Kinematic study of Moroccan Arabic simple and geminate obstruents: Evidence from transillumination

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Abstract. *In this study we provide transillumination data on the laryngeal gestures of Moroccan Arabic simple and geminate obstruents produced in [VCi(Ci)V-] context. Our data showed that the geminate obstruents are produced with a larger maximal glottal opening (MGO) than their simple cognates (214% for fricatives; 163% for the plosives). Additionally, the values for peak velocity of glottal abduction and adduction gestures are higher during geminates than during simple obstruents. The relative duration of acceleration and deceleration phases of the adduction gesture show that the latter is strongly influenced by aerodynamic parameters. Results are discussed with respect to the question of whether durational differences in the laryngeal gestures between simple and geminate obstruents are only a passive consequence of other control parameters (e.g. stiffness or aerodynamic parameters) or are explained by an active control ('intragestural and intergestural timing').*

1. Introduction

The question of whether timing is actively controlled or is a passive consequence of other control parameters is still a hot topic in the speech motor control domain. We will here focus on a comparison between simple consonants (Si) and geminates (SiSi) where the total duration of the acoustic signal constitutes the major difference. According to Löfqvist (2005: 858), "not much is known about possible differences in the articulation of long and short consonants". In fact, the segment's duration can vary not only for segmental and phonological reasons (opposition of quantity), but also due to secondary effects such as changes of the prosodic context or speech rate. Moreover, there are major differences in the kinds of movement targets involved in the different cases where duration is relevant, for example collision of upper and lower lips in bilabial consonants (Löfqvist, 2005), generating a specific mouth aperture for vocalic articulation (Hertrich & Ackermann, 1997), and opening the glottis where a specific spatial target may be only weakly defined. This study tests the predictions of selected kinematic hypotheses which were proposed in the literature to explain the articulatory mechanisms responsible for timing variations linked to the phonological opposition of quantity.

According to the "mass spring model" (Kelso et al. 1986; Turvey et al., 1986), variations in the time are passive consequences of a difference in the degree of stiffness (hypothesis1) and are not actively controlled: compared to its short cognate, a long segment has a lower degree of stiffness. Several measures have been proposed to quantify the degree of stiffness. Perhaps the most commonly used one is to estimate the gradient of the relationship between Vmax and amplitude.

Hertrich & Ackermann, 1997, found slightly shallower slopes (i.e. lower stiffness) for long vs. short vowels in German. Löfqvist, 2005, investigated bilabial consonants in Japanese and found higher amplitude for geminates vs. singletons but very similar peak velocity, again suggesting lower stiffness for the longer sounds (Löfqvist was actually principally interested in testing a rather different hypothesis, namely that geminates are mainly controlled via a higher virtual target for the lower lip with the expectation of a higher peak velocity, giving a longer and firmer closure).

Further issues concern the similarity of the velocity profiles of opening and closing movements, and, moreover, the symmetry of the velocity profiles, i.e. the relative duration of acceleration and deceleration phases. For example, Hertrich and Ackermann, 1997 found that opening and closing gestures behave differently for the realization of long vs. short vowels in German. Indeed, Hertrich et al. (1997: 523) observed "a longer deceleration phase of the opening and an increased acceleration interval of the closing movement in long as compared to short vowels" which permits, according to these authors, to maintain the active articulator close to its target as long as possible. Hertrich et al. (1997) attributed the lengthening of the relative acceleration phase of the closing gesture to another type of articulatory adjustment ('intragestural timing': hypothesis2). The lengthening of the deceleration phase is produced to avoid truncation of the opening gesture by anticipation of the closing gesture ('intergestural timing': hypothesis3). Although these results are obtained for movements of different articulators, we will use these ideas as possible speech motor control principles and examine their applicability to laryngeal movements.

These hypotheses will be discussed by focusing on the control of timing in laryngeal gestures (abduction + adduction) of intervocalic Moroccan Arabic (MA) simple and geminate consonants. We will also analyse the relations between kinematic properties of the laryngeal gestures and aerodynamic parameters, since aerodynamics plays a major role with respect to laryngeal behaviour.

