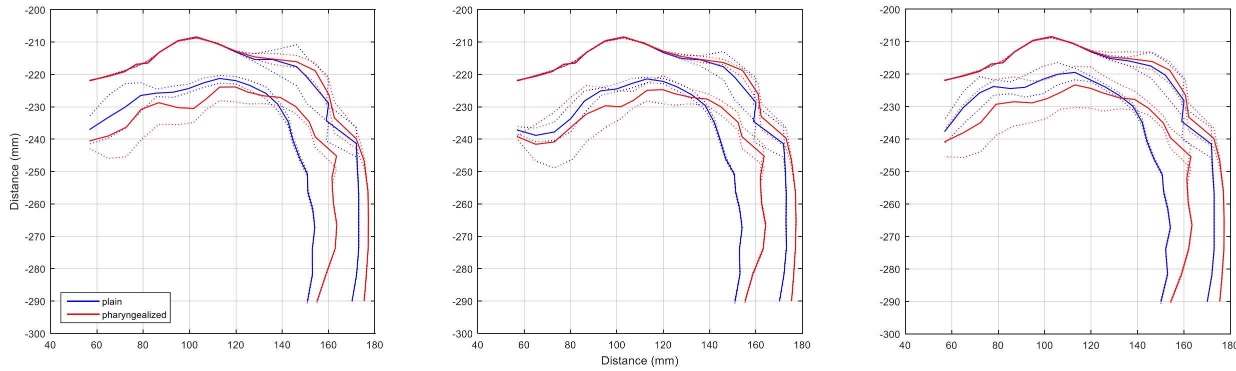

Figure A.61: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /ba:s/ in blue (‘he kissed’) and /ba:sˤ/ in red (‘bus’) from SP2.

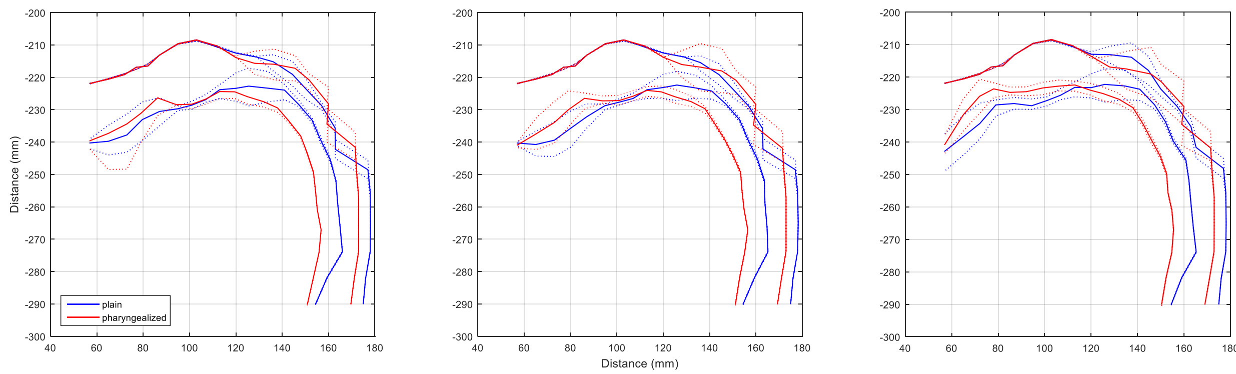

Figure A.62: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bass/ in blue (‘enough!’) and /basˤsˤ/ in red (‘he looked’) from SP2.

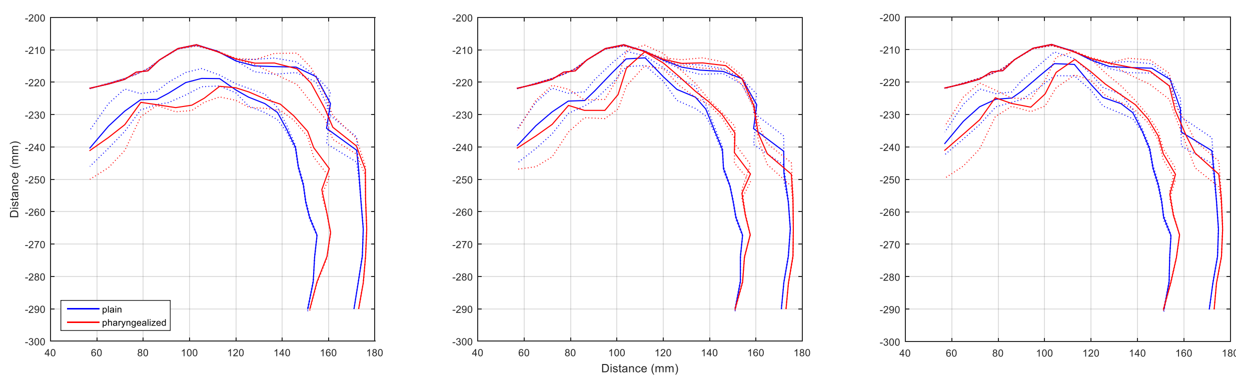

Figure A.63: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /si:n/ in blue (‘the Arabic letter /s/’) and /sˤi:n/ in red (‘China’) from SP2.

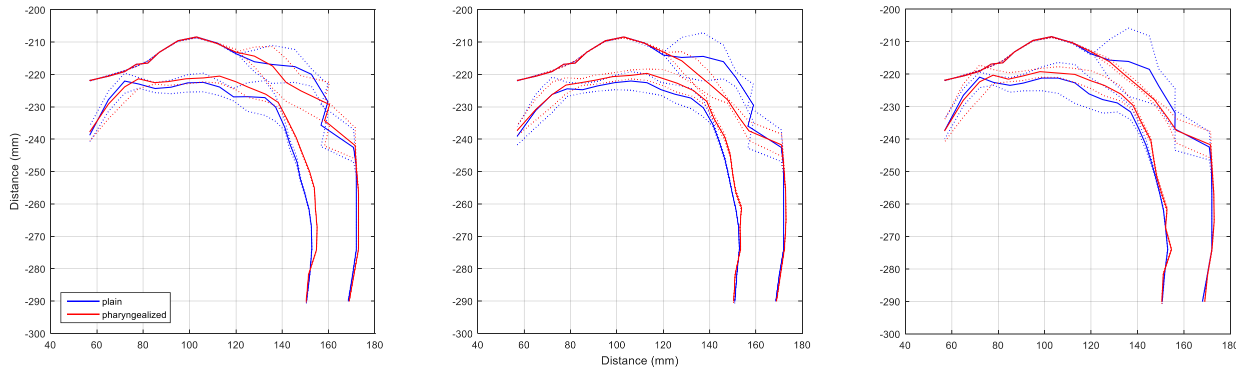

Figure A.64: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /azinn/ in blue (‘I whine’) and /az^{ʕ}inn/ in red (‘I think’) from SP2.

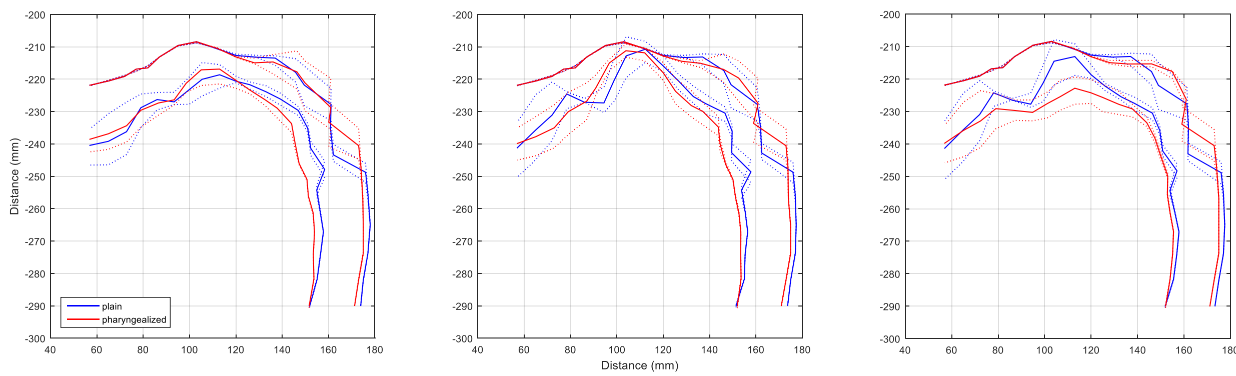

Figure A.65: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bi:d/ in blue (‘exterminate’) and /bi:d^{ʕ} / in red (‘white’) from SP2.

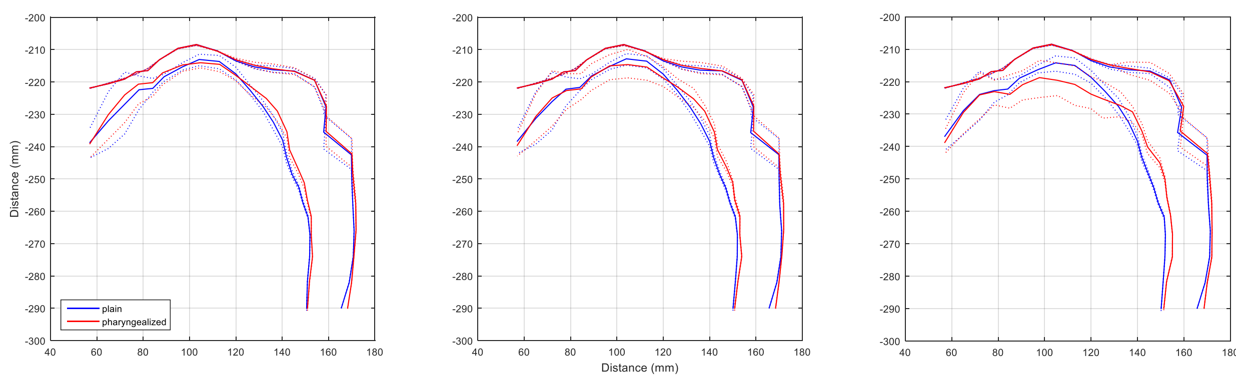

Figure A.66: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /fa:yid/ in blue (‘a town in Egypt’) and /fa:yi:d^{ʕ} / in red (‘remaining’) from SP2.

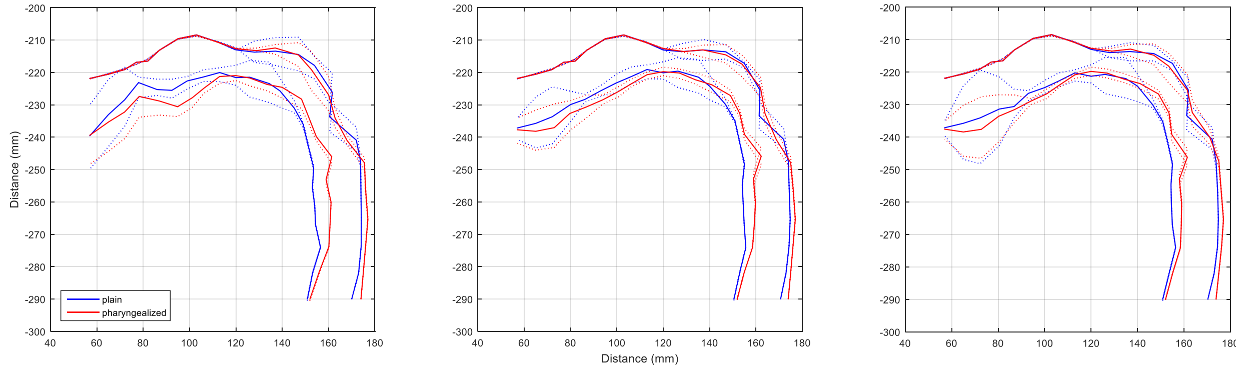

Figure A.67: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /tu:b/ in blue (‘repent) and /tˤu:b/ in red (‘stones’) from SP2.

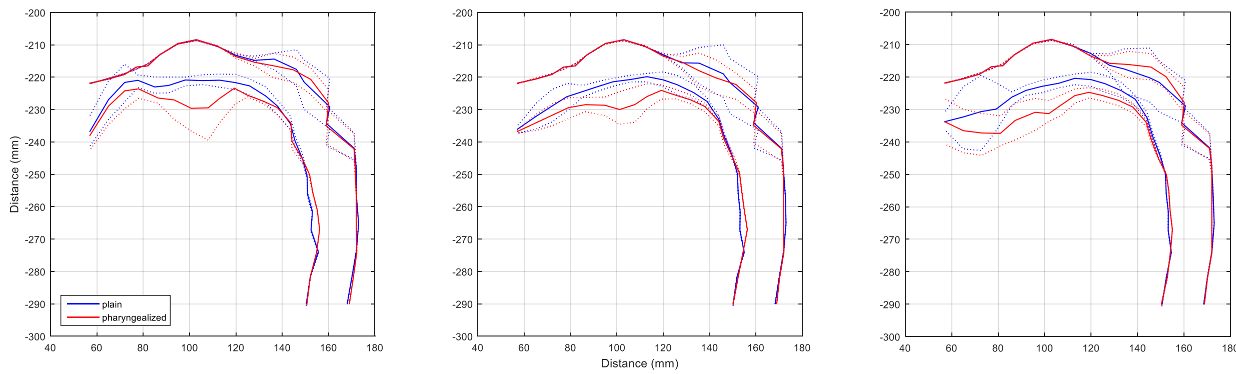

Figure A.68: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /tubʔa/ in blue (‘will become’) and /tˤubb/ in red (‘come unexpected’) from SP2.

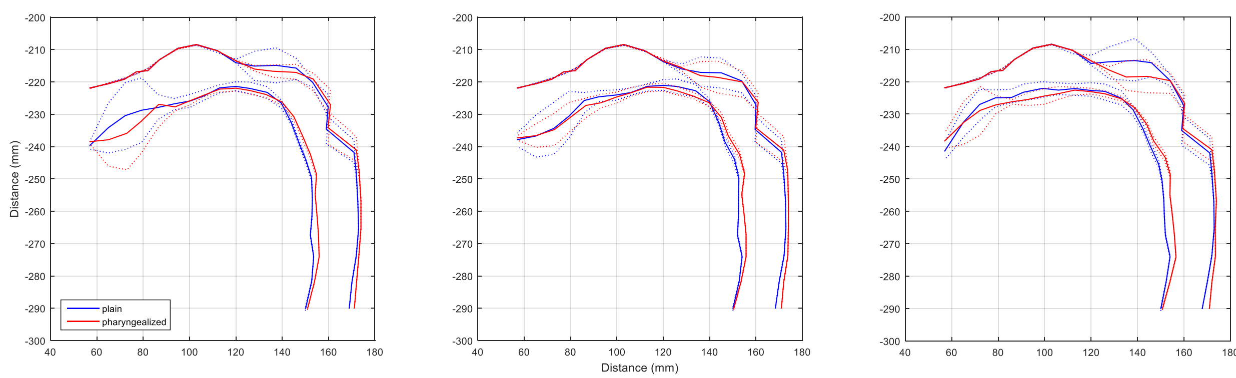

Figure A.69: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bu:z/ in blue (‘muzzle’) and /bu:zˤ/ in red (‘rot/damage’) from SP2.

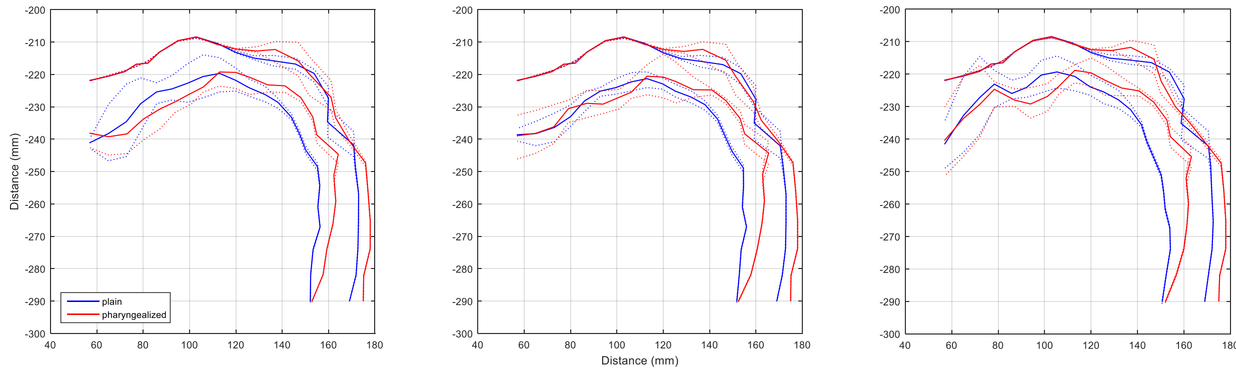

Figure A.70: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /yuʕud/ in blue (‘he sits’) and / yuʕudˤdˤ/ in red (‘he bites’) from SP2.

Speaker 4 – SP4

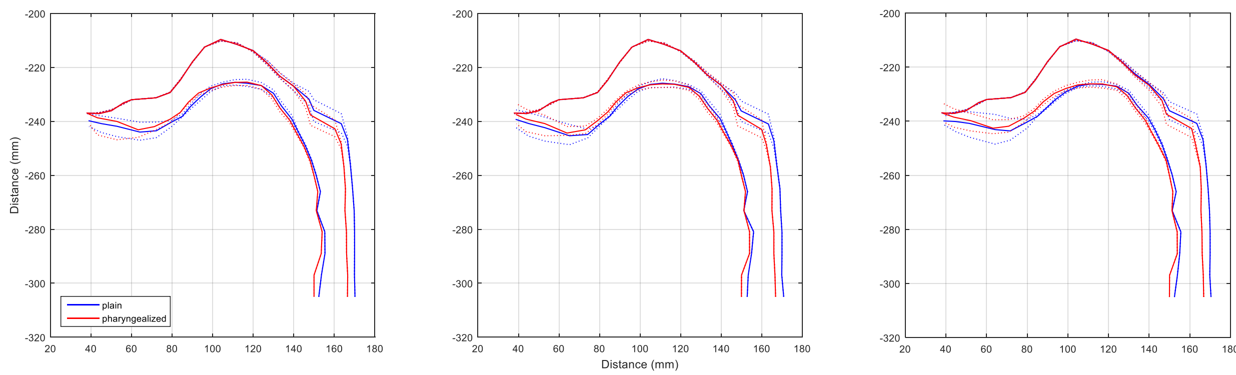

Figure A.71: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /sa:b/ in blue (‘he left’) and /sˤa:b/ in red (‘he hit’) from SP4.

