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Elgendy, A.M.; Pols, L.C.W.

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MECHANICAL VERSUS PERCEPTUAL CONSTRAINTS AS DETERMINANTS OF ARTICULATORY STRATEGY¹

Ahmed M. Elgendy and Louis C.W. Pols

Abstract

This paper summarizes the results of a series of experiments conducted to investigate various aspects of normal pharyngeal articulation and the nature of pharyngeal coarticulation. Video fiberoptic imaging, electromagnetography and acoustic analysis techniques were used to obtain empirical and quantitative data on the use of the pharynx in speech production. The overall results suggest that mechanical constraints determine to a great extent the articulatory strategy used by the speaker to achieve the perceptual/acoustic contrast essential for the process of speech encoding.

1 Introduction

Pharyngeal consonants have always been described as phonetically complex speech sounds, however, hardly any data verifying or explaining this claim can be found in the literature (cf. Elgendy 1982). Speech scientists and linguists dealing with articulatory modeling take for granted that the production of pharyngeal consonants is mainly attained by retracting the tongue root into the pharyngeal cavity. This phonetic description seems to be inadequate to explain the observations which motivated our study. From an anatomical viewpoint, pharyngeal activities, i.e., contraction of pharyngeal muscles at various points, certainly affect the state of several other articulators. Therefore, it is important to study the use of the pharynx in speech production, specially its dynamic aspects, since the pharynx constitutes more than half of the vocal tract length.

Numerous research questions were posited to motivate the current study which has resulted in a recently published Ph.D. thesis of the first author (Elgendy 2001). Some of these questions are:

- What is the connection, indicated by several phonological observations, between laryngeal, pharyngeal and nasal articulations?
- Why pharyngeal articulation is used as a substitute by cleft palate patients whose native language lacks pharyngeal sounds, e.g., English, Japanese and Swedish?

¹ Originally published in Proceedings of Eurospeech 2001. For more details see [4].

- Why pharyngeal consonants are rarely used in the sound inventories of the world languages?
- Why non-native speakers, when mimicking Arabic words, apparently have difficulty in producing intelligible pharyngeal consonants.
- Why native children take longer time to acquire the production of pharyngeal consonants compared to oral consonants?
- Why the jaw is open, a typical feature for vowels, during pharyngeal consonants as seen in published X-ray pictures? (cf. Elgendy 1982).

There are several observations which indicate that pharyngeal consonants are mechanically complex phonemes. During speech production, the complex muscular activities of the vocal tract organs are executed as a limited number of independently controllable articulatory gestures. Irrespective of their mechanical complexity they are temporally organized and coordinated in such a way to achieve sufficient perceptual contrast in order to contribute to the accessibility of the intended linguistic message. One of the main questions, crucial to our study, discusses the effect of the mechanical factors on shaping the structure of language. If the mechanical constraints and the acoustic consequences resulting from articulators movements are severe on a given class of consonants, then what is the articulatory strategy used by the speaker to achieve and retain the essential perceptual contrast among various segments in a sequence containing a pharyngeal consonant?

2 Method

In order to define pharyngeal coarticulation, we collected data on articulatory dynamics for Egyptian Arabic. We examined the movement patterns of various articulators and their acoustic consequences during the production of pharyngeal consonants. We used several methods to obtain empirical data on the use of the pharynx in speech production and to study the coarticulatory effect due to the presence of a pharyngeal consonant in a variety of phonetic contexts.

Video fiberoptic technique was used to collect the data on the dynamics of the pharyngeal wall, the velum, the epiglottis and the larynx (Elgendy 1985). For an example see Figure 1.

Jaw kinematics during pharyngeal consonant production was registered by using electromagnetography (Elgendy 1985 and 1999; see Figure 2 for an example of some results on jaw height). Acoustic analysis comprises the calculation of LPC spectra, formant amplitude, fundamental frequency values, and phoneme duration (For an example of some results on vowel duration, see Figure 3). These acoustic analyses were performed on the same set of words used as in the experiments studying articulatory movements. The purpose for conducting acoustic measurements was to examine to which extent the articulatory gestures associated with the production of utterances containing pharyngeal consonants are manifested in the acoustic signals.

