PHARYNGEAL AND UVULAR CONSONANTS ARE APPROXIMANTS: AN ACOUSTIC MODELING STUDY

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ABSTRACT

Idealized models based on realistic area functions are proposed for uvular /ʁ, χ/ and pharyngeal /ʕ, ħ/ of Arabic. Synthesis of speech from these idealized models was also obtained for [aCa] sequences. Findings of this study indicate that these consonants should not be considered fricatives but approximants. First, values of Ac and Ag were estimated to be higher than those for simple fricatives. Second, corresponding spectrograms usually show a vowel-like formant structure. Third, calculated and measured airflow values were outside the range for normal fricatives.

INTRODUCTION

Theoretical modeling of pharyngeal /ʕ,ħ/ was first given in [1], where formant-cavity affiliations were examined. In [2], idealized models were proposed for both pharyngeal /ʕ,ħ/ and uvular /ʁ, χ/. In this study, we propose similar models which are based on realistic area functions derived from x-ray profiles corresponding to these consonants. The x-ray profiles utilized came from [3].

1. IDEALIZED MODELS

1.1. Realistic area functions

In the process of deriving the realistic area functions, the method used for determining the sagittal distances consists of fitting circles inside the vocal tract and then defining a midline as the locus of their centers [4, 5] (see Figure 1).

Two vocal tract profiles, one for the pharyngeal /ʕ/ and the other for the uvular /χ/, were enlarged 400 % to facilitate the insertion of circles. The diameter of each circle, and the length of the segments joining these circles were measured. The area functions were derived from sagittal distances by the application of the relation $A=\alpha.d^{\beta}$, where d is the sagittal distance, and α and β are changing coefficients in function of different regions in the vocal tract. Figure 2 gives the derived area functions corresponding to pharyngeal /ʕ/ and to uvular /ʁ/ (for details see [6]).

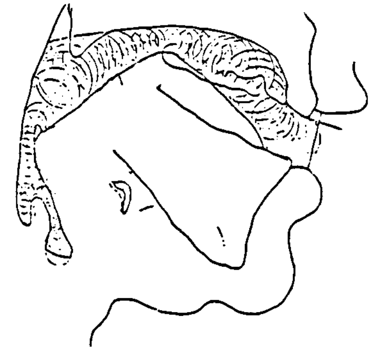


Figure 1. The 'fitting-circle' method used in deriving realistic area functions.

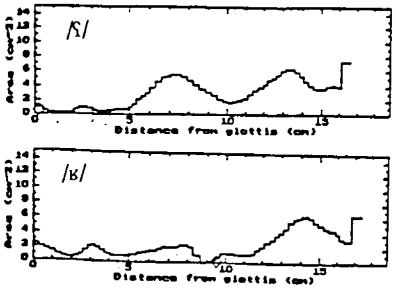


Figure 2. Area functions derived from x-ray profiles corresponding to pharyngeal /ʕ/ and to uvular /ʁ/.

The dimensions of these area functions conform to the articulatory descriptions given in [3]. For example, the vocal tract length for uvular /ʁ/ (17.2 cm) is longer than that for pharyngeal /ʕ/ (16.5 cm). This due to the elevation of larynx during the production of the latter.

1.2. Idealized area functions

Idealized models for the production of pharyngeal and uvular consonants are proposed on the basis of the dimensions provided by the realistic area functions (see Figure 3). The model consists of three uniform tubes corresponding to the back cavity, the constriction and the front cavity.

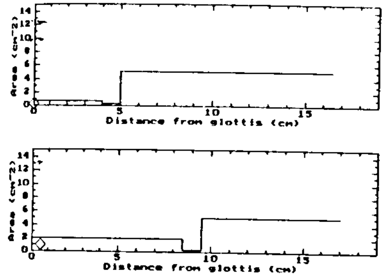


Figure 3. Idealized area functions for the production of pharyngeals (upper), and uvulars (bottom).

2. TRANSFER FUNCTIONS AND FORMANT FREQUENCIES

Many transfer functions corresponding to the idealized area functions were calculated by a simulation method of the vocal tract which includes radiation characteristics, boundary losses and the subglottic system [7]. The variable parameters changed were principally glottal area (Ag) and constriction area (Ac). The aim is to find a good correspondance between calculated and measured formant frequency values. Table 1 gives the calculated formant frequencies and airflow. It can be seen that Ag distinguish voiced consonants (Ag=0 cm^2) from their voiceless counterparts (Ag=0.20-0.25 cm^2). Moreover, the voiceless have narrower Ac than the voiced. The values for Ac and Ag given in Table 1 are found to be bigger than those appropriate for fricatives.