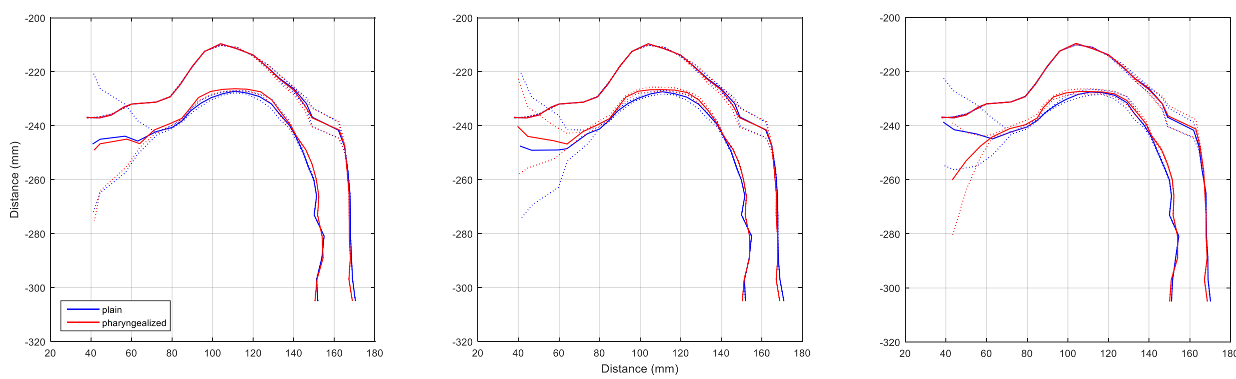

Figure A.72: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /sabb/ in blue (‘he insulted’) and /sˤabb/ in red (‘he poured’) from SP4.

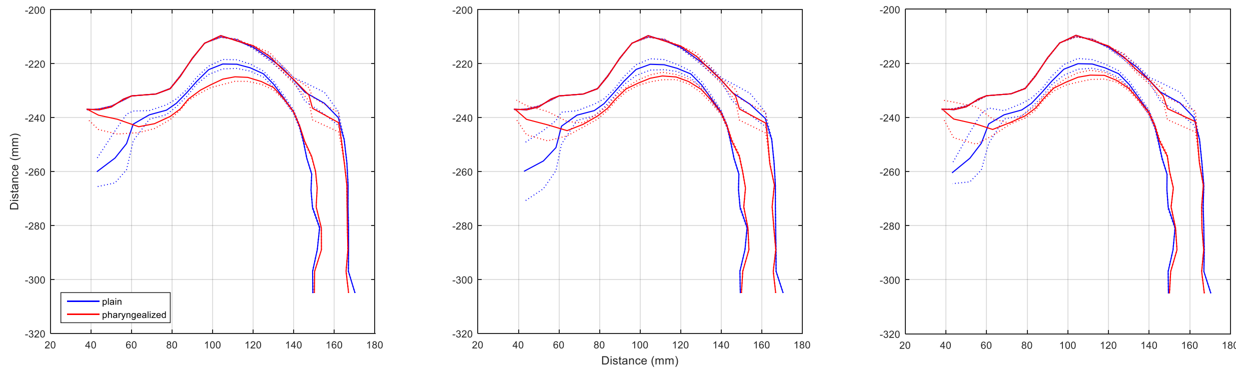

Figure A.73: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /ba:s/ in blue (‘he kissed’) and /ba:sˁ/ in red (‘bus’) from SP4.

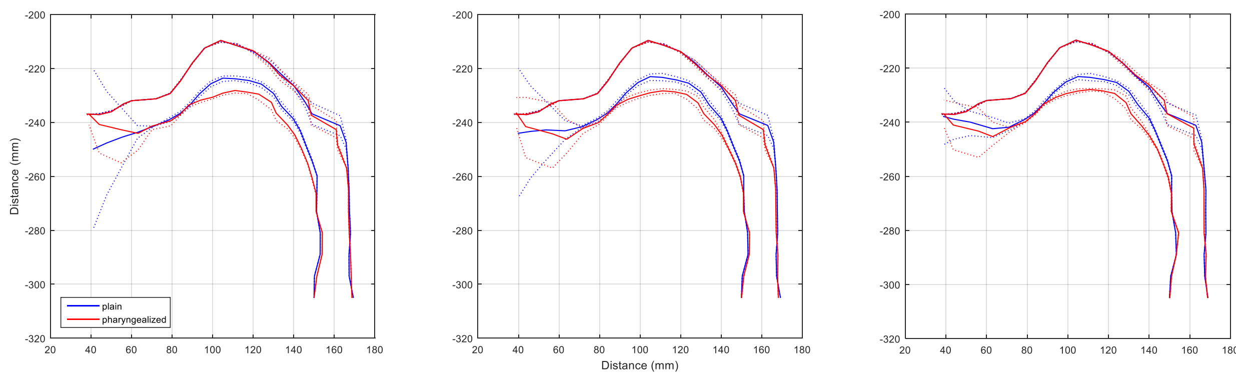

Figure A.74: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bass/ in blue (‘enough!’) and /basˁsˁ/ in red (‘he looked’) from SP4.

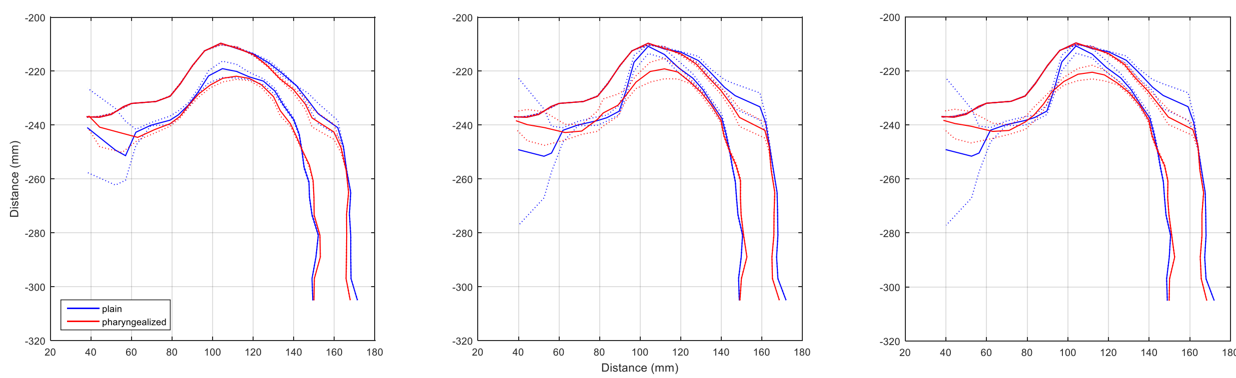

Figure A.75: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /si:n/ in blue (‘the Arabic letter /s/’) and /sˁi:n/ in red (‘China’) from SP4.

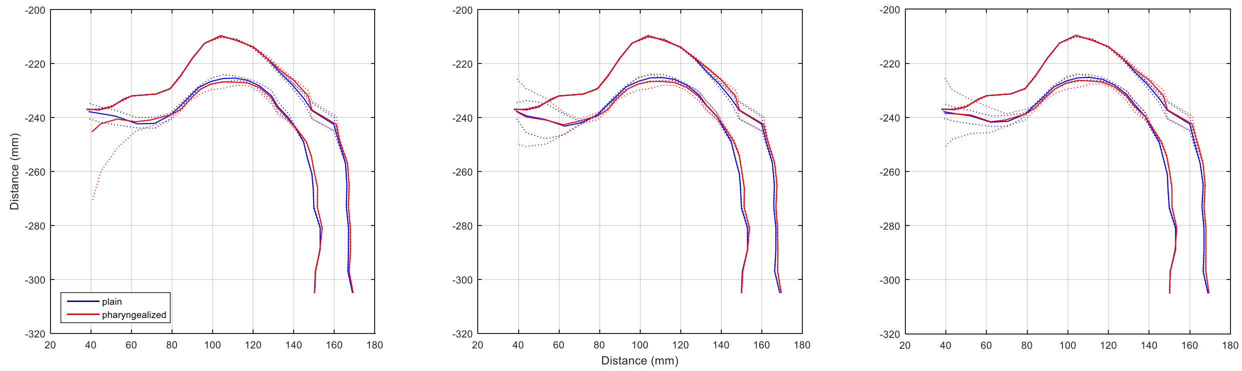

Figure A.76: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /azinn/ in blue (‘I whine’) and /az^{ʕ}inn/ in red (‘I think’) from SP4.

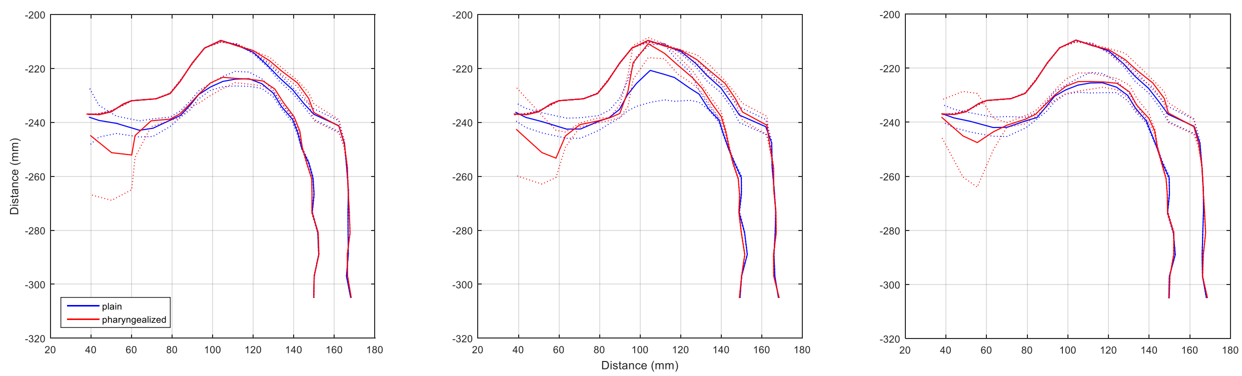

Figure A.77: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bi:d/ in blue (‘exterminate’) and /bi:d^{ʕ} / in red (‘white’) from SP4.

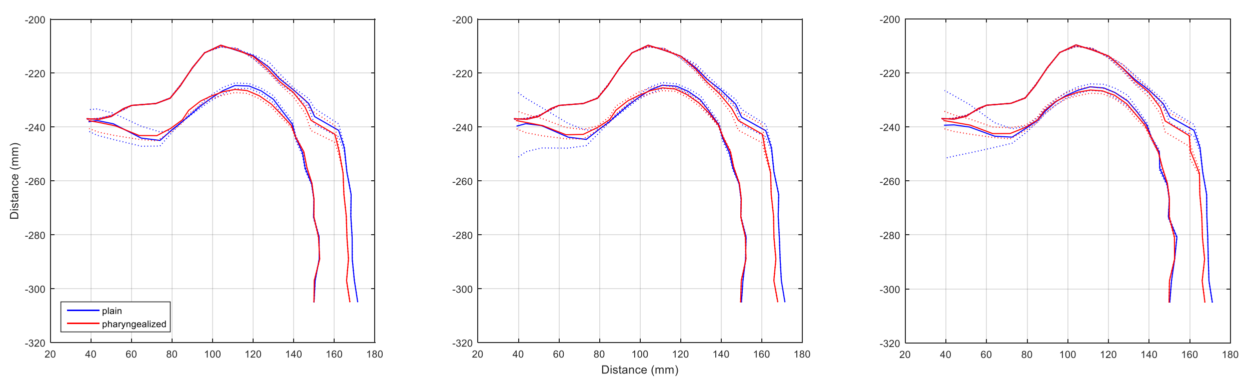

Figure A.78: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /fa:yid/ in blue (‘a town in Egypt’) and /fa:yi:d^{ʕ} / in red (‘remaining’) from SP4.

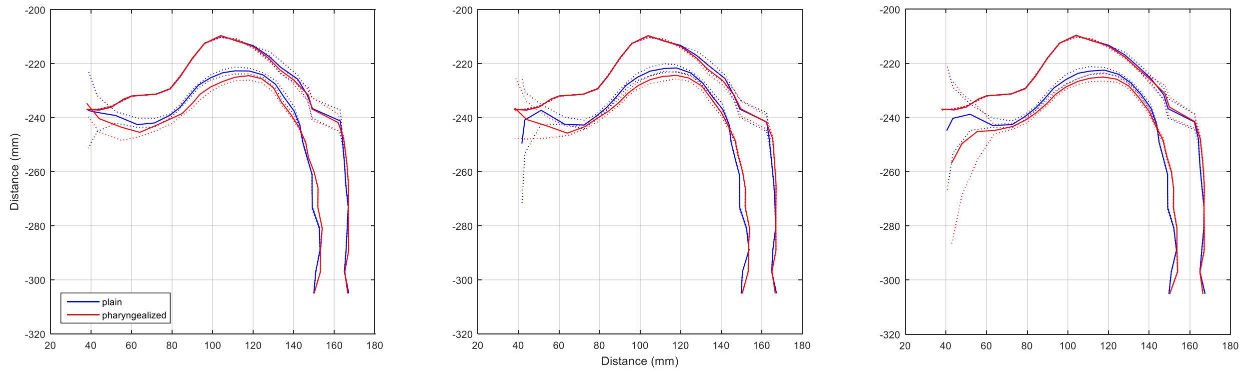

Figure A.79: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /tu:b/ in blue (‘repent) and /tˤu:b/ in red (‘stones’) from SP4.

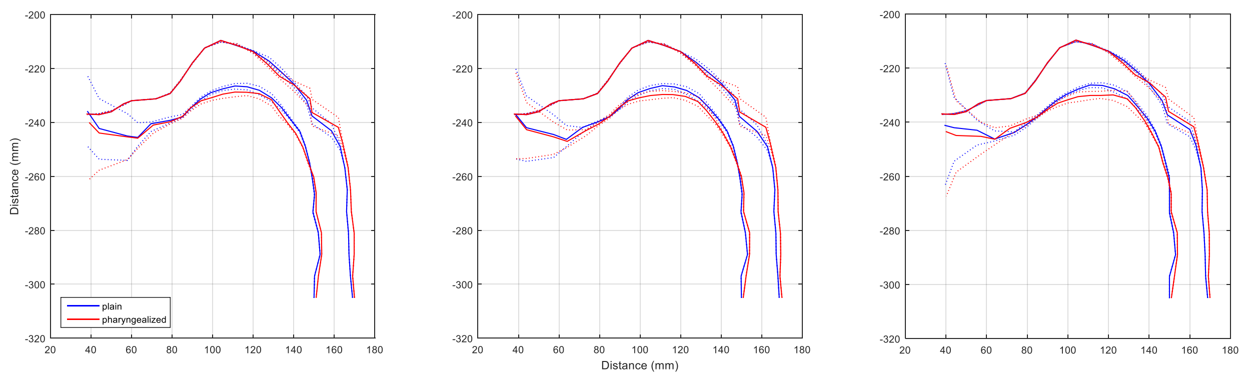

Figure A.80: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /tubʔa/ in blue (‘will become’) and /tˤubb/ in red (‘come unexpected’) from SP4.

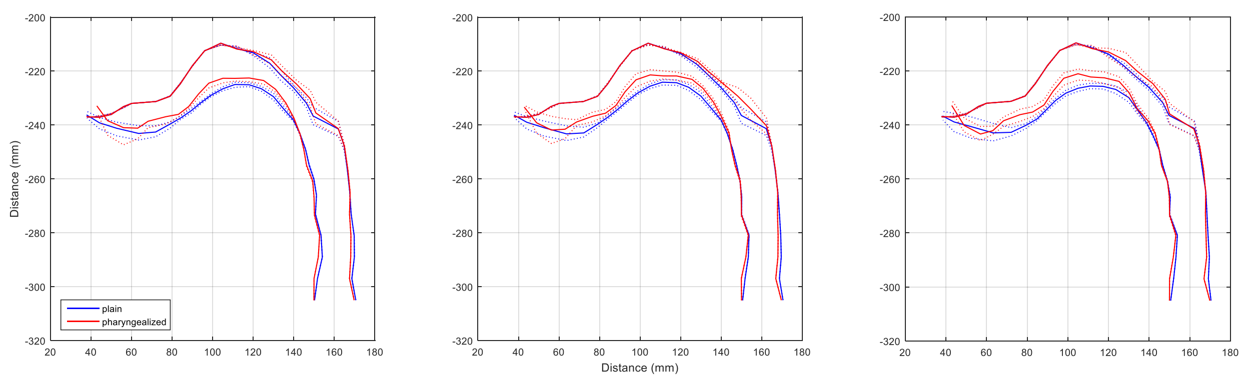

Figure A.81: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bu:z/ in blue (‘muzzle’) and /bu:zˤ/ in red (‘rot/damage’) from SP4.