We also investigated the process of acquisition of pharyngeal articulation by native and non-native speakers. In addition, we examined the phonotactics patterns governing pharyngeal consonant distribution (Elgendy 2001 and 1993).

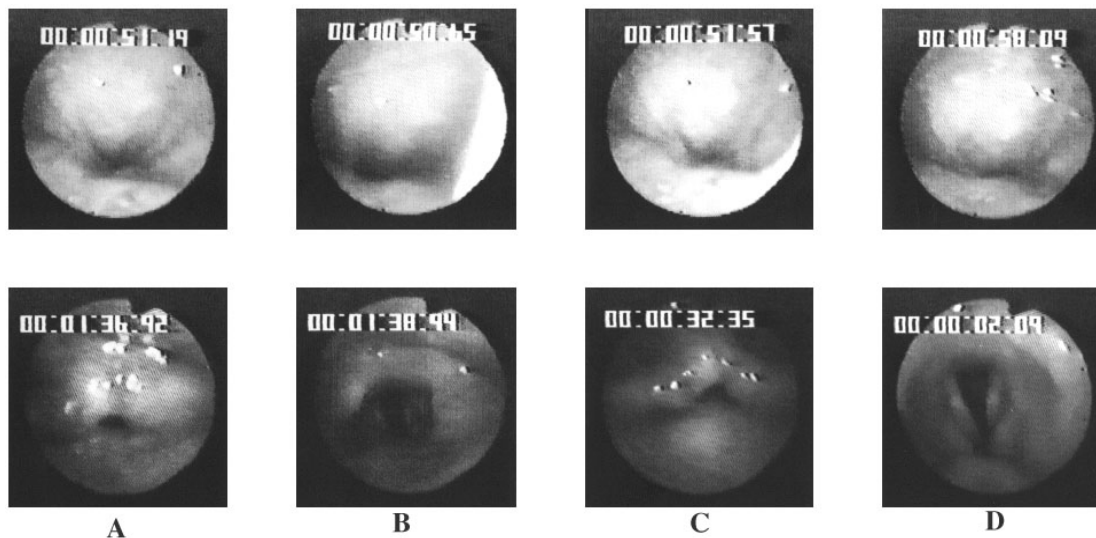


Figure 1. The shape of the velopharyngeal port (top row) and the shape of the laryngeal inlet (bottom row) during: (A) /ʕ/; (B) /ħ/; (C) /ħ/; (D) /ʔ/ as uttered by an Arabic male speaker. The two shapes represent the same moment of time as determined acoustically on the sound spectrogram.

3 Results

Data collected using fiberoptic monitoring of the top view of the pharynx at various points, revealed that the production of the pharyngeal consonants is characterized by a complex mechanism. This mechanism involves the control of coordinated activities of pharyngeal wall contraction, epiglottis bending and larynx raising and constriction. In addition, the velum was observed to be lowered, indicating a noticeable degree of nasality, during the production of pharyngeal consonants even in the non-nasal contexts. The reduction in size of the velopharyngeal port is achieved by a sphinctric contraction of the upper pharyngeal constrictor muscles while the laryngeal constriction under the bending epiglottis is achieved by the approximation of the arytenoids during the pharyngeal consonants /ʕ/, /ħ/ (see Figure 1).

Data on jaw kinematics obtained by means of electromagnetic coil registrations of the lips and the mandible excursions suggested that the coarticulatory effects resulting from the complexity of the pharyngeal consonant cause the jaw and the tongue to undergo certain mechanical constraints. Jaw displacement associated with pharyngeal consonant production was found to be considerably larger, especially for the lower pharyngeal consonants /ʕ, ħ/ compared to, for instance, oral consonants in the same vowel context. Figure 2 shows the inherent jaw height for each of the Arabic consonants in the environments /Cæ/ and /æCæ/ for initial and intermediate positions.

