Acoustic and Articulatory Analysis of the Gemination in Modern Standard Arabic

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Abstract

In this paper, we report the results of an experimental study of the acoustic and articulatory properties of the geminate consonants in Modern Standard Arabic (MSA). To extract the feature characteristics, we have carried out an acoustic analysis by computing the values of frequency formants, energy and duration of the consonants and subsequent vowels in the various [VCV] and [VCgV] utterances (Cg: geminate consonant). For this, we have used the sonagraph CSL 4300B of Kay Elemetrics, Praat speech analysis software and Matlab Software. For the articulatory analysis tool, we have used the Electromagnetic Midsagittal Articulograph EMA AG100 to track and record tongue movements during speech production. A range of kinematics parameters were analyzed from the phoneme productions including movement trajectories, distance, velocity, and duration of tongue movements. We have used also the Carstens Emalyse software to visualize and analyze the measurement data acquired by the Articulograph AG100 and corresponding to the various movements of the tongue tip (TT), tongue mid (TM), and tongue back (TB). Among the most important results, we note a longer duration of the vowel following a geminate consonant, a decreasing in levels of F_1 and F_2 formants and a rising in level of F_3 formant of this vowel.

Keywords:
Arabic language - gemination - acoustic analysis - articulatory analysis.

الملخّص

يتناول هذا البحث دراسة تجريبية حول الخصائص الفيزيائية والفيزيولوجية للحروف المشدَدة في اللغة العربية. لاستخراج الخصائص الفيزيائية، قمنا بتحليل فيزيائي يتمثل في استخراج قيم البواني الصوتية، الشدة والمدة الزمنية لنطق الصوامت والصوائت المجاورة في السياقات المختلفة [VCV] و[VCgV]، و(Cg : الحرف المشدَد). لهذا الغرض، استعملنا الجهاز الطيفي CSL4300B و كذا البرمجيات الحاسوبية Praat و Matlab. وفي ما يخص التحليل الفيزيولوجي، استعملنا الجهاز Articulograph AG100 لمتابعة وتسجيل حركات اللسان أثناء الكلام. وقمنا بدراسة عدة ظواهر فيزيولوجية تمثل حركة اللسان عند النطق بالحروف المشدَّدة مثل المسار، المسافة، السرعة، والمدة الزمنية لحركات اللسان. كما سمح لنا جهاز Emalyze بعرض صوري وتحليل جل المعطيات التي استخرجناها باستعمال الجهاز Articulograph AG100 والتي تمثل حركات طرفي اللسان ووسطه. ومن أهم النتائج المتحصل عليها، نذكر ارتفاع قيمة المدة الزمنية للحركة التي تتبع الحرف المشدَد وكذا انخفاض مستوى البواني الصوتية F_1 و F_2 وارتفاع مستوى F_3 لهذه الحركة.

الكلمات المفاتيح : اللغة العربية - التشديد - التحليل الفيزيائي - التحليل الفيزيولوجي.

Résumé

Dans le cadre de ce travail, nous présentons les résultats d'une étude expérimentale des propriétés acoustiques et articulatoires des consonnes géminées de l'Arabe Standard. Pour extraire les caractéristiques acoustiques, nous avons procédé à une analyse acoustique par extraction des valeurs des formants, de l'énergie et des durées des consonnes et des voyelles subséquentes dans les différents contextes [VCV] et [VCgV] (Cg: Consonne Géminée). Pour ce faire, nous avons utilisé le sonagraphe CSL 4300B de Kay Elemetrics, le logiciel d'analyse de la parole Praat ainsi que le logiciel Matlab. Pour le cas de l'analyse articulatoire, nous avons exploité l'articulographe EMA AG100 pour suivre et enregistrer les mouvements de la langue durant l'acte de parole. Un ensemble de données kinématiques sont analysées à partir des productions des phonèmes, incluant la trajectoire, la distance, la vélocité et la durée des mouvements de la langue. Nous avons également exploité le logiciel Carstens Emalyse pour visualiser et analyser les données de mesures relevées à partir de l'articulographe AG100 et correspondant aux mouvements de l'avant, le milieu et l'arrière de la langue. Parmi les résultats les plus importants de cette étude, nous notons une durée plus importante de la voyelle qui suit la géminée, ainsi qu'une chute des niveaux des formants F_1 et F_2 et une montée du niveau du formant F_3 de cette voyelle.

Mots clés: Langue arabe - gémination - analyse acoustique - analyse articulatoire.

