

Acoustic investigation of Georgian harmonic clusters

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Georgian coronal-dorsal and labio-dorsal harmonic clusters have been analyzed phonologically as complex segments. They are described as being phonetically simultaneous, consisting of only one closure and one final release. The present study shows that the treatment of harmonic clusters as complex segments is not supported by acoustic data. Acoustic evidence from the presence of bursts and timing differences contradicts the traditional description of the clusters, which are in fact simple sequences of segments. Additional differences in duration are argued to reflect differences in syllable structure. The paper also contains an acoustic description of single ejectives and ejective clusters in Georgian.

1. Introduction

Georgian is a South Caucasian language belonging to the Kartvelian family. Like all Caucasian languages, Georgian is characterized by a complex consonantal system, with a tendency to form long clusters. As argued by Vogt (1958, 1971), Tschenkeli (1958), Aronson (1982, 1991), and Deprez (1988), Georgian contains a series of two-member clusters which behave phonologically as single segments. They are known as "harmonic clusters" because the laryngeal feature is constant across the cluster, "harmonizing" the two members. The two members of the cluster are both voiced (dg, bg, dγ, bγ), aspirated (t^hk^h, ts^hk^h, t^hχ, ts^hχ), or ejective (t'k', ts'k', p'k', t'q', ts'q'), the 3-way opposition of the Georgian consonant-system. They can occur either word-initially or in word-medial position. Harmonic clusters can be compared with identical sequences of segments formed at the junction of two words. In this case it can no longer be argued that they behave as a single segment, unless a harmonic cluster is derived by some sort of restructuring. If the difference between a harmonic cluster and a simple sequence of segments is present in the phonology, then it should, in the best of cases, also be visible in the acoustic signal, for example in timing differences, as suggested by previous studies of complex vs. simple segments in various languages (Maddieson and Ladefoged 1989; Maddieson 1989, 1990).

The purpose of my study is to look for acoustic evidence that would motivate the distinction made in the literature between harmonic clusters, behaving as single segments, and simple sequences of consonants. The results of the study show that the treatment of Georgian harmonic clusters as complex segments has no acoustic basis.

The paper is organized as follows: section 2 presents the phonological behavior of consonant clusters in Georgian; section 3 reviews phonetic evidence for complex

segments. The experiment is described in section 4, followed by the presentation of results (section 5) and their discussion (section 6). Section 7 presents and discusses some additional results obtained in the study. The conclusions are presented in section 8. The two appendices contain the Georgian wordlist used in the experiment, and the description of ejective clusters.

2. Phonological behavior of clusters

Caucasian languages are (in)famous for the strong numerical predominance of consonantal versus vocalic segments in their phonetic inventories. Among these languages there are certain differences in the way they organize their consonant inventories. These differences were captured by Colarusso (1988), and used to characterize the 3 major groups of the linguistic area: Northwest, Northeast and Kartvelian Caucasian languages. The groups make use of all three logical possibilities of increasing their consonant inventories. Northwest Caucasian languages have complex consonantal systems, whose elements combine into long clusters. Northeast Caucasian languages also have complex consonantal systems, but a more limited tendency to form clusters. Kartvelian languages, which include Georgian, have more limited consonantal systems, but the clusters which they create are the most complex found in the three language groups. The consonantal inventory of Georgian, for instance, shows a smaller number of contrasts than Kabardian (NW Caucasian), but is more productive in creating new clusters out of a less rich inventory. The consonantal inventory of Georgian is given below:

		labial	coronal		dorsal	
			dental	palatal	velar	uvular
<u>stop</u>	voiced	b	d		g	
	aspirated	p ^h	t ^h		k ^h	
	ejective	p'	t'		k'	q' [q'χ]
<u>affricate</u>	voiced		dz	ɟʒ		
	aspirated		ts ^h	tʃ ^h		
	ejective		ts'	tʃ'		
<u>fricative</u>	voiced		z	ʒ		ɣ ¹
	vcless		s	ʃ		χ
nasal		m	n			
liquid			r, l			
glide		w/v				

Table 1. The consonant inventory of Georgian.

In the stop and affricate series Georgian has a three-way opposition: voiced, aspirated, ejective. There appear to be some gaps in the obstruent paradigm: first of all, it contains only one uvular stop (as pointed out by Deprez 1988), and secondly, the uvular fricatives do not have velar counterparts. Old Georgian had both /q/ and /q'/ (Fähnrich 1991), but the modern language has lost the distinction between the two. Deprez proposes that /ɣ/ and /χ/ pattern like stops, being actually the phonetic realizations of the phonological voiced and aspirated uvular stops. This assumption would make the consonant inventory more symmetrical, in the sense that the stop paradigm would be complete, and Georgian would contain only coronal fricatives, which are the unmarked type. According to this view the uvular stop in Georgian is a member of the ejective series, and the uvular fricatives /χ/, /ɣ/ pattern phonologically with stops.