The complexity of pharyngeal articulation has a delaying effect on the anticipation of the production of the phonetic segment(s) following the pharyngeal consonant. That is, the synergy involved in controlling the production of the pharyngeal consonant restricts the jaw and other articulators to anticipate the articulation of the upcoming segments until the associated motor commands for the pharyngeal consonant are fully executed (cf. Elgendy 1985 and 1999).

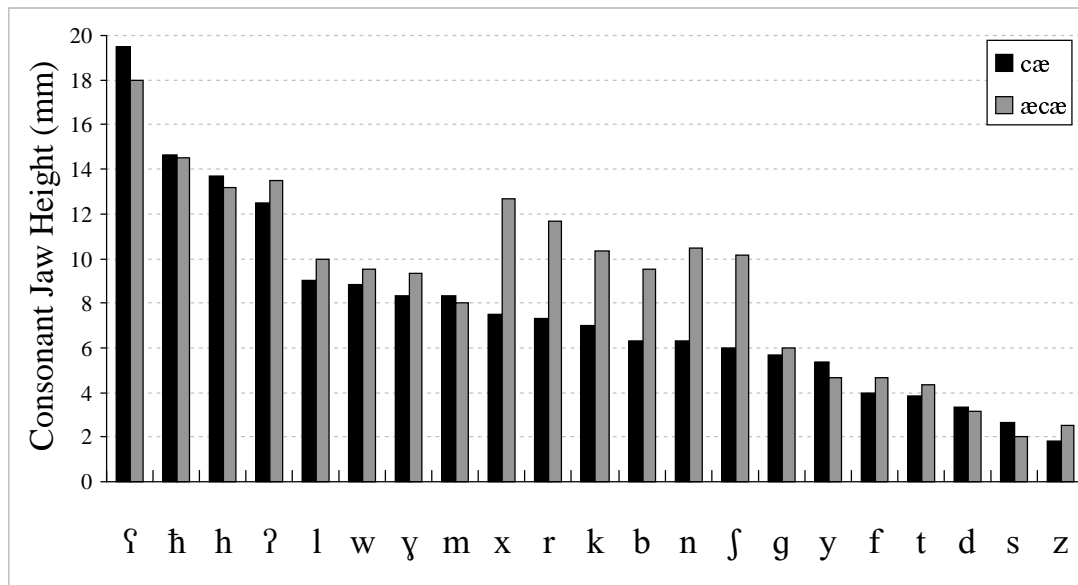


Figure 2. Inherent jaw height for each of the Arabic consonants in the environments /Ca/ and /aCa/ for initial and intermediate positions. The values of jaw height are plotted based on a descending order of the consonant in the initial position. The data are averaged over four repetitions of each test item for one Arabic male speaker.

Acoustic measurements revealed that the mechanical effect is mainly realized as a temporal re-organization of the syllable(s) within the Arabic word. Figure 3 represents the duration in ms of the short vowel /æ/ following /ʔ/ in initial position or preceding /ʔ/ in medial or final position in bisyllabic words. This shortening effect of the pharyngeal consonant, particularly on the following long back vowel, was found to be highly significant.