Table 1: Calculated formant frequencies and airflow (U) from the idealized area funtions.

	ʕ	ħ	ʁ	χ
F1 (Hz)	689	784	570	------
F2 (Hz)	1493	2040	1206	1328
F3 (Hz)	2181	2648	2304	------
F4 (Hz)	3525	3496	3157	?
Ac (cm^2)	0.35	0.30	0.35	0.20
Ag (cm^2)	0	0.25	0	0.20
U (cm^3/s)	------	596	------	439

The calculated transfer functions (Figure 4) show that only the formants associated with the front cavity are excited when the glottis is open (F2 and F4 for uvular /χ/; F1, F3 and F4 for pharyngeal /ħ/). It can also be seen that the F2 for /ħ/, though associated with the Helmoltz resonance involving the back cavity, appears to be excited. This can be explained by the fact the noise source seems to be located at the glottis for this consonant. This hypothesis is possible since Ac is larger than Ag (0.30 cm^2 vs. 0.25 cm^2), and a formant structure is well apparent in its sonogram.

3. ACOUSTIC ANALYSIS

An acoustic analysis was conducted in parallel with the acoustic modeling. Nonsense /CVV/ syllables (where /C/ is /χ,ʁ,ħ,ʕ/ and /VV/ is the long vowel /a:/) were produced in carrier phrases by 4 male Moroccan speakers. Table 2 gives the mean values for the formant frequencies taken in the middle of the consonant. Comparing these measured values (Table2) with those calculated from idealized area functions (Table1), we find a good correspondance between the two.

Table 2. Formant frequencies averaged across 4 speakers and 5 repetitions for uvular and pharyngeal consonants.

	ʕ	ħ	ʁ	χ
F1 (Hz)	710	777	616	------
F2 (Hz)	1494	1978	1252	1389
F3 (Hz)	2255	2536	2321	------
F4 (Hz)	?	3597	?	?

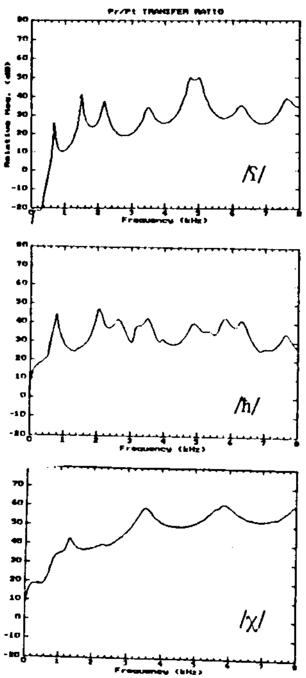
4. SYNTHESIS OF SPEECH

Synthesis of speech from these idealized area functions was obtained for [aCa] sequences, where C = /ʁ, χ, ʕ, ħ/. In the simulation method used [7], the noise generation is achieved by placing a pressure source along the vocal tract. Figure 6 illustrates the evolution of the parameters used in the synthesis of [aʁa]. Are shown in this figure the calculated speech waveform (signal), the glottal area (Ag), the constriction area (Ac), the fundamental frequency (F0), and the area function (AF). In an informal listening test involving 4 Moroccan listeners, the quality of the synthesized sequences was excellent in terms of both intelligibility and naturalness. Figure 7 shows the spectrograms of the synthesized sequences [aχa] and [aʕa].

5. FRICATIVES OR APPROXIMANTS

The modeling and the acoustic studies give us many indications pointing that pharyngeal and uvular consonants should not be considered as fricatives but as approximants. One definition of the difference between the former and the latter is given in [8] (cf. a phonological distinction [9] based on it). A fricative has a narrower area of constriction (Ac= 0.03-0.20 cm^2) and an airflow that is turbulent whether it is voiced or voiceless, while an approximant has a wider Ac (0.2-0.8 cm^2) and an airflow that is turbulent only when voiceless. According to this definition pharyngeal /ħ,ʕ/ and uvular /χ,ʁ/ should be considered as approximants, since their area of constriction appropriate for their modeling is in the order of 0.20-0.35 cm^2. Moreover, the spectrograms (Figure 5) corresponding to voiced /ʕ,ʁ/ indicate that the airflow is non-turbulent: absence of friction noise and presence of a vowel-like formant structure.

