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ARTICLE

Investigating Arabic Guttural Coarticulation: Correlations of Larynx and Hyoid Bone Vertical Displacement with Vowel Formant Patterns

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ABSTRACT

Guttural consonants in Arabic are characterized by articulation with an elevated larynx, a configuration that extends its influence to adjacent sounds. This coarticulatory effect produces measurable acoustic consequences, particularly in the formant structure of neighboring vowels. The present study investigates the relationship between larynx height, coarticulatory direction, and voicing in shaping the articulatory and acoustic modifications associated with guttural contexts. Using X-ray imaging, we examined the positional variations of the larynx during the production of the three short vowels /a, i, u/ adjacent to guttural consonants. Complementary acoustic analyses were conducted to evaluate the extent of formant shifts and changes in formant spacing induced by guttural spread. The findings indicate that guttural consonants exert a significant influence on vowel articulation and acoustics, with the magnitude of this effect strongly modulated by larynx height and voicing. By contrast, the direction of coarticulation (CV versus VC sequences) exhibited a comparatively weaker influence. Overall, the results provide clear evidence that laryngeal adjustments play a central role in the articulatory and acoustic properties of vowels in guttural environments. This study further demonstrates the utility of X-ray imaging for examining complex articulatory phenomena, offering valuable insights into the interplay between laryngeal movement and vowel acoustics in Arabic.

Keywords: Arabic Guttural Sounds; Coarticulatory Process; Larynx Height; Vowel Production; Speech Acoustics

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1. Introduction

The primary goal of studying speech production is to understand how individuals coordinate their articulatory movements to create spoken sounds. Prior to 1947 it was commonly believed that speech consisted of sounds with pauses between words. However the introduction of spectrograms in 1947 revealed that there are no breaks between words, and phonemes actually overlap in time[1]. The sound segments exhibit considerable influence from surrounding segments due to the different gestures that overlap in space and time during the speech production[2,3]. These intergestural timing relations exist between adjacent vowels, between vowels and preceding and following consonants, between consonants in sequences and can operate in both directions[4]. The influence of one segment on its following segment is known as carryover coarticulation, and when a segment influences a preceding segment it is known as anticipatory or forward coarticulation. Gestures are temporally coordinated with each other and due to their intrinsic timing, gestures can overlap during speech[3]. D. Byrd (1994, 1996) points out that these relationships allow gestures to overlap spatially and temporally resulting in an acoustic output which varies according to the behavior of active gestures[5].

Numerous experimental studies have been dedicated to investigating the production of Arabic guttural consonants across different dialects[6–8]. In Arabic phonology, guttural consonants comprise the pharyngeal, uvular, and laryngeal sounds, all articulated in the posterior region of the vocal tract. Pharyngeal consonants (/ʕ/, /ħ/) involve constriction of the tongue root against the pharyngeal wall near the mid-pharynx, whereas uvular consonants (/q/, /x/, /ɣ/) are produced with the dorsum of the tongue approaching the uvula. Emphatic or pharyngealized consonants (/sˤ/, /dˤ/, /tˤ/, /ðˤ/) exhibit a secondary articulation. Collectively, these segments are classified as back consonants because they share a posterior place of articulation and produce comparable coarticulatory effects on adjacent vowels. These studies have consistently observed a significant elevation of the larynx (referring to upward displacement of the larynx relative to rest position) during the articulation of these consonants[9–11] and the vertical movement of the larynx has been found to be essential in the production of Arabic back consonants[12,13]. Knowing that the larynx is influenced by various muscles, connected to neighboring organs such as the hyoid bone and tongue[14], as a result, the larynx may move in coordination with these two organs.

The hyoid bone, with its numerous muscular attachments, plays a crucial role in supporting speech and tongue movement[14]. As reported in the literature the raising or lowering of the larynx alters the length of the pharyngeal cavity and this alteration plays an important part in determining voice quality[14]. Thus, many studies on the acoustic consequences of change in the vertical dimension of the pharynx have been carried out. K. Honda et al. (1999) have studied the role of vertical larynx movement and cervical lordosis in *fo* control[13]. A. Bothorel (1980) established the incidence of vertical movements by the hyoid bone during speech and song from an acoustic and radiocinematographic study[15]. He found that the hyoid bone is systematically higher for voiceless consonants than for voiced ones. In vowels, he noticed a correlation between elevation of the hyoid bone and rises in *fo*. H. Takemoto et al. (2006) have shown that the hypopharynx, and in particular the piriform sinuses and the vestibular folds of the larynx, play an important part in determining the timbre of vowels[16]. The coarticulation is known to introduce acoustic variability for vowels. J. McCarthy (1994) states that the main effect of pharyngeal consonant coarticulation that has been observed is an elevation of the first formant F1 by about 100 Hz. This effect is typically observed in the steady-state portion of an adjacent vowel[17]. Similar results were reported by S. Al-Ani[18], A. Butcher & K. Ahmad[19] and B. Zawaydeh[20]. S. Ghazeli[10] suggested that emphatics caused lower F2 values in following vowels /i/ and /a/ while uvular caused lower F2 values in following vowel /u/. M. Bin-Muqbil[21] reported that uvular have higher F1 values when compared to plain coronals and he suggested that F2 values in vowels /i/, /a/ and /u/ after pharyngeals are not significantly different than those after plain consonants in almost all cases[21]. Other studies indicated some variation in F2 values after pharyngeal consonants[10,18–20]. The uvular consonants have similar coarticulatory effects to pharyngealized consonants in which they lower F2 values in adjacent vowels. Compared to plain coronals, S. Al-Ani[18] found that Arabic uvular [χ, ʁ, q] have lower F2 values in adjacent vowels. A. Alwan[22] conducted several perception experiments to determine the main perceptual cues of the articulation place for /ʕ/ using synthesized tokens. She found with synthesized speech that the primary perceptual correlate to coarticulation on a vowel for a pharyngeal segment was a high F1 and a low F2. By manipulating F1 and F2 trajectories, as well as bandwidth size for F1 and F2, she found that listeners prefer an F2-F1 value that is lower for pharyngeals and the lower F2 onset values received the highest naturalness ratings for pharyngeals [22]. According to A. Marchal [14], the consequences of change in the vertical dimension of the pharynx due to the laryngeal lowering for most vowels are: the drop in the first formant F1, the second formant generally drops for high front vowels such as /i/. For /u/, the effect is less marked than for /a/. The third formant remains fairly stable for all vowels except /u/, in which frequency drops. The fourth formant undergoes a moderate drop. A. Marchal stated that F2 is the formant most affected by laryngeal lowering and the net result of this movement is to bring F3 closer to F4 [14]. This phenomenon of reduced distance between F3 and F4 has also been observed in the singing voice by J. Sundberg [23], who considers this narrowing of the difference between the two upper formants as the principal characteristic of sung vowels when they are produced with a lowered larynx [23]. Although numerous studies have examined Arabic consonants, there remains a noticeable gap in research that combines articulatory and acoustic perspectives, making it difficult to establish a clear correlation between these two aspects of speech production.

Our study aims to address a central question concerning how substantial is the effect of coarticulation relative to the impact of larynx height for Moroccan Arabic (MA) vowels in guttural neighboring?

We examine how the variation in larynx height is influenced by both preceding and following voiced and voiceless guttural consonants, we utilize both acoustic and articulatory data to investigate the impact of guttural sounds on the vowel quality in MA. By analyzing the articulatory data, we gain insights into the coordination of various articulatory movements during the production of the MA guttural consonants, specifically focusing on the uvular (/q, ʁ, X/) and pharyngeal (/ʕ, ħ/) sounds. Moreover, we explore how these articulatory gesture spread through coarticulation during the production of adjacent vowels and we explore the acoustic impacts of anticipatory and carryover coarticulation on the MA vowels. We examine the formant frequencies F1, F2, F3, and F4, and we measure the distances between F2-F1 and F4-F3. Furthermore, our investigation includes a correlation analysis to examine the relationship between articulatory movements and acoustic effects on the adjacent vowels. By combining these approaches, we aim to gain a comprehensive understanding of how guttural consonants influence the vowel quality in MA.