2. Method

A flexible endoscope has been inserted through the nostril of a Moroccan Arabic speaker (38 years). Two photosensors have been placed on the external surface of the neck, PGG1 (between the thyroid and cricoid cartilages) and PGG2 (below the cricoid) to capture the quantity of light that passes through the glottis and that is proportional to its opening degree (Figure 1). The analysis has been made on the PGG2 signals since they were more stable. Additionally, we recorded the endoscopy on video to provide further qualitative evidence of glottal activity. Acoustics were recorded on DAT at 24 kHz sampling frequency. The speaker repeated seven times a corpus composed of words and nonsense words containing all MA simple consonants ([-iCi]) and geminates ([-ɨCCi-]). We present here results for [f s x t k k ff ss xx tt kk qq].

We analyzed the audio data using Praat, the glottal aperture by means of Matlab, and the statistics by means of StatView. Figure1 illustrates all the measures (except VOT).

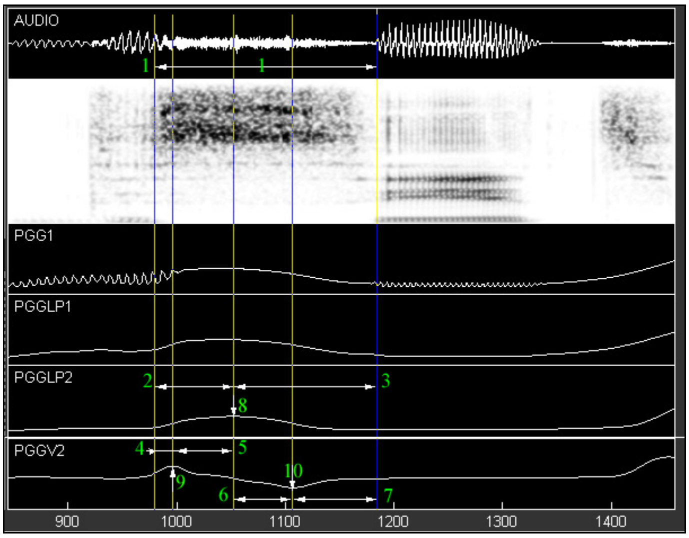

Figure 1: 1: Total duration (TLD); 2: Duration of the abduction phase (ABD); 3: Duration of the adduction phase (ADD); 4: Relative duration of the acceleration phase (measure4/measure2) of the abduction gesture (ACC-ABD); 5: Relative duration of the deceleration phase (measure5/measure2) of the abduction gesture (DEC-ABD); 6: Relative duration of the acceleration phase (measure6/measure3) of the adduction gesture (ACC-ADD); 7: Relative duration of the deceleration phase (measure7/measure3) of the adduction gesture (DEC-ADD); 8: Maximal glottal opening (MGO); 9: Maximal velocity of the abduction gesture (Vel-ABD); 10: Maximal value of the adduction gesture (Vel-ADD).

3. Results and discussion

The interpretation of our data is based on 8 one-factor ANOVAs. The independent variable for 7 tests is constituted by [f s x ff ss xx t k q tt kk qq] and [t k q tt kk qq] for the eighth (figure 1). The dependent variable varies with the consonant:

(i) Four duration measures: Total Duration (TLD: [$F(11, 72) = 105.484$ $p<0.0001$]), duration of the abduction (ABD: [$F(11, 72) = 45.670$ $p<0.0001$]) and adduction phases (ADD: [$F(11, 72) = 43.024$ $p<0.0001$]), Voice onset time (VOT ($F(5, 36) = 28.968$ $p<0.0001$]). (ii) Four kinematic measures: Maximal glottal opening (MGO: [$F(11, 72) = 39.890$ $p<0.0001$]), Maximal velocity of abduction and adduction gestures (VEL-ABD: [$F(11, 72) = 33.212$ $p<0.0001$]; VEL-ADD: [$F(11, 72) = 35.485$ $p<0.0001$]), and relative duration of acceleration and deceleration phases of abduction (ACC-ABD: [$F(11, 72) = 10.750$ $p<0.0001$]; DEC-ABD: [$F(11, 72) = 10.750$ $p<0.0001$]) and adduction gestures (ACC-ADD: [F(11, 72) = 18.214 p<0.0001]; DEC-ADD: [F(11, 72) = 18.214 p<0.0001]).