1. Introduction

The gemination process is very relevant in Modern Standard Arabic (MSA). Indeed, the sentence [ḥaḍara eddarsa] (حضر الدرس) (he attended the lesson) presents a different sense, compared to the sentence with gemination [ḥaḍḍara eddarsa] (حضّر الدرس) (he prepared the lesson). Also, the word [naqaba] (to dig) differs from the word [naqqaba] (to seek) by a gemination of the phoneme [q].

In this paper, we present the results of an experimental study of acoustic and articulatory properties of geminate consonants in MSA. The obtained results are compared to previous studies reported in the literature on gemination in the Arabic and in the other languages. In MSA, gemination can occur in word medial and final positions. In our work, we have considered the intervocalic context to study in particular the influence of gemination on the following vowel. For the final position and the influence of gemination on the preceding vowel, various studies have been conducted for the Arabic geminate consonants, such as the experimental study presented by Al-Tamimi on the Jordanian Arabic final geminates (Al-Tamimi et al., 2010).

2. Definition and Related Researches

Various definitions are given to the notion of gemination (also called [tachdīd] (تشديد) in Arabic Language). For Sibawayh, one of the greatest Arab linguists, it's heavy to employ one's tongue leaving a place of articulation for making at once return. Also, because of this tiredness during the successive realisation of two identical articulations, this realisation is rejected in favour of gemination of two identical phonemes, in order to have only one elevation of the tongue (Roman, 1983).

Phonetic studies in the domain of gemination report a lot of controversy from an acoustic and articulatory point of view. In many languages, the acoustic analysis shows that the durations of subsequent vowels and opposite geminate / non-geminate are different. Also, the ratio geminate/non geminate phoneme duration varies from one language to another: higher in Arabic (Obrecht, 1965; Zeroual et al., 2006; Zeroual et al., 2008), Japanese (Lahiri & Hankamer, 1988) and Italian (Stevens & Hajek, 2004), but lower in Swedish (Löfqvist, 2005). Furthermore, the intervocalic geminate plosives are usually produced with a very long closure, which constitutes their major acoustic and perceptive cue (Obrecht 1965; Lahiri & Hankamer, 1988; Zeroual et al., 2006; Zeroual et al., 2008). In Tashlhiyt Berber, Ridouane (2007) reports that the main correlate which distinguishes geminate consonants C_g and non geminate consonants C_{ng} is the duration. This primary correlate is enhanced by additional acoustic features (such as preceding vowel shortening). In this language, the gemination is interpreted as the manifestation of a tense articulation. A study of Galand (1997) shows also "tense consonants" instead of geminate consonants. The geminate consonants and their non geminate counterparts differ by the acoustic correlate of "tension" and not "duration".

Moreover, recent studies report a shortening of vowels preceding a geminate consonant in some languages like Italian (Stevens & Hajek, 2004; Esposito& Di Benedetto, 1999; Smith, 1995; Rossetti, 1994; Maddieson, 1985), Swedish (Hassan, 2002; Hassan, 2003), Tashlhiyt Berber (Ridouane, 2007), Indonesian languages (Cohn et al., 1999), Hindi (Shrotriya et al., 1995) and finally Malayalam (Local & Simpson, 1999). To explain this phenomenon of vowel shortening before a geminate consonant, Smith (1995) evokes the anticipation of the geminate gesture in the pronunciation of the preceding vowel causing its shortening (Smith, 1995). As opposed to the works cited above, other studies show that the geminate consonants don't induce shortening of their preceding vowel, and are produced without larger anticipation of their gesture in the preceding vowel compared to their simple counterparts. For the Arabic language, we can mention the studies of Hassan (2002), Khattab & Al-Tamimi (2008), Zeroual et al. (2008), and Trigui et al. (2010). We can also cite the studies of Lahiri & Hankamer (1988) for Japanese, and Arvaniti & Tserdanelis (2000) for Cypriot Greek which considers that the differences between the vowels preceding singleton and the vowels preceding geminate consonants were on average 12ms, and thus unlikely to be of perceptual relevance. In the same way, Ghalib (1984) and Hassan (2002) have concluded that such vowel duration differences are negligible. It is useful to note that unlike those studies, Al-Tamimi et al. (2010) consider the duration of the preceding vowel as an acoustic and perceptual relevant cue, with vowels preceding singletons longer by almost two milliseconds than those preceding the geminates, on average.