2. Materials and Methods

The data processed in the present work were taken from a data base « DOnnées Cinéradiographiques VAlorisées et recherches sur la Coarticulation, Inversion et évaluation de Modèles physiques » (DOCVACIM) [24]. This open-access database includes approximately twenty multilingual recordings, accompanied by synchronized acoustic signals, providing a unique and historically valuable corpus for phonetic and articulatory research. The cineradiography film used in this research comprises a total of 2777 vocal tract X-ray images recorded from a male speaker, the time interval between two consecutive images is 40 ms. During the recording, the speaker produced 60 phrases in the MA dialect, which is his native language at a normal speaking rate. As the study relies on a single male speaker, the findings should be interpreted with caution regarding their generalizability.

For our investigation, we specifically processed the vocal tract images corresponding to the production of MA guttural consonants (/q, ʁ, X, ħ, ʕ/) and the images corresponding to the adjacent vowels (/a, i, u/). In the data processing, we considered 3 to 5 vocal tract x-ray images for each phoneme, taking into account the duration of each phoneme in the sentence. Thus Articulatory images were obtained during consonant production and temporally aligned with the corresponding audio recordings. Each consonant was synchronized with its articulatory sequence, from which 3–5 representative frames were extracted to capture the consonant gesture. All produced tokens were analyzed irrespective of their duration, no minimum duration threshold was imposed.

From these images, we calculated the mean values in centimeters along to understand the variations in the articulatory movements during the production of different phonemes. We also investigated the correlation between the larynx center and the hyoid bone elevations during the production of the MA back consonants. Given that the larynx and the hyoid bone are connected by several muscles, studying their correlation provides insights into the coordinated movements of these articulators during speech production.

Additionally, we examined the correlation between the larynx elevation and the variations of the formants during the production of the three vowels /a, i, u/ adjacent to the back consonants. By conducting these correlation analyses, we aim to uncover potential relationships between the movements of the larynx and hyoid bone, as well as their impact on vowel formant frequencies; it helps us understand how changes in the larynx position may influence the acoustic characteristics of the adjacent vowels.

2.1. Audio Data Processing

We utilized the software Praat for both phrase segmentation into individual phonemes and phonetic annotation. The phonetic annotation of the acoustic signal gives the boundaries of sounds. We created and edit TextGrids to mark and label different segments in the speech signal, we have used a manual segmentation in this study. In our analysis, we ensured the synchronization of phoneme annotations with the corresponding X-ray images. This involves aligning the temporal information across these different modalities. Given that we have the time of the sequence beginning, time of the first phoneme, and time of the last phoneme in the annotated sequence, as well as the frequency rate of the X-ray images. First we calculate the frame index from time; we have to convert the time information to frame indices for both the X-ray images and the acoustic signal. This involves dividing the time by the frame duration. The frame indices provide a common reference point for both modalities. We align the X-ray images with the onset of the acoustic signal. Finally we visualize the synchronized data to ensure that the alignment is accurate. To account for possible minor misalignments due to onset or offset timing differences between the recording systems, the alignment was visually verified by comparing articulatory movements (e.g., tongue or lip gestures) with corresponding acoustic events. When necessary, small temporal adjustments were applied to ensure accurate correspondence.

Acoustic Analysis

Praat was employed for formant value calculations with specific settings:

- Method: Fourier
- Window shape: Gaussian
- Window length: 5 ms
- View range: 0.0 to 7000 Hz

The 5 ms window provides high temporal resolution, allowing accurate detection of rapid articulatory–acoustic transitions such as consonant releases and vowel onsets, while the Gaussian shape minimizes spectral leakage. A longer window (e.g., 10–20 ms) would improve frequency resolution but reduce temporal precision, which is less suitable for tracking fast articulatory events. The 0–7000 Hz frequency range was selected to include all relevant formant frequencies (F1-F4) and to exclude high-frequency noise, providing a clear representation of the spectral features associated with tongue and lip movements. **Figure 1** shows an example of a segmented phrase. Each formant (F1-F4) was measured at a steady-state portion of the vowel (typically mid-vowel), where formant trajectories are most stable.

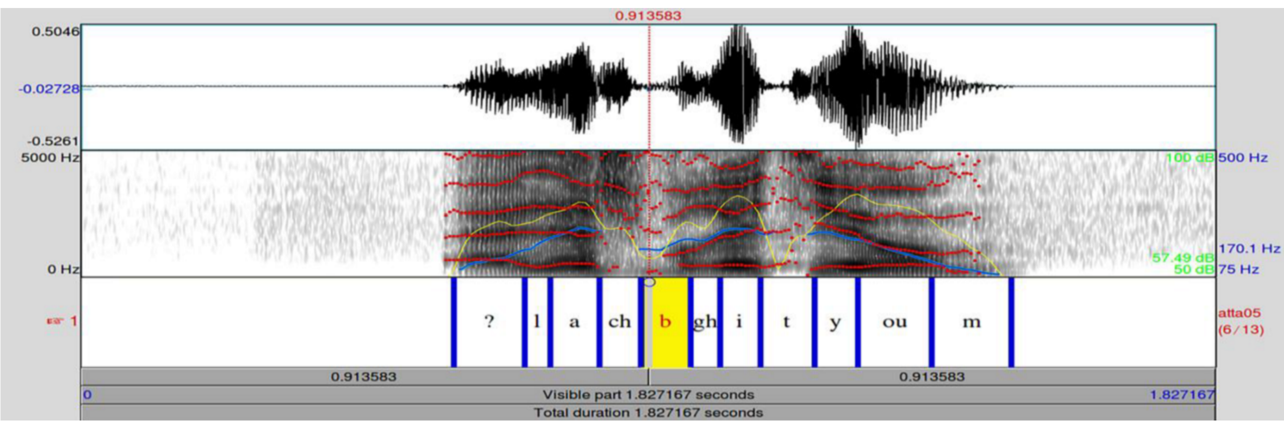

Figure 1. Segmentation of the phrase /ʕlaʃ/ /bʁit/ /yum/.

Below, we have provided Tables that encompass all the phonemes examined within various contexts as addressed in this study.

2.2. Articulatory Data Processing

In our study, we have drawn the contours of various organs involved in speech production, including the tongue, lips, larynx, glottis, jaw, hard palate, and hyoid bone. The manual delineation of the tongue was performed, recognizing that automatic tracking of the tongue contour can be challenging. The manual tracing of the tongue contour was performed by a single expert experienced in articulatory image analysis. To ensure consistency and reliability, the annotation software provided a verification function that allowed the annotator to review the preceding five frames while tracing each contour. Therefore, we focused on tracing the contour of the midsagittal plane of the tongue[25,26]. Regarding slightly overlapping organs, we utilized the algorithm proposed by F. Berthommier to track their movements accurately. Thus, we employed the retro-marking algorithm, which combines manual marking of geometrical features on a limited number of key images with automatic estimation for all frames in the sequence[27]. A subset of key images representing 10% of the total number of images to be processed, were manually marked with geometrical features (the 10% key images are randomly selected). To ensure randomness in the selection of the 10% key images, we used MATLAB's random sampling function (randsample) to draw frame indices uniformly from the total set of images, giving each frame an equal probability of being chosen. In addition, to ensure coverage across contexts, the image sequences were divided into temporal segments corresponding to different articulatory phases of speech production. Random sampling was then applied within each segment, ensuring that the selected key images collectively represented the full range of articulatory movements present in the dataset.

The contours of these key images were approximated using Bspline curves with a constant number of control points, ensuring smooth representations. To index the remaining non-key images, we measured the distance of their DCT features in comparison to those of the key images (equation 1). By employing this method, we were able to track the movements of organs during speech production and obtain valuable articulatory data for our analysis.

$$j = index_i(S_t) = argmin_i \sqrt{\sum_{p=2}^{24*24} (DCT_p(S_t - DCT_p(k_i))^2} \quad (1)$$

Where:

J: is the index corresponding to the number of the key image.

$index_i$ (S_t): represents the index i associated with the key image that minimizes the expression.

S_t : is the image to be analyzed.

k_i : is a key image.

$DCT_p(S_t)$ and $DCT_p(k_i)$: denote the DCT coefficients of the image S_t and the key image k_i, respectively.

The $argmin_i$ part indicates finding the value of i that minimizes the expression inside the square root.

The key image associated to the smallest distance allows defining for each image (S_t) of the sequence an index (j) corresponding to the number of this key image; the number of DCT components is fixed at 24*24, using fewer DCT components, without changing consistently the results, could have reduced the computation time. Thus each frame of the sequence is assigned by the index of the nearest key image. Finally, the new contour given by the control points of the spline is the weighted average of the contours of the three closest key images. If the visual evaluation of tracking shows that some images are not tracked correctly, because they are too far from key images, then they are added as key images[27]. Typically when the estimated contours deviated noticeably from the expected articulatory trajectory or appeared geometrically inconsistent with adjacent frames, they were manually corrected and added as new key images. This decision was made by the same expert annotator using the visualization tool, which allowed simultaneous inspection of the current and previous five frames, ensuring temporal continuity in the contour motion.