3.1 Temporal results

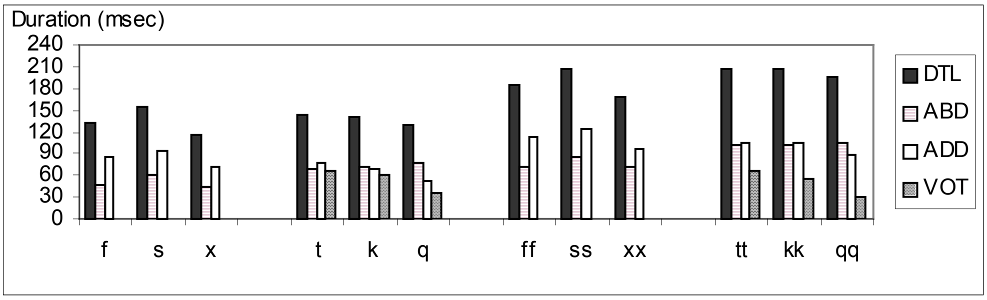

Figure 2. Mean values of total duration (TLD); duration of the abduction (ABD) and adduction (ADD) phases of [f s x t k q ff ss xx tt kk qq]; and VOT of [t k q tt kk qq] in $VC_i(C_i)V$ contexts (see Fig.1).

The aposteriori PLSD Fisher tests show that TLD of the geminates is significantly longer than that of their simple cognates (p<0.001). The adduction phase of fricatives is longer than the abduction. The plosives have similar duration of abduction and adduction gestures during [t k tt kk] and a shorter adduction is found during [q qq]. This difference between [t k tt kk] and [q qq] can be attributed to the VOT which is longer during the first than during the second (Figure 1).

3.2 Maximal glottal opening amplitude

During [f s], the MGO is identical ([f vs s] p=0.47), but significantly lower than that of [x] (p <0.001). Our previous aerodynamic analyses (Zeroual, 2003) showed that, inter-vocalically, the oral airflow (U) during [x] is higher than that of [s], even though their intraoral pressure (Po) values are not different. This result suggests that the mean cross-sectional area of the supralaryngeal (dorsal) constriction is larger during [x] compared to [s]. The larger opening of the glottis during [x] (figures 3 and 4) supports a higher transglottal airflow in order to produce a sufficient value of Po to generate a turbulence at the level of the supralaryngeal constriction even though the latter is large.

[t k q] possess an MGO that is statistically identical between them and to that of [f s], but lower than that of [x] (p <0.001). The absence of difference between, for example, [t k] and [f s] ([t vs f] p=0.88; [t vs s] p=0.38; [k vs f] p=0.66; [k vs s] p=0.47) doesn't agree with a general tendency according to which the glottis is more open during the fricatives that during the plosives (Hoole, 1999 for review). The fact that the VOT of [t] (67 ms) and [k] (61 ms) is substantial may explain why the amount of the glottal opening is identical during [t k f s].

The geminates possess an MGO that is larger than their simple correspondents (for all Ci vs CiCi oppositions p<0.02). The ratio geminate/simple for the fricatives (214%) is higher than for the plosives (163%). This asymmetry is in accordance with the results of Sawashima and Miyasaki (1973) who observed that the difference between the peak glottal opening of simple and geminate is significant for the fricatives and non-significant for the plosives. Notice that [xx] has a MGO that is larger than that of all the other geminate consonants, even larger than that of [ff ss] ($p < 0.001$).

