OPTIMIZING ARTICULATION: THE CASE OF ARABIC PHARYNGEALS

Raquel Willerman
University of Washington, Seattle, WA

ABSTRACT

Jaw position in Arabic pharyngeals is investigated to determine whether the open jaw observed by Ghazeli (1977) [1] was due to coarticulation with the following low vowel or to an intrinsic open jaw target for pharyngeals. Both factors were found to contribute to the anomalous open jaw position (jaw position is typically closed for consonants). The data are discussed in terms of biomechanical principles which suggest that pharyngeal consonants are articulatorily complex.

INTRODUCTION

Ghazeli's (1977) [1] x-ray tracing of the vocal tract during production of the Arabic pharyngeal fricative in the word /ʕæli/ revealed an open jaw. This seems anomalous given that jaws are typically open for vowels and closed for consonants. However, it is unclear whether the open jaw seen in Ghazeli's tracing was due to coarticulation with the following low vowel or to an intrinsically open jaw target for pharyngeals. The following study investigates jaw position in Arabic pharyngeals.

SPEAKERS

Five male native Arabic speakers participated in the study: two Egyptians, two Moroccans, and one Lebanese.

SPEECH MATERIALS

Two pharyngeal consonants and two coronal consonants: /ʕ, ħ, s, l/, were combined with the vowels, /a:, i:, u:/ into the twelve possible CV pairs. Each CV sequence is the beginning of a real Arabic word. The phonetic transcriptions and English glosses of these words are provided in Table 1.

Arabic	English gloss
/ʕa:da/	"he returned"
/ħa:ða/	"he goaded"
/sa:d/	"predominated"
/la:dan/	"laudanum"
/ʕi:d/	"holiday"
/ħi:n/	"time"
/si:na:/	"Sinai"
/li:n/	"softness"
/ʕu:d/	"lute"
/ħu:t/	"whale"
/su:d/	"blacks"
/lu:ða/	"weakness"

Table 1. Arabic speech materials and their English glosses.

The twelve words in Table 1 constitute one trial, the words in each trial appearing in random order. There were three trials of normal speech and three trials of loud speech which were at least fifteen dB louder than the normal speech trials. Speakers monitored their amplitude by looking at a sound pressure meter.

The words were presented in Arabic script. Speakers were instructed to clench their teeth together before reading each word. All jaw measurements refer to a displacement from clench position.

EQUIPMENT

Jaw movements were tracked with a head-mounted strain-gauge cantilever system (Barlow, Cole, & Abbs, 1983) [2]. Jaw movement was sampled in two channels at 1kHz each, and an audio channel was sampled at 10kHz. The principal direction of movement in an x-y plane was determined and a rotation was performed on the signals. The single channel representing jaw movement in this principal direction is used in all further analyses.

ANALYSIS

Jaw position was measured at two points in each word: the midpoint of the first consonant and the midpoint of the following vowel. Midpoints were determined acoustically, using only waveform and spectrographic displays. No special attempt was made to get the lowest jaw position for either segment.

RESULTS

Pharyngeal jaw positions were highly dependent on jaw positions of the following vowel. Jaw positions for /l/ were significantly less dependent on the following vowel and jaw positions for /s/ were the least dependent. There appear to be consonant-specific tendencies to coarticulate. In addition, the tendency for pharyngeal consonants to coarticulate with a following vowel suggests that Ghazeli's tracing of an open jaw is at least partially due to coarticulation with the following low vowel /æ/.

However, we can also ask whether pharyngeal jaw positions are even more open than jaw positions of following vowels. To answer this question, vowel jaw positions were subtracted from consonant jaw positions. These jaw(C) - jaw(V) differences are given in Table 2. A positive jaw(C) - jaw(V) difference means that the consonant jaw position is more open (more displaced from clench) than the jaw position of the following vowel. A negative jaw(C) - jaw(V) difference means that the consonant jaw position is higher (less displaced from clench) than the following vowel.

	Normal mean	(p)	Loud mean	(p)
/ʕ/	1.51	(<.01)	1.32	(<.01)
/ħ/	1.31	(<.01)	1.78	(<.01)
/s/	-3.41	(<.05)	-5.34	(<.01)
/l/	-.94	(<.05)	-2.38	(<.01)

Table 2. Mean jaw(C)-jaw(V) values in mm and p values averaged for five speakers and three vowels in normal and loud speech.

