Variation in overlap and phonological grammar in Moroccan Arabic clusters

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Abstract

This paper examines inter-consonantal temporal overlap in Moroccan Arabic cluster using electromagnetic articulography. We distinguish two types of variation in overlap: one is due to non-grammatical influences, the other is arguably linked to morpho-phonological distinctions in the grammar. From the first type, we extract a hypothesis that makes strong predictions on cluster overlap and should prove useful to future timing studies and their relevance to phonological patterns. From the second type of variation, we find evidence in support of the claim that aspects of the temporal dimension of phonetic form are at the same level of cognitive status as grammatical principles.

Index

Terms: overlap (consonant cluster), electromagnetic articulography (3D), morphology (concatenative), morphology (templatic), timing relations (consonants), Obligatory Contour Principle, place order effect, word position effect

Languages: English, Georgian, Moroccan Arabic, Russian, Tsou

1. Background

A unique claim of the dynamically-based theory of phonological form developed by Browman and Goldstein (1986, *et seq*.) is that certain aspects of timing are part of the phonological representation. A central hypothesis of that work is that gestures and their timing relations are primitives in the phonological component of linguistic grammars.

There are two key lines of research devoted to this hypothesis. The first attempts to elucidate the nature of phonological units like moras, segments and syllables in terms of the primitives, namely, gestures and their temporal relations—see, among others, Saltzman and Munhall (1989), Browman and Goldstein (1991, 2000), Byrd (1996), Cho (2001), Saltzman and Byrd (2000), Nam and Saltzman (2003).

The second line of research builds grammar models based on dynamical representations. In a study of the phonological system of Moroccan Arabic, Gafos (2002) argues that phonological knowledge can make reference to the temporal dimension of linguistic form. This proposal makes contact with Optimality Theory (Prince & Smolensky, 1993/2004, 1997) by expressing language-particular patterns as the result of optimization under a set of violable constraints, some of which must crucially refer to temporal relations among gestures. Angermeyer (2002), Benus, Smorodinsky and Gafos (2004), Bradley (2002), Davidson (2003, 2006), Hall (2003), and Borroff (2007) also pursue a model of grammar based on dynamical representations and Optimality Theory in analyzing independent phenomena in other languages.

The leading idea shared by these studies is that phonological knowledge is in part temporal. A fundamental starting point is that the basic units of phonological representation have internal temporal structure (Browman and Goldstein 1986).[1] For example, the action effecting the formation of the closure for a bilabial stop can be decomposed into a sequence of spatiotemporal events or *landmarks*, shown in Figure 1(a): ONSET, the beginning of movement toward closure; TARGET, the point in time at which the gesture achieves its closure; RELEASE, the beginning of movement away from closure; and OFFSET, the point in time at which control of the gesture ends. These landmarks delineate the *internal temporal structure* of gestures and, by hypothesis, of their corresponding phonological units. This temporal structure is accessible to the grammar. The phonological grammar refers to temporal relations of overlap between gestures of different segments, or inter-segmental timing relations.[2] This is done via *coordination relations*: a landmark within the temporal structure of the first gesture is synchronous to another landmark within the temporal structure of the second gesture. Examples of coordination relations are shown in Figure 1(b-d). Note that different coordination relations imply distinct amounts of temporal overlap or co-production of the articulatory movements corresponding to the gestures so coordinated. Thus, the relation in Figure 1(b) would be expected to show significant overlap at the level of articulatory execution. The relation depicted in Figure 1(c) would show much less overlap at that same level, and that in Figure 1(d) would show much more overlap than that in Figure 1(c). In principle, this is how we can tell apart different coordination relations from observing movement trajectories. But as emphasized and illustrated via simulations in Gafos (2002: 284-287), the mapping between coordination relations at the level of phonological encoding and resulting movement trajectories is not direct. Variation in factors such as the specific identities of the consonants in a cluster, rate of speech, and random fluctuations in motor output may produce very different movement patterns even if in all instances the abstract coordination relation is the same.

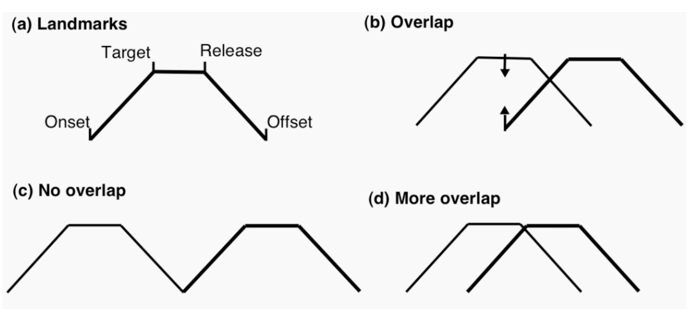

Figure 1. Gesture landmarks and coordination: (a) shows gestural landmarks, (b-d) show different amounts of overlap resulting from different coordination relations between the landmarks of the two gestures.

In developing a theory of how the temporal dimension of phonological form is threaded in language-particular grammars, the empirical base consists in facts that reveal the phonological relevance of distinct temporal relations between gestures. Examples include: allophonic variation expressed via a difference in terms of relations like those exemplified above, preference of one relation over another, assimilation under one relation but not under another, morphologically-specified temporal relations and so on.

Here we review just one example from allophonic variation. Consider the difference between 'clear' and 'dark' allophones of /l/ in many dialects of English, as in *lip, late, lie* versus *pill, feel, cool* ([l] versus [$l^{ɣ}$]). In a-temporal models of phonology, this difference is expressed by saying that the basic allophone is the clear /l/ and in syllable-final position this changes to the 'dark' or velarized version by a feature-change rule adding the feature [+back]. Looking closely at this variation with the X-ray microbeam system, Sproat and Fujimura (1993) discovered that English /l/ is composed of two gestures, a tongue tip 'consonantal' gesture and a tongue dorsum 'vocalic' gesture, and that the relative timing of these varies as a function of syllable position and adjoining prosodic boundary. In syllable-initial position, the two gestures show a synchronous pattern of relative timing, with tongue tip and tongue dorsum attaining their goals at the same time. In syllable-final position, the tongue dorsum gesture significantly precedes the tongue tip gesture, with the tongue dorsum attaining its target at the onset of the tongue tip gesture. In syllable-final position, then, the acoustic portion of the syllable corresponding to the vowel is significantly more overlapped with the tongue dorsum gesture. The acoustic consequence of this difference in overlap is what gives rise to the distinction between the 'clear' and 'dark' variants of /l/.

This finding is of considerable theoretical interest as it shows that what appears to be from a distributional point of view a single /l/ segment is in fact decomposed into two separate elements, a vowel-like gesture and a consonant-like gesture and that the timing of these two gestures is mainly responsible for the distinction between the 'clear' and 'dark' variants of /l/ (Sproat and Fujimura 1993; see also Browman and Goldstein 1995).

For further examples of the role of temporal relations in phonology, see the references above.

1.1. Specific claims

Our primary aim in this paper is to present evidence from Moroccan Arabic for the claim that phonological representations contain information about the temporal organization of segments. We discuss reasons for focusing on Moroccan Arabic in the next section. In this section, we outline the specific claims of the paper.

The empirical base of our claim resides in differences in overlap patterns, though not all such differences qualify as evidence for our claim. We make a distinction between 'non-grammatical' and 'grammatical' differences in overlap. The term 'non-grammatical' is construed in a broad sense. Any difference in overlap that does not derive from a statement about timing in the phonological plan is considered non-grammatical. Consequently, the sources of non-grammatical differences are diverse. They include idiolectal or task-specific speech rate settings, effects on overlap due to the sensorimotor systems involved in lexical access, effects of the phonetic context where a cluster is embedded, and random noise in articulatory execution.

Specifically, in this paper, we argue that the overlap differences between two heterorganic consonants in initial versus medial word position are not phonologically dictated. Equally, the differences between front-to-back and back-to-front clusters do not derive from a requirement at the level of phonological encoding. Note that this characterization does not preclude these or other "non-grammatical" differences in overlap leading over time to phonologized re-interpretations of such differences in language-particular grammars.

In contrast, we argue that other differences in overlap seem to be under grammatical control. Specifically, the overlap differences in clusters of homorganic consonants across a concatenative boundary versus within a template are due to a specification at the level of the phonological representation. Similarly, the overlap differences between a sequence of two heterorganic and a sequence of two homorganic consonants is also due to a phonological dictate.

1.2. Moroccan Arabic

In comparison to the better-studied languages to which most timing studies have been devoted, Moroccan Arabic permits a rather complex set of consonant combinations. Even limiting attention to two-consonant sequences of stops at the word-initial position, all combinations of labial, coronal and dorsal places of articulations are attested, e.g., [gd], [dg], [kb], [bk], [tb], [bt]. Unlike in Georgian, a language that also allows a relatively complex set of word-initial clusters and for which kinematic data are available (Chitoran, Goldstein and Byrd 2002), the laryngeal specifications of the constituent consonants in Moroccan Arabic seem unrestricted, e.g., [bk] and [bt] are not attested in Georgian.

A related characteristic of Moroccan Arabic is that in a sequence of two heterorganic stop consonants, the closure of the first stop must be released before that of the second stop is formed. Dell and Elmedlaoui (2002: 231) state this generalization in terms of a required intervening “audible release”. We will use the closely related but weaker notion of “open transition”, as defined by Catford (1988), because it can be stated in purely articulatory terms and thus can be tested with articulatory data: in open transition “the first stricture is *released* a moment before the second stricture is formed” (Catford 1988: 118; emphasis Catford’s; see also Bloomfield 1933: section 7.9). Open transitions have been observed in acoustic studies on Georgian (Chitoran 1999) and Tsou (Wright 1996) but their presence in the data of these studies does not seem to be systematically enforced in positions other than word-initially. In contrast, the hypothesis for Moroccan Arabic is that the requirement of open transition is independent of the cluster’s word position. One of our aims will be to test this hypothesis and also determine the extent to which it interacts with other factors controlling the precise amount of overlap in clusters.

Another relevant aspect of Moroccan Arabic is its rich system of templatic morphology. The core characteristic of word-formation in languages with this type of morphology is that the words of any given morphological category conform to a shape invariant, called the *template*. For example, in the Fez/Meknes dialect of Moroccan Arabic described in Heath (1987), a class of words known as Professional Nouns conforms to the invariant shape [CCaCC-i], a fixed sequence of consonants and vowels. Representative examples include: /ʒurˤnal/ ‘newspaper’ → [ʒrˤanl-i], /sʷkkar/ ‘sugar’ → [skakrˤ-i], /sˤbbən/ ‘wash clothes’ → [sˤbabn-i], and /brquq/ ‘plums’ → [braqq-i] (all derived words mean ‘dealer in Noun’). A rich system of templatic morphology like that of Moroccan Arabic allows for the control of morphological factors in the study of timing relations. Specifically, in the present study, it enables us to ask whether overlap in any given cluster depends on the morphological environment wherein that cluster is embedded.