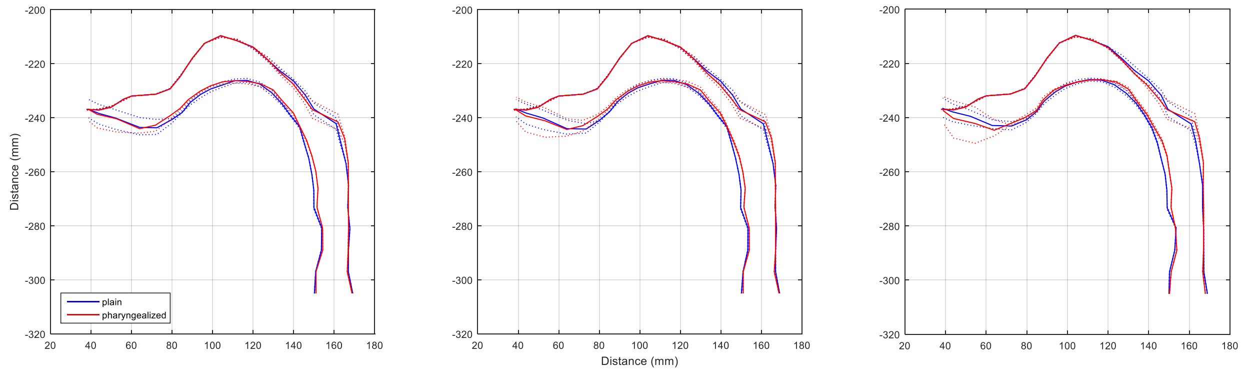

Figure A.82: Pharyngeal and lingual contours averaged from 20 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /yuʕud/ in blue (‘he sits’) and / yuʕud^{ʕ}d^{ʕ}/ in red (‘he bites’) from SP4.

Speaker 5 – SP5

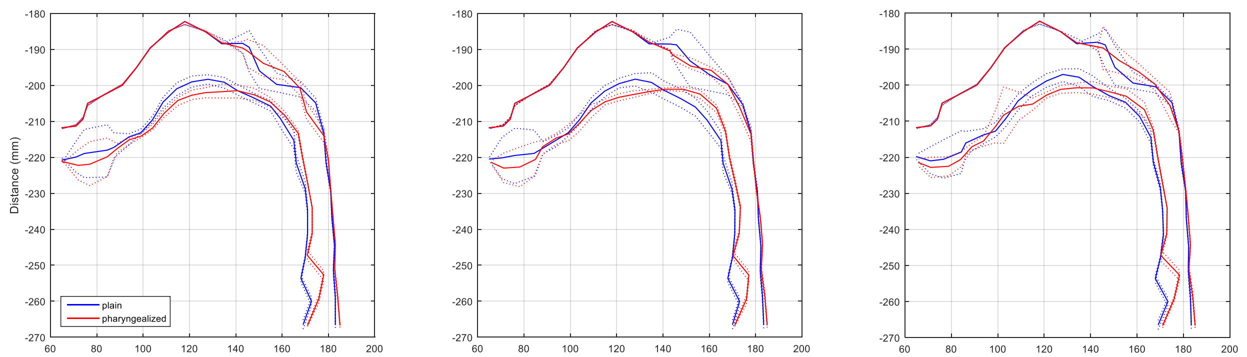

Figure A.83: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /sa:b/ in blue (‘he left’) and /s^{ʕ}a:b/ in red (‘he hit’) from SP5.

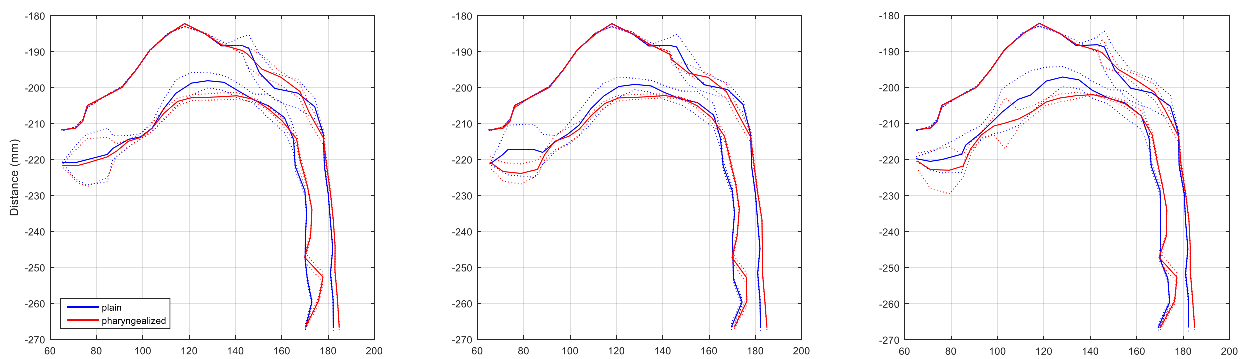

Figure A.84: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /sabb/ in blue (‘he insulted’) and /s^{ʕ}abb/ in red (‘he poured’) from SP5.

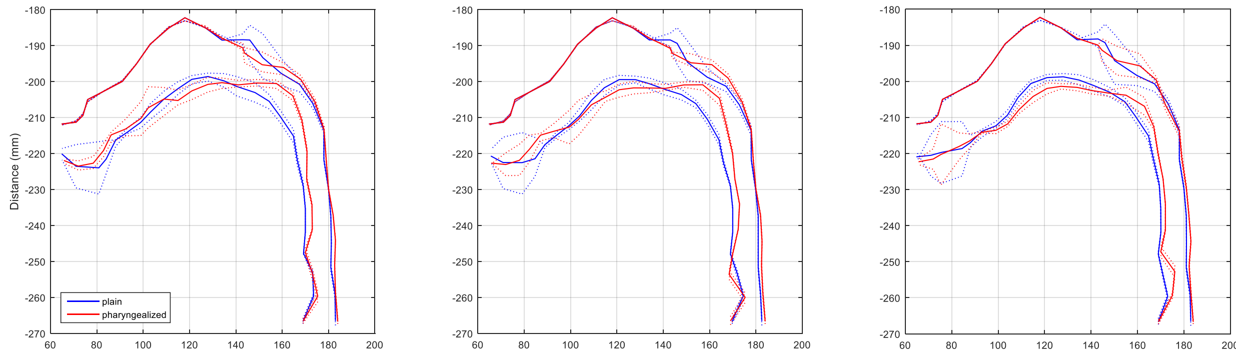

Figure A.85: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /ba:s/ in blue (‘he kissed’) and /ba:sˤ/ in red (‘bus’) from SP5.

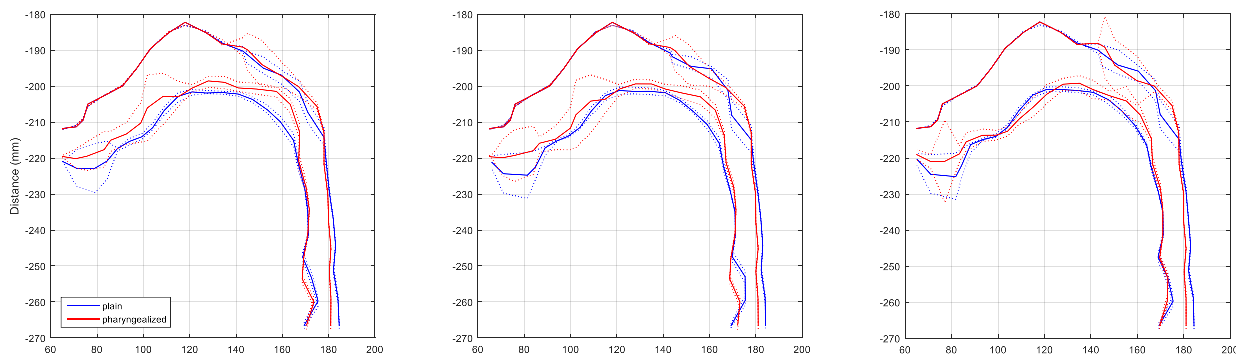

Figure A.86: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bass/ in blue (‘enough!’) and /basˤsˤ/ in red (‘he looked’) from SP5.

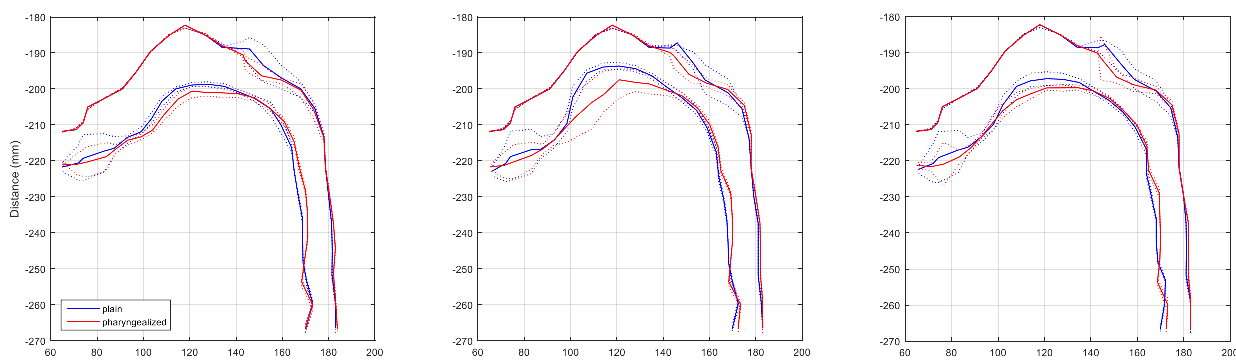

Figure A.87: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /si:n/ in blue (‘the Arabic letter /s/’) and /sˤi:n/ in red (‘China’) from SP5.

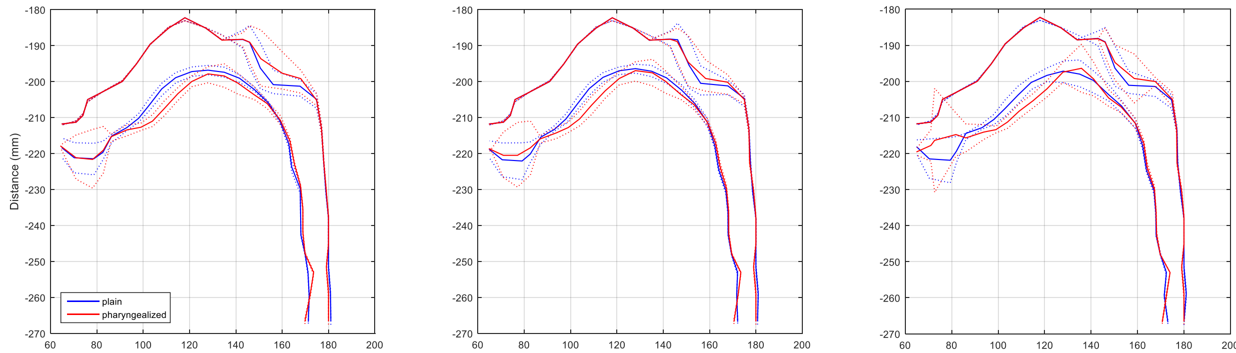

Figure A.88: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /azinn/ in blue ('I whine') and /azˤinn/ in red ('I think') from SP5.

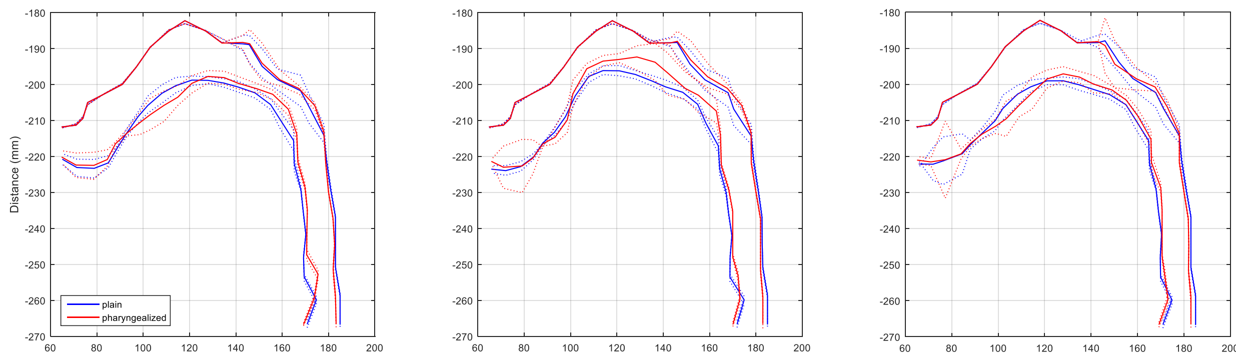

Figure A.89: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bi:d/ in blue ('exterminate') and /bi:dˤ / in red ('white') from SP5.

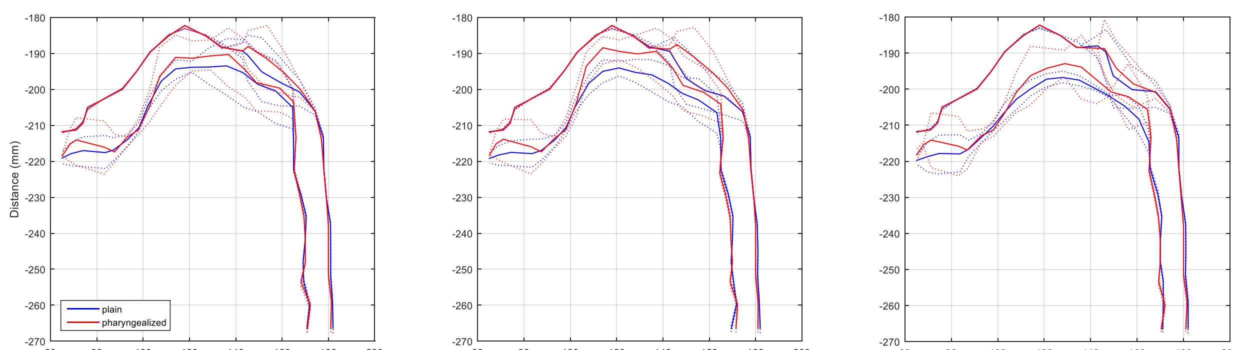

Figure A.90: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /fa:yid/ in blue ('a town in Egypt') and /fa:yi:dˤ / in red ('remaining') from SP5.

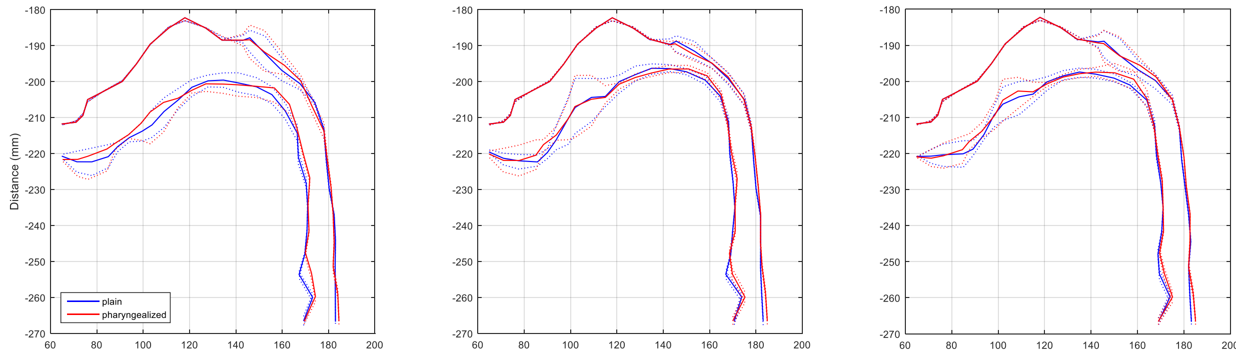

Figure A.91: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /tu:b/ in blue (‘repent) and /tˤu:b/ in red (‘stones’) from SP5.

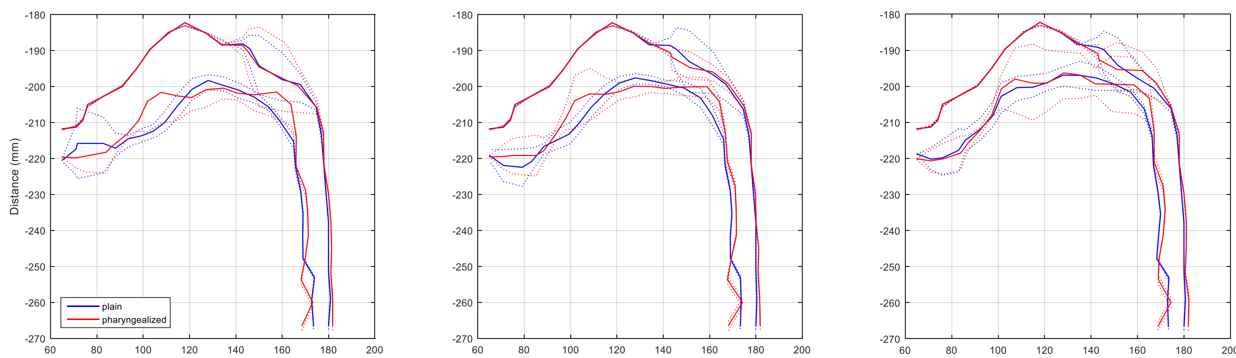

Figure A.92: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /tubʔa/ in blue (‘will become’) and /tˤubb/ in red (‘come unexpected’) from SP5.

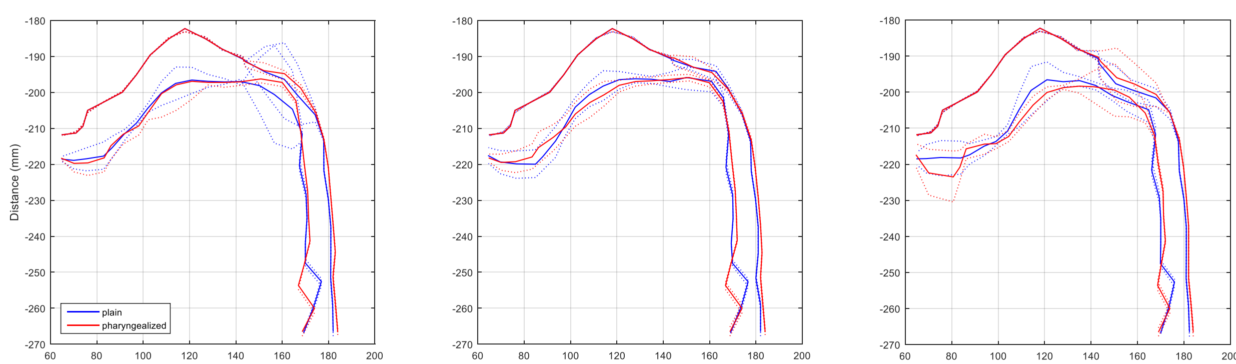

Figure A.93: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /bu:z/ in blue (‘muzzle’) and /bu:zˤ/ in red (‘rot/damage’) from SP5.