In this study, we used a software called "Xarticulators" to draw the articulators contours; "X-articulators"supports several tracking tools to be used according to the nature of articulators. It allows the addition of landmarks on contours to identify specific anatomical points (e.g., upper incisor). Landmarks may serve as reference points and anchor a coordinate system for analysis. Since it is important to relate contours to the uttered phonemes, the software supports the import of files containing phonetic annotations. X-articulators provides also tools to construct articulatory models from the articulator contours via Principal Component Analysis (PCA)[24–26].

The **Figures 2** and **3** show prototypes of the annotated contours of the phonatory organs during the production of the guttural consonant /ʁ/.

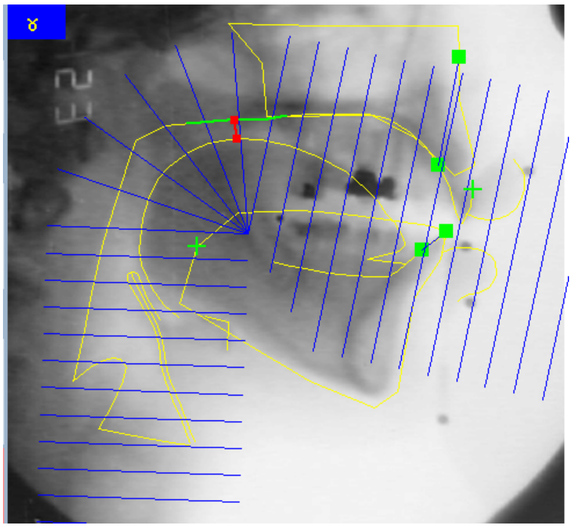

Figure 2. Prototypes of the vocal X-ray image processed with the adapted grid: the image synchronized with the production of the consonant /ʁ/.

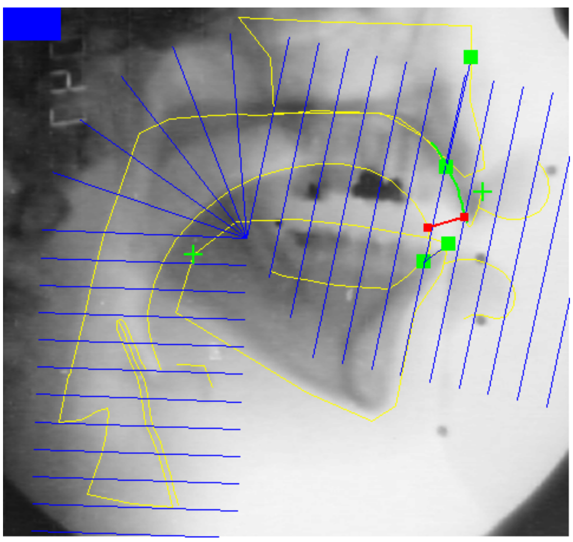

Figure 3. The vocal X-ray image processed with the adapted grid in the rest position.

Each image in the sequence is assigned a numerical order, which is likely based on the order of appearance in the sequence. The contours have been utilized for direct measurements of the displacement of the articulators. The displacement of the articulators will be measured relative to the rest position.

3. Measurement of the Articulators Contours

To ensure the precision of our measurements we used the following procedure:

We employed an angular reference system along with an adapted grid specific to the speaker's vocal tract configuration.To facilitate the measurements, an orthonormal basis was drawn (**Figure 4**), and superimposed on the measurement grid[25]. A reference image is carefully selected for its neutrality and clarity (the reference image should be clear with high resolution) in terms of contours, typically corresponding to a rest position. The rest position describes the neutral or default position of the articulators (speech organs, such as the tongue, lips, vocal cords, larynx…) when a person is not actively speaking or producing speech sounds. In this position, the vocal tract is in a neutral configuration. To ensure consistent measurements, the position of the upper incisor is used as a fixed reference point, and all other positions are calculated relative to this reference point. Since the upper incisor and hard palate are relatively stable during speech production[28]. The position of the hyoid bone is given by the second of the three points used to represent it on the image.

In this study, we focused on the larynx and hyoid bone vertical movement during the production of the three short vowels /a, i, u/ in guttural neighboring and in plain coronal contexts. All the measurement are compared to the rest position.

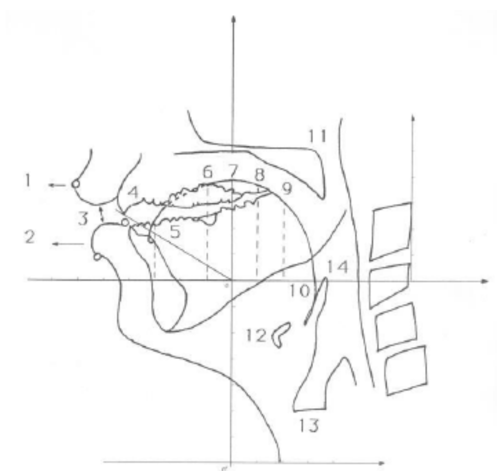

Figure 4. This figure illustrates the method used for applying an orthonormal basis[28].

Where the larynx center is at 6.17 cm relative to the upper incisor and the position of the hyoid bone is at 4.22 cm. This reference position is measured directly from the speaker images.

4. Results and Discussion

4.1. Larynx and Hyoid Bone Dynamics

The **Table 1** summarizes the vertical movements of both the larynx center (LC) and the hyoid bone (HB) relative to the rest position during the production of the studied uvular (/q, ʁ, X/) and pharyngeal (/ħ, ʕ/) consonants. All measurements are carried out relative to the reference point (the upper incisor). From the obtained measurements, it is evident that the MA guttural consonants are produced with a raised larynx. Specifically, during the production of the voiced uvular consonant /ʁ/, the mean value of the larynx center rising is 0.92 cm relative to the rest position. For the voiceless uvular /q/, it raises by 1.19 cm, and for the uvular /X/, it raises by 0.95 cm. Comparing these results with those obtained for the MA pharyngeal consonants, it is notable that the elevation of the larynx center during the production of the uvular consonants /q, X, ʁ/ falls within the same range as that of pharyngeal consonants. Thus, the pharyngeal consonant /ʕ/ involves a considerably elevation of 0.94 cm, and for the voiceless pharyngeal /ħ/, it raises by 1.48 cm. So for the voiceless /q/ the elevation of the larynx (1.19 cm) is close to that of the voiceless pharyngeal /ħ/ (1.48 cm), and the voiced /ʁ/ (0.92 cm) close to the voiced /ʕ/ (0.94 cm). For the hyoid bone, we observe that it raises from 0.44 cm to 1.32 cm during the production of the MA guttural consonants.

Table 1. The positions and the elevation of the larynx center and the hyoid bone in the rest position and during the production of /ʕ, ħ, q, ʁ, χ/ in the studied contexts, n is the number of images.

Consonants	LC Positions (cm)	HB Positions (cm)	LC Raising (cm)	HB Raising (cm)
Rest position	6.17	4.22	0.0	0.0
/ʕ/	5.11	3.28	1.06	0.94
/ʕlih/	5.24 4.90 5.03 5.04	3.35 3.61 3.52 3.81	0.92 1.26 1.14 1.12	0.87 0.61 0.70 0.41
/ʕlaʃ/	5.55 5.47 5.37	4.14 4.21 4.10	0.61 0.70 0.79	0.08 0.01 0.12
/ʕadawhum/	5.38 5.35 5.25 5.35	3.92 3.89 3.82 3.82	0.95 0.94 0.94 0.90	0.47 0.41 0.35 0.32
Mean values for /ʕ/ (SD) (n = 11)	**5.25**	**3.79**	**0.94 (0.18)**	**0.44 (0.29)**
/ħ/	**LC position**	**HB position**	**LC raising**	**HB raising**
/Lħala/	5.03 4.71 4.29 4.43 4.80	3.77 3.68 3.73 3.74 3.94	1.13 1.46 1.87 1.74 1.37	0.45 0.53 0.49 0.48 0.27
lbaraħ	4.55 4.52 4.31 4.75	3.76 3.84 3.76 4.00	1.62 1.64 1.85 1.41	0.46 0.37 0.46 0.22
Saħbu	5.19 4.97 4.60 4.69 4.73	3.29 3.30 3.42 3.55 3.78	0.98 1.20 1.56 1.48 1.44	0.93 0.91 0.80 0.67 0.44