In addition, the acoustic formants are also discussed in some papers. According to Arvaniti & Tserdanelis (2000), preliminary data regarding F_1 and F_2 formants of the surrounding vowels in the test words of the Cypriot Greek language strongly suggest that the presence of a geminate do not affect the quality of the surrounding vowels, either in their steady state or in the transitions to and from the geminate.

From an articulatory point of view, many papers report a larger and longer period of contact extents in presence of geminate consonants. In Moroccan Arabic, the geminate plosives are produced with a longer period of tongue tip contact (Zeroual et al., 2008). Videofluoroscopic data reveal that Jordanian Arabic final geminates are produced with "tighter and larger contact extents in comparison to the singleton consonants" (Al-Tamimi et al., 2010). In Tarifit Berber, X-ray analysis shows a significant contact of the back of the tongue with the velar region at the pronunciation of uvular geminate consonants (Bouarourou et al., 2008). Löfqvist (2007) has studied the tongue movement kinematics in long and short Japanese consonants, using a magnetometer system, and has observed a substantial difference in closure duration between the long and short consonants. An X-ray study of French consonants by Vaxelaire (1995) suggests that the area of tongue palate contact is larger for the long stop consonants than for the short ones. In addition, Payne (2006) has presented the results of an electropalatographic investigation of Italian geminate consonants and has suggested a more palatalized tongue configuration during the production of geminate coronal sonorants and stops than in their non-geminate counterparts. Also Smith (1995) has examined lip and tongue movements in single and geminate consonants in Japanese and Italian, and has reported that the closing movements of the lips were slower for the geminates compared with their single counterparts.

According to Dkhissi-Boff (1983), the geminate consonant do not present two distinct articulatory movements, but only one single movement, which differs from that of the simple consonant, by its important stability of articulation and its very significant duration. On the other hand, P. Delattre (1971) has suggested that the articulation of the geminate consonant achieves itself in two phases and presents two summits of activity.

3. Experimental Method

We have exploited a corpus of the singleton vs. geminate consonants appearing in the context of the three Arabic surrounding vowels [a, i, u]. This corpus was pronounced by five male, students at the University of Algiers II. All the speakers were native Arabic speakers from Algeria, with no history of speech or hearing disorders.

For the acoustic analysis, time and frequency related parameters were examined. The time parameters were all based on durational measurements performed within the consonant and surrounding vowels. The frequency parameters, formants and fundamental frequency, were computed at different points all through the analyzed speech. To extract the feature characteristics, we carried out an acoustic analysis by extracting the values of the frequency formants, energy and durations in the various [VCV] and [VC_gV] utterances (C_g: geminate consonant). For that, we used the sonagraph CSL 4300B of Kay Elemetrics, the Praat speech analysis software and the Matlab Software. For the articulatory analysis tool, several techniques were used to study the articulatory characteristics. Some authors used the X-Ray study; other authors used the video fluoroscopy and kinematics studies. In this work, we have brought another system to visualize the articulatory movements. This system consists of an audio recording device synchronised with a simultaneous Electromagnetic Midsagittal Articulograph EMA AG 100 to track and record tongue movements during speech production (Alfonso et al., 1993; Ferrat et al., 2007). The Articulograph AG100 is a device using alternating electromagnetic fields to track articulator movements over time during speech production. This system offers the possibility of monitoring articulatory movements in speech production by means of small electromagnetic receivers attached to the articulators in the Mediosagittal plane. A high quality microphone is used to record the acoustic signal simultaneously with the articulatory data. We note that the Articulograph is most frequently used to measure jaw, tongue and sometimes velum movements in the sagittal plane (Hoole, 1996).