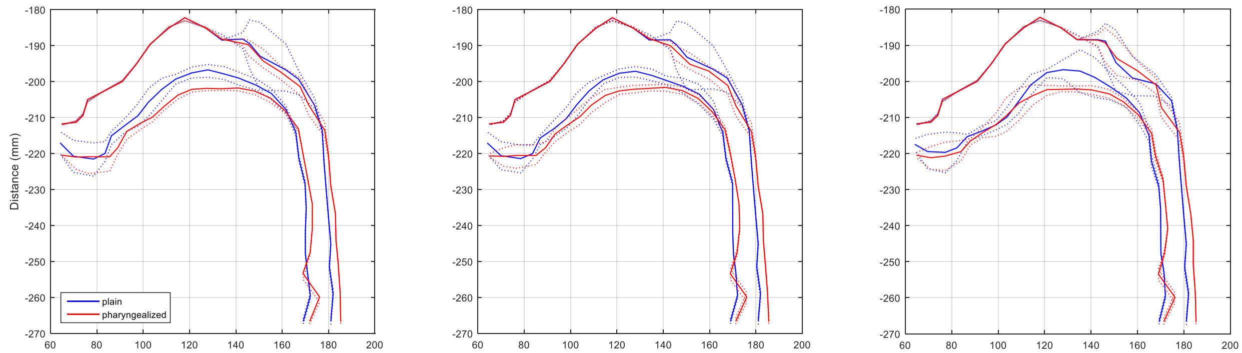

Figure A.94: Pharyngeal and lingual contours averaged from 14 repetitions and smoothed using a Savitzky-Golay filter with ±95% confidence intervals plotted in dashed lines. Target words are /yuʕud/ in blue ('he sits') and / yuʕud^{ʕ}d^{ʕ}/ in red ('he bites') from SP5.

Speaker 1 – SP1

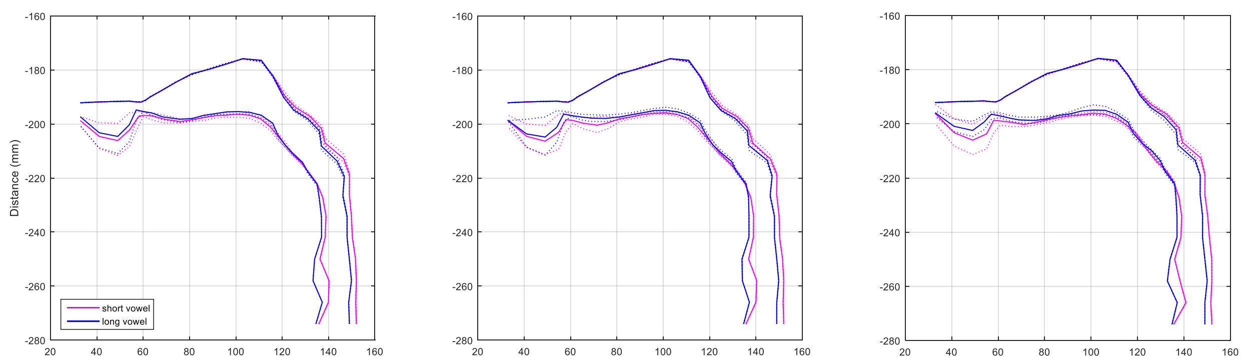

Figure A.95: Vocal tract contours during /s^{ʕ}a:b / ('he hit') in blue and /s^{ʕ}abb/ ('he poured') in magenta as produced by SP1.

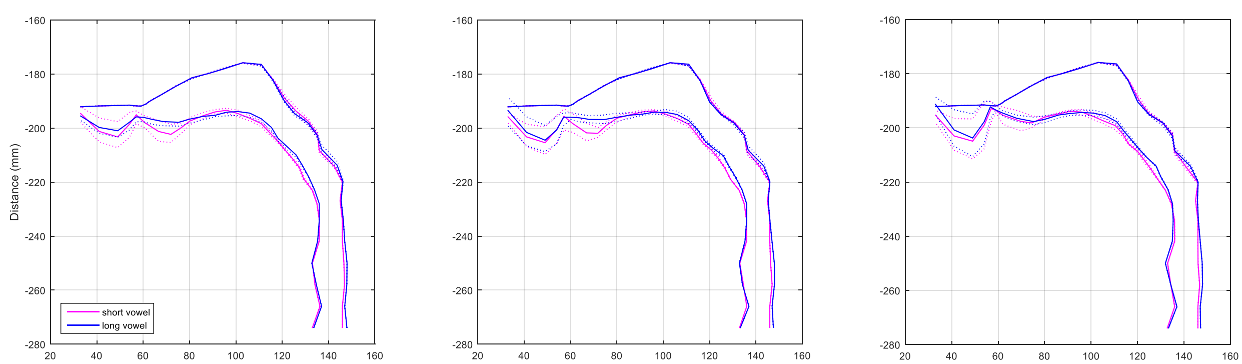

Figure A.96: Vocal tract contours during /ba:s^{ʕ}/ ('bus') in blue and /bas^{ʕ}s^{ʕ}/ ('he looked') in magenta as produced by SP1.

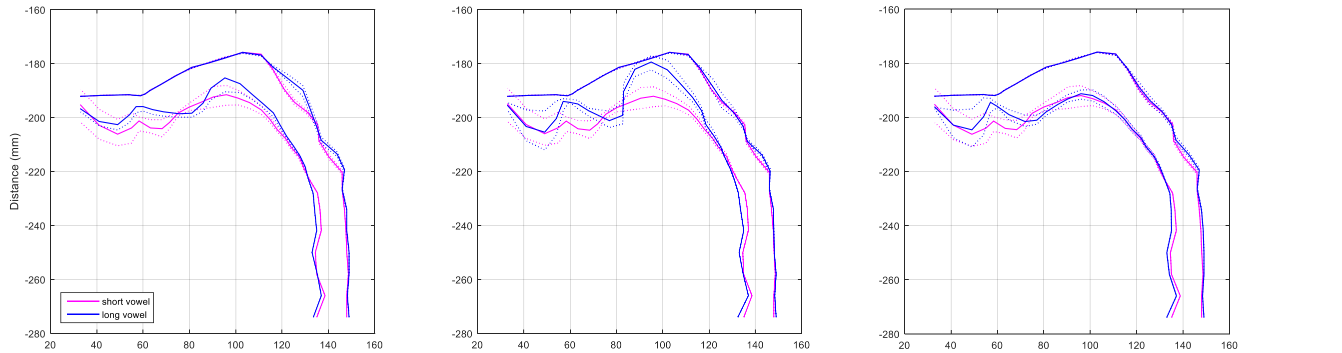

Figure A.97: Vocal tract contours during /bi:d^{ʕ}/ (‘white’) in blue and /fa:yid^{ʕ}/ (‘a town in Egypt’) in magenta as produced by SP1.

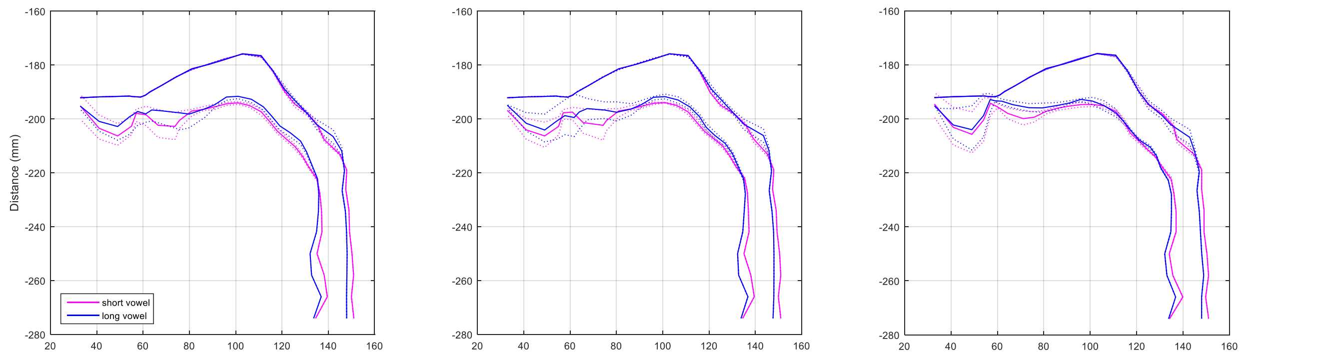

Figure A.98: Vocal tract contours during /bu:z^{ʕ}/ (‘rot/damage) in blue and /yuʕud^{ʕ}d^{ʕ}/ (‘he bites’) in magenta as produced by SP1.

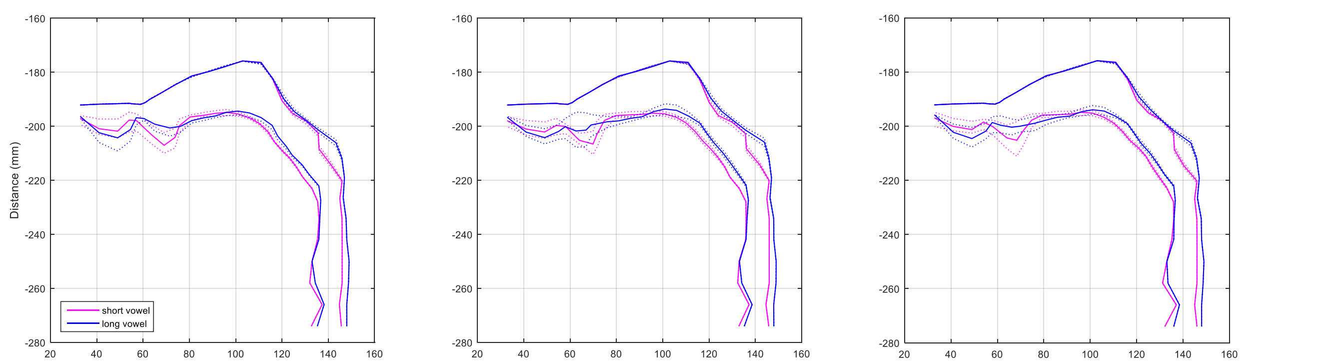

Figure A.99: Vocal tract contours during /t^{ʕ}u:b / (‘stones’) in blue and /t^{ʕ}ubb/ (‘come unexpectedly’) in magenta as produced by SP1.

Speaker 2 – SP2

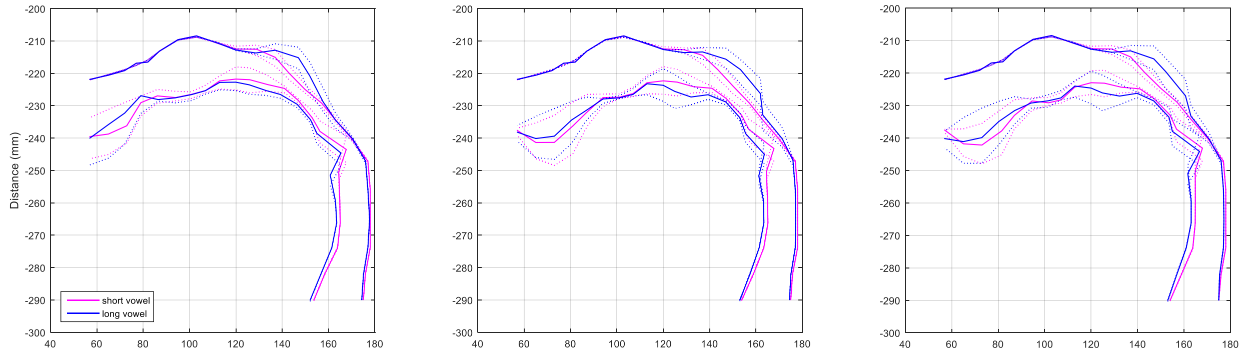

Figure A.100: Vocal tract contours during /s^{ʕ}a:b / (‘he hit’) in blue and /s^{ʕ}abb/ (‘he poured’) in magenta as produced by SP2.

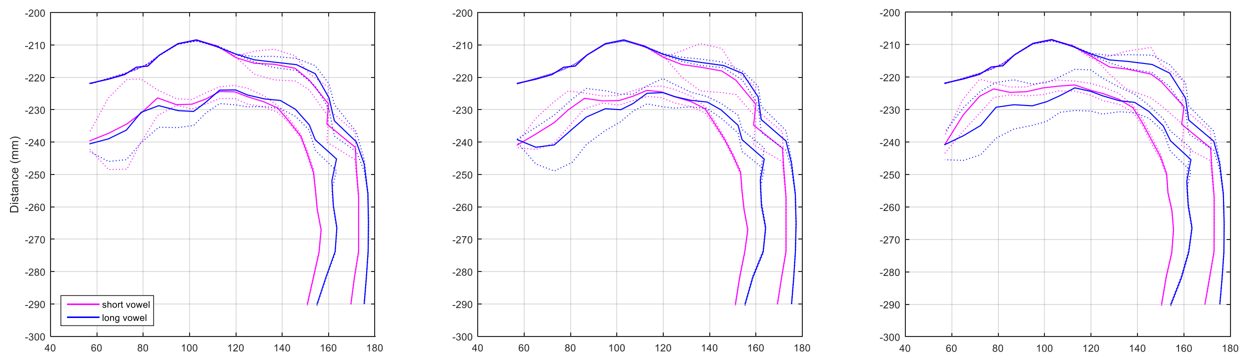

Figure A.101: Vocal tract contours during /ba:s^{ʕ}/ (‘bus’) in blue and /bas^{ʕ}s^{ʕ}/ (‘he looked’) in magenta as produced by SP2.

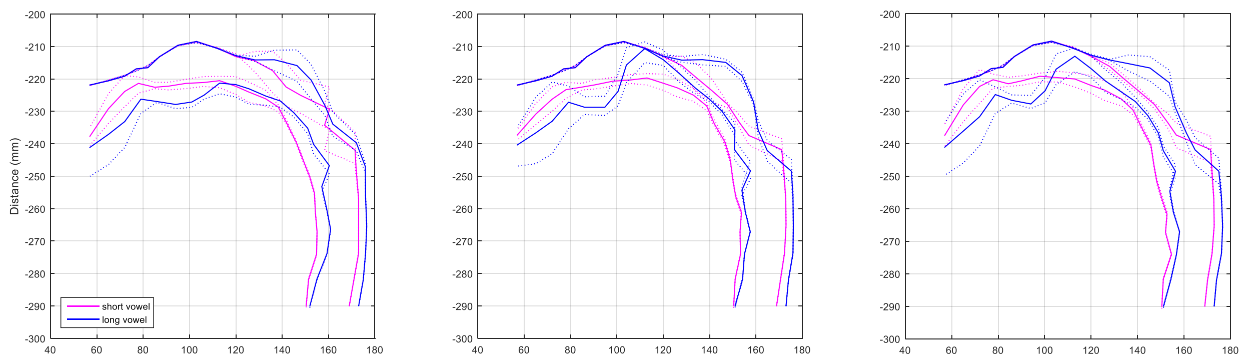

Figure A.102: Vocal tract contours during /s^{ʕ}i:n/ (‘China’) in blue and /az^{ʕ}inn/ (‘I think’) in magenta as produced by SP2.

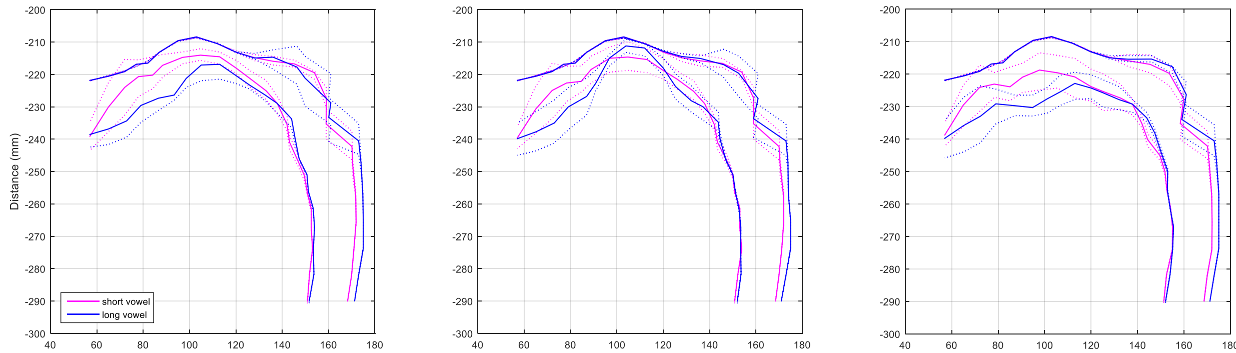

Figure A.103: Vocal tract contours during /bi:dˤ/ (‘white’) in blue and /fa:yidˤ/ (‘a town in Egypt’) in magenta as produced by SP2.

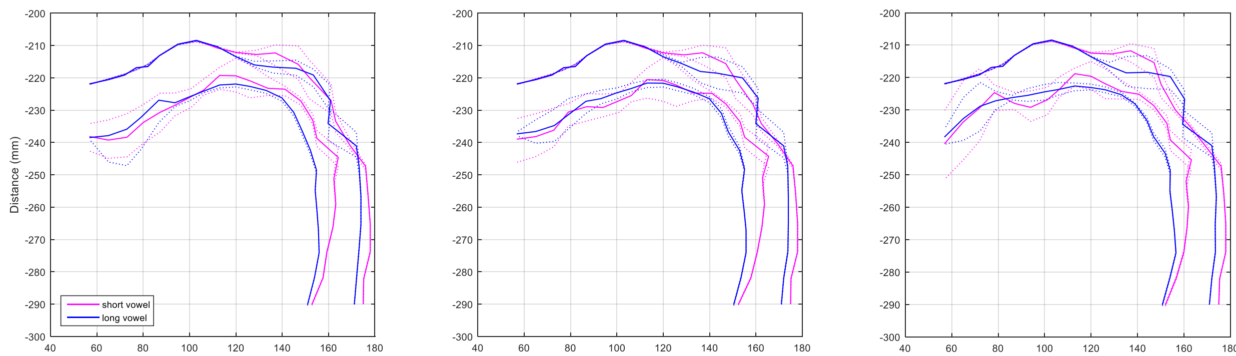

Figure A.104: Vocal tract contours during /bu:zˤ/ (‘rot/damage) in blue and /yuʕudˤdˤ/ (‘he bites’) in magenta as produced by SP2.