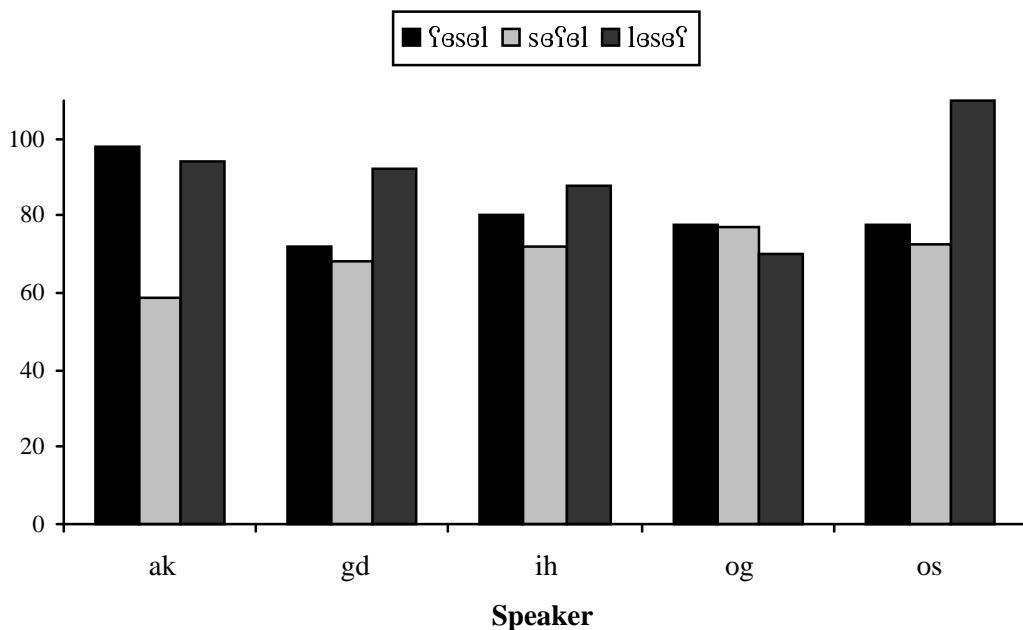


Figure 3. Duration in ms of the short vowel /a/ following /ʔ/ in initial position, or preceding /ʔ/ in medial or final position in bisyllabic C₁aC₂aC₃ words. The data are averaged over five repetitions for each of the five speakers indicated.

We also compared the effect of the position of the pharyngeal consonant in the word with that of other consonant types. As an example, see Figure 4 which shows a comparison between the effect of the pharyngeal consonant /ʕ/ as well as the lateral consonant /l/ on the long vowel duration in the context of the velar stop consonant /g/. It can be seen in that figure that this effect is reversed in the case of the lateral /l/. That is, the /ʕ/ in initial position causes the vowel duration to be longer than when /ʕ/ occurs in final position while the lateral /l/ in initial position shortens the vowel duration compared to that when /l/ occurs in final position. By comparing figures 3 and 5, the preference of pharyngeal consonants to occur in initial or final position rather than in medial position (Figure 3) can be seen as reflected on the distribution patterns of the overall consonants inventory (Figure 5).

These findings suggest that the compensatory effect on the vowel duration required to preserve a unitary syllable length (a characteristic prosodic feature in Arabic) is achieved by the jaw. Accordingly, we suggest that the jaw is used to control the temporal aspect of syllable structure and it should be incorporated in any articulatory model of speech. Our results revealed that pharyngeal consonants are distinguished by being subjected to severe bio-mechanical constraints which cause a considerable amount of temporal perturbation on the speech utterance.

Moreover, we found that the co-occurrence restrictions governing the Arabic phonotactics rules are based on a hierarchical ranking order depending on the inherent degree of consonant's jaw height. Accordingly, we classified the consonants in Arabic into three distinct categories, i.e., high, central and low.

We further suggested that the mandible accommodates the position of the pharyngeal consonant in order to preserve the temporal pattern organizing word structure. We found that the vowel adapts the jaw position assigned to the pharyngeal consonant in medial position and not in initial or final position. That the jaw accommodates the pharyngeal consonant position, and not the vowel position, suggests that the temporal pattern governing the syllable(s) is controlled by the jaw. The way this requirement is fulfilled depends significantly on the choice of compatible consonants in the vicinity of a pharyngeal consonant in terms of jaw opening associated with the consonantal composite. The duration of the vowel adjacent to the pharyngeal consonant seems to have a compensatory interrelationship with other phonemes in the word as a function of the overall distance the jaw has to travel between various levels along the utterance. The target is to preserve a certain temporal pattern among syllables.