Table 2 gives mean jaw(C) - jaw(V) values in mm for five subjects across three vowels. Positive numbers in the pharyngeal rows, /ʕ, ħ/, indicate that pharyngeal jaw positions were more open than jaw positions of the following vowel. Negative numbers for the /l, s/ rows indicate that jaw positions for these consonants were more closed than the following vowels. The p values are the results of one-tailed t-tests which ask whether the mean jaw(C) - jaw(V) values are significantly different from zero. In every case they are. Normal and loud speech pattern similarly, though jaw(C) - jaw(V) differences for /s/ and /l/ show a marked increase in loud speech.

The relationship between pharyngeal jaw position and each vowel is shown by the average jaw(C) - jaw(V) value of both pharyngeal consonants in each vowel context (Table 3). The pharyngeal consonants have significantly lower jaw positions than /i/ and /u/ vowels for both normal and loud speech. Pharyngeal jaw position is also lower than the jaw position of normal speech /a/. However, loud speech jaw positions for /a/ are virtually identical to loud speech pharyngeal jaw positions! In sum, the open jaw position during a pharyngeal consonant seen in Ghazeli's (1977) [1] tracings seems to be due to at least two factors: coarticulation with a following low vowel and a consonant- specific open jaw position which is at least as open as any following vowel.

	Normal mean	(p)	Loud mean	(p)
/a/	.70	(<.05)	-.02	(NS)
/i/	1.50	(<.01)	2.17	(<.00)
/u/	2.04	(<.00)	2.5	(<.00)

Table 3. Mean jaw(C)-jaw(V) in mm and p values from five speakers for pharyngeal consonants in each vowel context for normal and loud speech.

Formant frequencies of these pharyngeal consonants are typical: a high F1 which is close to F2 (Klatt & Stevens, 1969) [3]. For every /ʕV/ pair, the pharyngeal consonants have a higher F1 than the vowel that follows, a high F1 being correlated with a low jaw. This is illustrated in Figure 1 which shows averaged formant data from all five subjects for loud speech. The first and second formants of each vowel are graphed in an F1-F2 plane, yielding the familiar vowel triangle. Average formant values for the voiced pharyngeal fricative /ʕ/ in each vowel context are plotted in the same F1-F2 plane. Notice that the context-bound pharyngeals form a triangle around the /a/ vowel, as if /a/

formant values coincided with the ideal, context-free pharyngeal. Thus, both jaw targets and formant frequencies of pharyngeal consonants resemble those of the low vowel /a/.

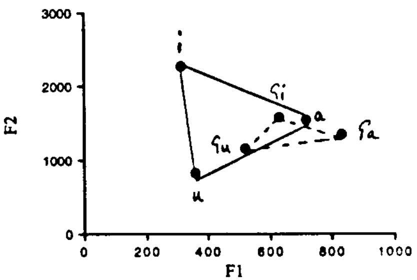

Figure 1. Formant data from loud speech.

DISCUSSION

Extreme displacements of the articulators may be biomechanically costly. Nelson (1983) [4] and Nelson, Perkell, and Westbury (1984) [5] observed that jaw movements are constrained by an economy of effort that can be quantified by peak velocity. In other words, as jaw movement times got shorter, movement distances also became smaller. This tradeoff between distance and time indicates a resistance to large increases in peak velocity. So why do Arabic speakers displace their jaws to such an extent during production of pharyngeal consonants?

The benefit of opening the jaw during pharyngeal consonants lies in the synergy between tongue and jaw movements. In addition to downward displacement in the vertical plane, jaw lowering is accompanied by rotation around the temporo-mandibular joint. This means that opening the jaw will displace the mandible in the dorsal direction as well. If the tongue remains in a neutral resting position with respect to the jaw, lowering the jaw will also back the tongue. This seems to be less costly than extreme displacements of the tongue alone. Arabic speakers may lower their jaws in order to reduce the extent of tongue displacement required for pharyngeals.

If pharyngeal jaw and tongue targets are similar to those of /a/, shouldn't pharyngeals be as biomechanically costly as the vowel /a/? The answer is no. Despite nearly identical articulatory topography, pharyngeal consonants and /a/ are produced under different timing constraints. For a given speaking rate, consonants are generally shorter than vowels (Crystal & House, 1982) [6]. Although jaw targets for pharyngeals and /a/ are nearly identical, the jaw has less time to reach its consonant target than its vowel target. More severe timing constraints on consonants means an increase in peak velocity for pharyngeals vis à vis /a/.