Finally, our study is informed by existing detailed analyses of the morpho-phonology of Moroccan Arabic dialects. Notably these include the monograph-length work of Heath (1987), an in-depth analysis of the morphology and phonology of the Fez/Meknes dialect, and the work of Dell and Elmedlaoui (2002) who devote two chapters of their book to the syllable structure of Lmnabha Moroccan Arabic. In the context of the analytical sophistication in these works, the goals of the present paper are necessarily limited. A prerequisite in evaluating proposals on the detailed workings of syllabification using phonetic data is an understanding of the basic phonetic properties of consonant clusters.

2. Methodology

2.1. Speakers

The subjects recorded for this experiment were 2 male native speakers of the Oujda dialect of Moroccan Arabic (spoken in Northeast Morocco, near the Algerian-Moroccan border), ages 38 and 28. The subjects were paid for their participation in the experiment.

2.2. 3D Electromagnetic Articulography

The movement of speech articulators was tracked with 3D Electromagnetic Articulography (Hoole, Zierdt, and Geng 2003) (EMA) at 200 Hz sampling rate, with concurrent audio recordings at 24 kHz. Recording sessions were conducted at the EMA lab in the Institut für Phonetik und Sprachliche Kommunikation, Ludwig-Maximilians-Universität München, Germany. EMA sensors used in the present analyses were attached to the speaker's lower lip, tongue tip, and tongue back. The tongue tip sensor was located about 1cm from the tongue apex. The tongue back sensor was located about 4 cm behind the tongue tip sensor. Additional sensors attached to upper incisors, bridge of nose and left and right side of head behind the ears were used to compensate for head movement.

2.3. Stimuli

For both speakers, data were collected for consonant sequences in three word positions: word-initial, -medial, and -final. Two types of dyadic consonant sequences were analyzed in each word position: "CC" (no vowel can appear inter-consonantally) and "C^C" (an optional schwa-like vocoid can appear between the two consonants).

All stimuli were real words produced within a carrier phrase presented on a computer screen in Arabic script. The session with Speaker 1 (author CZ) was a pilot study where our primary aim was to collect a lot of data with a large corpus. For subsequent sessions, we had to limit the corpus so as to make the study feasible with other subjects. This resulted in differences between the stimuli used for Speaker 1 and Speaker 2. The specific clusters and number of stimuli for each speaker are presented separately below. Since many stimuli are used for multiple analyses, a comprehensive list of all stimuli with glosses and template information is presented in Appendix A.

Speaker 1 read five randomizations of the stimuli at a normal self-paced rate. The carrier phrase for this speaker was *gal* _____ *tɨlt mɨrrˤat* 'he said _____ three times'. On occasion this resulted in the tongue tip gesture of the [l] in *gal* merging with word-initial tongue tip gestures in some tokens. Such tokens were excluded from all analyses. Speaker 2 read five randomizations of all stimuli at a normal self-paced rate. The carrier phrase for this speaker was changed to *galha* _____ *hnaya* 'he told him _____ here' to avoid the merged tongue tip problems encountered with Speaker 1.

2.4. Identifying gestures

Though at least in some cases gestures involve the synergistic activity of multiple articulators (or "coordinative structures"; Fowler *et al*. 1980), we make the simplifying assumption that (the temporal extent of) gestural units can be approximately delineated by limiting attention to movement captured in the kinematics of a single sensor. The EMA sensor used to delineate the gesture for each consonant was the one corresponding to the consonant's primary oral articulator— tongue tip: /d/, /t/; tongue back: /g/, /k/; lower lip: /b/ (as in Classical Arabic, there is no /p/ in Moroccan Arabic).

Gestural landmarks were identified using MATLAB-based code for analyzing EMA data, developed at Haskins Laboratories by Mark Tiede and adapted to our data by us. Identification was based on tangential velocity extrema—the maximum velocity of the primary oral articulator during the gesture's closing phase (that is, from Onset to Target) and the maximum velocity during the gesture's opening phase (that is, after Release). Gestural Onset was the point before the peak velocity of the closing phase when the velocity increased beyond a certain small percentage (20%) of the peak velocity. The Target was the point after the peak velocity of the closing phase when the velocity dropped below the 20% threshold. Finally, the Release is found in the same way, using the same velocity threshold value, only this threshold applies to the peak velocity of the opening movement. Note that landmarks such as Target identified in this way do not necessarily correspond to the time point of actual contact between a primary oral articulator and the palate.

2.5. Overlap measure

The index used to measure overlap was the difference between the time points of C2 Onset and C1 Target, divided by the duration of the C1 Plateau, as defined in Figure 2.

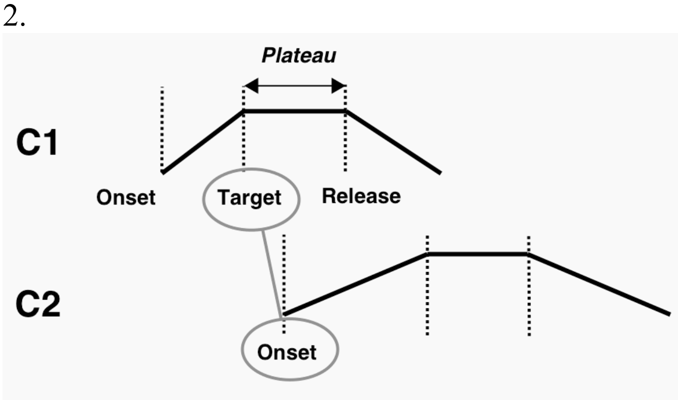

Figure 2. Overlap = 1 - (Onset C2 - Target C1)/(Plateau C1), where C1 and C2 are the first and second consonants in the cluster, respectively

This is essentially the same measure as that used by Chitoran *et al*. (2002) in that it quantifies overlap as the proportion of C1's closing phase that is coextensive with the unfolding C2 gesture. The only difference is that by subtracting (Onset C2 - Target C1)/Plateau C1 from 1, higher values indicate more overlap (whereas the inverse is true for Chitoran *et al*.'s index). Table I and Figure 3 show what different values of our measure indicate about the relative timing of the different gestural landmarks.

Table I. Meaning of ranges of overlap values

C2 Onset	Relative Overlap Value	Indicates
A	> 1	C2 Onset occurs before C1 Plateau
B	between 0 and 1	C2 Onset occurs sometime during C1 Plateau
C	= 0	C2 Onset occurs at same time as C1 Release
D	< 0	C2 Onset occurs after C1 Release

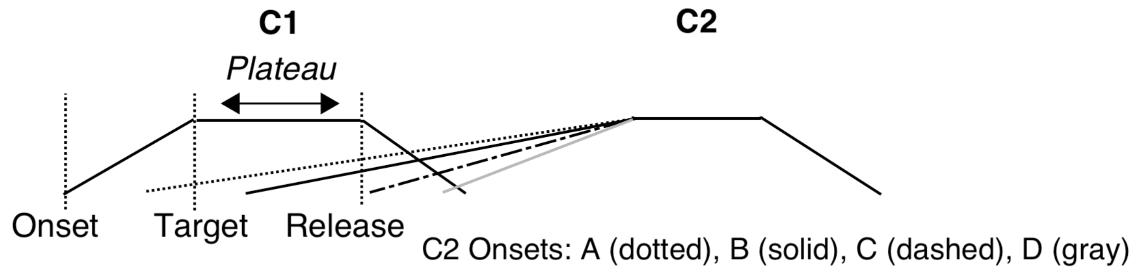

Figure 3. Overlap depictions corresponding to Table I

3. Non-grammatical differences in overlap

Our primary goal in this section is to examine which effects observed in previous studies of overlap in other languages hold or do not hold true in the Moroccan Arabic data we have collected. We also rationalize the absence of any such effects by revising previous hypotheses to incorporate our evidence from Moroccan Arabic. We report here on the effects of two factors on gestural overlap: position of cluster within the word and order of place of articulation.

3.1. Word position hypothesis

Previous studies have shown that consonant clusters exhibit less overlap word-initially than word-medially (on English see Hardcastle 1985, Byrd 1996; on Tsou see Wright 1996; on Georgian see Chitoran *et al*. 2002). Chitoran *et al*.'s interpretation of this effect has been that word-initial clusters have less overlap because word-initial clusters may also be utterance-initial and therefore lack a preceding vowel to provide acoustic cues to C1 stops (see discussion in Redford and Diehl 1999), and because word-initial phonetic detail is important for lexical access (Marslen-Wilson 1987).

3.1.1. Analysis

The effect of word position on overlap in CC clusters was examined. Space limitations only allow us to discuss results on stop-stop clusters. Most data on inter-consonantal overlap is on stop-stop clusters. Also, the interpretation of the word position effect discussed above seems particularly applicable to stop-stop clusters. Unlike fricatives or liquids, stops do not have acoustic cues during closure (see Jun 2004 for discussion) and therefore according to the interpretation of the word position effect above it is in the context of stop-stop sequences where substantial overlap most directly threatens recoverability of individual gestures. We limited attention to those clusters that existed in at least two word positions. This was done in order to control for consonant- or cluster-specific effects on the amount of overlap. For example, the data for Speaker 2 contained [gb] word-initial and -medial clusters but not word-final ones. Therefore [gb] clusters were included only in the initial vs. medial comparison.

Within each word position pair comparison (i.e., initial vs. medial, initial vs. final, medial vs. final), separate ANOVAs were run for each speaker with relative overlap as the dependent variable, and word position and cluster as independent variables. Each word position pair combination was analyzed separately for each speaker. Of main interest are the results of cluster word position. The effect of cluster and the interactions between cluster word position and cluster are reported, but a detailed cluster-by-cluster analysis is beyond the scope of the present study. The interested reader is referred to "Appendix B: Cluster effects by word position" for details.

Table II shows the clusters and number of tokens that were included for each word position comparison for Speaker 1.[3] Table III shows the clusters and number of tokens that were included for each word position comparison for Speaker 2. Since the number of tokens in each group were often different, we used the General Linear Model Type III Sum of Squares (using SPSS version 11.0.4) in these ANOVAs and those that follow in later sections. Table IV summarizes how the present study compares to previous studies of word position effects on overlap as far as the number and set of clusters used.