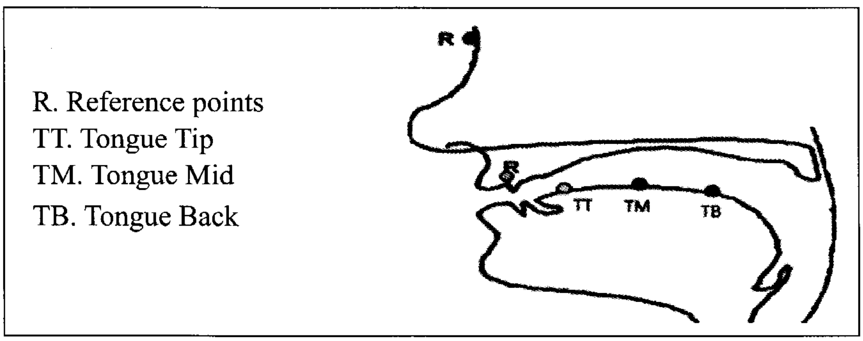


Figure 1 : *Placement of the receiver coils in EMA measurement*

In our study, the EMA system was used to track articulatory movements of the tongue tip (TT), the tongue mid (TM) and the tongue back (TB). Tongue displacements were transduced by three EMA receiver coils which describe the trajectories of the TT (left), TM (middle) and TB (right), as shown in Figure 1. The TT coil is placed approximately 1 cm from the tongue tip, the TM coil is about 3 cm from the TT coil, and the TB coil is about 5 cm from the tongue tip. The receiver coils R correspond to the fixed reference points (upper incisor and bridge of the nose). All the receiver coils were carefully located in the Mediosagittal plane, in order to ensure the best measurement accuracy. We used the Carstens Emalyse software to visualize and analyze the measurement data acquired by the Articulograph AG100 and corresponding to the various movements of the tongue tip (TT), the tongue mid (TM) and the tongue back (TB) (Ferrat et al. 2007).

We have used the IPA symbols to transcribe the specific Arabic phonemes:

- [ṭ] (ط) : voiceless alveolar emphatic plosive ;
- [ṣ] (ص) : voiceless alveolar emphatic fricative ;
- [ḍ] (ض) : voiced alveolar emphatic plosive ;
- [ḏ̣] (ظ) : voiced dental emphatic fricative ;
- [q] (ق) : voiceless uvular plosive :
- [ḥ] (ح) : voiceless pharyngeal fricative ;
- ['] (ء) : voiceless glottal plosive.

3.1. Acoustic Analysis

In this acoustic analysis, we aim to determine the temporal relationship between geminate consonant and the length of the preceding vowel V_p and following vowel V_f in [$V_pC_gV_f$] sequences. We have compared these values with those measured for a $V_pC_{ng}V_f$ sequences. The average temporal durations of geminate C_g, non geminate C_{ng}, and the vowels V_p and V_f, are shown in Table 1. In addition, we have studied the evolution of formant frequencies and energy, using spectrograms extracted from Praat speech analysis software.

Phoneme Labels	Arabic phoneme	Arabic Character	V_p (s)	V_f (s)	Duration (s)	K_1	K_2	K_3
1	[ṭ]	[ط]	0.056	0.065	0.121	0.69	1.10	1.89
	[ṭṭ]		0.039	0.072	0.229			
2	[ṣ]	[ص]	0.067	0.057	0.145	0.74	1.26	1.57
	[ṣṣ]		0.050	0.072	0.229			
3	[ḍ]	[ض]	0.088	0.068	0.103	0.38	1.27	2.28
	[ḍḍ]		0.034	0.087	0.235			
4	[ḏ̣]	[ظ]	0.095	0.078	0.072	0.56	1.21	2.91
	[ḏ̣ ḏ̣]		0.054	0.095	0.210			
5	[q]	[ق]	0.067	0.071	0.116	0.91	1.26	1.85
	[qq]		0.061	0.090	0.215			
6	[ḥ]	[ح]	0.062	0.068	0.109	0.83	1.14	2.28
	[ḥḥ]		0.052	0.078	0.229			
7	[']	[ء]	0.077	0.081	0.081	0.80	1.05	2.72
	["]		0.062	0.085	0.220			

Table 1: *Reports of the durations of C_g, C_{ng} and surrounding vowels V_p and V_f*

$K_1 = V_{p2}/V_{p1}$ with V_{p2} and V_{p1} durations of the vowel which precedes C_g and C_{ng}, respectively;

$K_2 = V_{f2}/V_{f1}$ with V_{f2} and V_{f1} durations of the vowel which follows C_g and C_{ng}, respectively;

$K_3 = d_2/d_1$ with d_2 and d_1 durations of consonants C_g and C_{ng}, respectively.