Our results showed that the jaw opening for pharyngeal consonants is greater than for low back vowels and that the extreme jaw lowering associated with pharyngeal consonant production is a result of biomechanical constraints and should not be seen as a coarticulatory effect induced on the consonant from the preceding or following low vowel as suggested by Keating et al (1994).

The complexity of pharyngeal consonant production seems to be due to several coordinated movements of various articulators. Mechanical constraints on the jaw movement owing to pharyngeal articulation are significantly affecting the structure of the Arabic language, both at the prosodic and the segmental level. This, considerably influences the phonotactics of the word structure of Arabic. Moreover, we found that the frequency of occurrence of pharyngeal consonants in Arabic is high, although they are rarely used in the languages of the world. Figure 5 shows the percentage of the frequency of occurrence of all initial, medial and final consonants in the Arabic

$C_1\text{æ}C_2C_3$ words. Figure 6 shows the ratio of consonant distribution among the three main categories as classified in our study.

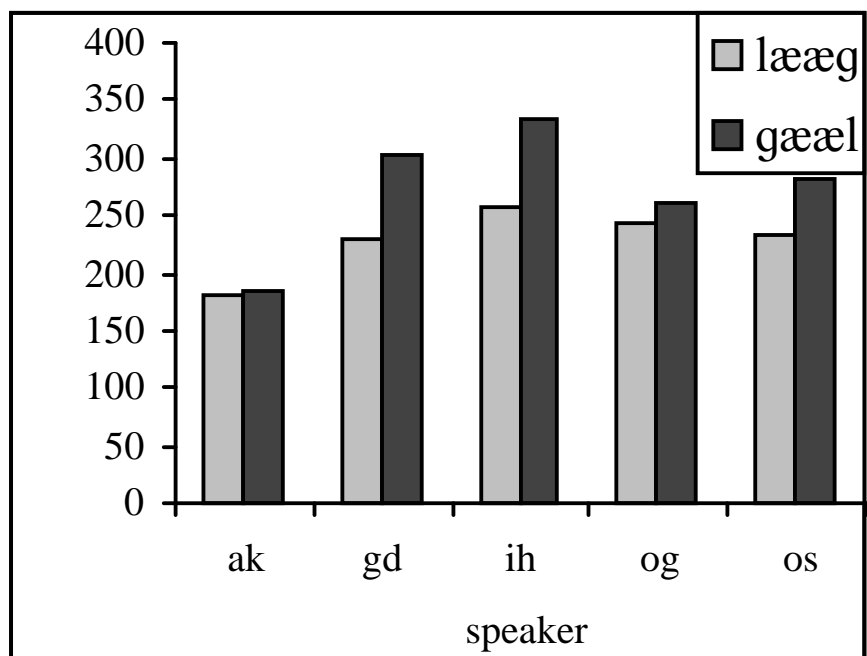
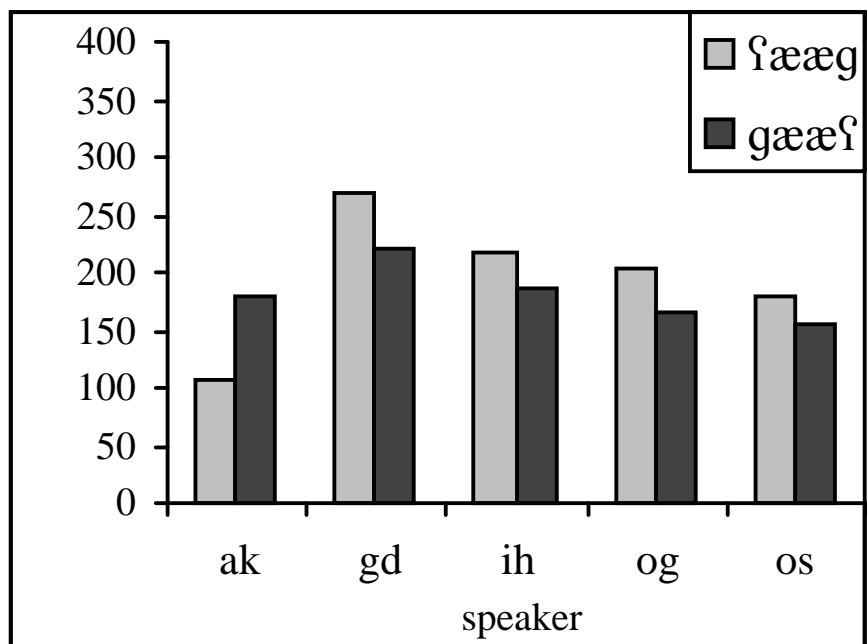