Table II. Cluster stimuli used to test Word Position Hypothesis for Speaker 1

Cluster	Initial vs. Medial	Initial vs. Final	Medial vs. Final
N tokens (clusters)	*47 vs. 50 (7)*	*32 vs. 30 (5)*	*41 vs. 35 (6)*
[bd]	*bdat* vs. *ʒabda*, *kɨbda*	*bdat* vs. *ʕɨbd*	*ʒabda*, *kɨbda* vs. *ʕɨbd*
[bk]	*b-kas*, *bkat* vs. *tqɨb-kum*		
[bt]	*b-taʒ*, *btas^m* vs. *nabta*, *tqɨb-tu-h*	*b-taʒ*, *btas^m* vs. *tqeb-t*, *ssɨbt*	*nabta*, *tqɨb-tu-h* vs. *tqeb-t*, *ssɨbt*
[db]			*kadba* vs. *kɨdb*

[dg]	*dgig* vs. *ħadga*	*dgig* vs. *fŭdg*	*ħadga* vs. *fŭdg*
[gd]	*gdat* vs. *ʕagda*	*gdat* vs. *ħɨgd*	*ʕagda* vs. *ħɨgd*
[kt]	*ktab*, *ktɨb* vs. *sakta*	*ktab*, *ktɨb* vs. *slɨk-t*	*sakta* vs. *slɨk-t*
[tb]	*tbɨʕ* vs. *kɨtba*, *ratba*		

Table III. Cluster stimuli used to test Word Position Hypothesis for Speaker 2

Cluster	Initial vs. Medial	Initial vs. Final	Medial Vs. Final
N tokens (clusters)	*35 vs. 35 (7)*	*19 vs. 19 (4)*	*20 vs. 19 (4)*
[bd]	*bdat* vs. *ʒabda*	*bdat* vs. *ʕɨbd*	*ʒabda* vs. *ʕɨbd*
[bg]	*bgɨr* vs. *sabga*		
[db]	*dbal* vs. *kadba*	*dbal* vs. *kɨdb*	*kadba* vs. *kɨdb*
[dg]	*dgig* vs. *ħadga*	*dgig* vs. *fŭdg*	*ħadga* vs. *fŭdg*
[gb]	*gbali* vs. *ragba*		
[gd]	*gdat* vs. *ragda*	*gdat* vs. *ħŭgd*	*ragda* vs. *ħŭgd*
[kt]	*ktab* vs. *sakta*		

Table IV. Number of clusters analyzed for word position effects in selected studies. The language investigated is indicated after the study reference.

Study	Initial vs. Medial	Initial vs. final	Medial vs. Final
Present *Moroccan Arabic*	**7** vs. **7** *(Spkr 1)* **7** vs. **7** *(Spkr 2)*	**5** vs. **5** *(Spkr 1)* **4** vs. **4** *(Spkr 2)*	**6** vs. **6** *(Spkr 1)* **4** vs. **4** *(Spkr 2)*
Hardcastle (1985) *English*	**1** [kl]	***none***	***none***
Byrd (1996) *English*	***none***	1 [sk]	***none***
Wright (1996), clusters not matched across word position *Tsou*	**6** vs. **6** [pt] vs. [pt] [pɓ] [pɓ] [pk] [tp] [tp] [tk] [tɓ] [tɓ] [kɗ] [kɗ]	***none***	***none***
Chitoran, Goldstein and Byrd (2002) *Georgian*	**6** vs. **6** [bg], [p^{h}t^h], [dg], [gb], [t^{h}b], [gd]	***none***	***none***

3.1.2. Results

The Word Position Hypothesis entails that word-initial clusters have less overlap than word-medial clusters. This prediction was supported for Speaker 1, as shown in Figure 4: there was a main effect of cluster word position, with word-initial clusters having significantly less overlap than word-medial clusters, $F(1, 83) = 39.028, p < 0.001$. In addition, the effect of cluster was significant ($p < 0.001$), as was the interaction between cluster and cluster word position ($p < 0.005$). As shown in Figure 5, word-initial clusters also had significantly less overlap than word-final clusters, $F(1, 52) = 17.782, p < 0.001$, and the effect of cluster was significant ($p < 0.001$), as was the interaction between cluster word position and cluster ($p < 0.01$). Word-medial and word-final clusters were also significantly different from each other, $F(1, 64) = 6.295, p < 0.05$, with word-final clusters having less overlap than word-medials, Figure 6. Again, the effect of cluster was significant ($p < 0.001$), as was the interaction of cluster and cluster word position ($p < 0.05$). Means and standard deviations of the cluster word position comparisons are shown in Table V.

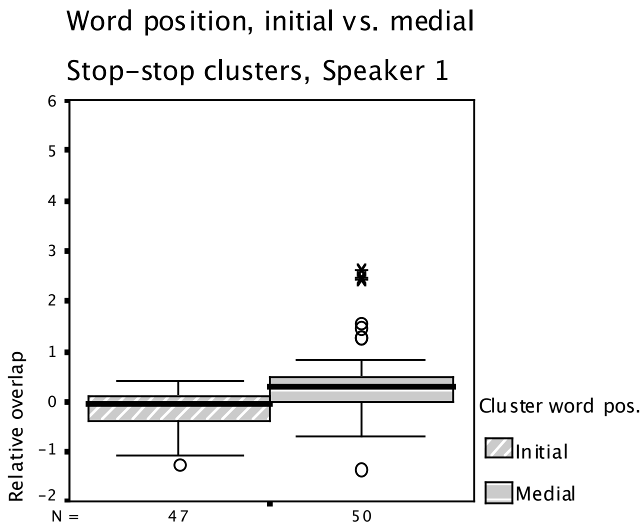

Figure 4. Boxplots showing initial vs. medial word position effects for Speaker 1. Here and in the following, the horizontal thick dark line within each boxplot shows the median overlap value. Boxes encompass values between the first and third quartiles. Circles and asterisks represent outliers and extreme values, respectively.

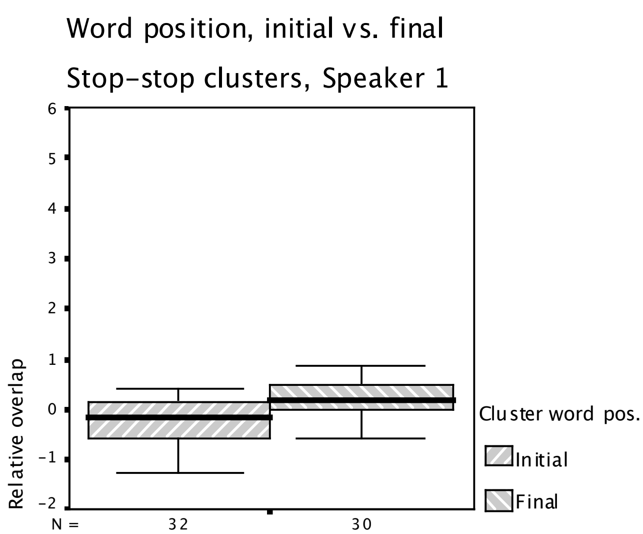

Figure 5. Initial vs. final word position effects for Speaker 1

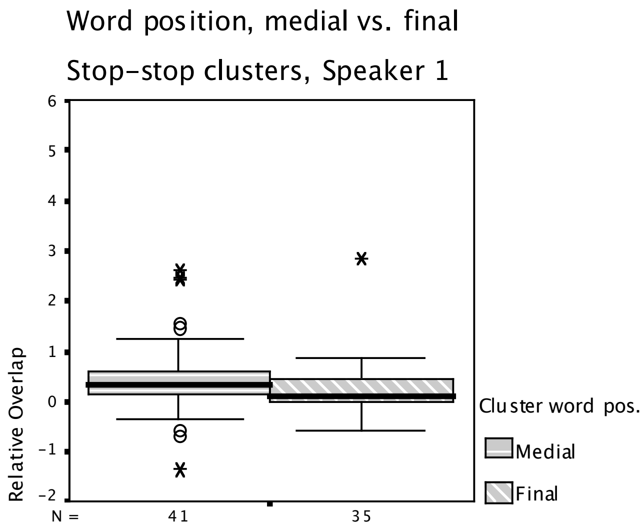

Figure 6. Medial vs. final word position effects for Speaker 1

Table V. Means and standard deviations of overlap in clusters by word position comparison, for Speaker 1. Significant differences are noted in the last column.

Word position:	initial		medial		final		
Comparison	**mean**	*SD*	**mean**	*SD*	**mean**	*SD*	sign.
initial vs. medial	**-0.18**	*0.40*	**0.38**	*0.74*			$p < 0.001$
initial vs. final	**-0.25**	*0.45*			**0.18**	*0.37*	$p < 0.001$
medial vs. final			**0.46**	*0.79*	**0.23**	*0.57*	$p < 0.05$

For Speaker 2, overlap patterns trended per hypothesis with initial clusters having the least overlap measured by the medians, as shown in Figure 7 and Figure 8. This trend was not significant, neither in the initial vs. medial ($p = 0.216$), nor in the initial vs. final ($p = 0.166$), nor the medial vs. final ($p = 0.575$) comparisons. The effect of cluster was significant in the initial vs. medial ($p < 0.05$) and initial vs. final ($p < 0.001$) comparisons, but not in the medial vs. final comparison ($p = 0.200$). The interaction of cluster and cluster word position was not significant in the initial vs. medial comparison ($p = 0.193$), but was significant in the initial vs. final ($p < 0.05$) and medial vs. final ($p < 0.001$) comparisons. Means and standard deviations for cluster word position are shown in Table VI.

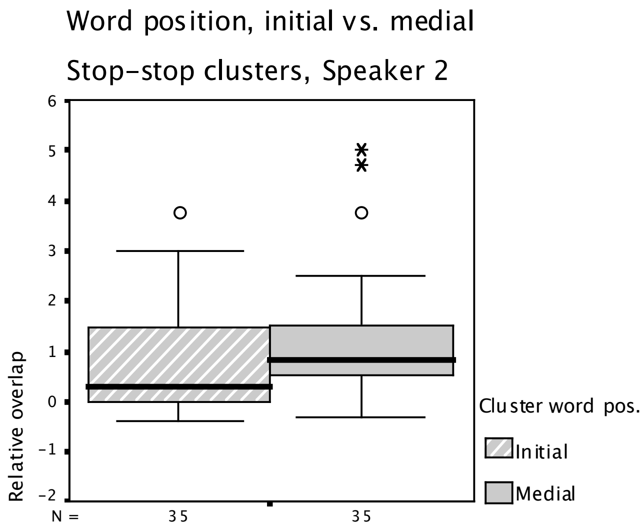

Figure 7. Lack of initial vs. medial word position effects for Speaker 2

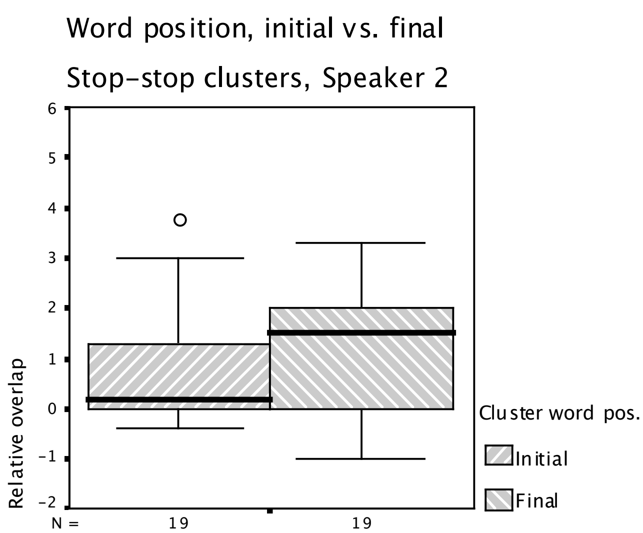

Figure 8. Lack of initial vs. final word position effects for Speaker 2

Table VI. Means and standard deviations of overlap in clusters by word position comparison, for Speaker 2. As noted in the last column, there were no significant differences.