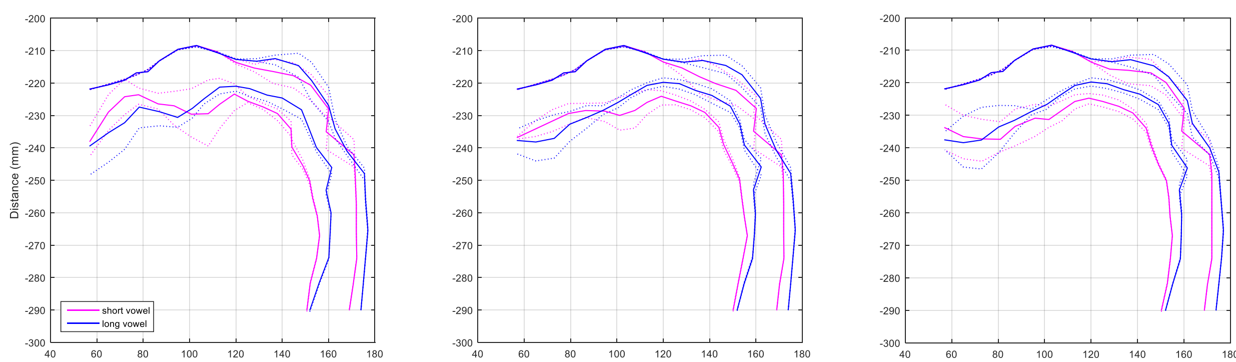

Figure A.105: Vocal tract contours during /tˤu:b / (‘stones’) in blue and /tˤubb/ (‘come unexpectedly’) in magenta as produced by SP2.

Speaker 4 – SP4

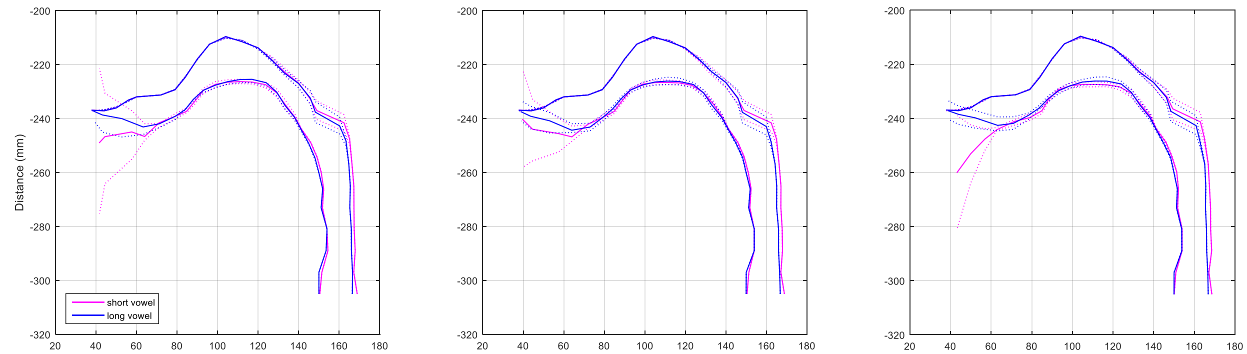

Figure A.106: Vocal tract contours during /sˤa:b / (‘he hit’) in blue and /sˤabb/ (‘he poured’) in magenta as produced by SP4.

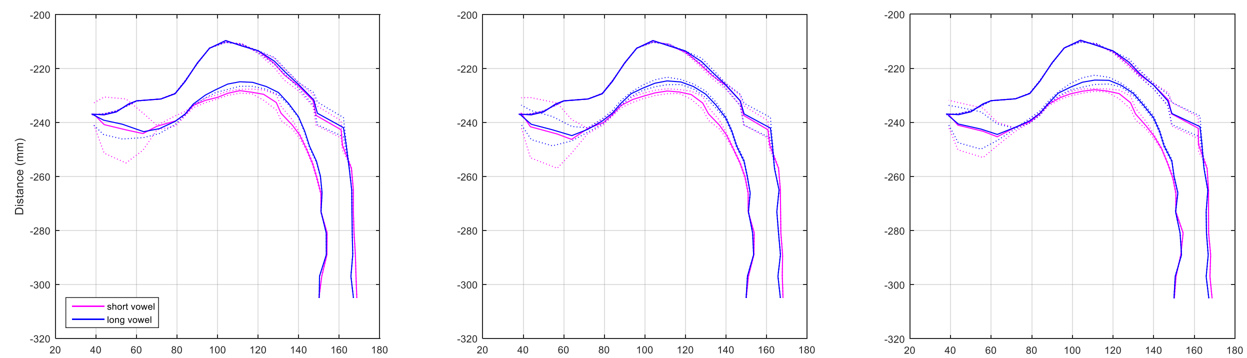

Figure A.107: Vocal tract contours during /ba:sˤ/ (‘bus’) in blue and /basˤsˤ/ (‘he looked’) in magenta as produced by SP4.

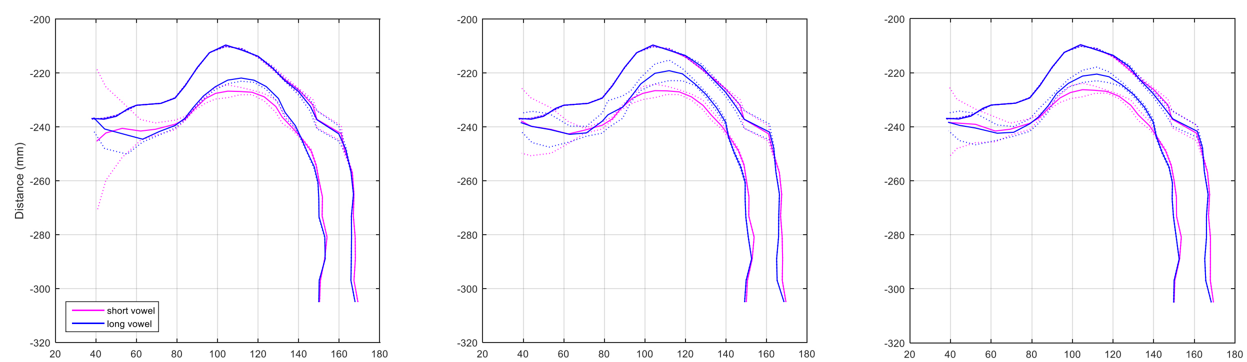

Figure A.108: Vocal tract contours during /sˤi:n/ (‘China’) in blue and /azˤinn/ (‘I think’) in magenta as produced by SP4.

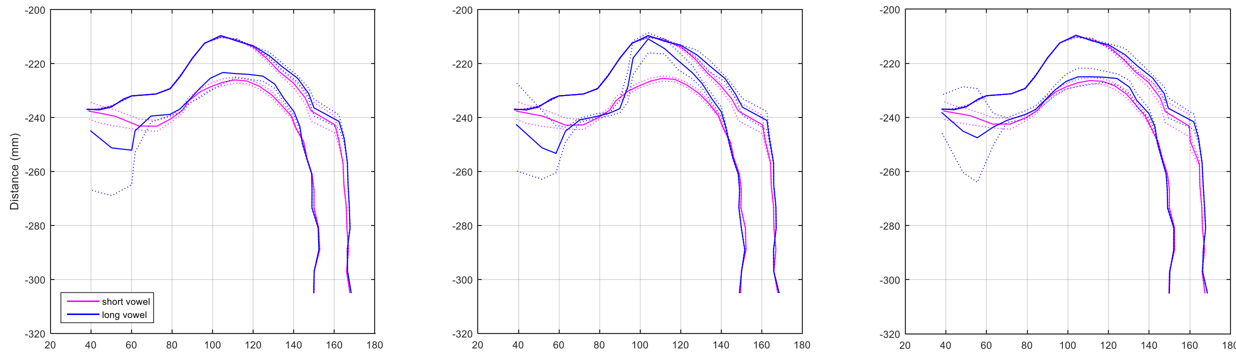

Figure A.109: Vocal tract contours during /bi:dˤ/ (‘white’) in blue and /fa:yidˤ/ (‘a town in Egypt’) in magenta as produced by SP4.

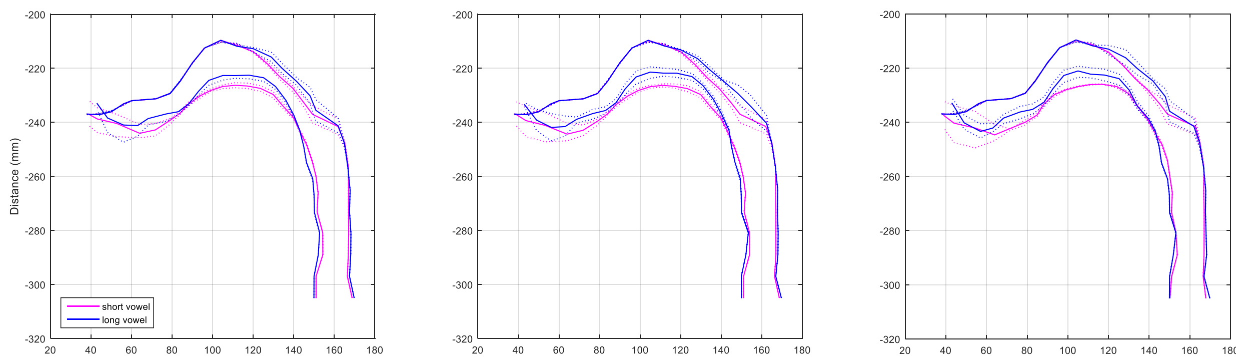

Figure A.110: Vocal tract contours during /bu:zˤ/ (‘rot/damage) in blue and /yuʕudˤdˤ/ (‘he bites’) in magenta as produced by SP4.

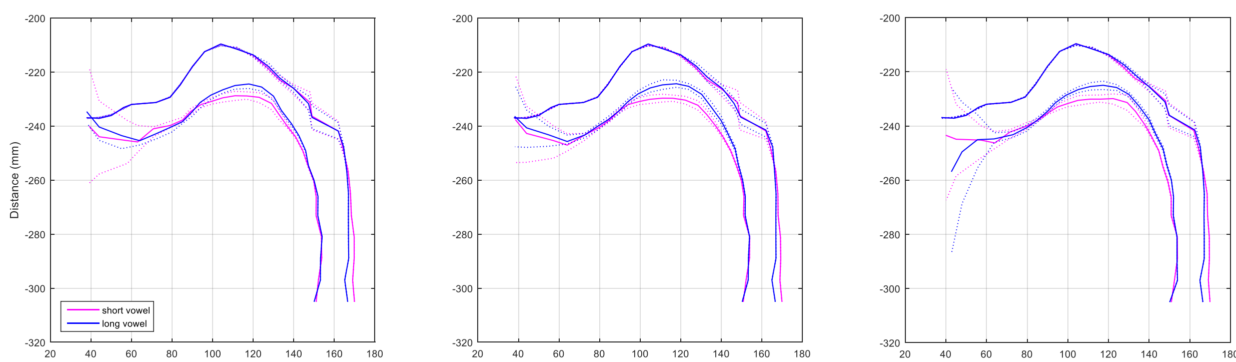

Figure A.111: Vocal tract contours during /tˤu:b / (‘stones’) in blue and /tˤubb/ (‘come unexpectedly’) in magenta as produced by SP4.

Speaker 5 – SP5

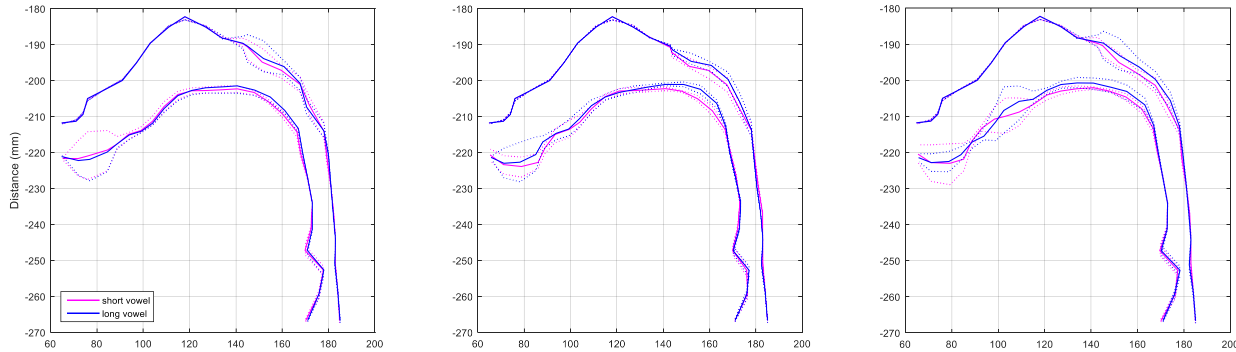

Figure A.112: Vocal tract contours during /s^{ʕ}a:b / (‘he hit’) in blue and /s^{ʕ}abb/ (‘he poured’) in magenta as produced by SP5.

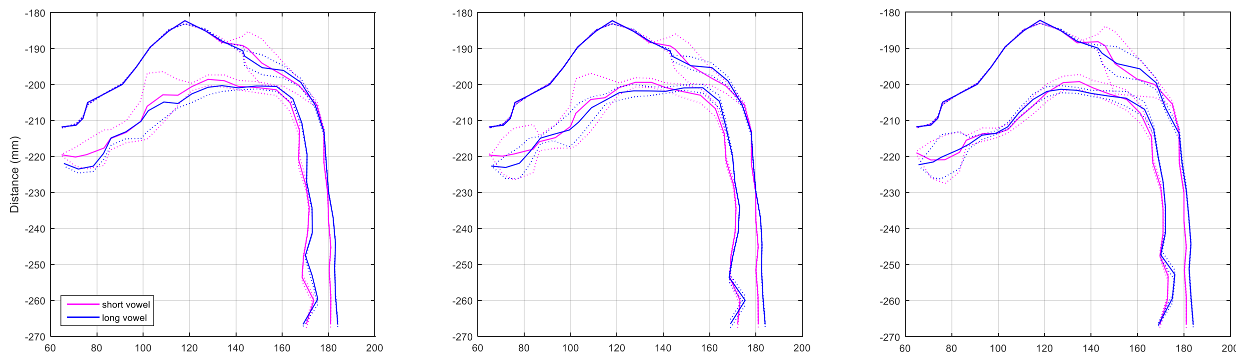

Figure A.113: Vocal tract contours during /ba:s^{ʕ}/ (‘bus’) in blue and /bas^{ʕ}s^{ʕ}/ (‘he looked’) in magenta as produced by SP5.

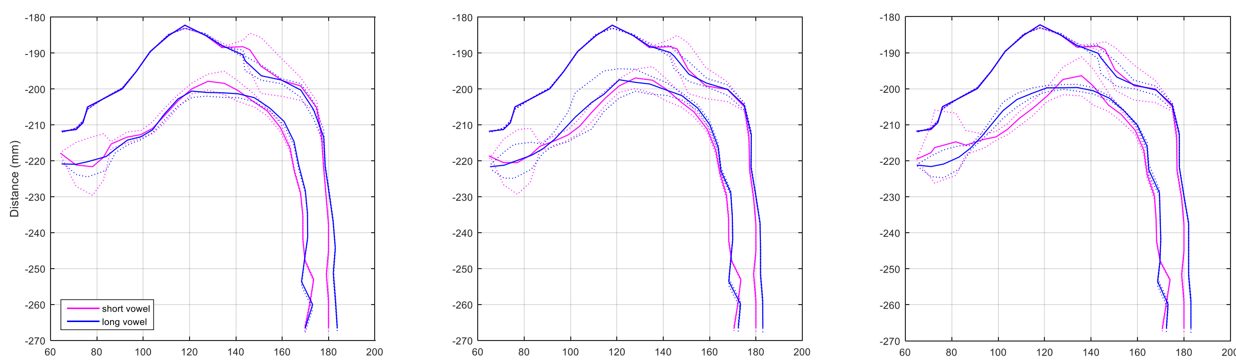

Figure A.114: Vocal tract contours during /s^{ʕ}i:n/ (‘China’) in blue and /az^{ʕ}inn/ (‘I think’) in magenta as produced by SP5.

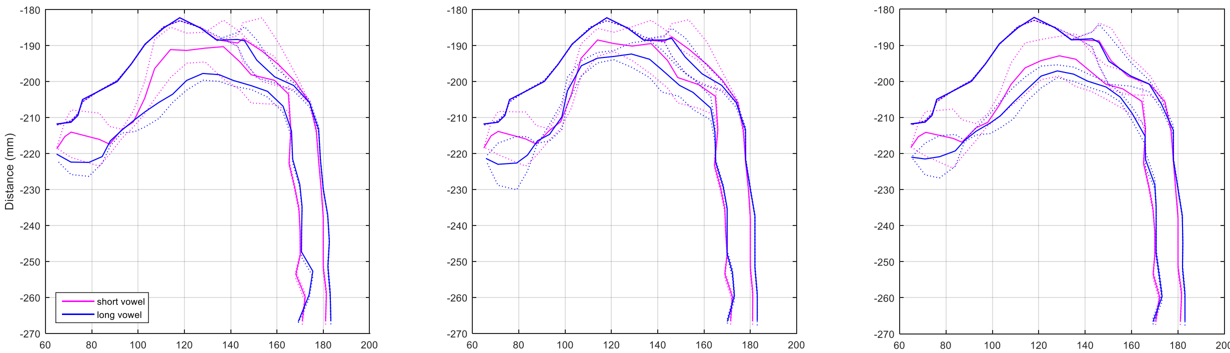

Figure A.115: Vocal tract contours during /bi:dˤ/ (‘white’) in blue and /fa:yidˤ/ (‘a town in Egypt’) in magenta as produced by SP5.