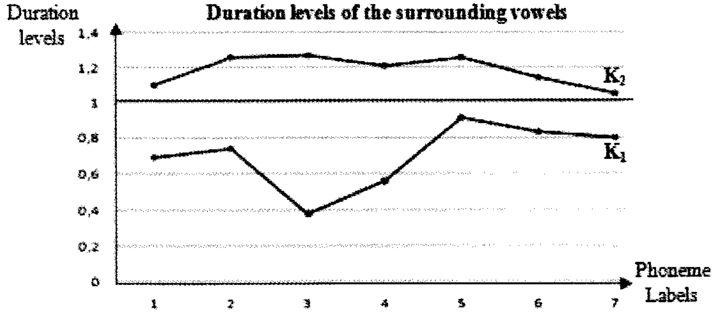


Figure 2: *Increase in duration of V_f and decrease in duration of V_p, in the C_g context*

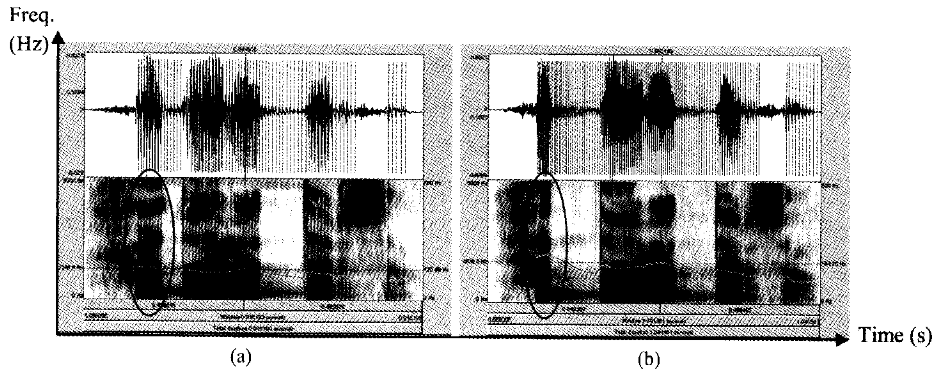


Figure 3: *Decrease of duration of V_p in the sentence* [ḥaḍḍara eddarsa] *with geminate consonant (b) compared to duration of V_p in* [ḥaḍḍara eddarsa] (a)

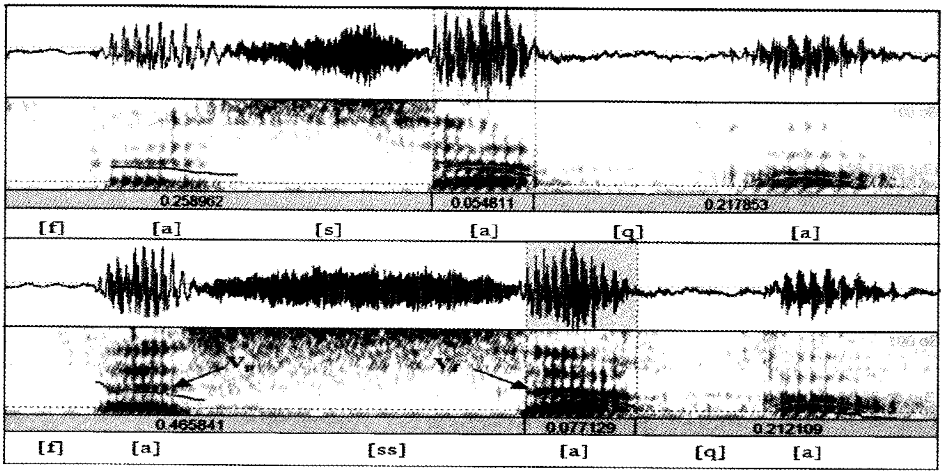


Figure 4: *Increase of the following vowel (V_f) in C_g context*

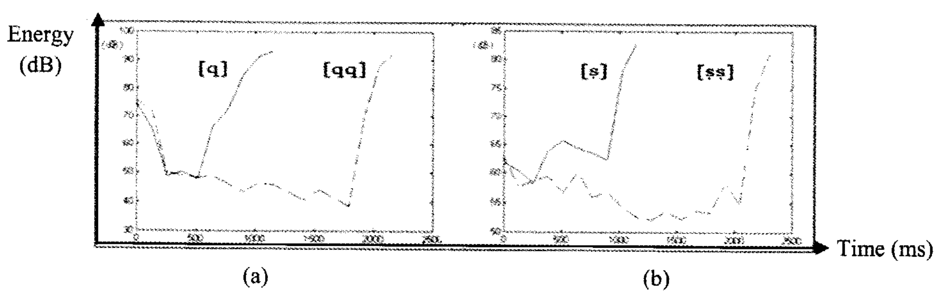


Figure 5: *Decrease of energy during pronunciation of geminate plosive (a) and geminate fricative (b) compared to their non geminate counterparts, in the context [VCV]*