Word position:	initial		medial		final		
Comparison	**mean**	*SD*	**mean**	*SD*	**mean**	*SD*	sign.
initial vs. medial	**0.90**	*1.16*	**1.23**	*1.18*			$p = 0.216$
initial vs. final	**0.74**	*1.22*			**1.14**	*1.28*	$p = 0.166$
medial vs. final			**1.37**	*1.52*	**1.14**	*1.28*	$p = 0.575$

3.2. Place order hypothesis

Previous studies provide evidence for an effect of place order on the degree of overlap in oral stop-stop clusters. This effect is that "front-to-back" clusters like [tk], [pt] show more overlap than "back-to-front" clusters like [kt], [tp] (Hardcastle and Roach 1979; Byrd 1992, 1996; Zsiga 1994; Surprenant and Goldstein 1998; Chitoran *et al.* 2002). In the former set of clusters, C1 constricts the vocal tract at a place of articulation anterior to that of C2, hence "front-to-back". In the latter, the relative order of constrictions is reversed, hence "back-to-front". The interpretation of this effect is that the degree of overlap in a stop-stop cluster is constrained in contexts where perceptual recoverability of C1 is at risk. This is the case when C2's closure is at a place of articulation anterior to that of C1, that is, the back-to-front order. Assume that in a cluster like [tp] the labial closure is formed while the tongue tip closure is still in place. Given this overlap pattern, the release of C1 closure will not have audible consequences (in IPA, [t̚p]) because the coronal constriction is posterior to the labial. In contrast, in a front-to-back cluster like [pt] and under the same overlap pattern, some acoustic information will necessarily be present at the release of C1 closure, because the labial constriction is anterior to the coronal. This asymmetry in the distribution of acoustic cues to C1 has been claimed to be responsible for the place order effect. In back-to-front clusters, overlap is constrained (more than in front-to-back clusters) because starting C2's closure too soon will obscure the acoustic cues of C1.

3.2.1. Analysis

The effect of place order on overlap in stop-stop CC clusters was examined for all clusters where C1 and C2 differed in place of articulation. Clusters were limited to those where in a given word position for each back-to-front C1C2 cluster there was a corresponding C2C1 front-to-back cluster, e.g., initial [bd] and [db], for the same reasons given in our analysis of word position effects.

Univariate ANOVAs were run to compare the effect of place order on relative overlap, across three word positions. Relative overlap was the dependent variable, with place order and cluster word position as the independent variables.

Table VII shows the clusters and number of tokens that were included for each place order comparison for Speaker 1. Table VIII shows the clusters and number of tokens that were included for each place order comparison for Speaker 2. Table IX summarizes how the present study compares to previous studies of place order effects on overlap as far as the number and set of clusters used.

Table VII. Cluster stimuli used to test the Place Order Hypothesis for Speaker 1

	word-initial	word-medial	word-final
N tokens, BF vs. FB (clusters)	*15 vs. 21 (6)*	*31 vs. 40 (10)*	*11 vs. 10 (4)*
Back-to-Front	[gd], [kb], [tb] *gdat* *kbaʃ* *tbɨʕ*	[db], [gd], [kb], [kt], [tb] *kadba* *ʕagda* *rakba*	[db], [gd] *kɨdb* *hɨgd*

		sakta *kɨtba, ratba*	
Front-to-Back	[dg], [bk], [bt] *dgig* *b-kas, bkat* *b-taʒ, btas^m*	[bd], [dg], [bk], [tk], [bt] *ʒabda, kɨbda* *ħadga* *tqɨb-kum* *ʃatka, ʃmɨt-kum* *nabta, tqɨb-tu-h*	[bd], [dg] *ʕɨbd* *fŭdg*

Table VIII. Cluster stimuli used to test the Place Order Hypothesis for Speaker 2

	word-initial	word-medial	word-final
N tokens, BF vs. FB (clusters)	*21 vs. 25 (8)*	*20 vs. 20 (8)*	*9 vs. 10 (4)*
Back-to-Front	[db], [gb], [gd], [kt] *dbal* *gbali* *gdat* *ktab*	[db], [gb], [gd], [kt] *kadba* *ragba* *ragda* *sakta*	[db], [gd] *kɨdb* *ħŭgd*
Front-to-Back	[bd], [bg], [dg], [tk] *bdat* *bgɨr* *dgig* *t-kat^b*	[bd], [bg], [dg], [tk] *ʒabda* *sabga* *ħadga* *ʃatka*	[bd], [dg] *ʕɨbd* *fŭdg*

Table IX. Number of clusters analyzed for place order effects in selected studies.

Study	word-initial	word-medial	word-final	across word boundary
Present *Moroccan Arabic*	**6** *(Spkr 1)* **8** *(Spkr 2)*	**10** *(Spkr 1)* **8** *(Spkr 2)*	**4** *(Spkr 1)* **4** *(Spkr 2)*	***none***
Byrd (1992) *English*	***none***	***none***	***none***	2 [bd] vs. [db]
Byrd (1996) *English*	***none***	***none***	***none***	4 [dg] vs. [gd] [sg] vs. [gs]
Surprenant and Goldstein (1998) *English*	***none***	***none***	***none***	4 [pt] vs. [tp] [pk] [tk]
Chitoran, Goldstein and Byrd (2002) *Georgian*	**6** [bg] vs. [gb] [p^ht^h] vs. [t^hb] [dg] vs. [gd]	**6** [bg] vs. [gb] [p^ht^h] vs. [t^hb] [dg] vs. [gd]	***none***	***none***

3.2.2. Results

The data from Speaker 1 do not support the Place Order Hypothesis. In fact, results from this speaker were contra the hypothesis with back-to-front clusters having significantly more overlap than front-to-back as a main effect, $F(1, 122) = 6.454, p < 0.05$. There is a main effect of cluster word position ($p < 0.001$) consistent with the results for this speaker reported in section 3.1.2. There is no significant interaction between place order and cluster word position ($p = 0.488$). Boxplots of overlap values by position are shown in Figure 9. There was no significant difference between front-to-back and back-to-front word-medial clusters.

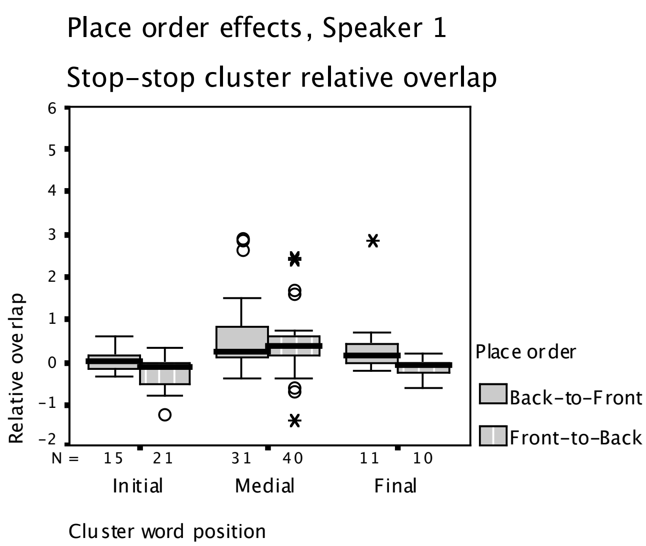

Figure 9. Lack of place order effects for Speaker 1

In contrast to Speaker 1, a main effect of place order was found for Speaker 2 with significantly more overlap in front-to-back than back-to-front clusters, $F(1, 99) = 5.025, p < 0.05$, as shown in Figure 10. Also consistent with the results for this speaker in section 3.1.2, there was no effect of cluster word position ($p = 0.185$). The interaction of place order and cluster word position was significant ($p < 0.05$). Further ANOVAs within each word position showed that interaction was due to place order being significant within word-initial clusters, $F(1, 44) = 8.594, p < 0.005$, and word-medial clusters, $F(1, 38) = 10.763, p < 0.005$, but not in word-final clusters, $p = 0.411$. Means and standard deviations of overlap by place order and cluster word position for both speakers are shown in Table X.

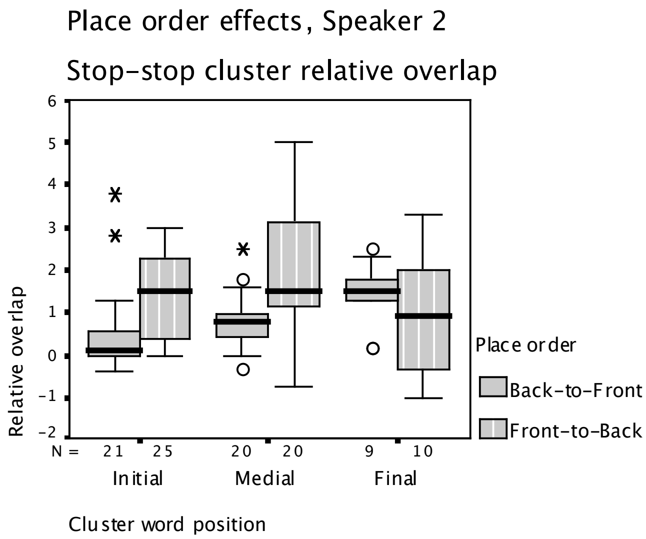

Figure 10. Place order effects for Speaker 2

Table X. Means and standard deviations of overlap in clusters by place order within each word position comparison, for each speaker. Significant differences are noted in the last column.

	back-to-front		front-to-back		
	mean	*SD*	**mean**	*SD*	sign.
Speaker 1 overall	**0.41**	*0.78*	**0.14**	*0.65*	$p < 0.05$, contra hypothesis
Speaker 2 overall	**0.76**	*0.90*	**1.51**	*1.36*	$p < 0.05$, per hypothesis
word-initial	**0.49**	*1.03*	**1.36**	*0.98*	$p < 0.005$
word-medial	**0.77**	*0.65*	**1.99**	*1.53*	$p < 0.005$
word-final	**1.40**	*0.82*	**0.90**	*1.60*	n.s.

3.3. Speaker-specific differences

To understand why there was a difference between the two speakers with respect to place order effects, we looked for systematic differences between the speakers. Two competing hypotheses were examined.

3.3.1. Open transitions

The lack of place order effects for Speaker 1 may be related to the claim that in Moroccan Arabic stop-stop clusters the closure of the first stop must be released before the closure of the second stop is formed (Dell and Elmedlaoui 2002). Given this open transition between stops, recoverability may be less of a concern in Moroccan Arabic than in languages that do not require open transitions. This would account for the differences in place order effects between our speakers only if Speaker 2 did not show open transitions, since his clusters did show a place order effect.

To evaluate this hypothesis, we first verified the status of open transitions by quantifying the lag between C1 and C2 plateaus in all stop-stop clusters in all three word positions for both speakers. For each token, we calculated the inter-plateau lag, that is, the time of C2 Target minus the time of C1 Release in milliseconds. If this value was positive, then there was a period of time between the two plateaus (during which an audible release is possible). If it was negative, it meant that the beginning of C2 Plateau (C2's Target) was achieved before C1 Release, an unfavorable condition for an audible release. For Speaker 1, 167 tokens were analyzed (57 initial, 75 medial, 35 final). For Speaker 2, 124 tokens were analyzed (40 initial, 65 medial, 19 final). Univariate ANOVAs were run to compare the inter-plateau lag across three word positions for both speakers. Inter-plateau lag was the dependent variable, with word position and speaker as the independent variables.