Georgian allows long consonant clusters even in word-initial position (a record of 6 in one root), although they violate sonority. 6 and 5-member clusters are less frequent, but 4-member clusters are very common (data from Tchikobava 1967):

- (1) p'rts'k'vna 'to peel'
 ts'vrt'na 'to train'
 brt'q'eli 'flat'
 ts'q'rt'a unit of length
 brts'q'inva 'to shine'

¹ The standard IPA symbol for a uvular fricative is /ʁ/, but /ɣ/ is used by all Georgian grammars, and will be used in this study.

At a prefix-root boundary a total of 7 consonants can be piled up. The first person plural object, for instance, is the prefix *gv-* attached to the verb root:

<i>gv-t^hχ ovs</i>	'will ask us'
<i>gv-ts'vrt^hnis</i>	'drills habits into us' (Tchikobava 1967)

The clusters considered to function as a unit are the following:

(2) (a) corono-velar	voiced	/dg/, /dzg/, /dʒg/
	aspirated	/t ^h k ^h /, /ts ^h k ^h /, /tʃ ^h k ^h /
	ejective	/t'k'/, /ts'k'/, /tʃ'k'/
(b) corono-uvular	voiced	/dɣ/, /dzɣ/, /dʒɣ/
	aspirated	/t ^h χ/, /ts ^h χ/, /tʃ ^h χ/
	ejective	/t'q'/, /ts'q'/, /tʃ'q'/
(c) labio-velar	voiced	/bg/
	aspirated	/p ^h k ^h /
	ejective	/p'k'/
(d) labio-uvular	voiced	/bɣ/
	aspirated	/p ^h χ/
	ejective	/p'q'/

Harmonic clusters consist of two members, the first of which is restricted to labials and coronals, and the second to velars and uvulars. Laryngeal characteristics are constant across the cluster. They can occur either word-initially or word-medially. The clusters are regressive in terms of articulation. They recede into the oral cavity, the second member always being posterior to the first (Catford 1977). The order back-front is "by no means allowed" (Tchikobava 1967).

According to Vogt (1958), Tschenkeli (1958), and Deprez (1988), there are four properties that distinguish harmonic clusters from true ones:

- (i) they show homogeneity of laryngeal features, as explained above;
- (ii) the two members of harmonic clusters have simultaneous closures and only one release;
- (iii) Harmonic clusters are the only obstruent groups allowed in stem-final position (corono-dorsals more than labio-dorsals):

(3) bert'q-	'to dust'
varts ^h χn-	'to comb'

It should be noted, though, that the stems never occur in isolation. In most cases when a Georgian word ends in a consonant cluster, the final consonant is a morphological marker, such as -s for the Dative :

(4)	<u>Nom</u>	<u>Dat</u>	
	ort'k'l-i	ort'k'l-s	'steam'
	marts'q'v-i	marts'q'v-s	'strawberry'

(iv) they are reported to be tautosyllabic:

si.ts ^h χe	* sits ^h .χe	'heat'	
si.t ^h χe	* sit ^h .χe	'liquid'	(Tschenkeli 1958)

Although all authors agree on the fact that harmonic clusters cannot be separated by a syllable boundary, there is almost no agreement on what the syllable structure of Georgian really is. Tschenkeli (1958) implies that syllabification is morphological. A cluster of several consonants can be separated mainly on morphological grounds, unless they form a harmonic cluster, as above. For nonharmonic clusters he gives the following syllabifications:

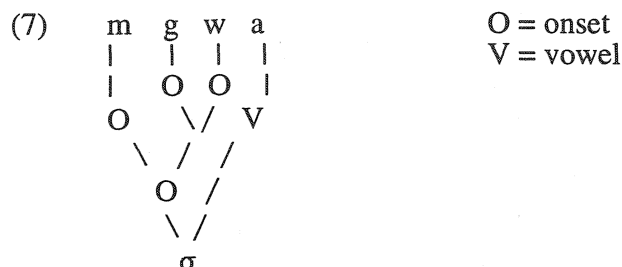
(5)	/saχl-/	sax.li	'house'
		mar.ts ^h va.li	'syllable'
		ts'in.svla	'progress' (lit. 'go forwards'; compound)
		mart ^h l.ts'era	'write properly' (compound)

All harmonic clusters are well-formed word-initial clusters:

(6)	dgoma	'standing'
	bgera	'sound'
	dʒgup ^h i	'group'
	t ^h k ^h ma	'saying'
	ts ^h k ^h era	'to stare'
	t'q'e	'forest'
	ts'q'ali	'water'

The fact that these clusters are commonly allowed word-initially constitutes some evidence for their tautosyllabicity word-internally, as well. At the same time they constitute surface violations of the principle of sonority. A well-formed onset must rise gradually in sonority toward the sonority peak formed by the syllable nucleus. Thus, the allowed sequence is obstruent-sonorant, in rising order of sonority. The onsets listed above do not follow this steady climb. They consist of sequences of obstruents, or of obtruments preceded by sonorants. The proposal has been made to analyze big onset clusters by making use of the constituent parts of the syllable, the onset and the rhyme.

Following Kurylowicz (1952), Gussmann (1992) treats Polish complex onsets as consisting of two subparts, each of which is a proper onset. The term 'proper onset' refers to the sequence: (s) obstruent-sonorant, which does not violate the sonority principle. Thus, a word like *mgwa* 'mist' is analyzed as one syllable with a double onset²:

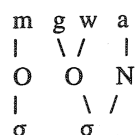


Gussmann's analysis is supported by the yer deletion in Slavic, which results in consonant clusters. It is not clear whether such an analysis would work for Georgian, where sonority violations seem to be more severe.