Figure 4. The effect of the position of the pharyngeal consonant /ʕ/ and the lateral /l/ on the long vowel /æ/ duration in the context of the velar stop /g/ in $/C_1\text{æ}C_2/$ words. The data are averaged over five repetitions for each of five male Arabic speakers indicated.

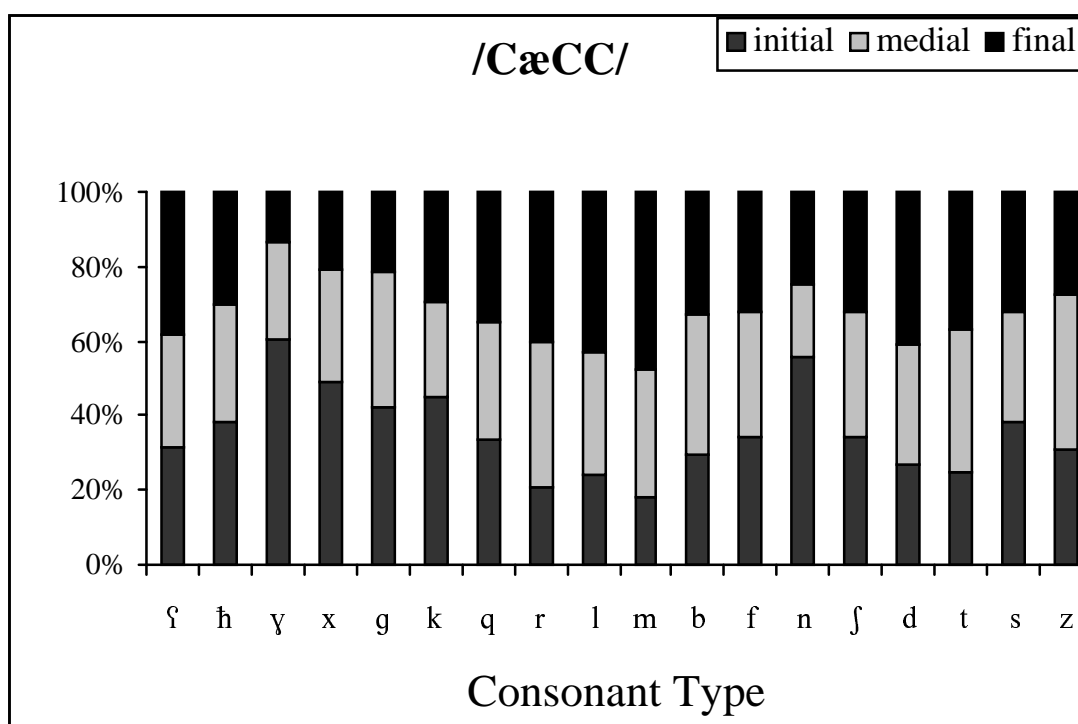


Figure 5. Percentage of the frequency of occurrence of all initial, medial and final consonants in C₁C₂C₃ words.