The data for both speakers provides strong evidence in support of the obligatory open transition in Moroccan Arabic. Of the 291 tokens analyzed, there were no tokens with a negative inter-plateau lag, and only one token where the lag was zero. Boxplots for Speakers 1 and 2 are shown in Figure 11. There was a significant main effect of speaker, with Speaker 1 having longer lags overall than Speaker 2, $F(1, 285) = 131.460, p < 0.001$. This is consistent with Speaker 1's clusters being less overlapped as shown in Figure 12. There was also a main effect of cluster word position, $F(2, 285) = 14.880, p < 0.001$. The interaction between speaker and cluster word position was also significant, $F(2, 285) = 6.820, p < 0.001$. Further ANOVAs within each speaker's data showed that there was a main effect of cluster word position for Speaker 1, $F(2, 164) = 18.252, p < 0.001$, with initial clusters significantly longer lag than medials or finals (both $p < 0.001$), which were not significantly different from each other. There was no main effect of cluster word position for Speaker 2. The overall main effect of cluster word position then is due to the larger lag of initial clusters for Speaker 1, which is consistent with the word position effects found for this speaker in 3.1.2. Means and standard deviations are shown in Table XI.

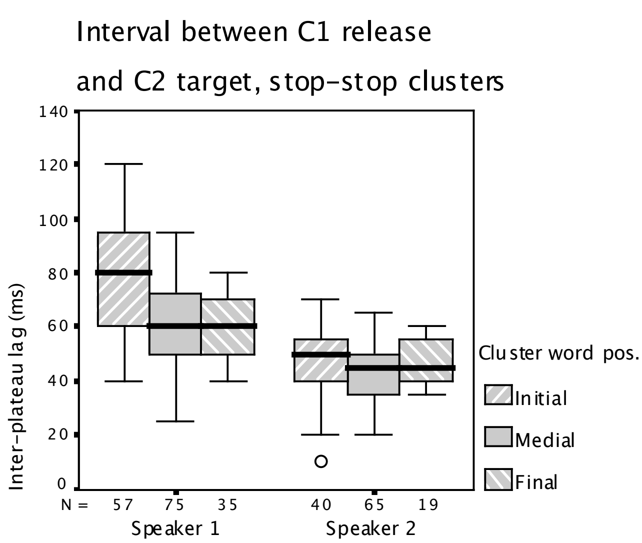

Figure 11. Inter-plateau lag for stop-stop clusters, by speaker and word position.

Table XI. Means of inter-plateau lag (milliseconds) and standard deviations within each word position, for each speaker.

	initial		medial		final	
	mean	*SD*	**mean**	*SD*	**mean**	*SD*
Speaker 1	**76.93**	*19.7*	**61.70**	*14.6*	**59.57**	*12.8*
Speaker 2	**46.71**	*11.9*	**42.0**	*10.5*	**46.32**	*7.6*

The presence of open transitions does not seem to provide a basis for an adequate explanation for the lack of place order effects for Speaker 1. Open transitions are present for both speakers, but Speaker 2 shows a robust place order effect.[4]

3.3.2. Relativized place order hypothesis

An alternative account for the lack of place order effects is that it is not the presence of the open transition *per se* that leads to the absence of place order effects for Speaker 1, but rather the relatively low degree of overlap that seems to be characteristic of Speaker 1's clusters. This leads us to the hypothesis that place order effects are relativized: the influence of recoverability factors on timing becomes stronger as degree of overlap increases. That is, if place order effects are found in one context but not in another, then it will be in the context with more overlap where the effects are observed, and not in the one with less. This hypothesis makes two specific predictions that we could test in our data (in the statements below 'POE' stands for 'place order effects'):

i. *Across-speaker prediction*: If Speaker A exhibits higher overlap than Speaker B, then all other things being equal "Speaker A shows POE and Speaker B does not show POE" is possible, but the reverse is not.

ii. *Within-speaker prediction*: If in Context 1, CC exhibits higher overlap than in Context 2, then all other things being equal "Context 1 shows POE and Context 2 does not show POE" is possible, but the reverse is not.

3.3.3. Relativized place order hypothesis: across-speaker prediction

Overlap between Speaker 1 and Speaker 2 was compared in all stop-stop clusters where in a given word position the same cluster existed in each speaker's data. A list of stimuli used is presented in Table XII. Univariate ANOVAs were run with relative overlap as the dependent variable and cluster word position, cluster, and speaker as the independent variables. A rather clear difference in overlap was seen between our speakers with Speaker 2 consistently showing more overlap than Speaker 1, as shown in Figure 12. Means and standard deviations are shown in Table XIII. This difference was significant overall with a main effect of speaker, $F(1, 117) = 37.755, p < 0.001$. The interaction between speaker and cluster word position was not significant, $p = 0.335$.

Table XII. Stimuli used to compare overlap between speakers.

Word position	Stimulus	Speaker 1	Speaker 2
Initial	*bdat*	√	√

	dgig	√	√
	gdat	√	√
	ktab	√	√
	ktɨb	√	√
Medial	*ʒabda*	√	√
	kadba	√	√
	ħadga	√	√
	ʕagda	√	
	ragda		√
	sakta	√	√
Final	*ʕɨbd*	√	√
	kɨdb	√	√
	fŭdg	√	√
	ħɨgd	√	
	ħŭgd		√

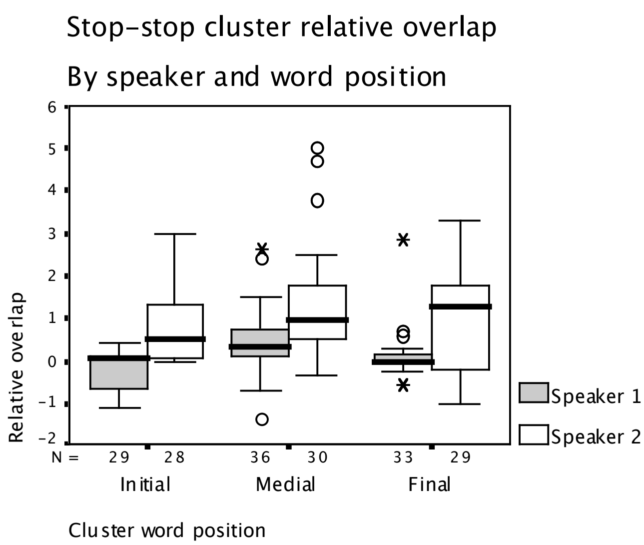

Figure 12. Speaker 2's clusters are significantly more overlapped than Speaker 1's

Table XIII. Means of relative overlap and standard deviations for each speaker within each word position.

	initial		medial		final	
	mean	*SD*	**mean**	*SD*	**mean**	*SD*
Speaker 1	**0.16**	*1.50*	**0.82**	*1.90*	**0.49**	*0.79*
Speaker 2	**0.47**	*1.04*	**1.30**	*3.37*	**1.46**	*1.47*

Speaker 2 systematically showed more overlap than Speaker 1. As shown earlier, Speaker 2 showed a main effect of place order whereas Speaker 1 did not. Therefore, the across-speaker prediction of the relativized place order hypothesis is borne out in our data.

3.3.4. Relativized place order hypothesis: within-speaker prediction

To test the within-speaker prediction of our hypothesis, we compared overlap of matched (C1C2/C2C1 pairs) stop-stop clusters for Speaker 2 in two minimally contrasting phonetic contexts, VCCa and VCCha. In VCCha, the cluster is followed by the glottal fricative. This is the minimal deviation from the former, inter-vocalic context. Clusters in the VCCa context had higher mean overlap (1.37) than those in VCCha (0.89), shown in Figure 13. Separate univariate ANOVA were run for each phonetic context, with relative overlap as the dependent variable and place order as the independent variable. The clusters in the VCCa context did show a significant place order effect, $F(1, 18) = 5.092, p < 0.05$, while those in the VCCha context did not, $F(1, 23) = 0.369, p = 0.549$, illustrated in Figure 14. Means and standard deviations are shown in Table XV. This supports the second, within-speaker prediction of the relativized place order hypothesis.

Table XIV. Medial cluster stimuli used for Speaker 2 to test the relativized place order hypothesis.

Cluster	VCCa	VCCha
[bd]	*ʒabda*	*ʕɨbdha*
[db]	*kadba*	*kadbha*
[dg]	*ħadga*	*fŭdgha*
[gd]	*ragda*	*ħŭgdha*

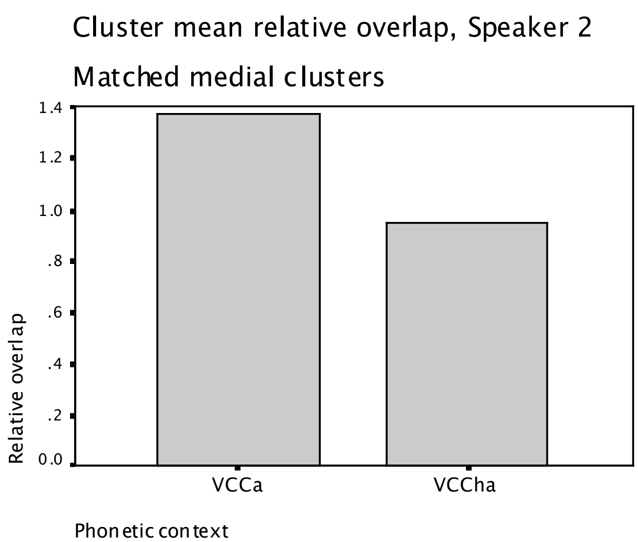

Figure 13. Mean overlap of medial clusters in two contexts for Speaker 2

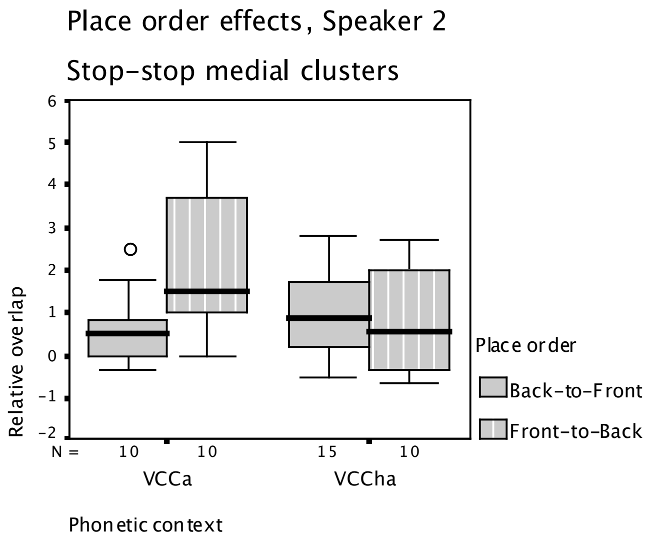

Figure 14. Place order effect for Speaker 2 in higher overlapped medial context of VCCa, but not VCCha

Table XV. Means and standard deviations of overlap in clusters by place order within each word position comparison, for each speaker. Significant differences are noted in the last column.

	back-to-front		front-to-back		
Speaker 1	**mean**	*SD*	**mean**	*SD*	sign.
VCCa	**0.67**	*0.85*	**2.07**	*1.75*	$p < 0.05$
VCCha	***1.07***	*1.05*	**0.78**	*1.29*	n.s.