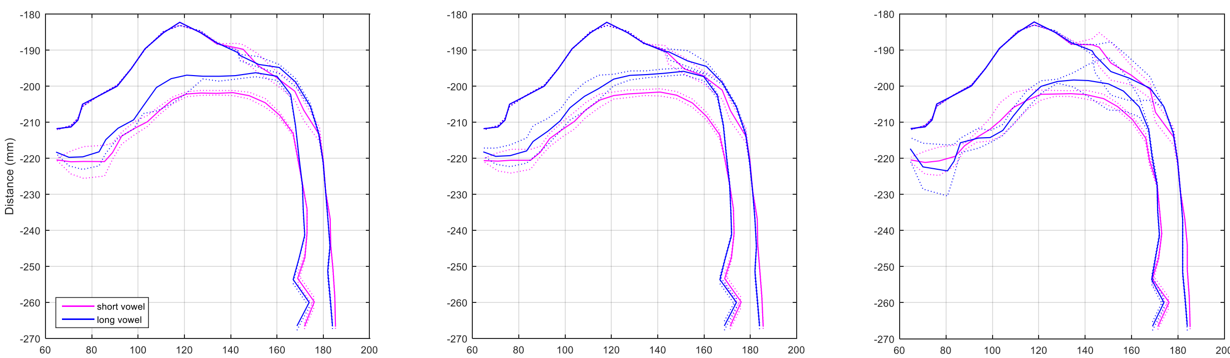

Figure A.116: Vocal tract contours during /bu:zˤ/ (‘rot/damage) in blue and /yuʕudˤdˤ/ (‘he bites’) in magenta as produced by SP5.

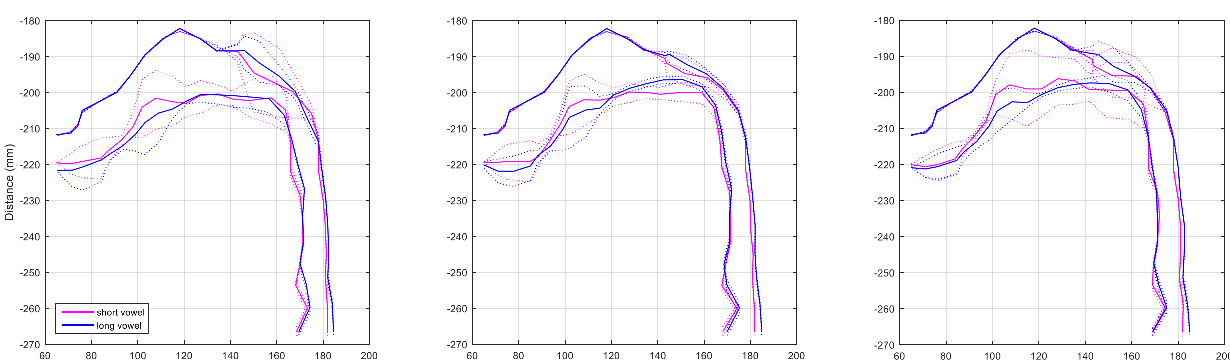

Figure A.117: Vocal tract contours during /tˤu:b / (‘stones’) in blue and /tˤubb/ (‘come unexpectedly’) in magenta as produced by SP5.

Speaker 1 – SP1

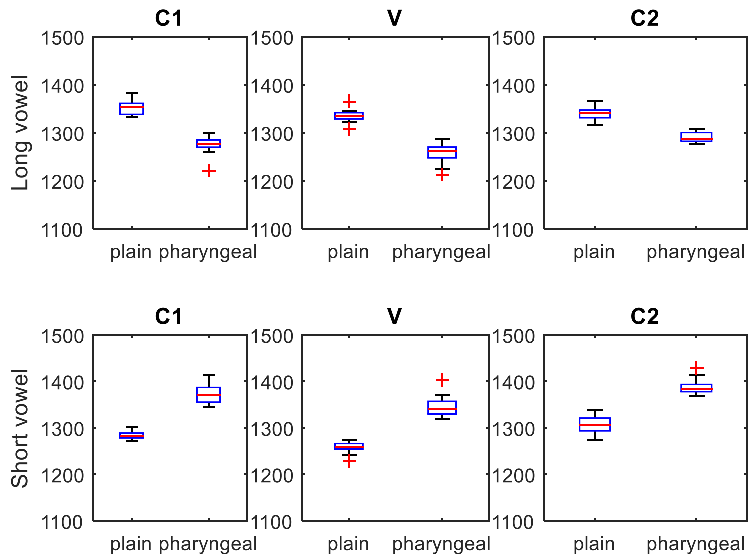

Figure A.118: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /sˤa:b / (‘he hit’) and /sa:b/ (‘he left’) (top) and the C1, V, C2 segments in /sˤabb/ (‘he poured’) and /sabb/ (‘he insulted’) (bottom) as produced by SP1.

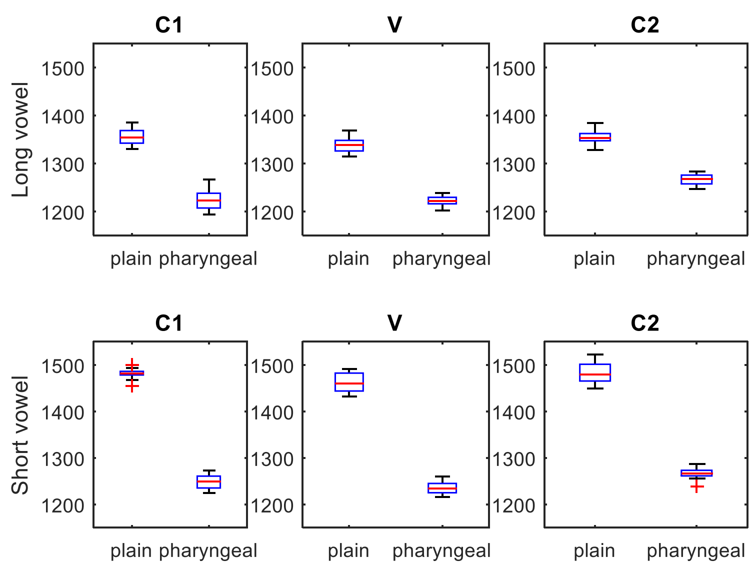

Figure A.119: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /ba:sˤ/ (‘bus’) and /ba:s/ (‘he kissed’) (top) and the C1, V, C2 segments in /basˤsˤ/ (‘he looked’) and /bass/ (‘enough!’) (bottom) as produced by SP1.

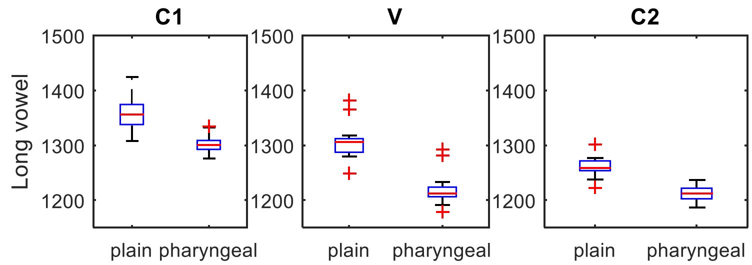

Figure A.120: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /sˤi:n/ (‘China’) and /si:n/ (‘the Arabic name for the letter /s/’) as produced by SP1.

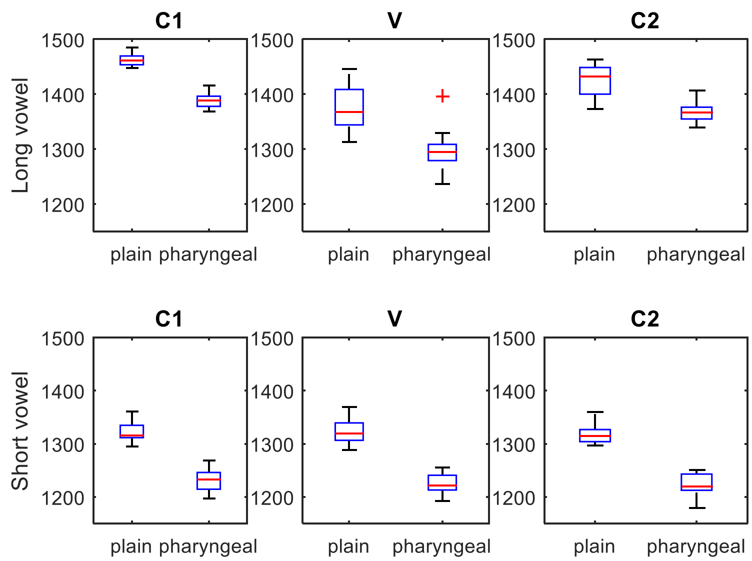

Figure A.121: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /bi:dˤ/ (‘white’) and /bi:d/ (‘exterminate’) (top) and the C1, V, C2 segments in /fa:yidˤ/ (‘remaining’) and /fay:id/ (‘a town in Egypt’) (bottom) as produced by SP1.

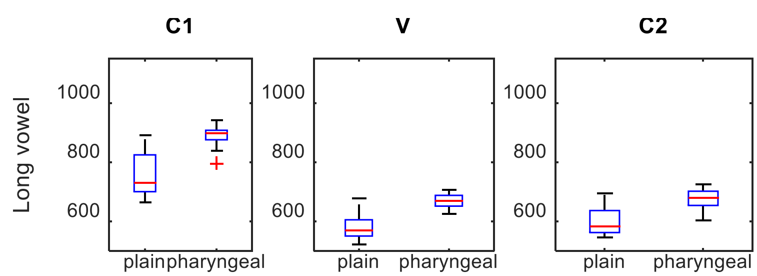

Figure A.122: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /sˤi:n/ (‘China’) and /si:n/ (‘the Arabic name for the letter /s/’) as produced by SP1.

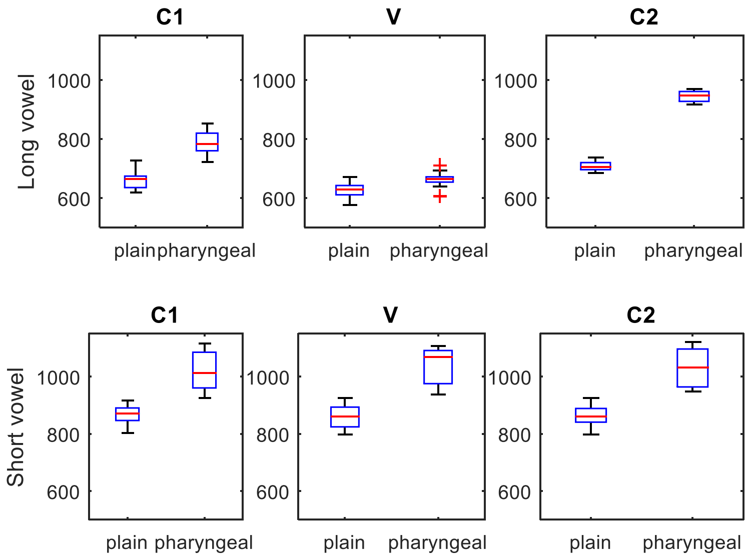

Figure A.123: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /bi:d^ʕ/ (‘white’) and /bi:d/ (‘exterminate’) (top) and the C1, V, C2 segments in /fa:yid^ʕ/ (‘remaining’) and /fay:id/ (‘a town in Egypt’) (bottom) as produced by SP1.

Speaker 2 – SP2

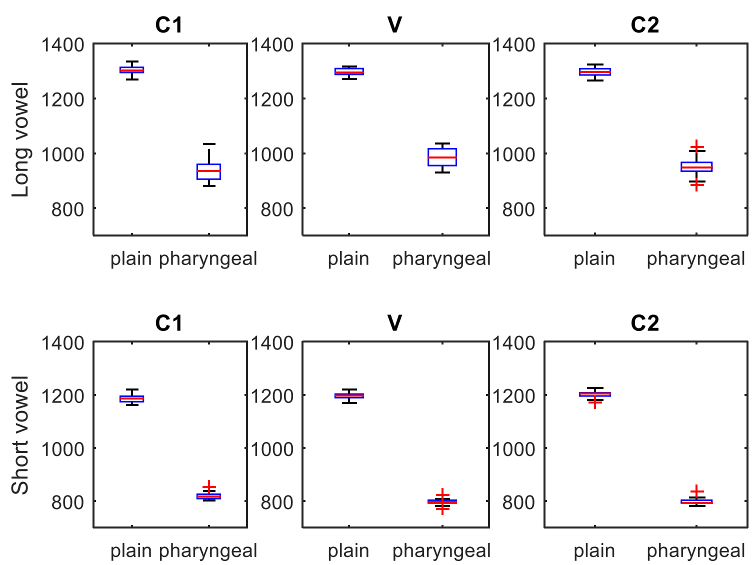

Figure A.124: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /s^{ʕ}a:b / (‘he hit’) and /sa:b/ (‘he left’) (top) and the C1, V, C2 segments in /s^{ʕ}abb/ (‘he poured’) and /sabb/ (‘he insulted’) (bottom) as produced by SP2.

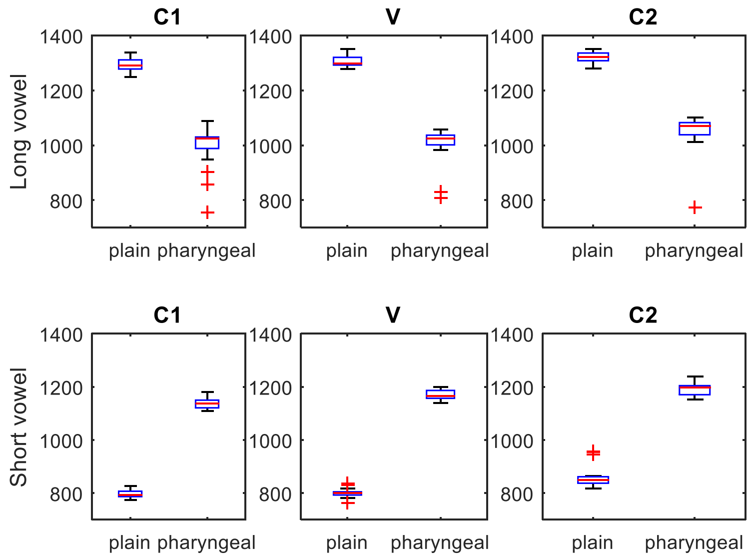

Figure A.125: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /ba:sˤ/ ('bus') and /ba:s/ ('he kissed') (top) and the C1, V, C2 segments in /basˤsˤ/ ('he looked') and /bass/ ('enough!') (bottom) as produced by SP2.

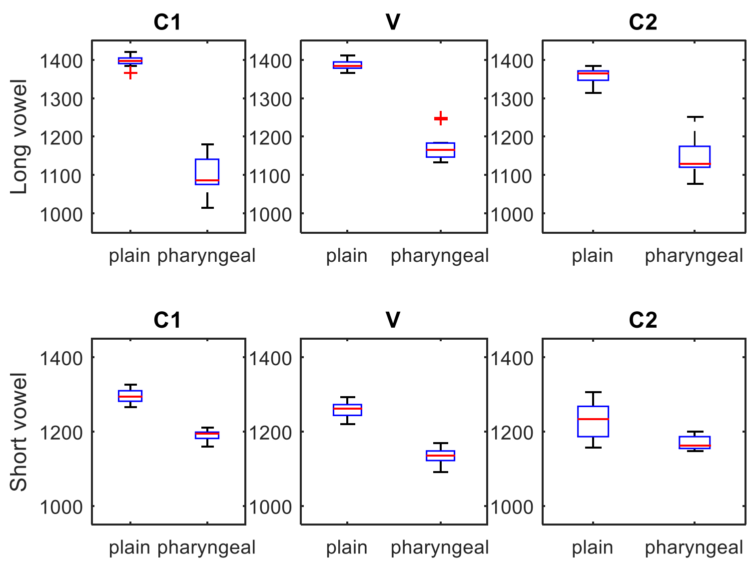

Figure A.126: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /sˤi:n/ ('China') and /si:n/ ('the Arabic name for the letter /s/') (top) and the C1, V, C2 segments in /azˤinn/ ('I think') and /azinn/ ('I whine') (bottom) as produced by SP2.

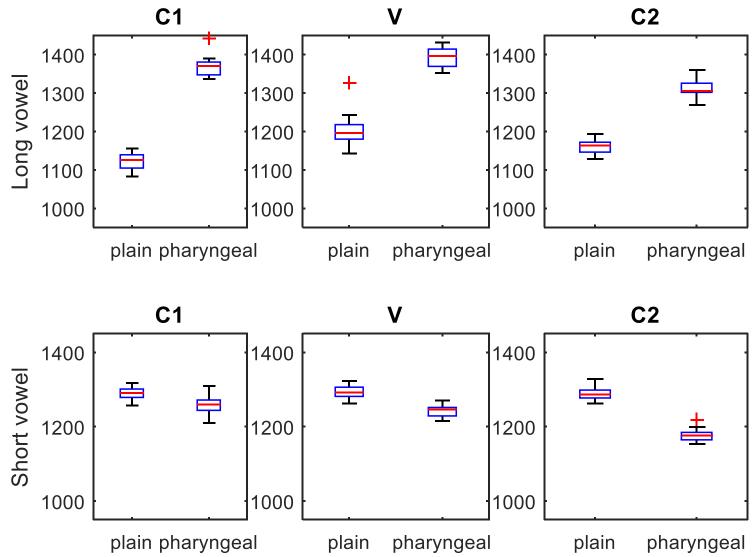

Figure A.127: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /bi:dˁ/ (‘white’) and /bi:d/ (‘exterminate’) (top) and the C1, V, C2 segments in /fa:yidˁ/ (‘remaining’) and /fay:id/ (‘a town in Egypt’) (bottom) as produced by SP2.