Two additional properties distinguish the corono-dorsal clusters from labio-dorsal ones:

- the two members of corono-dorsal harmonic clusters can never be split by an intervening /r/ (*dgoma* 'standing', **drg-*), whereas this is possible in labio-dorsal ones (*brge* 'high', *bgera* 'sound'), as well as in non-harmonic clusters which moreover allow free variation. Thus, *gdzeli*/*grdzeli* have the same meaning ('long'). If we adopt the view that Georgian has in its inventory the harmonic clusters /dg/ and /bg/ functioning as complex segments, then the existence of forms such as *brge* is evidence for the presence of a simple sequence *bg* as well. It needs to be explained then why a sequence *dg* does not coexist with the complex segment /dg/. On the other hand, if the harmonic clusters are not complex segments, then all the forms discussed above are simple sequences of phonemes, and no distinction needs to be made between corono-dorsal and labio-dorsal clusters³.

²Another possibility would be to treat such a word as disyllabic, with the first syllable consisting only of an onset:



³ Vogt (1958) suggests that the reason why forms like *bgera* 'sound' and *phkhureba* 'to disperse' do not allow an /r/ to break the cluster, is because there is already an /r/ in the onset of the syllable following the

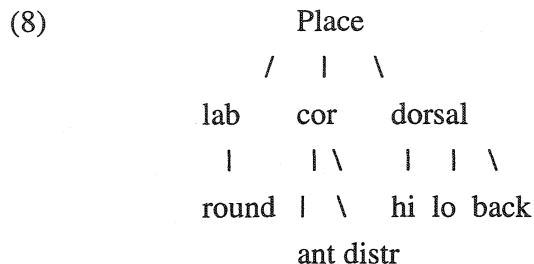
- corono-dorsals may be members of three-stop clusters, but labio-dorsals may not.

Corono-dorsals allow the combinations: X[cor-dors]

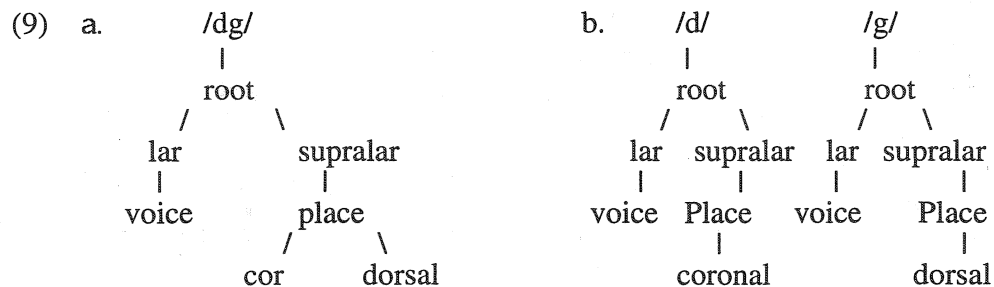
[cor-dors]X

t'k'bili 'sweet'

Deprez (1988) proposes to represent harmonic clusters as complex segments in the model developed by Sagey (1986):



In this model corono- and labio-dorsal harmonic groups can be represented as consisting of one root node (9a), as opposed to two separate root nodes (9b).



The representation in (9a) captures the basic properties of the clusters. . They pattern as a single consonant, they are phonetically simultaneous (their closures cannot be separated,

cluster. Thus, the presence or absence of /r/ may have nothing to do with the cluster type, but rather it seems to follow from cooccurrence restrictions attested in the language.

There is extensive evidence both from Old and Modern Georgian of /l/ and /r/ dissimilation (Fähnrich 1991, Aronson 1982, 1991, Fallon 1993). The adjectival suffix -ur becomes -ul if the stem already contains an /r/:

'Basque'	bask'i	bask'uri
'Physics'	phizik'a	phizik'uri
'Russian'	rusi	rusuli
'history'	ist'oria	ist'oriuli

This phenomenon can be accounted for by invoking an OCP effect on the feature [lat]: two identical values (-) of the feature, or specifications, if the feature is privative, cannot be adjacent on the same tier. It is therefore a property of /r/ rather than of the cluster, which prohibits such forms as: *brgera or *phrkhureba.

they have only one release). The laryngeal node will be filled by only one specification (either [voice], [spread glottis] or [constricted glottis]), which implies homogeneity of laryngeal features⁴. Deprez concludes that all coronal-dorsal harmonic clusters should be analyzed as complex segments. Labio-dorsal harmonic clusters can be either true clusters or complex segments, based on lexical distinction (whether they are broken up by /r/ or not). Word-medial labio-dorsal harmonic clusters are always complex segments. Other treatments of consonant clusters as complex segments are found in Anderson (1978) and Padgett (1990) for Kabardian. Anderson analyzes ejective clusters such as [t'p'] as complex segments. He relates their unitary phonological behavior to their articulatory nature, consisting of a sequence of two oral articulations associated with a single laryngeal gesture. If the two adjacent obstruents do not form a complex segment, they are represented as two separate root nodes, each of which contains only one place feature. A decision must be made, therefore, between representing a sequence of two place features within one segment (9a), versus a sequence of two segments with different place features (9b). The goal of this study is to determine whether the former or the latter representation is in any way motivated by acoustic evidence.