3.4. Non-grammatical differences in overlap: summary

We examined inter-consonantal temporal overlap in Moroccan Arabic clusters as a function of word position and place order. The effects of these two variables on overlap are not shared by our two speakers. Speaker 1 shows significant word position effects but Speaker 2 does not. Place order contributes to the precise amount of overlap for Speaker 2 but not so for Speaker 1.

We showed that place order effects are independent of the requirement for an inter-consonantal open transition in clusters. Both speakers invariably had a positive lag between C1 and C2 plateaus, but only Speaker 2 showed place order effects. A key difference between the two speakers seems to be that Speaker 2 showed significantly more overlap than Speaker 1. The specific pattern of results in our data provides evidence that the place order effect should not be seen as a static property of individual speakers or languages, but rather as a dynamic effect of the sensorimotor system. When the various factors controlling inter-consonantal overlap conspire to provide a context of higher overlap, place order effects are more likely to emerge in that context than in a context of lower overlap – the relativized place order hypothesis. This is different from previous formulations of the place order hypothesis as in “front-back clusters should show more overlap than back-front clusters” (Chitoran et al. 2002). Note that our revision may seem as a retreat from the previous absolute statement, but the relativized hypothesis is in fact stronger than the absolute version above. This is because the relativized hypothesis makes predictions even in cases where the absolute statement is unsupported—see section 3.3.4.

More broadly, the relativized hypothesis is consistent with the fact that place order effects have been observed in speakers from a set of unrelated languages: English, Georgian, Moroccan Arabic, Russian and Tsou. Yet, crucially, place order effects are not uniformly present for all speakers of these languages. Our revised hypothesis makes a strong prediction about these cases: the presence of the effect should be modulated, in the asymmetric way stated in our hypothesis, by independently determined speaker- or context-specific amounts of overlap.

4. Grammatical differences in overlap

The specific goal of this section is to identify differences in overlap that have a grammatical source. Our strategy is to uncover distinct stable states of temporal organization under variation in various extra-grammatical variables such as idiolectal or task-specific speech rate settings, word position and incidental phonetic context. If under such variation, overlap differences persist, we ascribe their source to qualitatively distinct temporal coordination relations.

4.1. Phonology and overlap

Previous work on Moroccan Arabic suggests candidate areas where the phonology may specify a distinction in terms of temporal organization (Gafos 2002). Specifically, in this section we focus on differences in the temporal organization between homorganic and heterorganic clusters.

Relevant to this distinction is a well-known phonological principle, the Obligatory Contour Principle (henceforth, OCP). The autosegmental version of the OCP (Goldsmith 1976, McCarthy 1986, Odden 1988) states that adjacent identical elements are prohibited. In this statement of the OCP, the notion of adjacency is defined over linear sequences of static units, i.e., auto-segments. In gestural terms, adjacency translates to the notion of overlap defined over sequences of units with internal temporal structure (gestures). Therefore, the gestural version of the OCP states that overlapping identical gestures are prohibited. Figure 15 shows two possible coordination relations between two gestures. We will refer to the relation in Figure 15(a) as the "overlapped" relation and to that in Figure 15(b) as the "non-overlapped" relation. The gestural version of the OCP prohibits the overlapped relation if the two gestures are identical. No such prohibition exists if the gestures are not identical. From these schematized coordination relations, we can project a prediction in terms of overlap at the level of articulatory execution. The prediction is that a sequence of two identical oral gestures shows significantly less overlap than a sequence of two non-identical oral gestures.

As cross-linguistic work on anti-identity effects shows, the notion of "identical elements" targeted by the OCP is language-specific. For Moroccan Arabic, it is identity in the oral tier that matters. Anti-identity effects are seen for segments from the set /t d tˤ dˤ/. Thus, /t–dˤ/ and /t–t/ show such effects, but /s–t, ʃ–t/ sequences do not. Sonority is potentially another important dimension. We know with certainty that /tˤ–d/ shows anti-identity effects but the situation is less clear for /t–n, l–d, n–t, r–t/ sequences. Therefore, when talking about "identical elements" we limit attention to sequences of consonants with identical oral gestures that belong to segments of equal sonority. The notion of gestural identity "$g^1 = g^2$" is defined as follows. Two oral gestures g^1 and g^2 are identical, $g^1 = g^2$, iff they employ the same *articulator* and the same values for the *constriction degree* (CD) and *constriction location* (CL) tract variables.

Overlap patterns in stop-stop clusters were examined across two phonological profiles, heterorganic (different oral gestures involved) vs. homorganic (identical oral gestures involved). For example, heterorganic [kat^b] 'write.active-participle' vs. homorganic [!znat^t] 'tail.plural' (the exclamation mark indicates dorso-pharyngealization of each segment in the word). In both cases, the final clusters are described as having the same acoustic profile [C^C], with "^" indicating an intervening vowel-like transition between the two final consonants (Heath 1987: 55).[5]

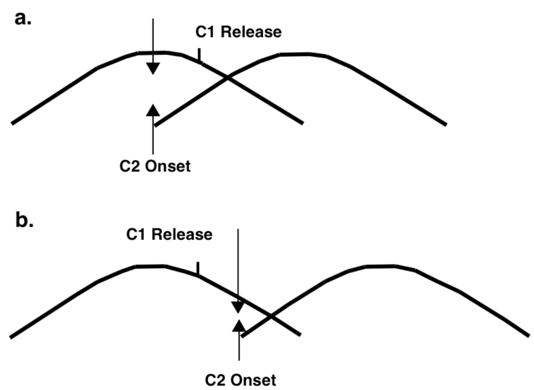

Figure 15. (a) Overlapped and (b) non-overlapped coordination relations between gestures

4.1.1. Analysis

For each speaker, we examined overlap between hetero- and homorganic stop-stop C^C clusters in the final and medial word positions. There is a relatively small number of tokens in the homorganic category. There are two reasons for this. The first is that Moroccan Arabic shares with Classical Arabic the well-known restrictions against partial consonantal identity within roots (Cantineau 1946, Greenberg 1950). Thus, for example, there are no stems that end in […t-vowel-d] (Heath 1987: 249), and equally strong restrictions apply to the other places of articulation. The second reason for the limited number of stimuli is that we know only two Moroccan Arabic words that have a final sequence of two homorganic stop consonants in the relevant morphological contexts, [!znat^t] '(dog's) tail.plural' and [!frat^t] 'kind of butterfly.plural'. For the same clusters, we collected movement data when they appear in word-medial position before the Third Feminine Singular /-ha/, as in [!znat^tha] 'her tails', [!frat^tha] 'her butterflies'.

Table XVI. Cluster stimuli used to test the effects of the OCP for Speaker 1

Position:	Medial	Final

Heterorganic	*N tokens (clusters)*	*33 (6)*	*47 (9)*
	[b^d]	*ʒab^dha*	*ʒab^d*
	[b^g]	*sab^gha*	*sab^g*
	[b^t]		*nab^t*
	[d^b]	*kad^bha*	*kad^b*
	[d^g]		*ħad^g*
	[g^d]	*ʕag^dha*	*ʕag^d*
	[k^b]	*rak^bha*	*rak^b*
	[k^t]		*sak^t*
	[t^b]	*kat^bha*	*kat^b*
			tkat^eb
Homorganic	*N tokens (clusters)*	*10 (1)*	*9 (1)*
	[!t^t]	*frat^tha*	*frat^t*
		znat^tha	*znat^t*

Speaker 2's kinematic patterns in [!...t^t(-ha)] sequences showed movements of relatively small amplitude. This did not allow reliable use of the automatic procedures for identifying the landmarks that enter into the calculation of the measure defined in 2.5. Other landmarks were readily identifiable using the tangential velocity signals. Specifically, for each tongue tip gesture, the times of peak velocity to and from the oral constriction phase of the consonant along with the time of the intervening velocity minimum during the constriction phase, were used to index overlap (for both [!t^t] and heterorganic sequences). The measure used for Speaker 2 is shown in (1).

(1) $$\text{Relative Overlap} = 1 - \frac{(\text{time of C2 velocity minimum} - \text{time of peak velocity to C1})}{(\text{time of peak velocity from C1} - \text{time of peak velocity to C1})}$$

For Speaker 1, we used two overlap measures. The first was the same as elsewhere in this study so as to make the results comparable to those in previous sections. The second measure was the one just introduced for Speaker 2. This allows us to evaluate the robustness of the OCP effect across the speakers.

The number of clusters and tokens analyzed for Speaker 1 are shown in Table XVI, and those for Speaker 2 are shown in Table XVII. All stimuli were collected as part of the same recording session described in section 2.3. The relative overlap measures for these clusters were then subject to separate univariate ANOVAs per speaker, with relative overlap as the dependent variable, and cluster word position and whether the cluster was hetero- or homorganic as the independent variables.

Table XVII. Cluster stimuli used to test the effects of the OCP for Speaker 2

Position:		Medial	Final
Heterorganic	*N tokens (clusters)*	*43 (8)*	*46 (9)*
	[b^d]	*ʒab^dha*	*ʒab^d*
	[b^g]	*sab^gha*	*sab^g*
	[d^b]	*kad^bha*	*kad^b*

	[d^g]	*fad^gha*	*ħad^g*
	[g^b]	*ʕag^bha*	*rag^b*
	[g^d]	*ʕag^dha*	*rag^d*
	[k^t]	*nak^tha*	*sak^t*
	[t^b]		*t-kat^b*
	[t^k]	*hat^kha*	*hat^k*
Homorganic	*N tokens (clusters)*	*9 (1)*	*10 (1)*
	[!t^t]	*!frat^tha*	*!frat^t*
		!znat^tha	*!znat^t*

4.1.2. Results

Speaker 1 and Speaker 2 both showed significantly more overlap in heterorganic clusters than in homorganic clusters, both within word-medial and word-final clusters, as shown in Figure 16 and Figure 17.

For Speaker 1, using the first overlap measure, there was a main effect of hetero/homorganic, $F(1, 95) = 39.303, p < 0.001$, with heterorganic clusters having significantly more overlap than homorganic clusters. There was also a significant main effect of cluster word position, $F(1, 95) = 10.266, p < 0.005$, with medial clusters having higher overlap than finals (consistent with the results for this speaker in section 3.1). There was no significant interaction between hetero/homorganic and cluster word position ($p = 0.905$). Means and standard deviations are shown in Table XVIII.

For Speaker 1, using the second overlap measure, the result was qualitatively identical to the previous one. There was a main effect of hetero/homorganic, $F(1, 95) = 120.338, p < 0.001$, with heterorganic clusters having significantly more overlap than homorganic clusters. There was also a similar significant main effect of cluster word position, $F(1, 95) = 25.208, p < 0.001$, with medial clusters having higher overlap than finals. The interaction between hetero/homorganic and cluster word position was marginal ($p = 0.059$). That this effect is reliably found regardless of measure used shows the robustness of the effect.