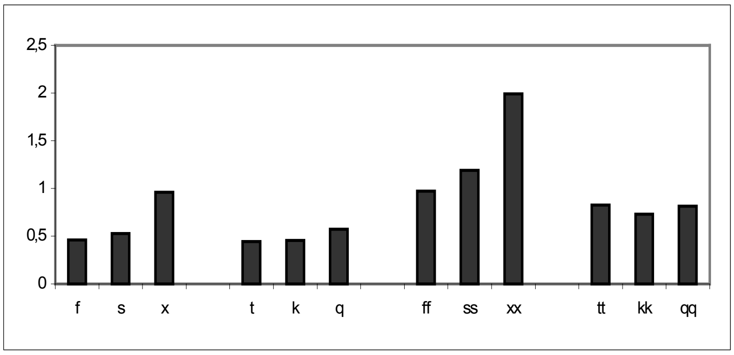

Figure 3. Maximal glottal opening during simple and geminate obstruent production: y-axis: glottal opening of PGG2 in mV, x-axis: obstruents.

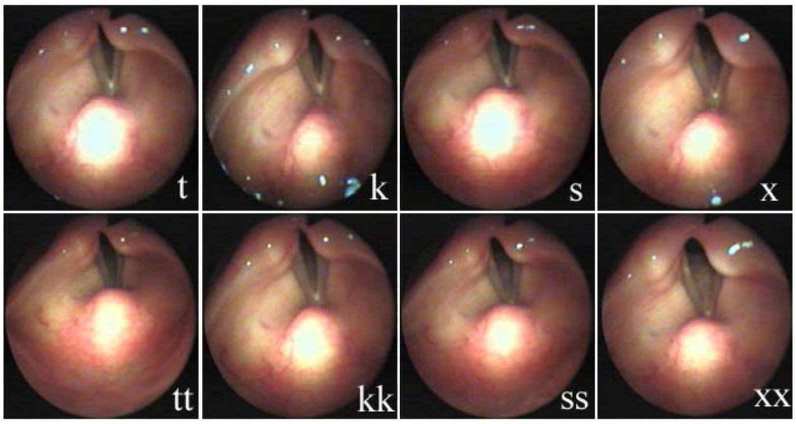

Figure 4. Laryngeal postures during maximal glottal opening of simple and geminate obstruent [t k s x tt kk ss xx]: endoscopic data.

3.3 Velocity of abduction and adduction gestures

The velocity of the abduction and adduction gestures is greater during [x] compared to [f s] ($p<0.01$; $p<0.01$) and [xx] to [ff ss] ($p<0.001$; $p<0.001$). These results are expected, since the MGO is larger during [x] and [xx] compared to their correspondents [f s] and [ff ss]. Indeed, several previous articulatory analyses, show a positive linear correlation between the values of the amplitude and the velocity.

The values of abduction and adduction Vmax of [ff ss xx] and [tt kk qq] are statistically greater than those of their simple cognates [f s x] et [t k q] ([f] vs. [ff], [s] vs. [ss] and [x] vs. [xx]; VEL-ABD $p<0.001$; VEL-ADD $p<0.001$; [t] vs. [tt] $p<0.03$, $p<0.01$; [k] vs. [kk] $p<0.05$, $p<0,011$). Only the [q] vs. [qq] opposition develops asymmetric behaviour (VEL-ABD $p=0.15$; VEL-ADD $p<0.05$). These results are also expected, since the plosives and the geminate fricatives have MGOs that are significantly higher than that of the corresponding singleton.