The physiological constraints affecting segments involving the pharynx in their production, have a severe impact on the overall distribution patterns. Our results did point out the predominant effect the biomechanical factor has over the acoustical/perceptual factors on the observed phonotactics patterns. McCarthy (1994) and Goldstein (1994) proposed to ascribe the “place feature” [pharyngeal] to the set of guttural consonants as a natural class. Their proposal presupposes that the members of this set, i.e., laryngeals, pharyngeals, uvulars and velars, should have in common certain physical basis. As our results revealed (Elgendy 2001), no evidence was found to show that these consonants share certain physical basis.

Both McCarthy’s and Goldstein’s proposals are expressed within the framework of the distinctive feature theory (Jakobson et al, 1952). Distinctive feature theory is based on *active* involvement of articulators during speech production. This theory has defined *place* features in terms of the “active articulator” participating in shaping the vocal tract for a given phoneme. For instance, the feature [labial] for the lips, [coronal] for the tongue tip or blade, [dorsal] for tongue body and [pharyngeal] for gutturals, etc. The aroused conflict regarding the guttural group of consonants stems from the fact that there are several different active articulators involved in the production of gutturals.

The laryngeals involve only the glottis, the pharyngeals involve coordinated activities of the larynx, the epiglottis, the pharyngeal wall and the jaw, while the uvulars involve the body of the tongue and its root (cf. Elgendy 2001).

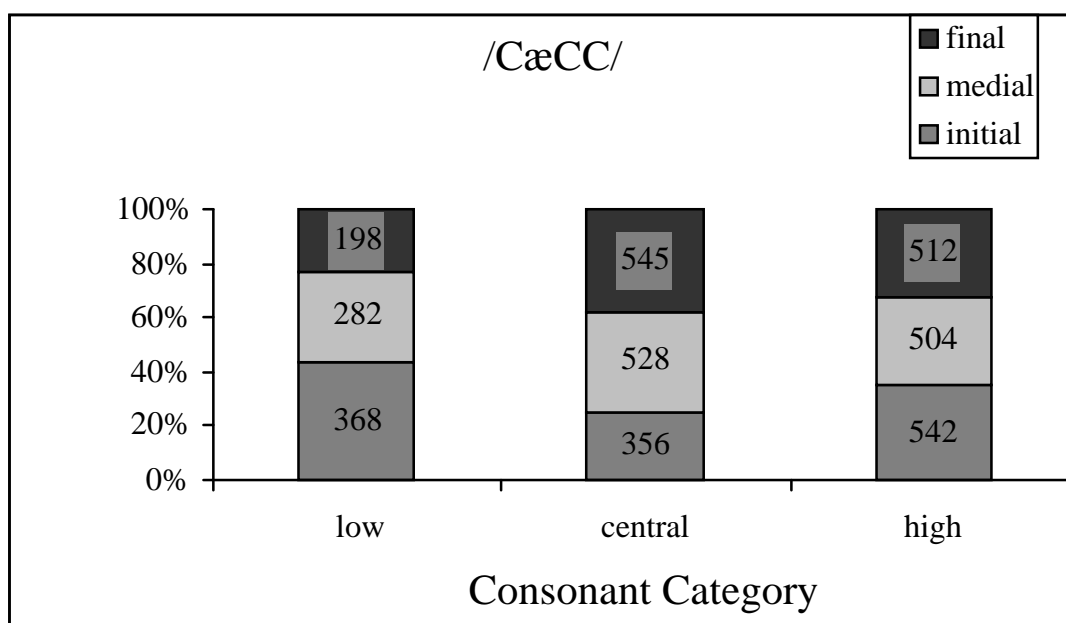
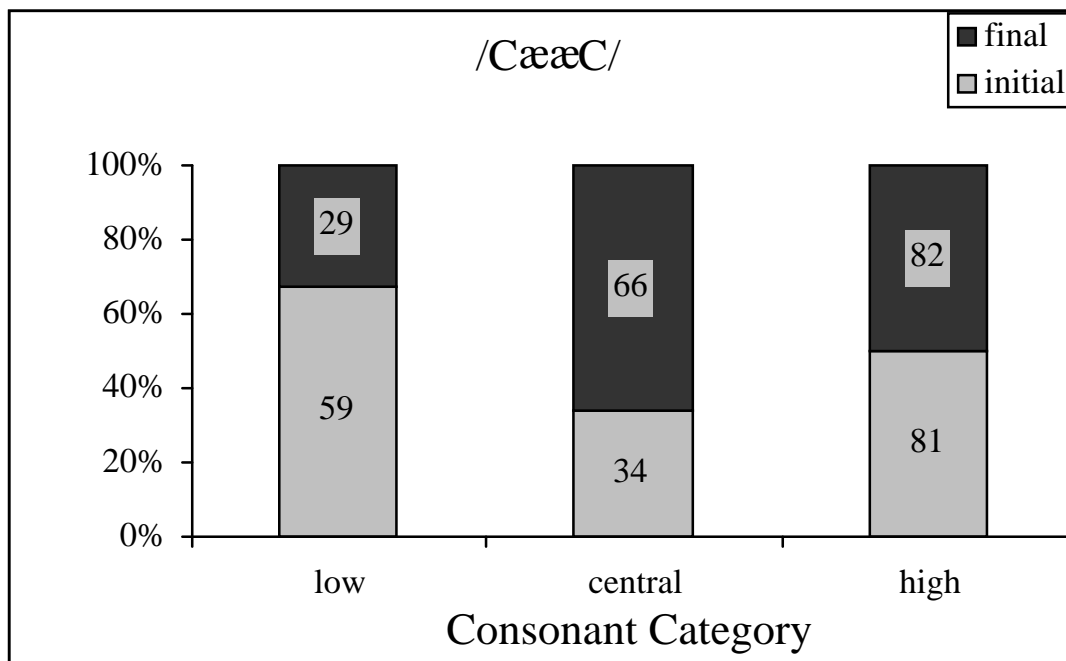