3. Phonetic evidence for complex vs. simple segments

From an articulatory point of view, complex segments are characterized as segments with double, simultaneous articulations, as opposed to sequential articulations for a sequence of simple segments. For a complex segment whose two members are stops, simultaneous articulation implies that the closure of the second stop is formed before the closure of the first stop is released (Maddieson and Ladefoged 1989).

From an acoustic perspective, an important cue in distinguishing the doubly-articulated segment from the sequence is segment duration. Doubly articulated stops and nasals have very similar durations to stops and nasals with single articulations. For example, Maddieson and Ladefoged (1989) found that Yoruba /g̃b/ and /b/ have similar durations. /g̃b/ in *àg̃bà* 'jaw' has a mean duration of 132 ms, and a simple /b/ 128 ms. The difference is statistically non-significant. Sequences of two segments were found to be typically one and a half to two times the duration of single segments of similar type.

⁴ The focus of our discussion is the representation in (4), but there are further issues which remain to be addressed: one is specifying the adequate place of the feature [cont] in this representation. If we assume Deprez's consonant inventory, the feature is not needed, because harmonic clusters consist phonologically only of stops. The issue can no longer be avoided, though, in the case of clusters whose first member is an affricate. They will not be addressed in this paper.

Thus, the sequence in Eggon /kpu/ 'kneel' has roughly twice the duration of the labio-velar in /kpu/ 'die'.

A similar result was found for prenasalized stops vs. nasal-stop sequences. The duration of prenasalized stops is comparable to that of single segments (Burton, Blumstein and Stevens 1992 for Moru; Maddieson 1989 for Fijian; Herbert 1975, 1986 for Luganda).

The results of these studies make the following predictions for Georgian: a first difference should be apparent in the presence/absence of release bursts. If harmonic clusters are complex segments, then the first member of the cluster should systematically lack a release burst, as opposed to a sequence of stops, where each stop has its own release. Secondly, if a segment with two simultaneous articulations is roughly as long as a single articulation segment, then harmonic clusters as complex segments are expected to be shorter than a sequence of two single segments. A harmonic cluster functioning as a unit should have the duration of one single segment, while a sequence should have the duration of one and a half to two single segments.

4. Methods

4.1 Stimuli

A list of near minimal pairs was prepared (see Appendix 2), consisting, on the one hand, of lexical items in which the coronal-dorsal and labio-dorsal harmonic clusters occur in word-initial and word-medial position (e.g. *bgera* 'sound', *dzibgiri* 'hooligan'), and on the other hand, of a number of phrases or full sentences in which the cluster is formed at the junction of words (e.g. *egeb gip'ovis* 'perhaps he will find you'). This particular environment was chosen to contrast with the word-medial clusters, since there are no word-medial non-harmonic clusters. None of the clusters occurred word-finally. It should also be noted that the cluster /p'k/ occurs only word-medially. The discussion is based exclusively on the voiced and aspirated clusters, which could be accurately measured. The word list contained 24 tokens:

- 8 containing word-initial harmonic clusters (4 voiced, 4 aspirated);
- 8 containing word-medial clusters (4 voiced, 4 aspirated);
- 8 containing word-medial stop sequences (4 voiced, 4 aspirated).

Each token was repeated three times. The tokens were written in Georgian orthography, and read in isolation. Ejective clusters were left out for two reasons: first, the relevant measurements could not be made for them, given their rather varied acoustic shape; second, no tokens were found containing a simple sequence of ejective consonants, since

no ejectives occur word-finally. However, an acoustic description of the ejective clusters is provided in Appendix 1.

4.2 Subjects

Six speakers were recorded for this study, four male and two female. Four speakers were in their 20s, two in their 50s. None had any speech or hearing disorders. They were all from the Tbilisi area (the capital city), and were bilingual native speakers of Georgian and Russian. Outside of the rural area there are few Georgians who are monolingual native speakers of the language. The speakers had been away from Georgia for less than a week (three speakers), two years (two speakers), and 10 years (one speaker), but they continue to speak Georgian in their communities.

4.3 Recording

One speaker was recorded in a sound-proof booth. The rest were recorded in their homes. All speakers were recorded using a high-quality cassette recorder (Marantz, model PMD 222). The speakers read the wordlist at a normal rate. They were instructed to read the phrases/sentences containing consonant sequences, trying not to pause between words, as if they occurred word-medially. Thus both the harmonic and the true clusters occur in the same, medial position.