3.2. Articulatory Analysis

In this study, we aim to determine the articulatory parameters in [VC_gV] sequences compared to their non geminate counterparts [$VC_{ng}V$]. The vowels selected are the three Arabic vowels [a, i, u]. This EMA corpus was recorded at the Speech Processing Laboratory of the CRSTDLA, Algiers, in 2007. This corpus was pronounced by five male, researchers at the CRSTDLA. All the speakers were native speakers of Algeria with no history of speech or hearing disorders. All movement data were sampled at 400 Hz, while time-aligned speech data were acquired simultaneously through the AG100 system at 16 kHz. We have visualized and analyzed the measurement data corresponding to the various movements of the tongue tip (TT), the tongue mid (TM) and the tongue back (TB) by using the Carstens Emalyse software (Ferrat et al. 2007). In the examples of Figures 6 and 7, the acoustic signal, and the positions (x ,y) over time of the three EMA coil receivers, corresponding to TT, TM and TB, during the realization of the utterances in the two dimensions (x, t) and (y, t).

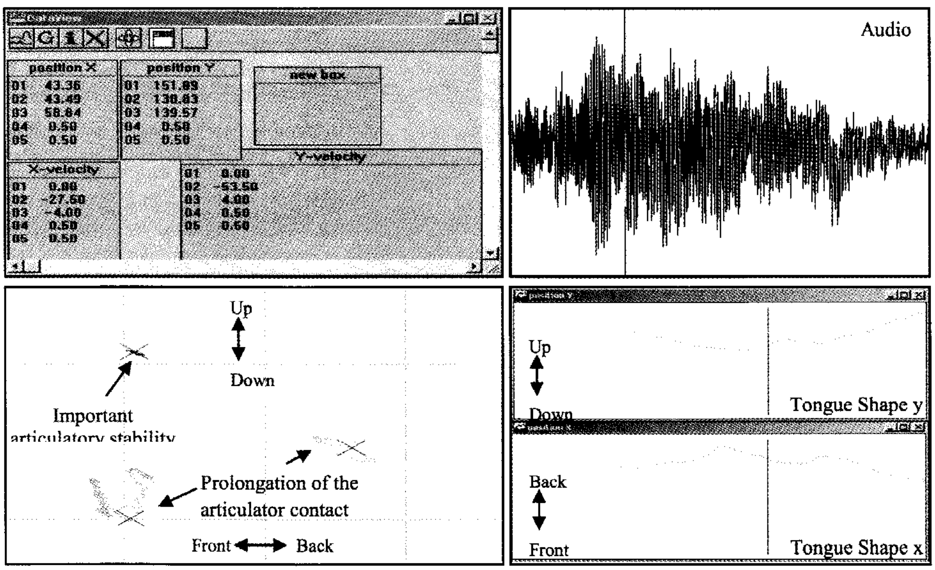


Figure 6: *Movements of the TT, TM and TB during achievement of the geminate plosive* [ṭṭ].