Figure 6. 100% stacked column compares the percentage of each consonant category (low: /ʕ, ħ, ʔ, h, x, ɣ/ central: /j, r, l, m, w, b, f/ high: /n, ŋ, d, t, z, s./) as a function of three different positions, i.e., initial, medial, final in CææC and CæCC words.

The activities of these organs during speech may have acoustical impact on the phonetic quality of these phonemes. The severe bio-mechanical constraints exerted on pharyngeal consonant production have a prevailing effect on the construction of the entire production system of the Arabic language. Consonants in a given sequence are selected according to their compatibility to preserve the temporal aspects of the syllable structure. That is, the organization of consonants in a sequence depends, to a great extent, on their relative degree of jaw height. The co-occurrence of different

consonants in a word is based on the consonant's inherent degree of jaw height. The word length can be expressed as the trajectory the jaw takes from one consonant to the next along the word.

4 Concluding remarks

The mechanical constraints exerted on the mandible due to the physiologically complex pharyngeal consonant entail that mechanical factors, arising from bio-physical properties of the human motor system, are interchanging with aerodynamics factors determined by the limitations of the auditory system. In the case of pharyngeal consonant production, mechanical factors are predominant and they globally affect the entire structure of Arabic language. The present study offers a more precise definition of pharyngeal articulation in general and sheds some light on the nature of coarticulation in the pharynx. It also offers an innovated phonetic classification of Arabic consonants. That is, we classified Arabic consonants in terms of their inherent degree of jaw height, relative to the clench position, as low, central, and high. Jaw movements as an articulatory parameter are not actively integrated in the framework of current articulatory models of speech (e.g., task dynamics model).

Our results suggest that the efficiency of these models can possibly be improved once the jaw activities are linked in their score of articulatory gestures. The results further suggest that any model seeking a universal framework of presentation should consider the jaw as an articulator that handles temporal specifications of syllable structure. One important implication attributable to the present study is that physiological constraints affecting the biomechanical system governing the vocal apparatus are centrally taken into account while planning the articulatory process. The results further suggest that physical constraints as a determining factor of the structure of human language should be considered in improving methods of constructing articulatory models of speech.

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