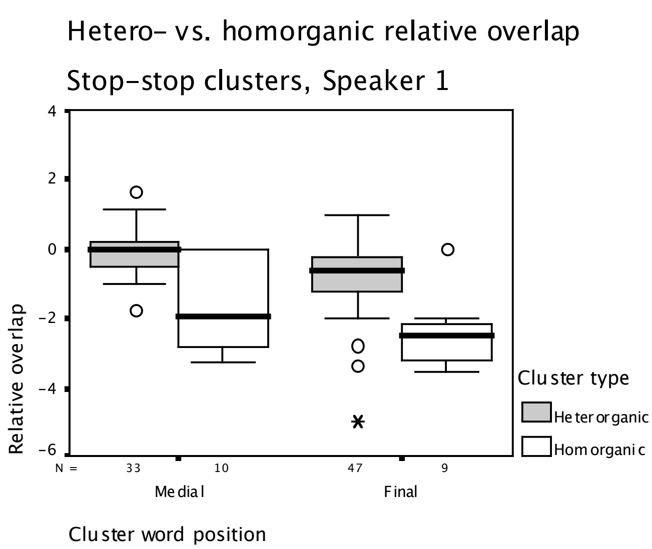

Figure 16. Differences in overlap for hetero- vs. homorganic clusters, Speaker 1 (first overlap measure)

Table XVIII. Means and standard deviations of overlap in hetero- and homorganic, stop-stop clusters, by word position for Speaker 1 (first overlap measure)

Word position:	medial		final	
	mean	*SD*	**mean**	*SD*
Heterorganic	**-0.07**	*0.63*	**-0.83**	*1.02*
Homorganic	**-1.58**	*1.43*	**-2.39**	*1.04*

For Speaker 2, there was a main effect of hetero/homorganic, $F(1, 104) = 850.120, p < 0.001$, with heterorganic clusters having significantly more overlap than homorganics. There was no main effect of cluster word position (consistent with the results for this speaker from section 3.1), $p = 0.833$. The interaction between hetero/homorganic and cluster word position was significant, $F(1, 104) = 10.615, p < 0.005$, due to heterorganic clusters having more overlap medially than finally. Means and standard deviations are shown in Table XIX.

Since Speaker 2 showed place order effects (as shown in section 3.2.2), we performed a post-hoc analysis on his data to see whether the homorganicity effect was present compared to the back-to-front clusters. This speaker's back-to-front clusters show less overlap than front-to-back clusters, and therefore back-to-front heterorganic clusters might not be different from homorganic clusters. Since place order only applies in heterorganic clusters, each cluster was marked as 'back-to-front' (N=41), 'front-to-back' (N=48), or 'homorganic' (N=19). All of the clusters shown in Table XVII were subject to another ANOVA with overlap as the dependent variable, and word position and place order (with the three-way distinction including 'homorganic') as independent variables. The phonological effect was still found, with homorganic clusters having significantly less overlap than heterorganic back-to-front and front-to-back clusters, both $p < 0.001$.

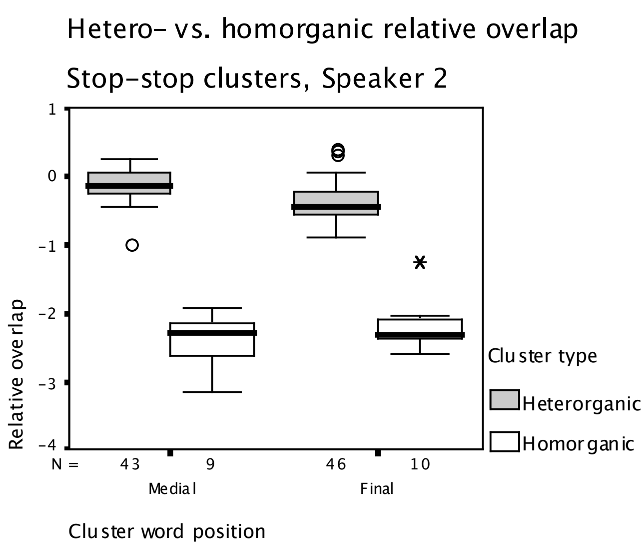

Figure 17. Differences in overlap for hetero- vs. homorganic clusters, Speaker 2 (second overlap measure)

Table XIX. Means and standard deviations of overlap in hetero- and homorganic, stop-stop clusters, by word position for Speaker 2 (second overlap measure)

Word position:	medial		final	
	mean	*SD*	**mean**	*SD*
Heterorganic	**-0.14**	*0.21*	**-0.38**	*0.28*
Homorganic	**-2.41**	*0.40*	**-2.19**	*0.36*

Finally, though space limitations do not allow us to discuss more data, we note that our analyses showed that OCP effects are robustly observed also in the fast rate condition for both Speakers.

4.2. Morphology and overlap

In Moroccan Arabic, as in all languages known to have templatic word-formation, templatic morphology coexists with concatenative or affixal morphology. The coexistence of these two morphology types allows us to tease apart the respective contributions of word-formation type and phonology in overlap patterns.

When we fix the phonological make-up of clusters to those comprising two homorganic stops and vary morphology type, the following difference can be observed. In templatic morphology, two homorganic stops are timed with the non-overlapped coordination relation, but in affixal morphology they are timed with the overlapped relation. In effect, timing depends on morphology type.

We have already illustrated the part of this generalization referring to templatic morphology. In [!znat^t] the plural of [!zntɨt] '(dog's) tail' formed on the CCaC^C template, the identical oral gestures of the final two stops are produced with two distinct closures, one for each [!t] as shown in Figure 18.

Turning to affixal morphology, two identical oral gestures across a morpheme boundary like those of [d] and [t] in [ʒbɨd-t(-u)] 'I pulled (him)' or [t] and [t] in [ʃmɨt-t(-u)] 'I conned (him)' show a single long closure spanning the two oral gestures of their respective consonants [d], [t] or [t], [t]. This is shown in Figure 19 using the example of the [d-t] cluster because it allows one to see that the resulting long closure can be produced with heterogeneous voicing.[6] This is not possible with lexical true geminate consonants which must be homogeneous in voicing, [tt] or [dd].

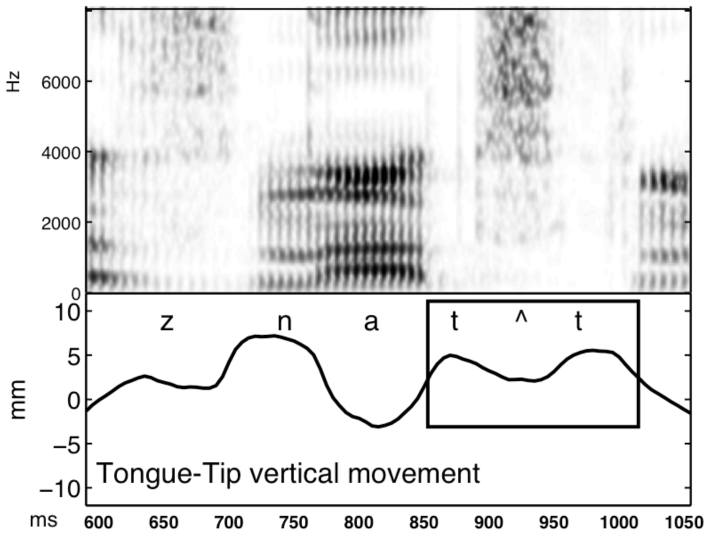

Figure 18. Non-overlapped homorganic gestures within templatic morphology, Speaker 2. The bottom portion of the figure shows two movement peaks of the tongue tip (in the box), one for each [!t] of [!znat^t]. There is an audible release visible in the spectrogram. The second [!t] is followed by the rest of the carrier phrase, *hnaya* ‘here’.

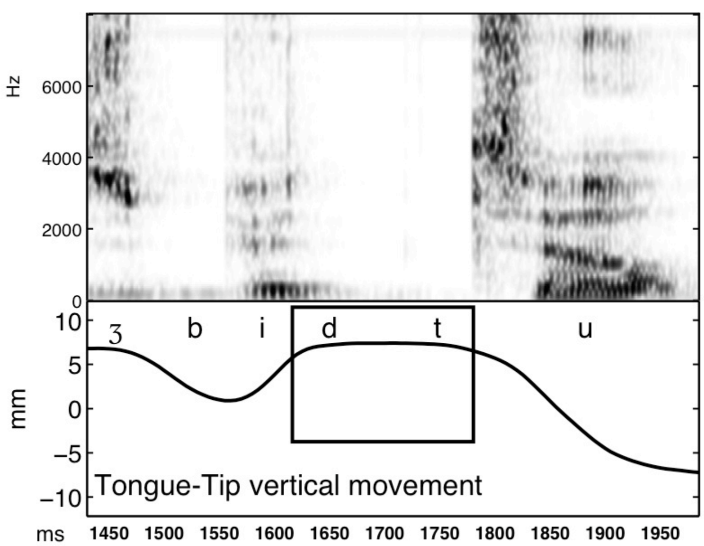

Figure 19. Overlapped homorganic gestures with affixal morphology, Speaker 1. The bottom portion of the figure shows one long tongue tip closure (in the box), with no separation between [d] and [t] of [ʒbɨd-t-u]. There is also no audible release visible in the spectrogram.

In terms of temporal coordination relations, the contrast illustrated in Figures 18 and 19 shows that in templatic morphology a sequence of two homorganic stops is timed with a non-overlapped relation. In affixal morphology, instead, the single long closure indicates that the two homorganic stops are timed with an overlapped coordination relation. Therefore, two distinct timing relations are involved. This state of affairs cannot be expressed in an a-temporal phonology, where such temporal relations are not part of the representations.

4.3. Grammatical factors and timing: summary

We have presented evidence that heterorganic clusters show significantly more overlap than homorganic clusters in word-medial and -final sequences. This effect was shown to be independent of other non-grammatical influences on overlap. Specifically, the effect is independent of speaker, word position, and place order. A version of the well-known Obligatory Contour Principle is implicated, crucially augmented via reference to the temporal dimension.

Moreover, we have seen that overlap in homorganic clusters depends on morphology type. Within templates, two homorganic stops are timed with the non-overlapped coordination relation, but across an affixal boundary they are timed with the overlapped relation.

Both of these differences provide evidence for the claim that phonological representations contain information about the temporal organization of the consonantal segments.

5. Conclusion

Variation in inter-consonantal temporal overlap in Moroccan Arabic clusters has been examined as a function of word position and place order. The effects of these two variables on overlap patterns are speaker-specific. In contrast, we have argued that other overlap patterns seem to be under grammatical control. In these latter cases, the grammar specifies temporal distinctions in the phonological plan. These distinctions supply the stably different patterns of overlap seen in homorganic versus heterorganic clusters, and in homorganic clusters striding an affixal boundary versus within a template.