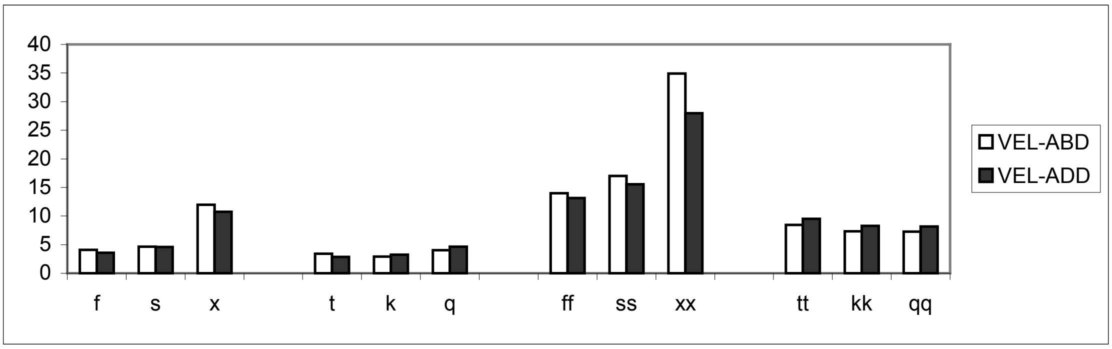

Figure 4. Peak velocity in mV/s for the abduction (white bars) and adduction gestures (black bars). Obstruents are given on the x-axis.

Löfqvist (2005) showed that Vmax of the lower-lip closing gesture of the intervocalic oral and nasal geminate plosives in Japanese is generally lower (but not significantly) than that of simple consonants, even though the amplitude of the geminates is generally larger. This result indicates, according to Löfqvist (2005), that a significant positive correlation between amplitude and Vmax is observed only when it is calculated for the same gesture produced in the same context (i.e. for the simple and the geminate analyzed separately). Similar statistical analyses carried out on our dataset (Table 1) for the gestures of abduction and adduction show, however, that all velocity vs. amplitude correlations are positive and significant whether they are calculated for each context individually or for the two contexts together.

This suggests that in our data there is less difference in stiffness between singletons and geminates than was found in Löfqvist's study. Examining the stiffness directly, i.e. the gradient of the velocity-amplitude relation, we actually found a significant difference contrary to the expected direction of lower values for the geminates. In view of possible non-linearities in the transillumination signal it might be hazardous to assume that geminates genuinely show higher stiffness. However, at least it appears very unlikely that their longer duration is regulated via lower stiffness.

	[f s x t k q]	[ff ss xx tt kk qq]	[f s x ff ss xx t k q tt kk qq]
Abduction	0.871	0.968	0.962
Adduction	0.878	0.975	0.973

Table 1: Values for the Pearson correlation coefficient (r) between peak glottal opening (OGM) and peak velocity in the abduction and adduction gestures calculated for the different obstruent groups (column 2-4); All data are significant at $p<0.001$.

3.4 Relative duration of acceleration and deceleration phases.

For the abduction movement, the predominant pattern was that the acceleration phase was shorter than the deceleration phase (figure 5). This applied to both single and geminate fricatives, and to single plosives. The only exceptions to this were the two geminate plosives /tt/ and /kk/ where acceleration and deceleration were fairly similar in duration. For the adduction movement the relative durations of acceleration and deceleration were very similar, with only single /q/ being a major exception.

Larynx movements thus appear to behave differently from e.g. the vowel-related lip movements studied by Hertrich & Ackerman: They found quite a clear mirror-image pattern with relative duration of the acceleration phase longer for the short vowels on the opening movement (assuming this to correspond to abduction in our case), but longer for the long vowels on the closing movement (see also Hoole & Mooshammer, 2002, for similar findings). The fact that we found clearest departures from a symmetrical velocity profile for fricatives in general, together with the short plosives, may reflect the aerodynamic requirements for fast initiation of glottal abduction: geminate plosives on the other hand, may simply be the sound category with the weakest constraints on initiation of this movement.