Table 1. *Cont.*

Mean value for /ħ/ (SD), (n = 14)	**4.68**	**3.68**	**1.48 (0.25)**	**0.53 (0.21)**
/χ/	**LC**	**HB**	**LC raising**	**HB raising**
/sχune/	5.18 5.14 5.13 5.40	2.96 2.92 2.77 2.92	0.98 1.03 1.04 0.76	1.25 1.30 1.44 1.30
Mean value for /χ/, (n = 4)	**5.21**	**2.89**	**0.95**	**1.32**
/ʁ/	**LC**	**HB**	**LC raising**	**HB raising**
/ʃʁul/	5.45 5.49 5.17 5.24	3.28 3.26 3.19 3.03	0.71 0.68 0.99 0.92	0.94 0.95 1.03 1.18
/bʁit/	5.11 4.97 5.25	3.13 3.24 3.25	1.06 1.20 0.92	1.09 0.97 0.97
Mean value for /ʁ/ (SD), (n = 7)	**5.24**	**3.20**	**0.92 (0.17)**	**0.97 (0.08)**
/q/	**LC**	**HB**	**LC raising**	**HB raising**
/tlaqaw/	4.99 4.85 4.75 4.85	2.79 2.74 2.96 2.74	1.18 1.32 1.42 1.32	1.43 1.48 1.26 1.48
/maqasuʃ/	5.43 5.02 4.79	3.28 2.97 2.96	0.74 1.15 1.38	0.94 1.25 1.26
/tamaqariʃ/	5.31 4.93 5.04	2.88 2.82 2.82	0.86 1.24 1.13	1.34 1.4 1.4
/maqalhaʃ/	4.90 5.07 4.91 4.83	3.36 3.05 2.96 2.85	1.27 1.1 1.26 1.34	0.86 1.17 1.26 1.37
Mean value for /q/ (SD), (n = 14)	**4.97**	**2.94**	**1.19 (0.19)**	**1.27 (0.18)**

In this study, our emphasis was on exploring the variations in the positions of the larynx and hyoid bone during the articulation of vowels within guttural contexts and plain coronal contexts. So, we also focused on contexts outside the guttural context, referred to as simple coronal context, the specific measurements related to the elevation of the larynx and hyoid bone for the vowels /a, i, u/ are presented in **Tables 2–4** respectively. Our objective was to assess and compare the impact of guttural consonants on the neighboring vowels in contrast to plain coronal consonants.

In **Table 2**, measurements for the vowel /a/ in plain coronal contexts reveal a mean larynx elevation of approximately 0.36 cm, and the hyoid bone exhibits a mean raise of about 0.28 cm in the studied contexts (the number of tokens is denoted by n). **Table 3**, presents measurements for the vowel /i/ in plain coronal contexts, we observe a mean larynx elevation of 0.71 cm, while the hyoid bone registers a mean raise of 0.4 cm. **Table 4** provides results for the vowel /u/, showing that the larynx center elevation does not exceed 0.43 cm, and the hyoid bone raises by a mean of 0.29 cm. To evaluate measurement consistency, we calculated the standard deviation (SD) of the articulatory measures (larynx center and hyoid bone elevations) across tokens for each consonantal and vowel context. The SD values ranged between 0.05 and 0.33 cm, indicating a high degree of reliability in the articulatory tracking. Specifically, SDs for the larynx center ranged from 0.05 to 0.27 cm and for the hyoid bone from 0.08 to 0.33 cm.

Table 2. The positions and elevations of the larynx center and the hyoid bone, during the production of the vowel /a/ in the studied plain coronal contexts.

Vowel /a/ in Plain Coronal Contexts	LC Position (cm)	LC Raising (cm)	HB Position (cm)	HB Raising (cm)
/a_1/ in /ma_1za_2l/	5.92	0.24	4.14	0.08
/a_1/	6.10	−0.02	4.65	−0.43
/a_1/	6.13	0.01	3.93	0.29
/a_2/	6.15	0.02	3.92	0.3
/a_2/	6.03	0.14	4.23	−0.01
/a_2/	5.85	0.32	3.69	0.53
/a1/ in /ma$_1$ta$_2$buʃ/	5.98	0.19	3.84	0.38
/a_1/	5.85	0.32	4.18	0.04
/a_1/	5.37	0.80	3.19	0.03
/a_2/	5.47	0.69	3.72	0.5
/a_2/	5.57	0.60	3.54	0.68
/a_2/	5.55	0.61	3.82	0.4
/a_1/ in /$ya_1ga_2sa_3$ /	5.85	0.32	3.92	0.3
/a_1/	5.26	0.90	3.26	0.96
/a_1/	5.58	0.59	3.62	0.6
/a_2/	6.29	−0.12	3.97	0.25
/a_2/	5.68	0.48	4.26	−0.04
/a_2/	5.79	0.37	4.13	0.09
/a_2/	5.72	0.44	4.08	0.14
/a_3/	5.73	0.43	4.09	0.13
/a_3/	5.93	0.23	4.21	0.01
/a_3/	5.83	0.34	4.10	0.12
Mean value, (for n = 22)	**5.80**	**0.36**	**3.93**	**0.28**
SD		**0.27**		**0.33**

Table 3. The positions and elevations of the larynx center and the hyoid bone, during the production of the vowel /i/ in plain coronal contexts.

Vowel /i/	LC Position (cm)	LC Raising (cm)	HB Position (cm)	HB Raising (cm)
/i_1/in /ʃri$_1$ti$_2$/	5.40	0.77	3.70	0.52
/i_1/	5.53	0.64	3.74	0.48
/i_1/	5.26	0.91	3.99	0.23
/i_2/	5.83	0.34	4.04	0.18
/i_2/	5.55	0.62	3.79	0.43
/i_2/	5.51	0.66	3.93	0.29
/i/ in /maʃi/	5.48	0.69	4.63	−0.41
	5.35	0.82	3.44	0.78
	5.52	0.65	3.70	0.52
/i/ in /madania/	5.42	0.75	3.67	0.55
	5.16	1.01	3.62	0.6
	5.51	0.66	3.54	0.68
	5.39	0.78	3.85	0.37
Mean value, (n = 13)	**5.45**	**0.71**	**3.82**	**0.40**
SD		**0.16**		**0.29**

Table 4. The positions and elevations of the larynx center and the hyoid bone, during the production of the vowel /u/ in plain coronal contexts.

Vowel /u/	LC Position (cm)	LC Raising (cm)	HB Position (cm)	HB Raising (cm)
/u/ in /matabuʃ/	6.02	0.15	4.19	0.03
	5.67	0.5	3.84	0.38

Table 4. *Cont.*

Vowel /u/	LC Position (cm)	LC Raising (cm)	HB Position (cm)	HB Raising (cm)
	6.08	0.09	3.83	0.39
/u/ in/makanuʃ/	5.38	0.79	3.34	0.88
	5.60	0.57	4.28	−0.06
	6.37	−0.2	4.17	0.05
/u/ in /hadu/	6.45	−0.28	4.53	−0.31
	5.49	0.68	3.92	0.3
	5.56	0.61	4.00	0.22
/u/ in /huma/	5.57	0.6	4.07	0.15
	5.60	0.57	3.84	0.38
	5.47	0.7	3.33	0.89
	5.88	0.29	3.93	0.29
/u/in /maţaruʃ/	5.57	0.6	3.47	0.75
	5.70	0.47	3.54	0.68
	5.77	0.4	4.09	0.13
	5.64	0.53	4.13	0.09
/u/ in /yum/	5.37	0.8	3.51	0.71
	5.85	0.32	4.07	0.15
	5.76	0.41	4.34	−0.12
Mean value, (n = 20)	**5.74**	**0.43**	**3.92**	**0.29**
SD		**0.05**		**0.33**

When comparing the larynx positions during the production of /a, i, u/ in plain coronal contexts with the guttural contexts, the elevation of the larynx center is more substantial, as indicated by the measurements presented in **Table 5**.

Table 5. The elevations of the larynx center (LC) and the hyoid bone (HB), during the production of the vowels /a, i, u// in guttural contexts (CV and VC sequences), the corresponding formants values and the Pearson coefficient between LC/HB raising and formants.