Future work will address the effects of manner of articulation, voicing, and speech rate on overlap. Another central question is the relation between overlap and timing. The key issue here is inferring the form of timing relations underlying the surface kinematic patterns we have called "overlapped" and "non-overlapped". Finally, we plan to address the issue of whether a temporal basis for higher units of phonological organization such as syllables can be identified in the relatively complex range of hypothesized syllable types of this language.

Acknowledgements

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Appendix A: Stimuli and glosses

All stimuli from all analyses are listed below with glosses.

surface form	template		gloss
bdat	CCa-et	weak perfective verb-subject suffix	'to begin'
bgɨr	CCɨC	noun (collective form)	'cows'
b-kas	b-CaC	instrumental prefix-noun	'with a cup'

bkat	CCa-et	weak perfective verb-subject suffix	‘to cry’
btas^m	CtaCeC	verb	‘to smile’
b-taʒ	b-CaC	instrumental prefix-noun	‘with a crown’
dbal	CCaC	perfective (inchoative) verb	‘to fade’
dgig	CCiC	noun	‘flour’
fad^gha	CaC^C-ha	active participle-3prs fem sg object suffix	‘to pierce an abscess"
!frat^t	CCaCeC	noun	‘tails’
!frat^tha	CCaCeC-ha	noun-fem possessive suffix	‘her tails’
fŭdg	CeCC	noun	‘abscess’
fŭdgha	CeCC-ha	noun-fem possessive suffix	‘her abscess’
gbali	CCaC-i	preposition-masc possessive suffix	‘in front of (me)"
gdat	CCa-et	weak perfective verb-subject suffix	‘to burn’
ħad^g	CaC^C	active participle	‘ambitious’
ħadga	CaCeC-a	active participle-feminine suffix	‘ambitious’
ħat^k	CaC^C	active participle	‘to tear (a drum)’
ħat^kha	CaC^C-ha	active participle-3prs fem sg object suffix	‘to tear (a drum)’
ħɨgd	CeCC	verbal noun	‘jealousy’
ħŭgd	CeCC	verbal noun	‘jealousy’
ħŭgdha	CeCC-ha	verbal noun-fem possessive suffix	‘her jealousy’
kadba	CaCeC-a	active participle-feminine suffix	‘to lie (say something untrue)’
kad^b	CaC^C	active participle	‘to lie’
kad^bha	CCaC^C-ha	active participle-3prs fem sg object suffix	‘to lie’
kat^b	CaC^C	active participle	‘to write’
kat^bha	CCaC^C-ha	active participle-3prs fem sg object suffix	‘to write’
kbaʃ	CCaC	noun (plural)	‘sheep’
kɨbda	CeCCa	noun	‘liver’ (the organ)
kɨdb	CeCC	verbal noun	‘to lie (say something untrue)’
kɨtba	CeCCa	instantiating verbal noun	‘to write’
ktab	CCaC	noun	‘book’
ktɨb	CCeC	perfective verb	‘to write’
nab^t	CaC^C	active participle	‘to grow in earth’
nabta	CaCeC-a	active participle-feminine suffix	‘to grow in earth’
nak^tha	CaC^C-ha	active participle-3prs fem sg object suffix	‘make love’
rag^b	CaC^C	active participle	‘to be informed’
ragba	CaC^C-a	active participle-feminine suffix	‘to be informed’
rag^d	CaC^C	active participle	‘to sleep’
ragda	CaCC-a	active participle-feminine suffix	‘to sleep’
rak^b	CaC^C	active participle	‘to ride’
rakba	CaC^C-a	active participle-feminine suffix	‘to ride’
rak^bha	CaC^C-ha	active participle-3prs fem sg object suffix	‘to ride’
ratba	CaCeC-a	active participle-feminine suffix	‘to fix’
sabga	CaCeC-a	active participle-feminine suffix	‘to be ahead of’
sab^g	CaC^C	active participle	‘to be ahead of’
sab^gha	CaC^C-ha	active participle-3prs fem sg object suffix	‘to be ahead of’
sakta	CaCeC-a	active participle-feminine suffix	‘to be quiet’
sak^t	CaC^C	active participle	‘to be quiet’
slɨk-t	CCeC-t	perfective verb-subject prefix	‘to save’
ssɨbt	l-CeCC	definite article prefix-noun	‘Saturday’
tbɨʕ	CCeC	perfective verb	‘to follow’
t-kat^b	t-CaCeC	mediopassive prefix-perfective verb	‘to wet’

tqɨb-kum	CCeC-kum	perfective verb-2prs pl object suffix	'to pierce'
tqɨb-tu-h	CCeC-tu-h	perfective verb-2prs pl subject affix-3prs masc sing object suffix	'to pierce'
tqeb-t	CCeC-t	perfective verb-subject prefix	'to pierce'
!znat^t	CCaCeC	noun	'the tails'
!znat^tha	CCaCeC-ha	quadriliteral plural noun-3prs fem sg object suffix	'her tails'
ʃatka	CCaCa	noun	'a cover for a bed'
ʃmɨt-kum	CCeC-kum	perfective verb-2prs pl object suffix	'to con'
ʒabda	CaCeC-a	active participle-feminine suffix	'to pull'
ʒab^d	CaC^C	active participle	'to pull'
ʒab^dha	CaC^C-ha	active participle-3prs fem sg object suffix	'to pull'
ʕag^bha	CaC^C-ha	active participle-3prs fem sg object suffix	'to follow'
ʕagda	CaCeC-a	active participle-feminine suffix	'to tie'
ʕag^d	CaC^C	active participle	'to tie'
ʕag^dha	CaC^C-ha	active participle-3prs fem sg object suffix	'to tie'
ʕɨbd	CeCC	noun	'a slave'
ʕɨbdha	CeCC-ha	noun-fem possessive suffix	'a slave'

Appendix B: Cluster effects by word position

The tables below show the means and standard deviations of relative overlap by cluster word position and cluster for the Word Position effects reported in section 3.1.2.

Speaker 1

	Word	*initial*		*Word*	*medial*		*Word*	*final*	
Cluster	Mean	SD	N	Mean	SD	N	Mean	SD	N
bd	-0.76	.335	6	-0.30	.520	10	-0.15	.325	4
bk	0.03	.165	10	0.32	.155	5	*n/a*		
bt	-0.53	.324	10	0.57	.670	10	0.24	.320	9
db	*n/a*			0.22	.125	6	0.53	1.292	5
dg	0.13		1	0.85	.871	5	-0.14	.246	6
gd	0.11	.230	5	0.60	.529	5	0.33	.240	6
kt	0.13	.050	10	1.50	.661	5	0.56	.224	5
tb	-0.18	.159	5	0.01	.264	10	*n/a*		

Speaker 2: Initial vs. medial

	Word	*initial*		*Word*	*medial*		*Word*	*final*	
Cluster	Mean	SD	N	Mean	SD	N	Mean	SD	N
bd	1.44	1.070	5	1.35	.224	5	2.35	.578	5
bg	2.14	.739	5	1.39	.369	5	*n/a*		
db	0.62	1.758	5	0.52	1.140	5	2.05	.438	4
dg	0.86	1.275	4	2.78	2.364	5	-0.55	.417	5
gb	0.69	1.167	6	0.79	.506	5	*n/a*		
gd	0.08	.108	5	0.83	.529	5	0.88	.660	5
kt	0.54	.441	5	0.92	.210	5	*n/a*		

Notes

[1] Guenther's (1995) DIVA is another well-developed model focusing on the control and execution of speech movements. However, units specified at the "speech sound

level" in this model are static in nature, with their content expressed in terms of spatial dimensions. Hence, though this model has certain unique attractive properties (it offers, among other things, plausible accounts for the learning of coordinative structures and for the economy of speech movements), it does not provide, at this stage at least, sufficient expressive power for describing distinct overlap relations between phonological units.

[2] Although we refer to a notion of "inter-segmental consonant (cluster) timing", the primitives related by our measures are gestures, not segments. The background necessary to give content to the notion of inter-segmental timing is in Gafos (2002). Here are the relevant definition and key assumption. Definition: Inter-segmental coordination, "Two segments S1, S2 are coordinated with some coordination relation λ, /S1 λ S2/, if the head gestures of these segments are coordinated as in λ." (Gafos 2002: 284). It is assumed that the oral gestures of consonants are heads. The assumption that oral gestures drive timing relations among consonants is also justified therein (Gafos 2002: 296).

[3] All clusters are tautomorphemic, with four exceptions where "-" indicates a morpheme boundary.

[4] An anonymous reviewer pointed out that the clusters for Speaker 1 contained mixed voicing, e.g., initial [kb]/[bk], while the clusters for Speaker 2 did not, and that this may account for the reverse place order effect for Speaker 1. Mixed voicing in the clusters does not seem to explain the result: restricting the analyses to matched-voicing clusters showed the same trend as with the mixed-voicing clusters included, although no longer significant. We repeated the analyses for Speaker 1 including only clusters that matched for voicing, e.g., initial [gd]/[dg] and medial [kt]/[tk]. While the result reported above for Speaker 1 was that there was a significant result contra the hypothesis, the results for the matched-voicing clusters only were no longer significant, with no main effect of place order, $F(1, 62) = 1.134, p = 0.291$. This lack of result is most likely due the low number of tokens when thus restricted. An ANOVA of only the medial clusters (the word position for which the most matched-voicing-cluster tokens were available) still showed a trend contra the place order hypothesis with back-to-front clusters still having more overlap (mean = 0.73) than front-to-back clusters (mean = 0.37), $F(1, 39) = 2.270, p = 0.140$.

[5] Phonological analyses of Moroccan Arabic are not in agreement on the nature of the vocoid in C^C sequences. Heath (1987: 105, 248) views it as an actual short vowel [ɨ̆] introduced at a late stage in the phonological derivation (see 'Schwa Insertion', Heath 1987: 55), but subsequently potentially deleted by an optional syncope rule or under fast speech ('Forward Syncope', Heath 1987: 248). Dell and Elmedlaoui (2002: 300) propose that this vocoid may correspond to an actual vowel but only under certain special intonational conditions. Gafos (2002: 287-289, 293, 294) argues that the vocoid in C^C is not a vowel, but rather the acoustic manifestation of a specific pattern of overlap between the two consonants. In what follows, we require that some version of the latter two proposals is correct, at least for some context where an OCP effect would be implicated in our interpretation. This is because if a vowel intervened between two identical gestures, the classic OCP would be silent. Indeed, such a context can be identified under any of the views outlined above. That is, even under Heath's (1987) proposal, the one that assumes that the vocoid is an actual short vowel, that vowel should be absent in a well-defined subset of our stimuli, namely, the word-medial clusters presented below. In that context the vowel of the suffix [-ha] causes deletion of the preceding short vowel by

another syncope rule ("Backward Syncope", Heath 1987: 247, 253). Therefore, the OCP should in principle be applicable at least in this context.

[6] Data for the affixal morphology example come from Speaker 1. We did not collect data from Speaker 2 on the same combinations. The reason: it is taken as an uncontroversial given in all descriptions of Moroccan Arabic we know of that across the relevant inflectional boundary the cluster [d-t] is realized with a single closure (see references in section 1.2).

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