4.4 Analysis

The tokens were digitized on a SUN 3/160 computer at a sampling rate of 11kHz, and processed by the WAVES+ software package. Measurements were made on waveform and wideband spectrogram. I measured the duration of the entire cluster, as well as the duration of each individual acoustic parameter of each member of the cluster, as shown in Figure 1:

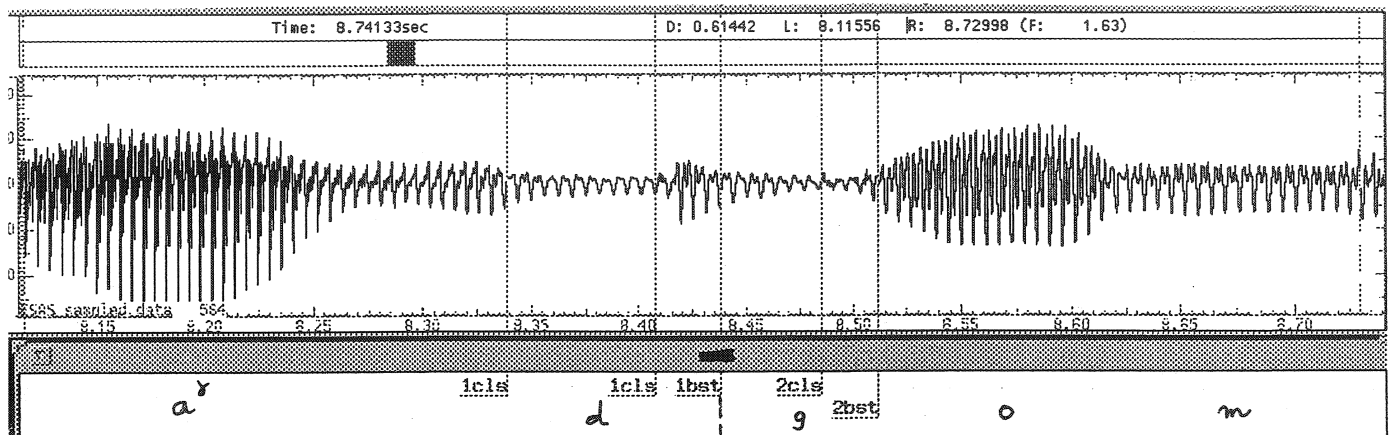


Figure 1. Labeled waveform of the word /aYdgoma/ (speaker Dim).

-cls1 the closure of the first consonant (except for word-initial clusters);

If the consonant is preceded by a vowel the duration was measured from F2 offset to C1 burst onset; if C1 is preceded by a fricative (/s/, /ʃ/), from the offset of frication to C1 burst onset.

-bst1 the burst of the first consonant;

The first burst of energy after C1 closure. For affricates (/ts/, /tʃ/), the frication part was included in the measurement;

-cls2 the closure of the second member of the cluster;

Measured from offset of C1 burst to onset of C2 burst.

-bst2 the burst of the second member;

The first burst of energy after C2 closure. For clusters whose second members are uvular fricatives (/ɣ/, /χ/) I measured the duration of frication.

5. Results

A significant finding, obvious from waveforms and spectrograms, is the clear presence of a release burst after the closure of the first stop. Most of the harmonic clusters, voiced, aspirated and ejective, have two release bursts, one for each member of the cluster, as opposed to only one final release, predicted by previous studies. Two bursts are visible both in word-initial and word-medial harmonic clusters. The frequency of occurrence of release bursts is shown in Table 2 below:

	<u>wd-initial clusters</u>	<u>wd-medial clusters</u>	<u>sequences</u>	
burst1 present (total: 54)	51 (94%)	51 (94%)	38 (70%)	$\chi^2=17.82$
burst2 present (total: 72)	71 (99%)	63 (88%)	72 (100%)	$\chi^2=15.76$

Table 2. Frequency of occurrence of release bursts.

Word-initially and word-medially, clusters pattern together with respect to the frequency of occurrence of the first burst. 51 (94%) of word-initial clusters and the same percentage of word-medial clusters have a first burst, as opposed to only 38 (70%) for sequences. The difference was significant by a chi square test [$\chi^2=17.82$, $p<.01$]. The burst of the second consonant was almost always present: 71 (99%) of word-initial consonant clusters have a second burst, and 72 (100%) of the sequences. Fewer word-medial clusters (88%) have a second burst. This difference was also significant by a chi square test [$\chi^2=15.76$, $p<.01$]⁵.

In the word /dgoma/, for example, two bursts are visible in the waveform and spectrogram in Figure2.

⁵ In computing the frequency of occurrence of the first burst, the clusters and sequences ending in the uvular fricatives /x/ and /ɣ/ were left out. The fact that in these cases the first burst was always present was attributed to the more favorable environment, a following fricative being less likely to impede the release of a stop closure than another stop. The frequency of occurrence of bursts was calculated over the clusters [dg], [bg], and [tʰkʰ], including [tsʰkʰ] for the second burst only.