	LC Raising	HB Raising	F1	F2	F2-F1	F3	F4	F4-F3
/a/in /ʕadaw/	0.71	0.39	664	1784	1120	2640	3867	1227
/a/ in /ba$_1$ʕ/	0.82	0.41	687	1626	939	2454	3748	1294
/a/ in /sa$_2$ʕ/	0.77	0.38	692	1699	1007	2597	3726	1129
/a/ in /lʕaqliya/	0.75	0.42	738	1417	679	2485	3685	1200
/a/ in /lħa$_1$la/	1.54	0.41	723	1769	1046	2709	4042	1333
/a/in /imtiħa$_2$nat/	1.49	0.36	777	1695	918	2621	3720	1099
/a/ in /ħa$_3$ţaha/	1.52	0.39	730	1373	643	2433	3798	1365
/a/ in /ħa$_4$kaha/	1.51	0.38	744	1600	856	2263	3775	1512
a/ in /lbara$_1$ħ/	1.71	0.44	743	1646	903	2249	3913	1664
/a/ in /S^{ʕ}a$_2$ħbu/	0.78	0.96	767	1286	519	2534	3735	1201
/a/ in plain coronal	0.36	0.28	440	1418	978	2566	3794	1228
P (LC /HB rising /Formants) for /a/	**P(LC/HB) = 0.1**		**0.6/0.4**	**0.2/−0.4**		**−0.3/0.0**	**0.4/−0.1**	
/a/ in /maqa$_1$suʃ/	1.31	1.33	680	1297	617	2508	3734	1226
/a/ in /tamaqa$_2$riʃ/	1.01	1.1	745	1332	587	2506	3633	1127
/a/ in /tlaqa$_3$w/	1.12	0.92	711	1203	492	2547	3601	1054
/a/ in /maqa$_4$lhaʃ/	1.52	1.15	694	1434	740	2473	3752	1279
/a/ in /ma$_1$qasuʃ/	0.75	0.57	697	1098	401	2367	3548	1181
/a/ in /tama$_2$qariʃ/	0.67	0.73	721	1200	479	2575	3664	1089
/a/ in /tla$_3$qaw/	1.39	1.12	688	1311	623	2591	3595	1004
/a/ in /ma$_4$qalhaʃ/	0.91	0.69	707	1254	547	2462	3557	1095
/a/ in plain coronal	0.36	0.29	440	1418	978	2566	3794	1228
P (LC /HB /Formants) for /aqa/	**P(LC/HB) = 0.9**		**0.5/0.6**	**0.2/0.1**		**0.0/0.1**	**0.0/0.0**	

Table 5. *Cont.*

	LC Raising	HB Raising	F1	F2	F2-F1	F3	F4	F4-F3
/u/ in /ʃʁul/	0.86	0.96	538	1238	700	2567	3712	1145
/u$_2$/ in /ʕu$_1$qu$_2$ba/	0.93	1.07	514	1240	726	2815	3797	982
/u/ in /sχun/	0.45	0.62	523	1232	709	2606	3589	983
/u$_1$/ in /ʕu$_1$qu$_2$ba/	0.53	0.22	704	1119	415	2631	3735	1104
/u/ in plain coronal	0.43	0.29	460	943	483	2390	3571	1181
P (LC /HB /Formants) for /u/	**P(LC/HB) = 0.7**		**0.0/−0.3**	**0.6/0.7**		**0.6/0.2**	**0.8/0.1**	
/i$_1$/ in /bʁit/	0.78	0.96	477	1735	1258	2661	3652	991
/i$_2$/ in /tʃqi$_{2ha}$/	1.05	1.01	587	1647	1060	2532	3549	1017
/i$_3$/ in /dqina/	0.99	0.89	489	1687	1198	2606	3720	1114
/i$_4$/ in /bɣina/	0.81	0.98	491	1584	1093	2584	3497	913
/i/ in /tarix/	0.81	1.01	614	1583	969	2365	3722	1357
/i/ in /liʕadaw/	0.60	0.4	560	1971	1411	2816	3987	1171
/i/ in plain coronal context	0.71	0.4	357	1929	1572	2834	3714	880
P(LC/HB/Formants) for /i/	**P(LC/HB) = 0.7**		**0.5/0.8**	**−0.4/−0.9**		**−0.3/−0.8**	**−0.2/−0.4**	

The results indicate that when producing the vowel /a/ in the context of /ʕ/ neighboring, there is an elevation of the larynx by 0.35 to 0.46 cm compared to a plain coronal context, while the hyoid bone shows an elevation of 0.1 to 0.14 cm. In the context of /ħ/ neighboring, the larynx center exhibits an elevation ranging from 0.42 to 1.34 cm higher than in a plain coronal context. Similarly, the hyoid bone demonstrates an elevation ranging from 0.36 to 0.96 cm. In /q/ neighboring, the la larynx ranging elevation is from 0.67 cm to 1.52 cm higher than plain coronal context, while the hyoid bone ranging is from 0.57 cm to 1.33 cm.

We conducted a paired t-test between the larynx center (LC) and hyoid bone (HB) measurements to assess the degree of coordinated movement between the two articulators during guttural contexts: for /a/ in pharyngeal context: t(9) = 4.42, $p = 0.0017$ → significant difference between LC and HB. Uvular context: t(7) = 2.24, $p = 0.06$ → not significant at $p < 0.05$, though it shows a trend toward significance. In the pharyngeal context, the larynx center (LC) and hyoid bone (HB) elevations differ significantly, indicating distinct articulatory behaviors. In the uvular context, LC and HB movements are more closely coordinated, with no statistically significant difference between them. The measured paired *t*-test between the larynx center (LC) and hyoid bone (HB) during the production of /i/ is t(5) = −0.50, $p \approx 0.64$. there is no significant difference between larynx center (LC) and hyoid bone (HB) movement in this context their elevations are statistically similar, indicating coordinated movement.

We also report effect-size estimates to quantify the magnitude of the observed articulatory coupling. Converting the Pearson correlations to Cohen's d yields very large effects in uvular contexts (for /a/, $p = 0.90 \rightarrow d \approx 4.13$, $p^2 = 0.81$ very large effect; for /i/ and /u/, $p = 0.70 \rightarrow d \approx 1.96$, $p^2 = 0.49$ large effect), indicating strong coordination between larynx and hyoid elevation. By contrast, pharyngeal contexts show negligible association ($p \approx 0.10 \rightarrow d \approx 0.20$, $p^2 \approx 0.01$ negligible effect). Paired t-tests comparing larynx elevation between guttural and coronal contexts showed a significant difference for /a/: t(7) = 6.70, $p = 0.0003$, $p < 0.001$, confirming that larynx elevation was greater in uvular contexts. In pharyngeal context, (t(9) = 6.57 corresponds to $p < 0.001$.

For the vowel /i/, the larynx ranging elevation is from 0.07 to 0.34 cm higher than plain coronal contexts and the hyoid bone is in the range of 0.49 to 0.61 cm. No significant difference was found (t(3) = −1.52, $p = 0.23$).

For the vowel /u/, the larynx range elevation is from 0.02 to 0.5 higher than plain coronal context and the hyoid bone is in 0 to 0.78 cm. For /u/, the difference did not reach significance (t(5) = −2.08, $p = 0.09$), though a trend toward higher values in the coronal context was observed.

These results indicate that the articulatory contribution of laryngeal elevation varies across vowels, being strongest for /a/, moderate for /u/, and minimal for /i/.

Considering for the vowel /a/ both CV and VC directions, the results show differences in larynx height between anticipatory (CV) and carryover (VC) coarticulation. On average, the larynx is raised by approximately 0.20 cm in

/ħa/ compared to /aħ/, by 0.07 cm in /ʕa/ vs. /aʕ/, and by 0.44 cm in /qa/ vs. /aq/. This indicates that laryngeal elevation is more pronounced in the anticipatory direction, particularly for the uvular /q/, while the pharyngeal contexts show more limited adjustments. Given the small number of tokens per context, each case was examined individually.

4.2. Discusion of the Results

The obtained results regarding the MA uvular and pharyngeal consonants articulation, indicate that both the uvular and pharyngeal consonants in MA require significant larynx elevation during their production. The similarity in the range of larynx elevation for these consonants suggests a common pattern in the articulatory strategies employed to produce guttural sounds in MA.