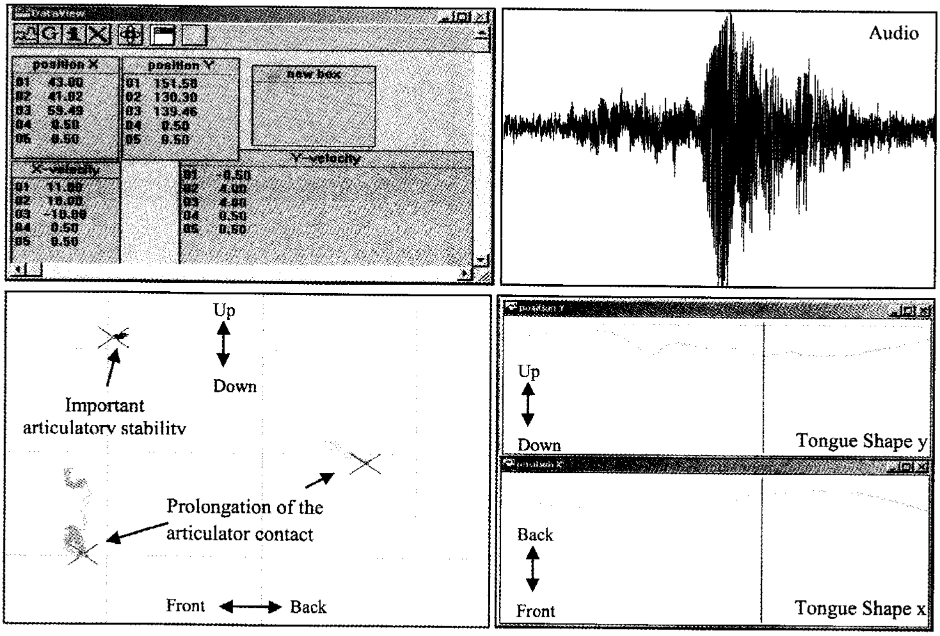
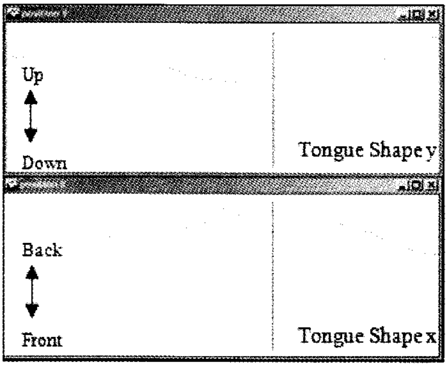
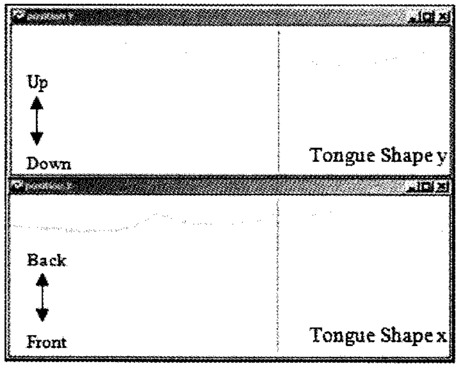


Figure 7: *Movements of the TT, TM and TB during achievement of the geminate fricative* [ṣṣ].

In the plane (x, t) (bottom right), an upward movement represents a backward shift of the tongue while a downward shift represents a forward movement of the tongue. In the plane (y, t) (top right), an upward movement represents an elevation of the tongue, while a downward shift represents a lowering of the tongue. The fixed set of windows, as shown in the examples of figures 6 and 7, consists of X/Y display with a selectable line marking the cursor position (tongue shape), acoustic signal window and data View to show the numerical values at the current cursor position. The X/Y display, as illustrated in figure 8, shows the movement and the articulatory stability during the pronunciation of the geminate consonants (plosive consonant in the left window and fricative consonant in the right window).



[ṭṭ]



[ṣṣ]

Figure 8: *Only one movement with higher articulatory stability during pronunciation of the geminate consonants*

4. Results and Discussion

4.1. Acoustic Analysis

The results show a more important duration of C_g, compared to C. Moreover, we note an increase in duration of the V_f in C_g context and a decrease in duration of V_p (Figures 2, 3). The Figure 4 shows an increase of the following vowel V_f in C_g context (V_f = 77.1 ms) compared to its non geminate counterparts (V_f = 54.8 ms). So the gemination influences the duration of the preceding vowel by lowering its value, and the duration of the following vowel by increasing its value. In this study, the extending of duration of the geminate consonants is globally comparable to what has been found for the Jordanian Arabic (Al-Tamimi, 2004), Lebanese Arabic (Khattab & Al-Tamimi, 2008), Iraqi Arabic (Hassan, 2003), Moroccan Arabic (Zeroual et al., 2006, 2008), Japanese (Lahiri & Hankamer, 1988), Italian language (Stevens & Hajek, 2004), and also for the Berber (Ridouane, 2007). For the shortening of the preceding vowel in contact of geminate, the results are rather similar to what has been found by some authors (Al-Tamimi et al., 2010; Khattab & Al-Tamimi, 2008; Ridouane, 2007; Hassan, 2002; Hassan, 2003; Cohn et al., 1999; Esposito & Di Benedetto, 1999; Local & Simpson, 1999; Shrotriya et al. 1995; Smith, 1995; Rossetti, 1994; Maddieson, 1985), but differ with results reported by other authors (Ghalib, 1984; Lahiri & Hankamer, 1988; Arvaniti and Tserdanelis, 2000; Zeroual et al., 2008; Trigui et al., 2010). In general, we can interpret the gemination as a reinforcement of the phoneme's articulation which leads to the lengthening of duration of these phonemes (Ferrat, 2005). As a result, it causes a prolongation of decreasing of energy during the pronunciation of plosive and fricative phonemes, as illustrated in Figure 5. This acoustic cue is not mentioned by the consulted studies. Furthermore, our study shows a greater duration of the following vowel in presence of geminate consonant. This observation has not been also reported by the previously cited works. This is also true for the decreasing in levels of F_1 and F_2 formants and rising in level of F_3 formant of the following vowel, which is not reported by any of the previously cited works. For Arvaniti & Tserdanelis (2000), the geminate do not affect the quality of the surrounding vowels in the Cypriot Greek language, either in their steady state or in the transitions to and from the geminate.