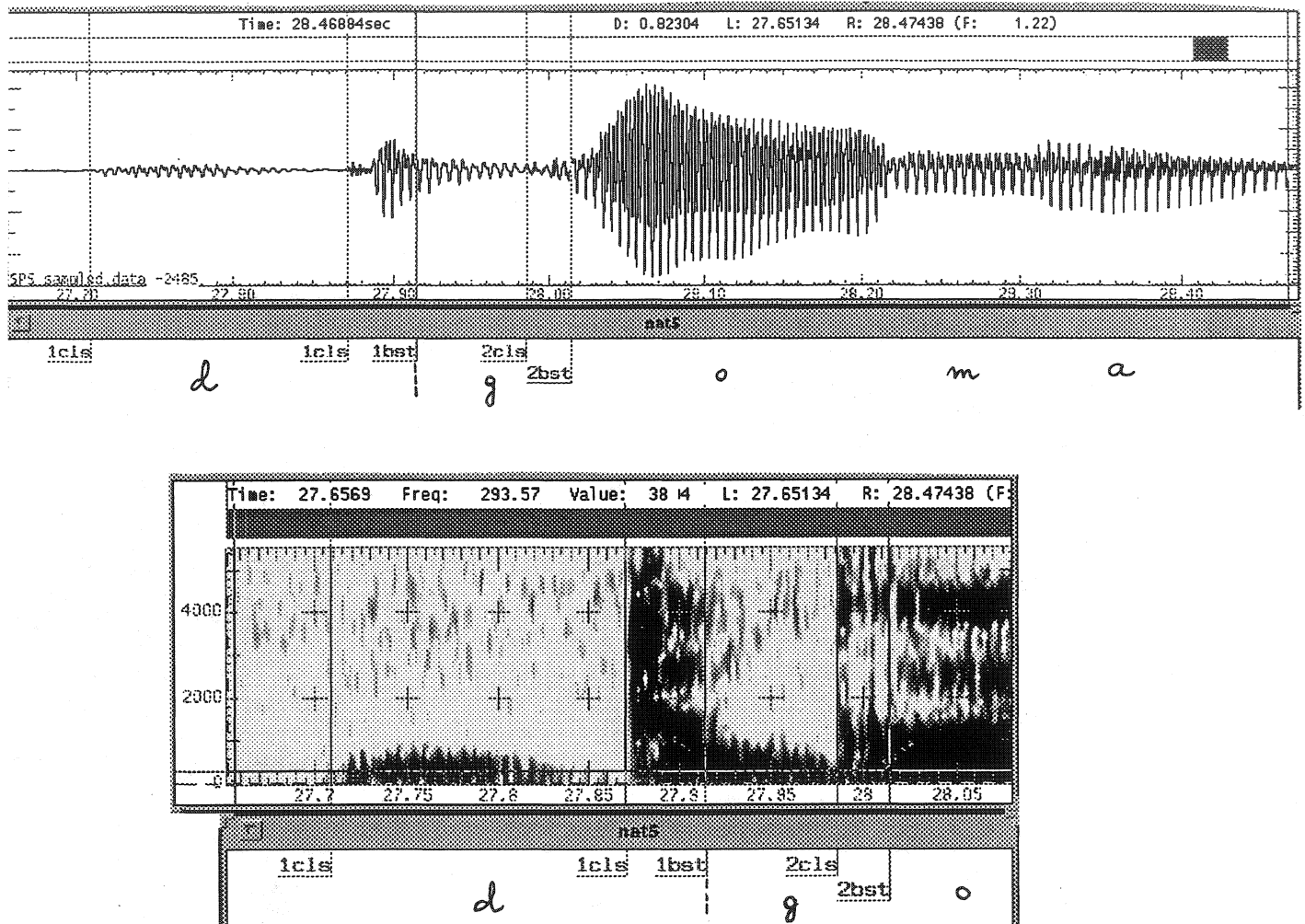


Figure 2. Waveform and spectrogram of the word /dgoma/ (speaker Nat).

Word-medial clusters also have two distinct bursts, as shown in Figure 3.

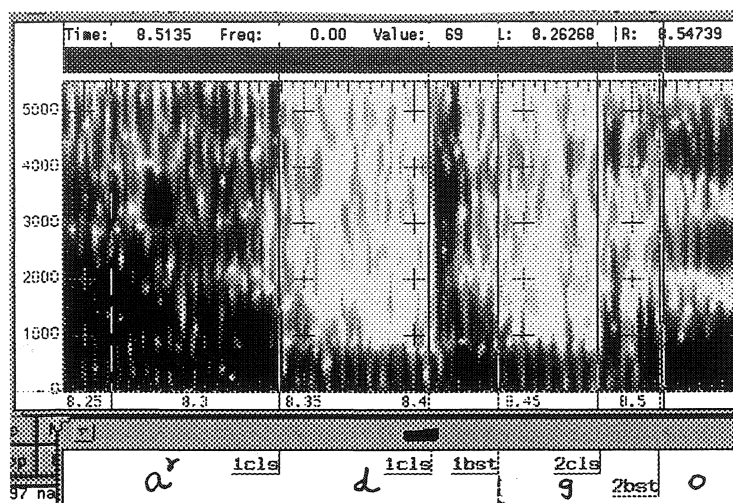


Figure 3. Spectrogram of the word /aʔdgoma/ (speaker Dim).

Figures 4 and 5 show the words /tʰkʰma/ and /datʰkʰma/ with an aspirated release for each stop, word-initially and word-medially. The aspiration for the first stop is weaker than for the second one.