The larynx gesture for uvular consonants in MA spreads on adjacent vowels in a manner similar to pharyngeal consonants (/q/ and /ħ/); this suggests a consistent articulatory strategy in MA for handling guttural sounds, regardless of whether they are uvular or pharyngeal. We noted that as the larynx center raises, there is a tendency for the hyoid bone to also raise, and the strength of this relationship is moderate to strong during the production of the MA guttural consonants. In the uvular context, the Pearson coefficient calculated for larynx elevation and hyoid bone raising is 0.7 for /i/ and /u/, and 0.9 for /a/. In contrast, in the pharyngeal context, the coefficient is approximately 0.1 (**Table 5**). This coordinated elevation is likely due to the interconnected muscles and structures that control both the larynx and the hyoid bone. The effect-size shows a very large effect in uvular context for /a/ (81%), for /i/ and /u/ (49%). In pharyngeal context show negligible association.

As we have noted, the produced acoustic signal is influenced by the behavior of these active gestures, below we presented the acoustics consequence of changes in laryngeal gesture.

4.3. Vowel Specific Effects

The configuration of the vocal tract during articulation result in specific formant frequencies. Analyzing the frequency modifications of the affected vowels' formants, calculating the variation in the distance between F1 and F2, and between F3 and F4 is a critical step in understanding how articulatory adjustments influence vowel acoustics. **Table 5** shows the changes in formant frequencies and formant distance for the vowels in different guttural contexts. We calculated Pearson correlation coefficients between the formants values and larynx elevation. Below we summarise the effect that different contexts have on each vowel.

Vowel /a/ in /q/ Neighboring: the most significant changes are the decrease in F2 and the increase in F1. F3 decreases slightly, and F4 also shows a decrease. The differences range in F2-F1 between uvular contexts and plain coronal contexts is from 238 Hz to 577Hz suggest a strong coarticulatory effect exerted by the uvular consonants on the vowel /a/. F4-F3, decreases by 100 Hz to 200 Hz in most cases. The correlation coefficient for F1 and F2 with larynx elevation in /q/ neighboring (P = 0.5 and P = 0.2 respectively). We convert Pearson correlation into its effect size (Cohen's d): The correlation between larynx elevation and F1 was moderately strong (P = 0.5, d = 1.16), indicating a large effect size. The relationship with F2 was weaker (P = 0.2, d = 0.41), while no association was found for F3 or F4 (P = 0.0, d = 0.00).

/a/ in pharyngeal neighboring: There is a correlation between the elevation of the larynx and the increasing of F1 (P = 0.6), indicating that F1 increases significantly with the larynx's rise during the production of vowels /a/. Regarding F2, its correlation with larynx elevation is approximately P = 0.2, indicating a weaker relationship compared to F1. Notably, the distance between F2 and F1 expands ranging from approximately 29 to 142 Hz for three cases, and contracts for the remaining cases by about 39 to 335 Hz. In the case of the sequence /Sˤaħbu/.The distance between F4-F3 increases in pharyngeal neighboring contexts for four tokens by about 66 Hz to 436 Hz, and remain close the plain coronal context for the other tokens. The correlation analysis revealed a moderate to strong relationship between larynx elevation and F1 (P = 0.6, d = 1.50), suggesting that vertical laryngeal movement substantially affects the first formant frequency. The relationship with F2 was weaker (P = 0.2, d = 0.41), while F3 showed a modest negative correlation (P = −0.3, d = −0.63). The correlation between larynx elevation and F4 was moderate to strong (P = 0.4, d = 0.87). Despite the limited token count (n = 10), these effect sizes indicate notable articulatory–acoustic coupling patterns. These findings indicate that while F1 behaves similarly in uvular and pharyngeal neighboring contexts for the vowel /a/ (with a rise in frequency), F2 exhibits a more significant decrease in uvular neighboring compared to pharyngeal neighboring.

/i/ in uvular neighboring: Likewise for /i/, F1 increases over 100 Hz in uvular contexts and F2 drops considerably by over 200 Hz. F2-F1 decreases by 300 to 600 Hz. F4-F3 increases in uvular contexts by 33 Hz to 477 Hz. The obtained Pearson coefficient for F1 ($P = 0.5$) is similar to that of the vowel /a/. These findings suggest that for the vowel /i/ in uvular neighboring, F1 increases notably while F2 decreases significantly as the larynx rises. This observation aligns with the broader pattern seen in uvular neighboring contexts, where there is a coarticulatory effect on both F1 and F2 for the two vowels. The strength and direction of the relationship between larynx elevation and formant frequencies varied across formants. The correlation with F1 was positive and strong ($P = 0.5$, d = 1.15), while negative associations were found with F2 ($P = -0.4$, d = −0.87), F3 ($P = -0.3$, d = −0.63), and F4 ($P = -0.2$, d = −0.41). These results indicate that as the larynx rises, F1 tends to increase, whereas higher formants (F2–F4) tend to decrease, reflecting differential acoustic consequences of laryngeal elevation.

Vowel /u/ in uvular neighboring: In contrast to the vowels /a/ and /i/, the distance F2-F1 for /u/ undergoes an increase in uvular contexts, specifically by approximately 243 Hz compared to plain coronal contexts. Notably, there is no correlation between the elevation of the larynx and the increase in F1; however, F2, F3, and F4 exhibit a significant correlation (P = 0.6 and 0.8). Additionally, the F4-F3 interval experiences a considerable decrease by 36 Hz to 199 Hz. An exception is noted in the context /ʕuq/, where the F2-F1 distance decreases by about 62 Hz. This variation is attributed to the influence of the pharyngeal sound /ʕ/, suggesting a potential dominance of the pharyngeal /ʕ/ effect over that of /q/. The vowel /u/ in /ʕuq/ context, F1 exhibits a behavior similar to that of the vowels /a/ and /i/ in pharyngeal neighboring. It increases by about 200 Hz as the larynx center rises beyond 0.8 cm. F2 shows a similar pattern as well, with an increase of about 150 Hz in pharyngeal neighboring. These findings reveal that, for the vowel /u/ in uvular neighboring, there is an elevation for F1 with larynx elevation. Notably, unlike the other vowels, F2 remains relatively stable, indicating a less pronounced effect of uvular neighboring on F2 for the vowel /u/. The correlation between larynx elevation and formant frequencies varied in strength. No association was observed for F1 ($P = 0.0$, d = 0.00). In contrast, correlations with F2 and F3 were strong ($P = 0.6$, d = 1.50), and the association with F4 was particularly strong ($P = 0.8$, d = 2.67), suggesting a robust articulatory–acoustic coupling for higher formants.

The figures below illustrate how F2-F1 values change in response to larynx elevation; the variation of F2-F1 (coordinate axis on Hz) according to the elevation of the larynx (abscissa axis on cm, the larynx center in the rest position is at about 6.17 cm from the reference point). In plain coronal contexts, F2-F1 values are represented in green. We have added a horizontal line passing through this point to visually indicate which simples have F2-F1 values below and above those observed in plain coronal contexts. So, **Figures 5–8** plot the acoustic measure F2-F1 (Hz) against vertical displacement (cm) of the larynx center (LC) or hyoid bone (HB)**.** For each figure we describe visible clusters and ranges, tokens that deviate from the main pattern (outliers), and likely interpretations in terms of coarticulation and articulatory interaction.

The **Figure 5** shows that in the context of /ħ/, 5/6 of the tokens have F2-F1 lower than F2-F1 in plain coronal contexts with the larynx elevation upper to 1cm. for /ʕ/, 1/3 of the tokens have F2-F1 lower relative to plain coronal contexts with the larynx elevation lower to 0.8 cm. the effect of the voiceless /ħ/ is more pronounced compared to the voiced /ʕ/. The tokens cluster near LC ≈ 1.5 cm for /ħ/, one token does not follow this pattern and 0.8 cm for the voiced consonant /ʕ/.

The **Figure 6** illustrates the acoustic behavior of the vowel /a/ in /q/ neighboring compared to plain coronal contexts. We noticed that all tokens have F2-F1 lower than that in plain coronal contexts (red line) with larynx elevation upper to 0.7 cm. This reveals a strong effect of /q/ on the adjacent vowel /a/. LC values spread from 0.6 to 1.6 cm. The **Figure 6** shows also that F2-F1 for the vowel /i/, has a similar variation as for the vowel /a/. All the tokens have F2-F1 lower than that of plain coronal contexts (blue line), the larynx elevation is upper to 0.7 cm.Thus, the uvular consonants exert a strong coarticulatory effect on F1 and F2, leading to a narrowing of the distance between F2-F1. This effect is more pronounced for some consonants, such as /ħ/, and /q, x/ on the vowels /a/ and /i/. LC values are distributed between 0.75 and 1.05 cm, clustering near ~1.0 cm. For the vowel /u/, the tokens have F2-F1 upper than that in plain coronal context (yellow line) except for the context /ʕuq/ which has an F2-F1 lower relative to plain coronal context, with the larynx elevation lower than 0.53 cm. The vowel /u/ is less influenced by uvular contexts compared to /a/ and /i/. LC values span 0.3–0.9 cm. Having noted a correlation between larynx elevation and the hyoid bone, the figures below chow the acoustic results relative to the hyoid bone elevation.