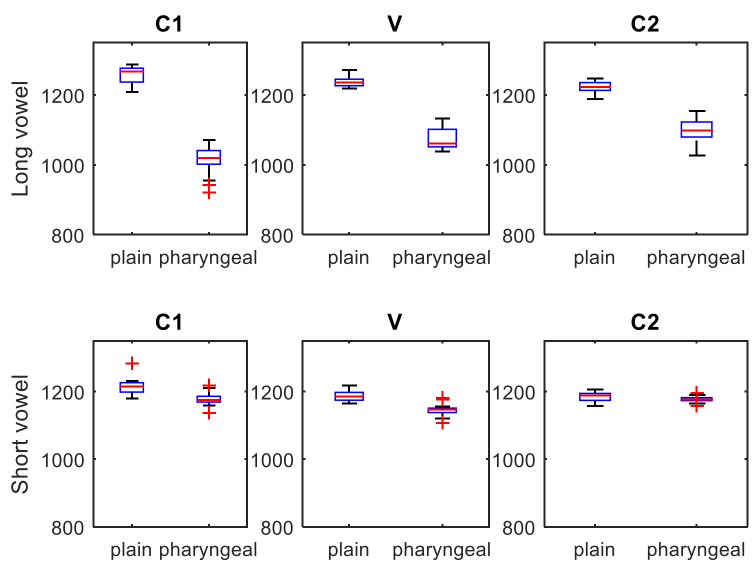

Figure A.128: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /tˁu:b/ (‘stones’) and /tu:b/ (‘repent’) (top) and the C1, V, C2 segments in /tˁubb/ (‘come unexpected’) and /tubʔa/ (‘will become’) (bottom) as produced by SP2.

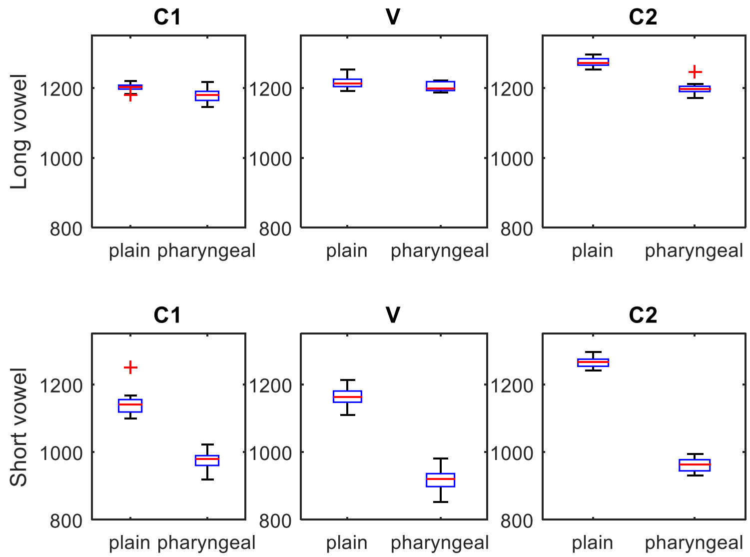

Figure A.129: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /bu:zˤ/ (‘rot/damage’) and /bu:z/ (‘muzzle’) (top) and the C1, V, C2 segments in /yuʕudˤdˤ/ (‘he bites’) and /yuʕud/ (‘he sites’) (bottom) as produced by SP2.

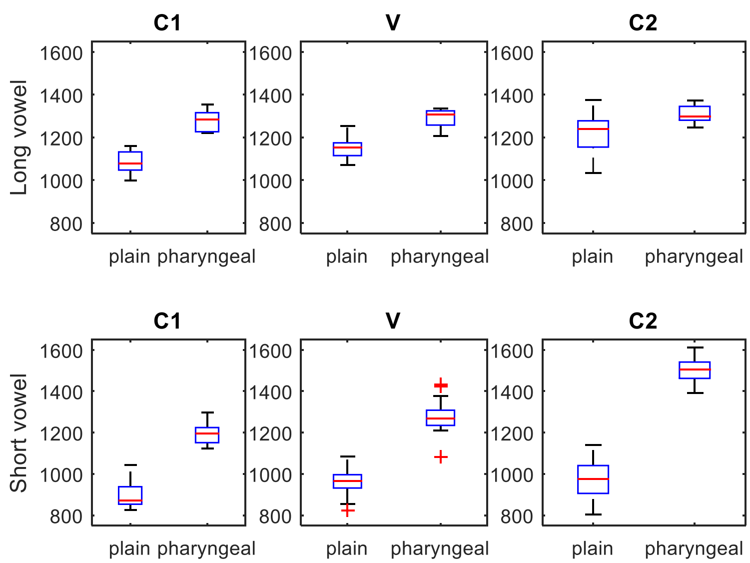

Figure A.130: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /tˤu:b/ (‘stones’) and /tu:b/ (‘repent’) (top) and the C1, V, C2 segments in /tˤubb/ (‘come unexpected’) and /tubʔa/ (‘will become’) (bottom) as produced by SP2.

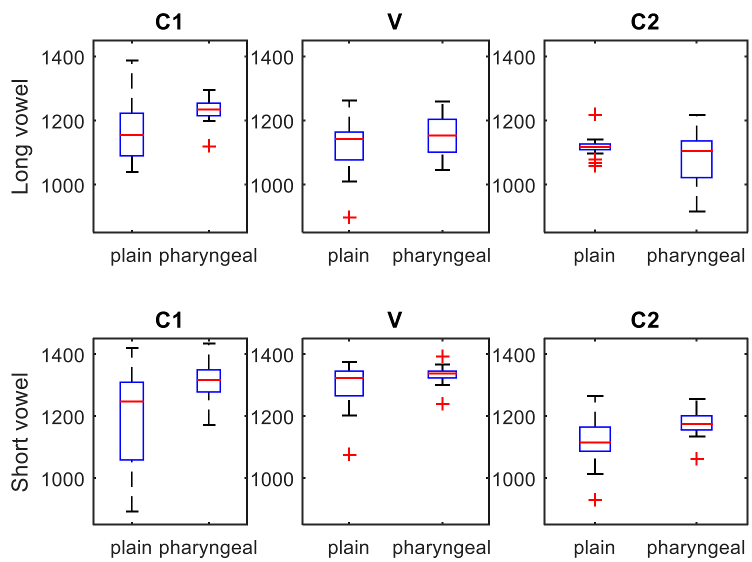

Figure A.131: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /bu:zˤ/ (‘rot/damage’) and /bu:z/ (‘muzzle’) (top) and the C1, V, C2 segments in /yuʕudˤdˤ/ (‘he bites’) and /yuʕud/ (‘he sites’) (bottom) as produced by SP2.

Speaker 4 – SP4

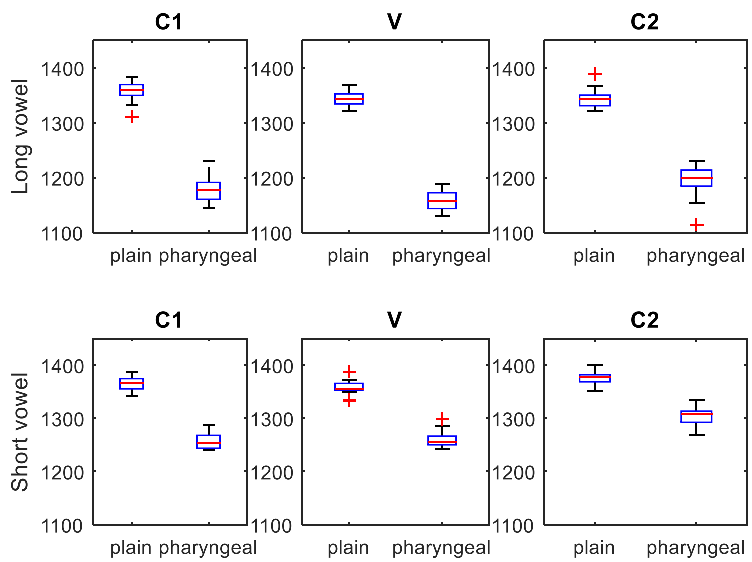

Figure A.132: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /sˤa:b / (‘he hit’) and /sa:b/ (‘he left’) (top) and the C1, V, C2 segments in /sˤabb/ (‘he poured’) and /sabb/ (‘he insulted’) (bottom) as produced by SP4.

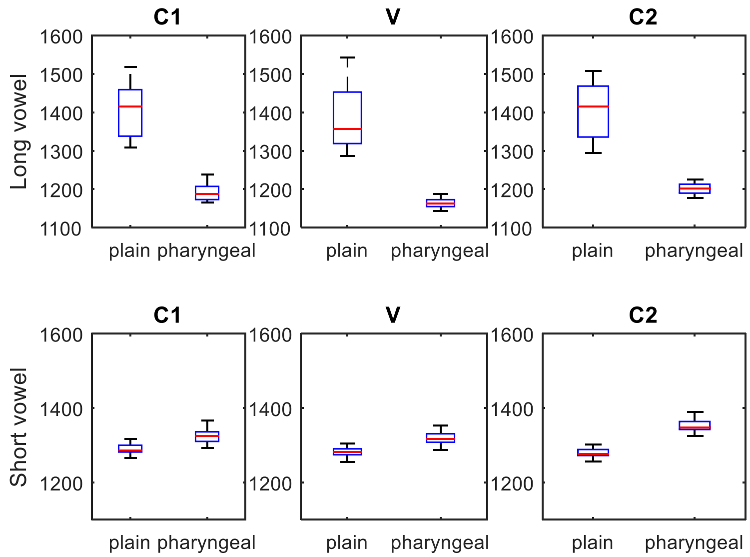

Figure A.133: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /ba:$s^{ʕ}$/ (‘bus’) and /ba:s/ (‘he kissed’) (top) and the C1, V, C2 segments in /ba$s^{ʕ}s^{ʕ}$/ (‘he looked’) and /bass/ (‘enough!’) (bottom) as produced by SP4.

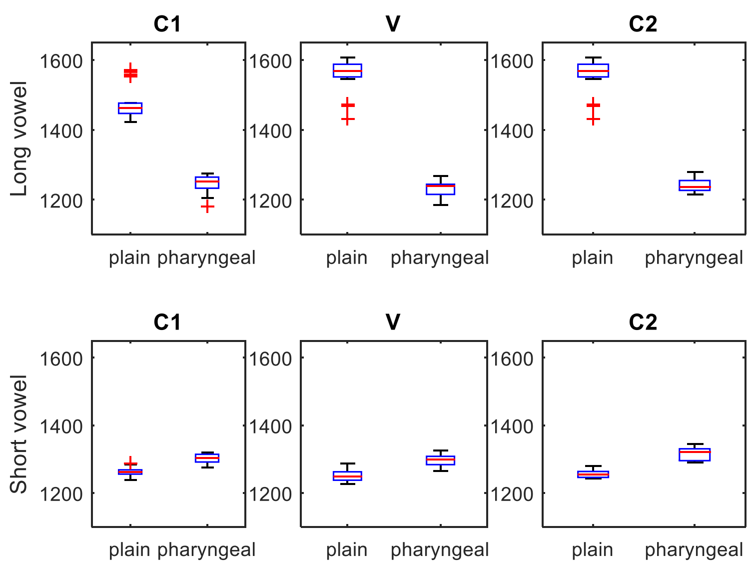

Figure A.134: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /$s^{ʕ}$i:n/ (‘China’) and /si:n/ (‘the Arabic name for the letter /s/’) (top) and the C1, V, C2 segments in /a$z^{ʕ}$inn/ (‘I think’) and /azinn/ (‘I whine’) (bottom) as produced by SP4.

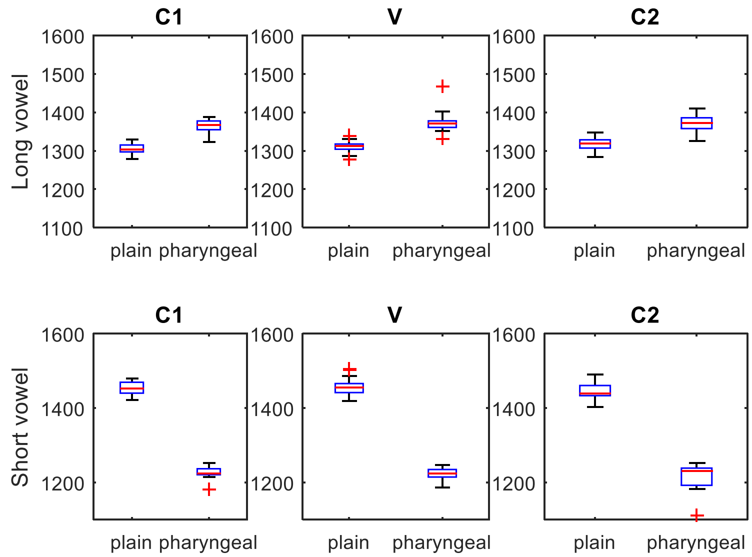

Figure A.135: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /bi:dˤ/ (‘white’) and /bi:d/ (‘exterminate’) (top) and the C1, V, C2 segments in /fa:yidˤ/ (‘remaining’) and /fay:id/ (‘a town in Egypt’) (bottom) as produced by SP4.

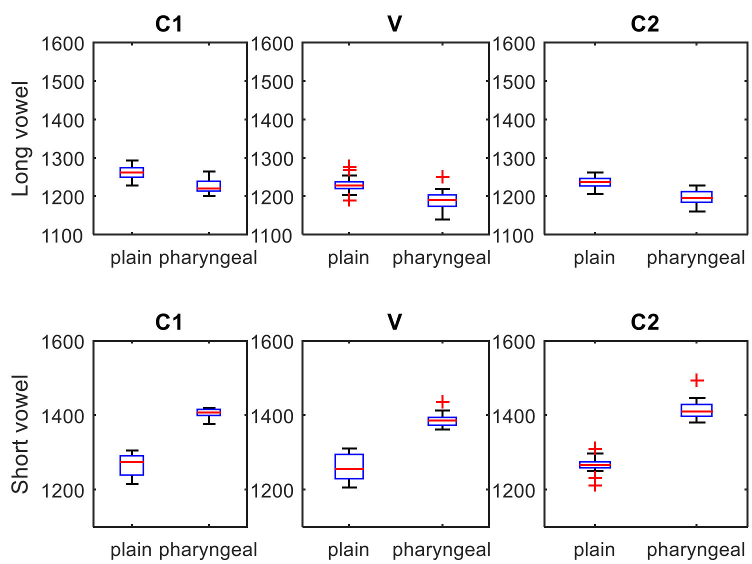

Figure A.136: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /tˤu:b/ (‘stones’) and /tu:b/ (‘repent’) (top) and the C1, V, C2 segments in /tˤubb/ (‘come unexpected’) and /tubʔa/ (‘will become’) (bottom) as produced by SP4.

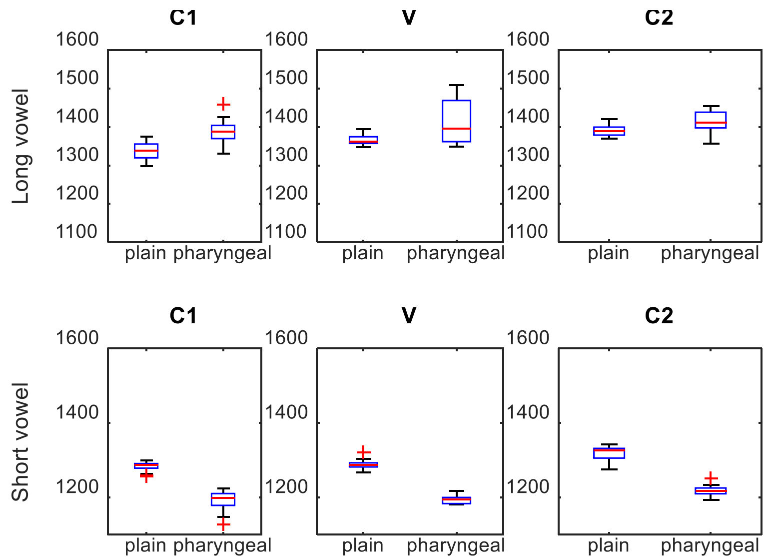

Figure A.137: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /bu:zˤ/ (‘rot/damage’) and /bu:z/ (‘muzzle’) (top) and the C1, V, C2 segments in /yuʕudˤdˤ/ (‘he bites’) and /yuʕud/ (‘he sites’) (bottom) as produced by SP4.

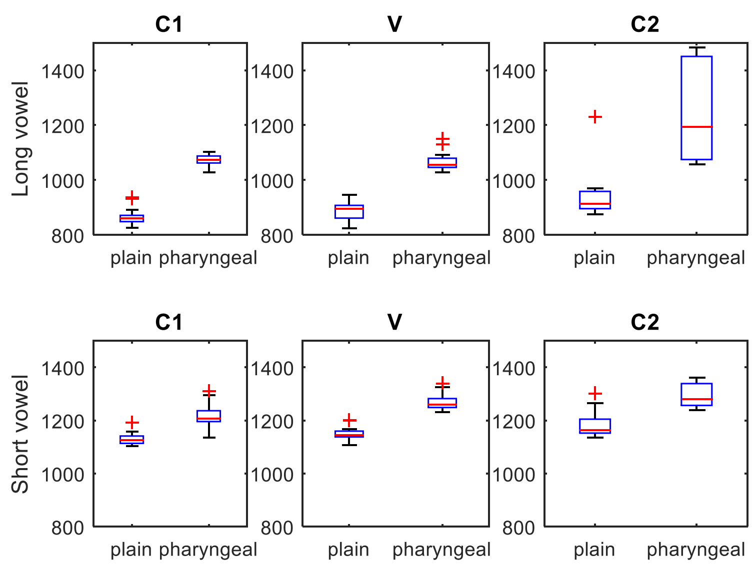

Figure A.138: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /tˤu:b/ (‘stones’) and /tu:b/ (‘repent’) (top) and the C1, V, C2 segments in /tˤubb/ (‘come unexpected’) and /tubʔa/ (‘will become’) (bottom) as produced by SP4.