CONCLUSION

This leaves Arabic speakers two choices for producing a pharyngeal consonant. One articulatory strategy is to exploit the synergy between tongue and jaw; that is, the speaker lowers the jaw during the consonant to bring the tongue closer to its pharyngeal target. In this case, the jaw must move fast in order to reach the pharyngeal jaw position in the relatively short amount of time that is allotted to consonants. This strategy is biomechanically costly in terms of having to apply more force to the jaw in order to achieve a faster rate.

On the other hand, the speaker can forgo tongue-jaw synergy. In this case, the speaker must "superpharyngealize" the tongue to reach the back and low constriction without help from the jaw. With a relatively high jaw, the tongue must move a greater distance from its resting position with respect to the jaw in order to reach the pharyngeal target. This is biomechanically more costly in terms of extreme displacement of the tongue from neutral.

Both scenarios were used by the Arabic speakers in this study. Articulatory strategies are inferred from the individual jaw(C)-jaw(V) values. Four out of five speakers had pharyngeal jaw positions which were consistently lower than the following vowel. This indicates that these speakers exploit the synergy between tongue and jaw, at the supposed biomechanic cost of increased rate of jaw movement. One speaker had pharyngeal jaw positions which were consistently higher than the following vowel. This indicates that the speaker uses a "superpharyngealized" shape of the tongue, at the biomechanic cost of increased displacement from neutral.

Yet, acoustic measurements from the pharyngeal consonant portions of the spectrograms showed that all five subjects attained the high F1 and closely hovering F2 that is correlated with pharyngeal constriction. Thus, phonetic reduction can be ruled out as an explanation for the singular speaker's not-so-low pharyngeal jaw position; and, superpharyngealization seems more likely.

Is it significant that four out of five speakers increased extent and possibly rate of jaw displacement in order to decrease extent of tongue displacement; whereas, only one speaker minimized jaw displacement at the cost of increased tongue displacement? For now, the fact that extreme displacements of the tongue are more often avoided through synergistic movements of the jaw seems to suggest that jaw displacement is relatively cheaper than tongue displacement. The idea that jaw movement may be virtually free of charge biomechanically seems more plausible upon considering the primary function of the jaw: to grind food between the teeth. The mandible has powerful masticatory muscles capable of delivering great force, much more force than is required for speech movements. Thus, the mandible is in a sense overpowered for speech purposes. This leads to the following asymmetry: tongue movements are biomechanically more costly than jaw movements. Further support for asymmetrical treatment of jaw and tongue comes from comparing the range of displacement used for speech to the total anatomically possible range of displacement. Jaw displacements used in speech range between 5-15mm from clench; whereas, displacements are much greater for loud speech and yawning. In contrast, the range of tongue displacements used in speech is near the total range of possible displacement.

By either articulatory strategy, tongue-jaw synergy or "superpharyngealization" of the tongue, pharyngeals are biomechanically costly and should be avoided in the world's languages. Indeed, Maddieson's (1984) [7] survey of 317 languages reveals that pharyngeals are relatively rare in phonetic inventories; they occur in only three to four percent of the languages which have fricatives. Yet, the results of this investigation show that speakers have ways of minimizing the effort required in pharyngeal production. Furthermore, this study indicates that different articulators may be weighted differently with respect to constraints on peak velocity and economy of effort. It is hoped that non-data-driven measures such as peak velocity can be used to construct a metric of articulatory complexity in order to assess the complexity of phonetic sound systems.

REFERENCES

[1] Ghazeli, S. (1970), *Back consonants and backing coarticulation in Arabic*, Unpublished doctoral dissertation, University of Texas, Austin.

[2] Barlow, S., Cole, K., & Abbs, J. (1983), A new head-mounted lip-jaw movement transduction system for the study of motor speech disorders, *Journal of Speech and Hearing Research*, vol. 26, pp. 283-288.

[3] Klatt, D., & Stevens, K. (1969), Pharyngeal consonants, *MIT Quarterly Progress Report*, vol. 93, pp. 207-216.

[4] Nelson, W. (1983), Physical principles for economies of skilled movements, *Biological Cybernetics*, vol. 46, pp. 135-147.

[5] Nelson, W., Perkell, J., & Westbury, J. (1984), Mandible movements during increasingly rapid articulations of single syllables: Preliminary observations, *Journal of the Acoustical Society of America*, vol. 75, pp. 945-951.

[6] Crystal, T., & House, A. (1982), Segmental durations in connected speech signals: Preliminary results. *Journal of the Acoustical Society of America*, vol. 72, pp. 705-716.

[7] Maddieson, I. (1984), *Patterns of sounds*, Cambridge: Cambridge University.