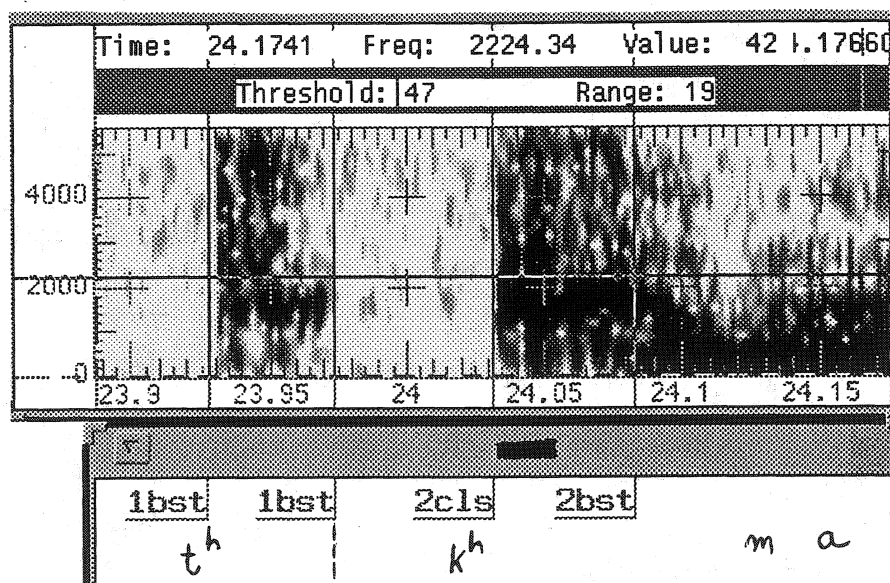
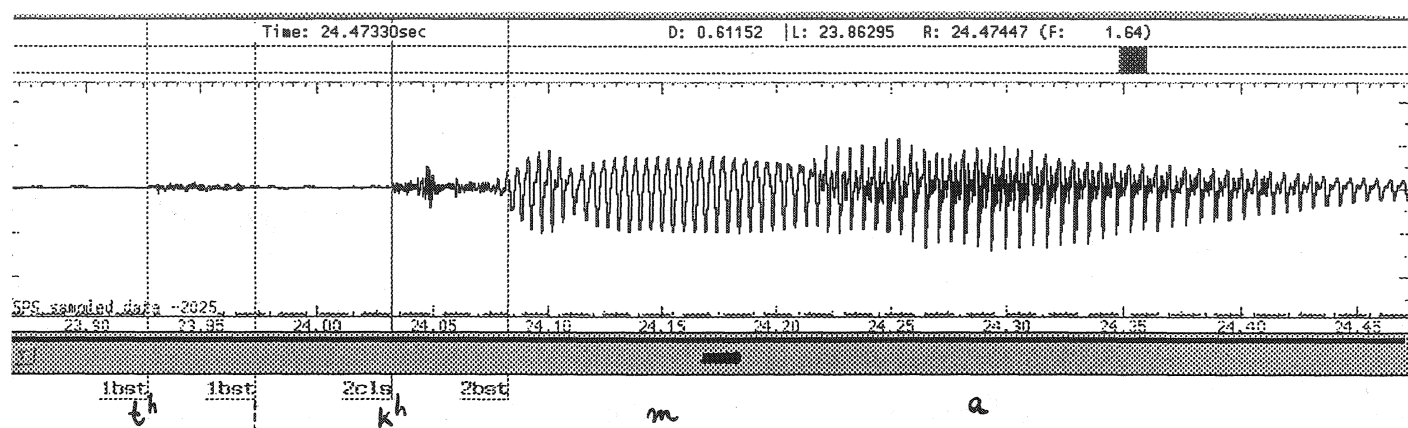


Figure 4. Waveform and spectrogram of the word /t^hk^hma/ (speaker Dim).