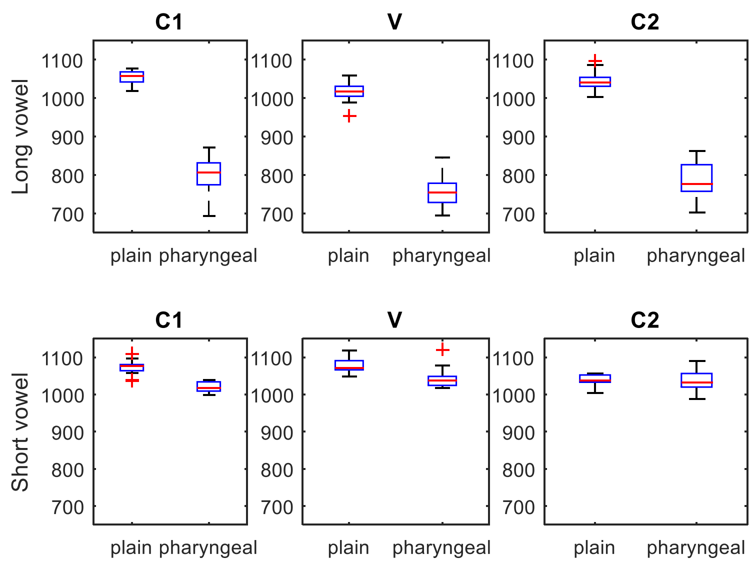

Figure A.139: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /bu:zˤ/ (‘rot/damage’) and /bu:z/ (‘muzzle’) (top) and the C1, V, C2 segments in /yuʕudˤdˤ/ (‘he bites’) and /yuʕud/ (‘he sites’) (bottom) as produced by SP4.

Speaker 5 – SP5

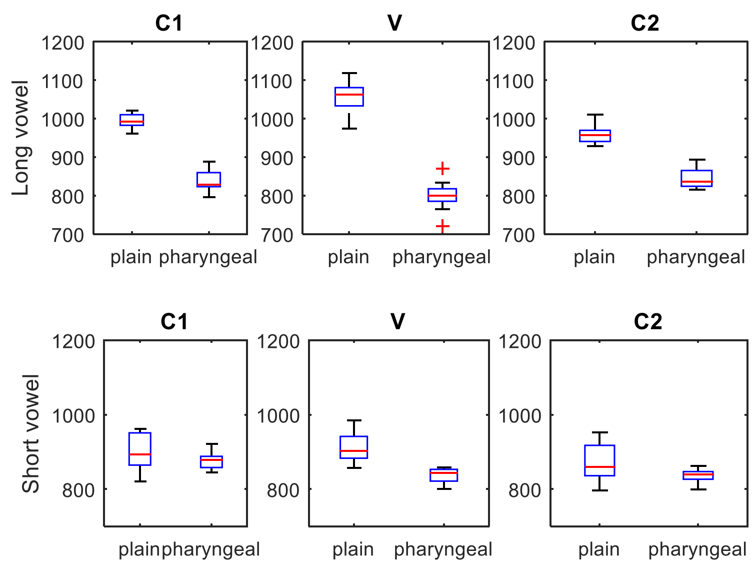

Figure A.140: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /sˤa:b / (‘he hit’) and /sa:b/ (‘he left’) (top) and the C1, V, C2 segments in /sˤabb/ (‘he poured’) and /sabb/ (‘he insulted’) (bottom) as produced by SP5.

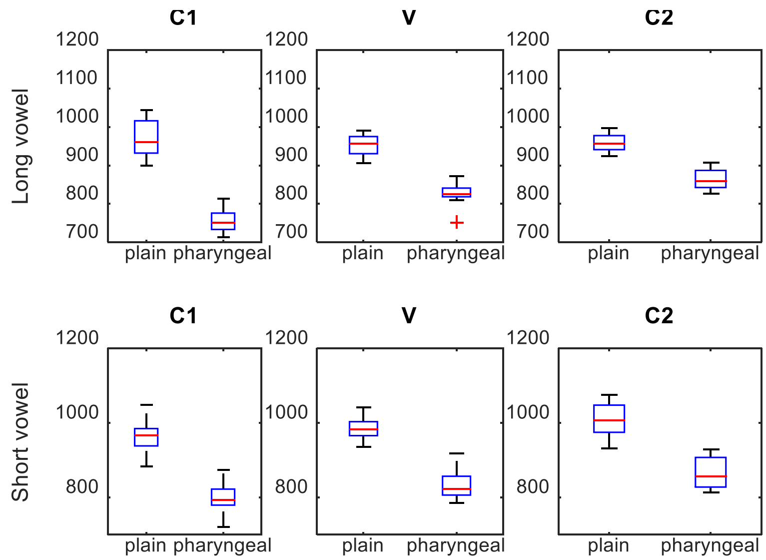

Figure A.141: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /ba:sˤ/ (‘bus’) and /ba:s/ (‘he kissed’) (top) and the C1, V, C2 segments in /basˤsˤ/ (‘he looked’) and /bass/ (‘enough!’) (bottom) as produced by SP5.

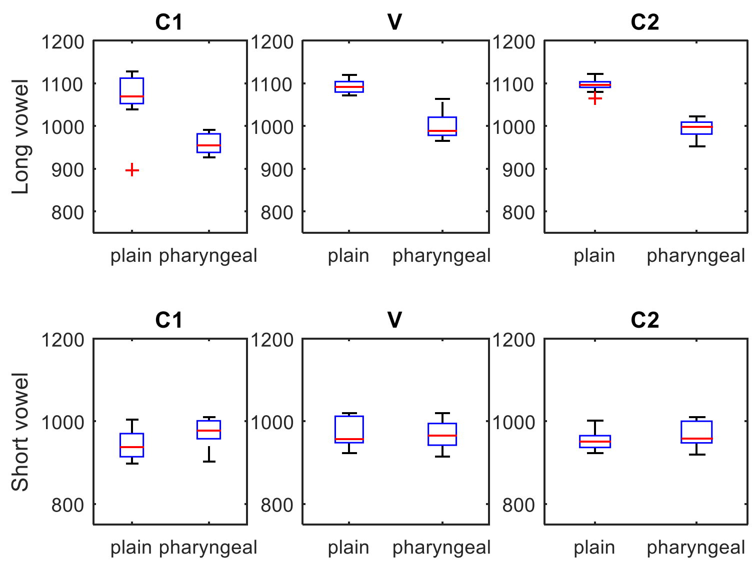

Figure A.142: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /sˤi:n/ (‘China’) and /si:n/ (‘the Arabic name for the letter /s/’) (top) and the C1, V, C2 segments in /azˤinn/ (‘I think’) and /azinn/ (‘I whine’) (bottom) as produced by SP5.

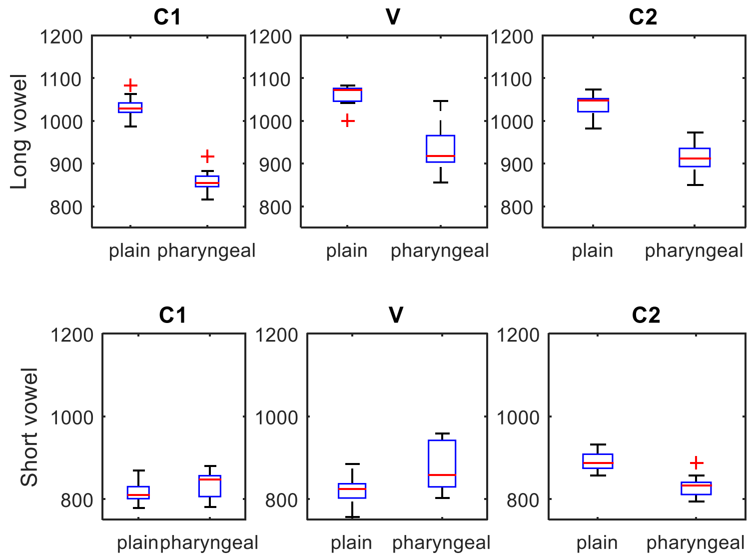

Figure A.143: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /bi:d^ʕ/ (‘white’) and /bi:d/ (‘exterminate’) (top) and the C1, V, C2 segments in /fa:yid^ʕ/ (‘remaining’) and /fay:id/ (‘a town in Egypt’) (bottom) as produced by SP5.

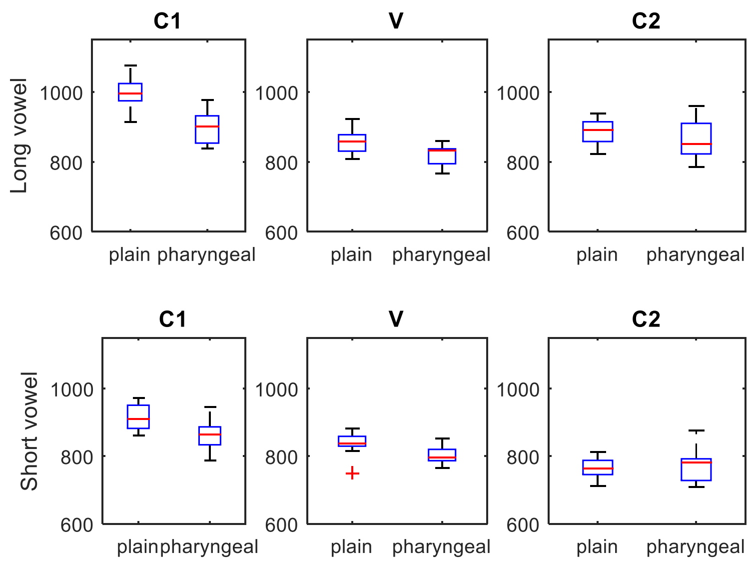

Figure A.144: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /t^{ʕ}u:b/ (‘stones’) and /tu:b/ (‘repent’) (top) and the C1, V, C2 segments in /t^{ʕ}ubb/ (‘come unexpected’) and /tubʔa/ (‘will become’) (bottom) as produced by SP5.

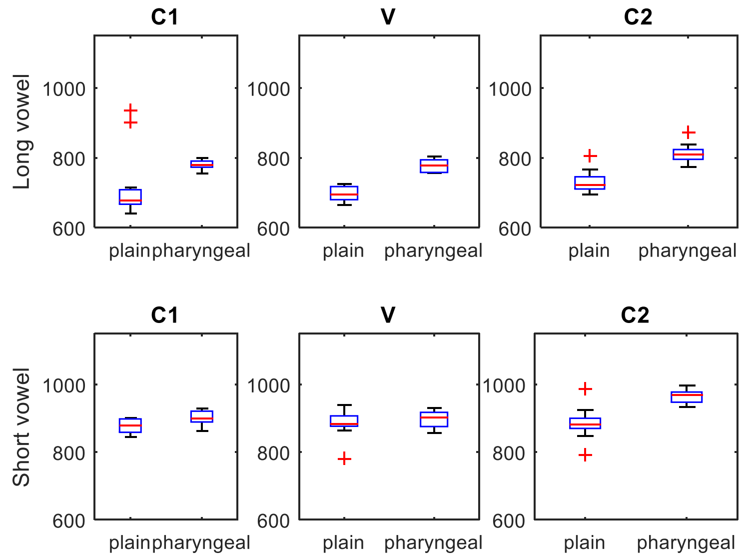

Figure A.145: 2D pharyngeal areas in (mm^2) for the C1, V, and C2 segments in /bu:zˤ/ (‘rot/damage’) and /bu:z/ (‘muzzle’) (top) and the C1, V, C2 segments in /yuʕudˤdˤ/ (‘he bites’) and /yuʕud/ (‘he sites’) (bottom) as produced by SP5.

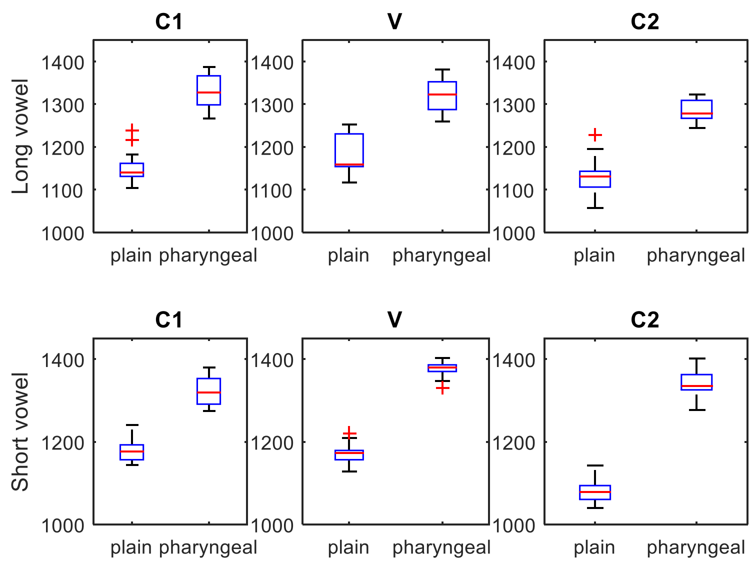

Figure A.146: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /sˤa:b / (‘he hit’) and /sa:b/ (‘he left’) (top) and the C1, V, C2 segments in /sˤabb/ (‘he poured’) and /sabb/ (‘he insulted’) (bottom) as produced by SP5.

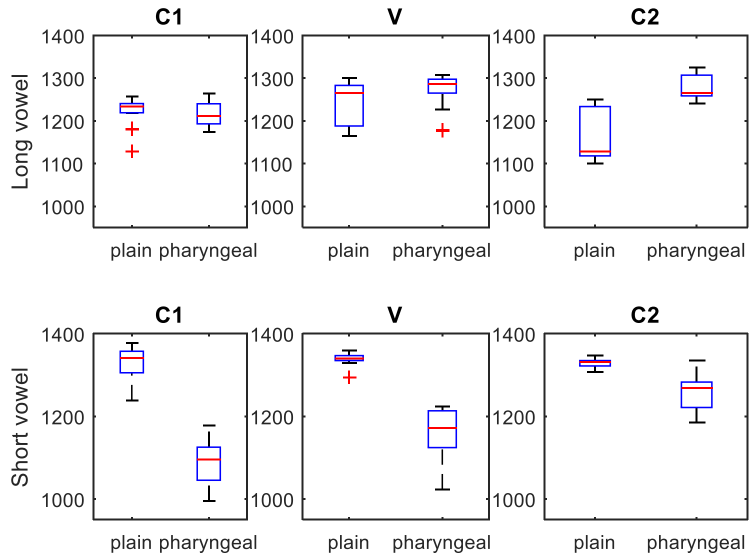

Figure A.147: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /ba:sˤ/ ('bus') and /ba:s/ ('he kissed') (top) and the C1, V, C2 segments in /basˤsˤ/ ('he looked') and /bass/ ('enough!') (bottom) as produced by SP5.

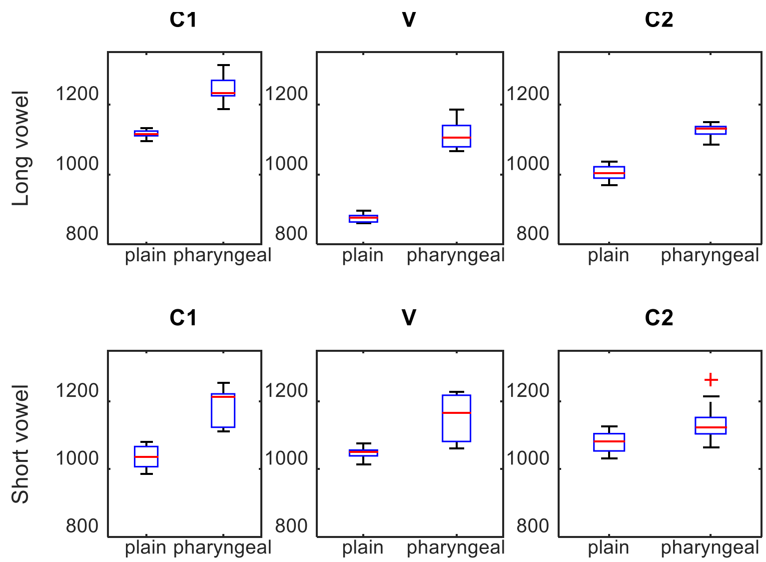

Figure A.148: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /sˤi:n/ ('China') and /si:n/ ('the Arabic name for the letter /s/') (top) and the C1, V, C2 segments in /azˤinn/ ('I think') and /azinn/ ('I whine') (bottom) as produced by SP5.

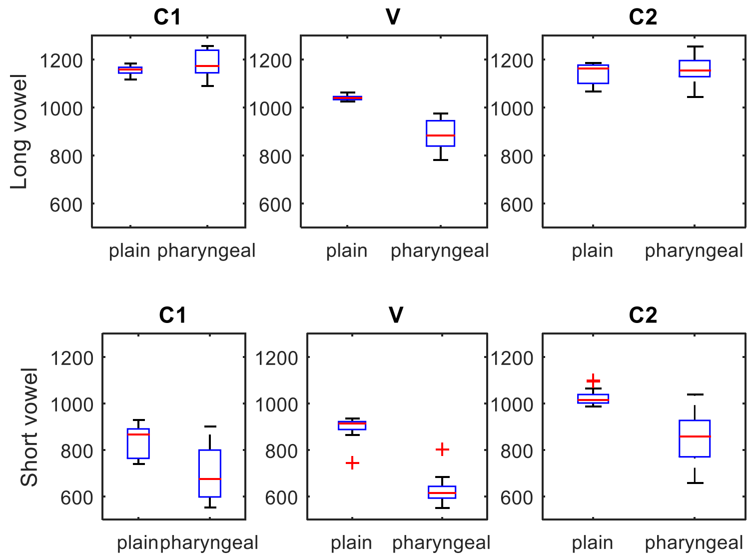

Figure A.149: 2D oral areas in (mm^2) for the C1, V, and C2 segments in /bi:dˤ/ (‘white’) and /bi:d/ (‘exterminate’) (top) and the C1, V, C2 segments in /fa:yidˤ/ (‘remaining’) and /fay:id/ (‘a town in Egypt’) (bottom) as produced by SP5.