The extension of the contact at the place of the geminate consonant's articulation and the significantly slower movement of the tongue body and dorsum (as reported in the articulatory analysis) maintain the oral and pharyngeal cavities with a restricted volume for a long enough period during the gemination. So this probably has an impact on the following vowel which results acoustically in a decreasing in levels of F_1 and F_2 and a rising in level of F_3. This prolongation of the contact relies in part on the following vowel, which also results in a longer duration of this vowel to facilitate the transition of the geminate consonant towards the following sounds.

4.2. Articulatory Analysis

Measurements obtained from mid sagittal profiles show that contact extents (maximum value for contact) are longer for geminate consonants than for the singleton counterparts, as shown in Figures 6 and 7. We note a maximum contact in the palatal region and a presence of an important articulatory stability during the phase of gemination. So the prolongation of the articulator contact at the point of articulation can be considered as a significant feature. The figure 8 shows that the geminate consonant do not present two distinct articulatory movements, unlike that reported by Delattre (1971), but only one movement which differs from that of the non geminate consonant by its important articulatory stability. Furthermore, our study shows that the movement of the tongue body and the tongue dorsum is significantly slower in presence of geminates, such as reported by Löfqvist (2007) and Smith (1995). This can be justified by the fact that these adjustments in tongue movements permit to maintain the contact between the tongue and the palate during the phase of gemination. Therefore, we have noted an important closure duration in the geminate context. Löfqvist (2005) proposes a plausible mechanism to explain how this duration is controlled. According to him, if the duration of the oral closure for the consonant is increased, a speaker is still constrained to maintain the contact between the tongue and the palate to make the closure or constriction for the consonant. For that, the geminates are produced with a more extreme target position, compared to the singleton counterparts. With a more extreme constriction target, the articulators will keep moving longer towards that goal, and thus the closure interval will be longer. The contact extensions at the place of articulation is also reported by other studies (Al-Tamimi et al., 2010; Bouarourou et al., 2008; Zeroual, 2008; Vaxelaire, 2007; Payne, 2006), but the presence of an important articulatory stability during the phase of gemination is not reported by those studies.

5. Conclusion

In this study, we have presented the main features of the gemination process in MSA. In the acoustic domain, it was observed that the respective durations of the preceding vowel and the geminate consonant are significantly different compared to their counterparts in non geminate context. The gemination influences the duration of the preceding vowel by decreasing its value and the duration of the following vowel by increasing its value. In addition, there is a decreasing in levels of F_1 and F_2 formants and a rising in level of F_3 formant of the following vowel. This result has not been reported in other works on the Arabic language cited in this paper. Furthermore, we note a continuation of lowering of energy during pronunciation of plosive phonemes and fricative phonemes in geminated context. In the articulatory domain, we observe a higher tongue velocity at oral closure and an important articulatory force, and consequently enhanced tongue palate impacts, resulting in additional increase in linguopalatal contact. These results suggest also that the geminate consonant do not present two distinct articulatory movements, but only one movement which differs from that of the non geminate counterpart by an important closure interval and a higher articulatory stability.

In future perspective, this work may be exploited in Automatic Speech Processing (ASP). In Concatenative Speech Synthesis (CSS), the number of pre-stored units of the database can be diminished to the half by the modelling of the [VC_gV] units, where C_g represents the geminate consonant. In Automatic Speech Recognition (ASR), it can minimize confusions between the geminate consonant and its non-geminate counterpart. As mentioned in the introduction, the gemination process is very relevant to the Arabic Language. So contextual information is necessary in order to determine the appropriate pronunciation and the meaning of the word. A simple confusion between C_g and C_{ng} may change significantly the meaning of the word and therefore the meaning of the sentence or the Arabic text. Hence the importance of the control of acoustic and articulatory parameters of the gemination process to improve the rate of ASR in the Arabic language, by discrimination of phoneme's durations.

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