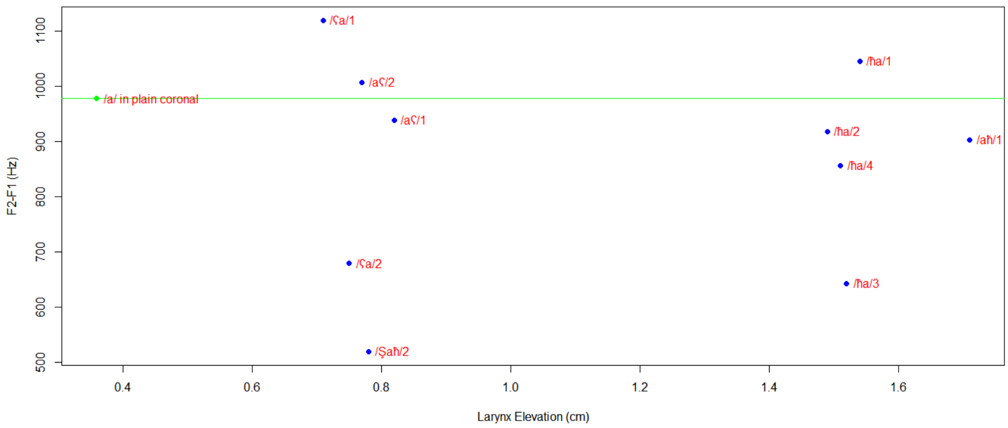

Figure 5. F2-F1 variation according to larynx center elevation for the vowel /a/ in pharyngeal neighboring.

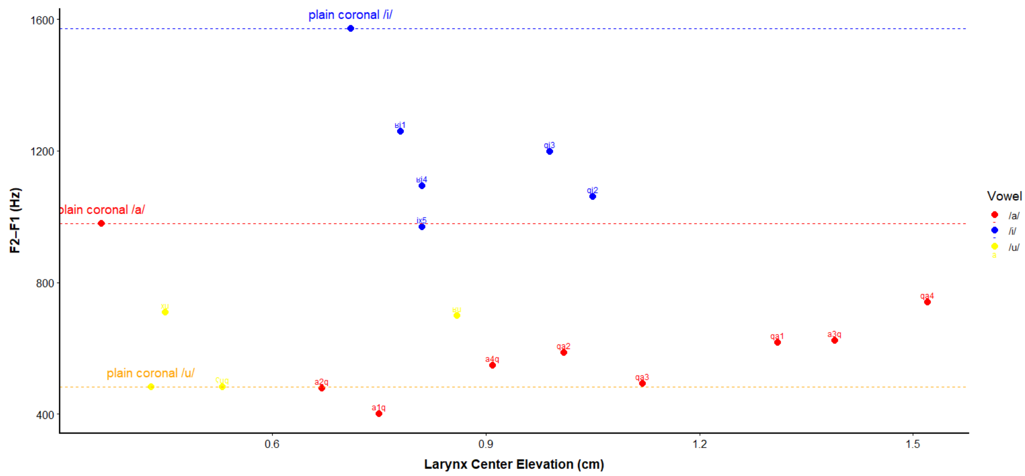

Figure 6. F2-F1 variation according to larynx center elevation for the vowels /a, i, u/ in uvular neighboring.

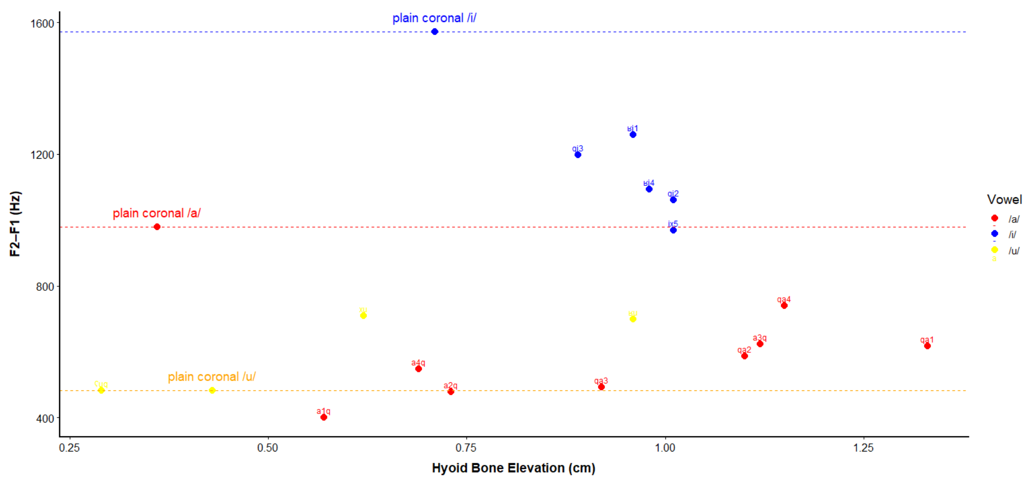

Figure 7. F2-F1 variation according to hyoid bone elevation for the vowels /a, i, u/ in uvular neighboring.

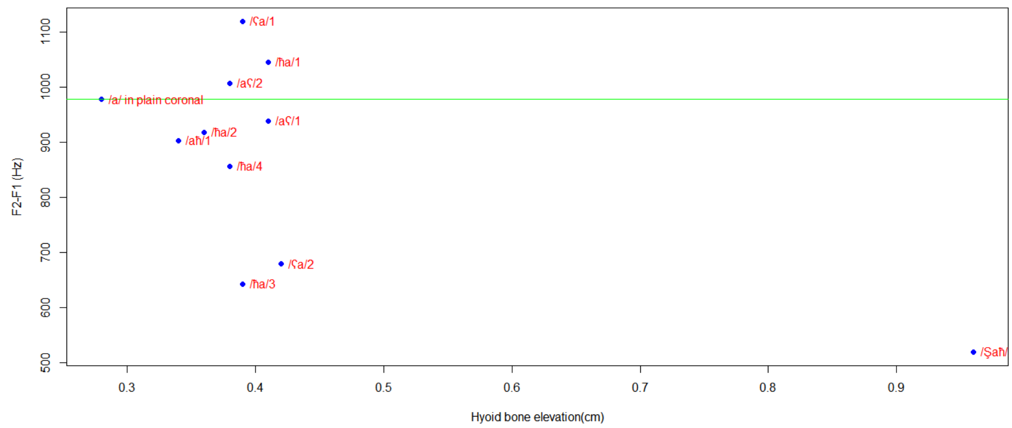

Figure 8. F2-F1 variation according to the hyoid bone elevation for the vowel /a/ in pharyngeal neighboring.

The hyoid data for /a/ in pharyngeal contexts show a similar pattern to LC, with a cluster around HB ≈ 0.4 cm.

HB values distribute across 0.5–1.35 cm, mirroring the LC distribution for /q/. Acoustic reduction in F2-F1 occurs across this HB range.

HB values for /i/ cluster around ~1.0 cm, similar to LC clustering. All tokens show reduced F2-F1 relative to plain coronal contexts.

HB distributions mirror the LC pattern for /u/. The /ʕuq/ outlier is at HB ≈ 0.6 cm. Most tokens lie above the plain coronal baseline.

The variation in F2-F1 corresponding to the elevation of the hyoid bone for the three vowels displays a similar pattern to that observed with the elevation of the larynx center. This reaffirms the coordination of movement between these two articulators, as previously indicated and underscores their acoustic effects.