There is further evidence from aerodynamic data in favor of the approximant categorization. The measured airflow values for these consonants are outside the typical range for fricatives [3, 10]. Our preliminary airflow data for these consonants are in accordance with this finding. Figure 8 shows that the airflow of /χ, ħ/ is significantly higher than that of /s/. Furthermore, the airflow shape for /χ, ħ/ is single-peaked while for /s/ is double-peaked. Single-peaked airflow is characteristic of approximant consonants [11] since their supraglottal constriction area is larger than their glottal area.



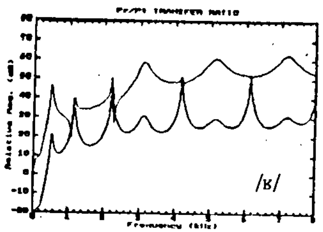


Figure 4. Transfer functions calculated from the idealized area functions. The source for /ʁ/ is both at the glottis and at 1 cm after the constriction (hence two transfer functions). For /ʕ/ and /ħ/ the source is at the glottis only, and for /χ/ it is placed at 1 cm after the constriction.

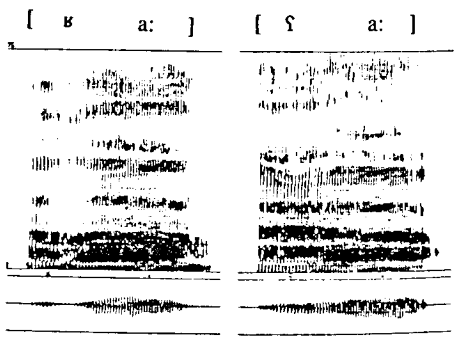


Figure 5. Spectrograms corresponding to voiced pharyngeal /ʕ/ (right) and voiced uvular /ʁ/ (left) in the context of the long vowel /a:/.

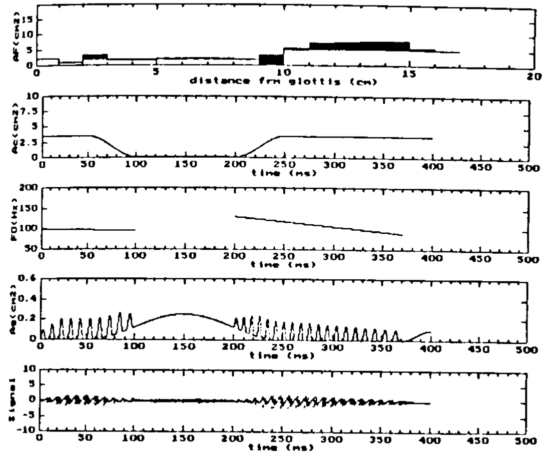


Figure 6. An illustration of some parameters used in the synthesis of [aχa]: the area function (AF), the supraglottal constriction (Ac), the fundamental (F0), the glottal area (Ag) and the speech waveform (signal).

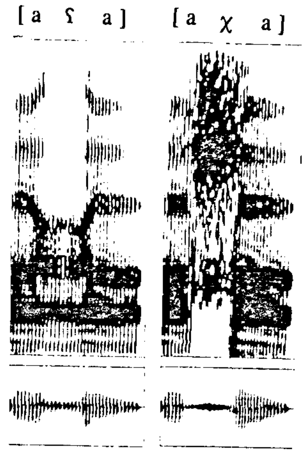


Figure 7. Spectrograms of the synthesized sequences: [aʕa] (left), and [aχa] (right).

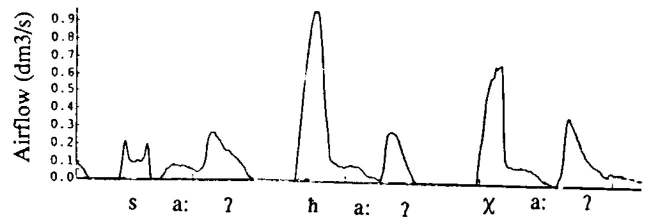


Figure 8. Airflow data (in dm^3/s) for [sa:ʔ], [ħa:ʔ] and [χa:ʔ] from one individual speaker.

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