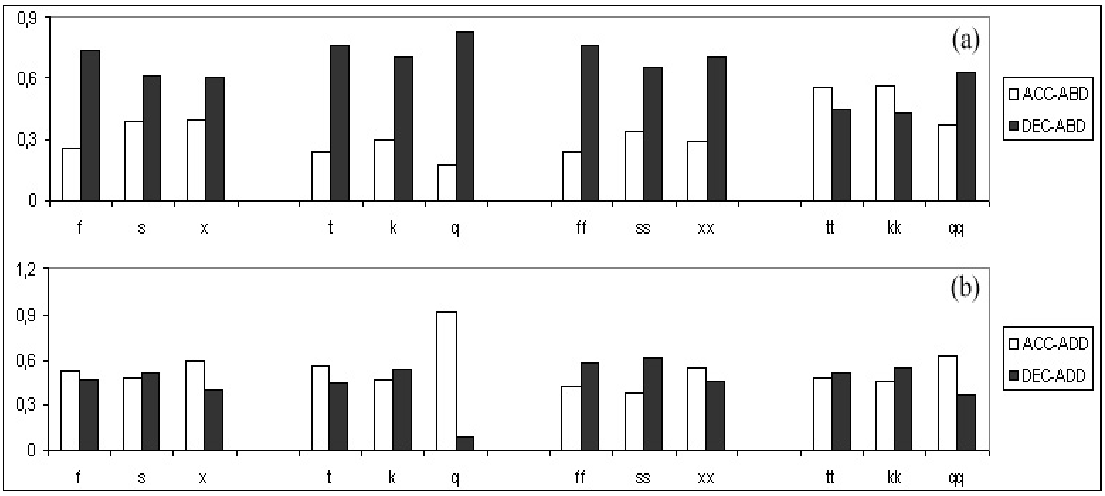

Figure 5. Mean values of the relative duration of (a) the acceleration (ACC-ABD) and deceleration (DEC-ABD) phases of the abduction gesture and of (b) the acceleration (ACC-ADD) and deceleration (DEC-ADD) phases of the adduction gesture in [$VC_i(C_i)V$] contexts for all obstruents.

The adduction gesture of [q] has a relative duration of its acceleration phase that is very long, and a relative duration of its deceleration phase that is very short compared to [t k] ($p<0.001$). It seems that these differences are indirect consequences of the aerodynamic factors. Indeed, the truncation of the deceleration phase of the adduction gesture during [q] is not due to an adjustment of intergestural timing, but to the fact that Po lowers more quickly during [q] compared to [t k] (Zeroual, 2002). The longer duration of the acceleration phase of the adduction gesture is not due to an adjustment of intragestural timing, but to the adduction that begins before the oral release during [q] (-23ms) and at the moment of the oral release (-4ms; -7ms) during [k t] (Zeroual et al. 2006). Indeed, the adduction of the glottis, which starts at the moment of the release during [t k], is accelerated by the decrease of the Po.

Compared to [ff ss], [xx] possesses a relative duration of the deceleration phase of its abduction gesture that is statistically identical to that of [ff ss] ([xx] vs. [ff] $p=0.37$; [xx] vs. [ss] $p=0.29$), the relative duration of the acceleration phase of its adduction gesture is longer ([xx] vs. [ff] $p<0.01$; [xx] vs. [ss] $p<0.001$). We suggest that this second difference is bound to the fact that the MGO is larger during [xx]. It seems that [xx] involves a supplementary adjustment of the intragestural timing that permits lengthening the acceleration phase of its adduction gesture to maintain the glottis very open.

4. Conclusion

This study dealt with the laryngeal kinematic parameters which contribute to the phonological opposition of quantity between intervocalic simple and geminate Moroccan Arabic obstruents. Our main results showed that the obstruents are produced with a larger maximal glottal opening (MGO) than their simple cognates. This ratio is (214%) for fricatives and (163%) for the plosives. The values of maximal velocity of abduction and adduction gestures are higher during geminate than during simple obstruents. This result is expected since velocity and amplitude are generally positively correlated. The relative durations of the acceleration and deceleration phases of the adduction and abduction gestures are strongly influenced by aerodynamic constraints. Our data show that timing is not only a passive consequence of other control parameters such as stiffness or aerodynamic parameters but can also be actively controlled ('intragestural and intergestural timing').

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