4.4. Discussion of the Acoustic Results

The data suggests that the influence of uvular contexts on F1 and F2 is less significant for /u/ compared to /a/ and /i/. As the larynx raises during uvular neighboring, F2-F1 decreases for /a/ and /i/, but interestingly, it increases for /u/. Moreover, F4-F3 increases for /a/ and /i/, this effect contrasts with the general trend observed in lowered larynx conditions, while for /u/, the decrease in F4-F3 is noted. These findings indicate that for the vowel /u/ in pharyngeal /ʕ/ neighboring, there is a notable increase in both F1 and F2 as the larynx raises. This observation aligns with the broader pattern seen in pharyngeal neighboring contexts, where there is a coarticulatory effect on both F1 and F2 for vowels.

From these results, we reported that the uvular consonants exert a strong effect on F1 and F2 for the vowels /a/ and /i/, for /u/ the effect is less marked.

For the acoustic parameters, in pharyngeal contexts, F1 remains nearly identical between directions (7–47 Hz difference), while F2 varies between 85 Hz and 158 Hz, and F3-F4 fluctuate up to 150 Hz and 140 Hz, respectively. In the uvular context, F1 again shows minimal directional difference (≤26 Hz), whereas F2 varies substantially (100–199 Hz), with similar fluctuations for F3 and F4 (≈100 Hz). These results suggest that laryngeal and acoustic coarticulation effects are stronger in uvular than pharyngeal contexts, especially in the anticipatory direction.

The articulatory and acoustic findings together show that laryngeal height plays a role in shaping the acoustic realization of guttural contexts in MA. Uvular consonants show the largest laryngeal elevation (≈1.2 cm) and the most pronounced acoustic impact particularly reductions in F2-F1 for /a/ and /i/. Pharyngeals, while also involving laryngeal raising, exert somewhat milder effects, consistent with their lower constriction zone. For /a/ in / $S^ʕ$ aħbu/ context, the decrease is particularly pronounced at around 459 Hz, potentially attributed to the substantial impact of the pharyngealized consonant /$S^ʕ$/, as S. Ghazeli [10] suggested that emphatics caused lower F2 values in following vowels /i/ and /a/ [10]. Regarding the CV context, the larynx adjusts earlier in preparation for the guttural, leading to higher elevation and stronger spectral shifts in CV sequences. Importantly, the observed laryngeal displacements (0.17–0.61 cm) fall within the perceptually relevant range identified by R. Janssen et al. [12], who showed that even small vertical shifts (≈0.2–0.4 cm) can measurably alter vowel formants, though active articulator control tends to preserve vowel identity. The fact that the recorded changes in F2–F1 reach up to 500–600 Hz supports Janssen's finding that laryngeal height variation interacts dynamically with other articulators, rather than acting in isolation. Finally, the differential pattern for /u/ where F2-F1 increases with larynx elevation suggests gesture antagonism refers to competing or opposing movements of the speech organs: the high back tongue position of /u/ resists further constriction in the pharyngeal area, moderating the acoustic consequences of laryngeal raising. This difference is attributed to the antagonism between the gestures of the vowels and those of the uvular consonants; the vowel /u/ is characterized as a back, high, rounded vowel, involving the elevation of the back of the tongue towards the velum. This articulation aligns with the uvular gesture, where the back of the tongue is also prominently involved. Uvular consonants are characterized by a rising of the larynx, as noted previously. This laryngeal gesture stands in opposition to the laryngeal behavior associated with vowel production. In the case of the vowel /u/, which engages the back of the tongue, and uvular consonants, which involve a raised larynx and a raised hyoid bone, these articulators are interconnected through muscles, ensuring coordinated movement. In contrast, the open /a/ and front /i/ are more flexible, allowing stronger coupling between vertical laryngeal motion and formant shifts. Visual inspection of **Figures 5–8** shows clear clustering patterns. Tokens with higher larynx elevations (>0.8 cm) tend to exhibit lower F2-F1 values for /a/ and /i/, reflecting stronger coarticulatory influence of guttural consonants. In contrast, tokens in pharyngeal contexts cluster closer to the plain coronal range. A few outliers were observed for instance, the token /ʕuq/ for /u/ likely results from pharyngeal dominance and the context /Saħbu/ for /a/ which display atypical F2-F1 relationships likely due to the influence of adjacent emphatic or pharyngealized sounds. Despite minor variability, the overall trend indicates a consistent coupling between laryngeal elevation and spectral change. The consistency of the HB cluster with the LC distribution in uvular contexts further supports coordinated suprahyoid–laryngeal activity underlying the acoustic effect. suggesting a motor synergy rather than an isolated laryngeal adjustment.

The present findings can be interpreted within the framework of Articulatory Phonology [3], which conceptualizes speech as the coordination of overlapping articulatory gestures rather than discrete segmental units. The observed anticipatory coarticulation, particularly evident in uvular contexts, suggests an asymmetric temporal overlap between consonantal and vocalic gestures. This supports the view that guttural consonants initiate early activation of laryngeal and tongue root gestures that extend into the vowel domain, consistent with gestural coupling and articulatory inertia models [29]. The relatively smaller carryover effects indicate that recovery from these gestures is faster, possibly reflecting biomechanical constraints of laryngeal raising.

Although the present study provides detailed articulatory and acoustic observations on the production of guttural consonants in Moroccan Arabic, limitations must be acknowledged. First, the data were obtained from a single male speaker of the MA. Consequently, the results cannot be generalized to all speakers or dialects of Arabic. Dialectal variation is well documented in Arabic phonetics, especially concerning guttural articulation such as differences in the degree of constriction, tongue root advancement, or laryngeal raising across Arabic dialect varieties. Future work should include multiple speakers representing different regional and social backgrounds to evaluate the consistency of the observed articulatory patterns. Since coarticulatory and laryngeal gestures can vary with speech rate, prosodic position, and surrounding segmental context, future studies should explore a broader range of speaking conditions to determine the stability of these effects in more natural speech. Finally, the present analysis was based on 2D lateral X-ray imaging (40 fps), which provides excellent temporal resolution but limited spatial coverage. This method cannot capture three-dimensional articulatory movements. Complementary imaging techniques such as real-time MRI could provide more complete information about tongue root and pharyngeal wall movement, allowing for more precise modeling of the articulatory mechanisms involved in guttural production.

5. Conclusions

Our study identified that Moroccan Arabic uvular and pharyngeal consonants are produced with a significant elevation of the larynx and hyoid bone compared to plain coronal consonants. We observed anticipatory larynx movements during the production of vowels followed by guttural sounds (as in /aħ/, /aq/) and noted also that when these consonants precede vowels (as in /ħa/, /qa/) the larynx remains raised, although not as high as during the production of the consonants. We concluded that the vertical movement of the larynx during the production of guttural consonants results in coarticulatory spread to adjacent vowels. This suggests that the larynx's position and movement play a crucial role in shaping vowel articulation in Moroccan Arabic.

In the following, a summary of the highlighted points regarding the correlation between larynx height and acoustic effects in the context of guttural articulation:

1. Correlation with Larynx Height: We have pointed out that the height of the larynx correlates with the extent of acoustic effects on adjacent vowels; a higher position of the larynx corresponds to a closer distance between F2-F1, indicating a stronger coarticulatory effect of the consonant on the adjacent vowel. Conversely, when the larynx is lower, F2-F1 increases, reflecting a reduced coarticulatory effect.
2. Formants Affected: We have noted that F1 and F2 are the formants most affected by laryngeal raising for the vowels /a, i, u/. Furthermore, we have observed that the effects of voiceless consonants are more pronounced than those of voiced consonants.
3. Similarity between Uvular and Pharyngeal Contexts: This similarity likely arises because both pharyngeal and uvular consonants have primary places of articulation in the pharynx region of the vocal tract, with pharyngeal consonants produced near the midpoint and uvular consonants at the top of this region.
4. F4-F3 Distance: the distance between F4-F3 increases in pharyngeal neighboring for /a, i, u/, and F4-F3 is decreased by the uvular context for the vowel /u/.
5. Variability in Guttural Spread: the vowels are not affected in the same way by the adjacent uvular consonants. The effect of uvular contexts on the vowel /u/ is less pronounced compared to /a/ and /i/.

The present study is constrained by its reliance on data from a single speaker. To generalize our findings and draw broader conclusions regarding the articulatory and acoustic effects of guttural sounds on adjacent vowels, we emphasize the significance of future research that incorporates data from multiple speakers and more considering variations in age and gender using MRI imaging, in consideration of the potential harm posed by long exposure to X-rays for the human subject.

Author Contributions

F.K. conceived the theoretical framework, processed the experimental data, performed the measurements and analysis, and prepared the manuscript. R.D. and A.D. supervised the research, provided critical discussion of the results, and contributed to the final revision of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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