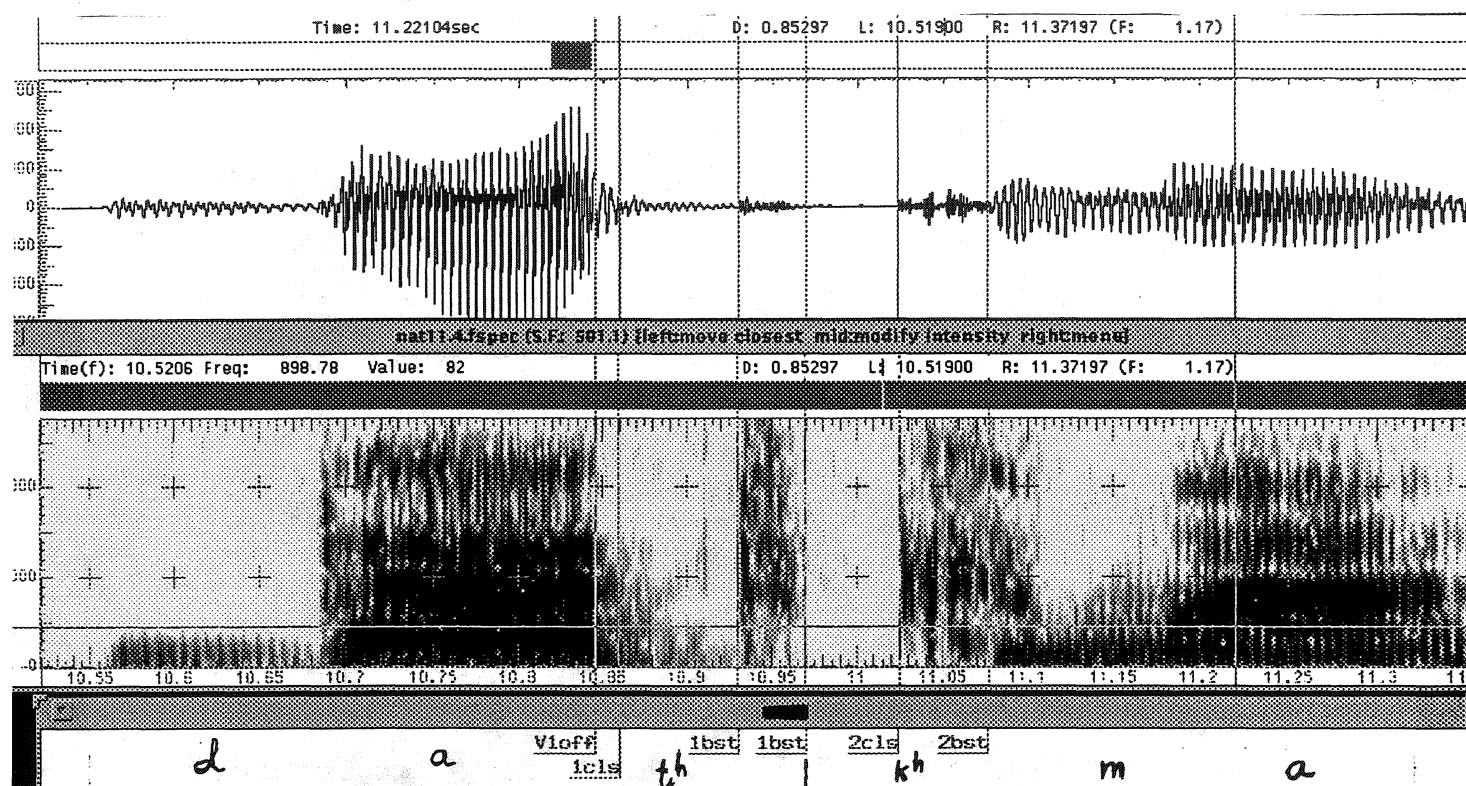


Figure 5. Waveform and spectrogram of the word /dat^hma/ (speaker Nat).

Interestingly, several of the waveforms and spectrograms of voiced and aspirated consonant sequences lack a release burst for the first stop. In Figure 6, for instance, where /dg/ is a sequence of two heterosyllabic stops, the /d/ burst is absent.

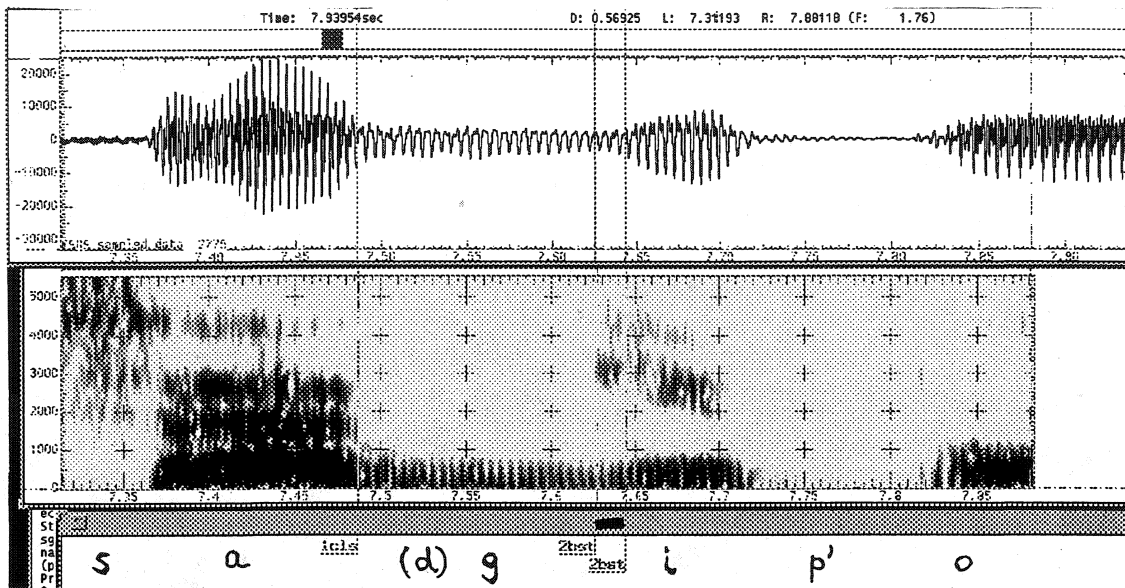


Figure 6. Waveform and spectrogram of the phrase /sad gip'ovo/ (speaker Nat).

In a sequence of aspirated stops shown in Figure 7, the aspiration of the first burst is shorter than that of the second burst.

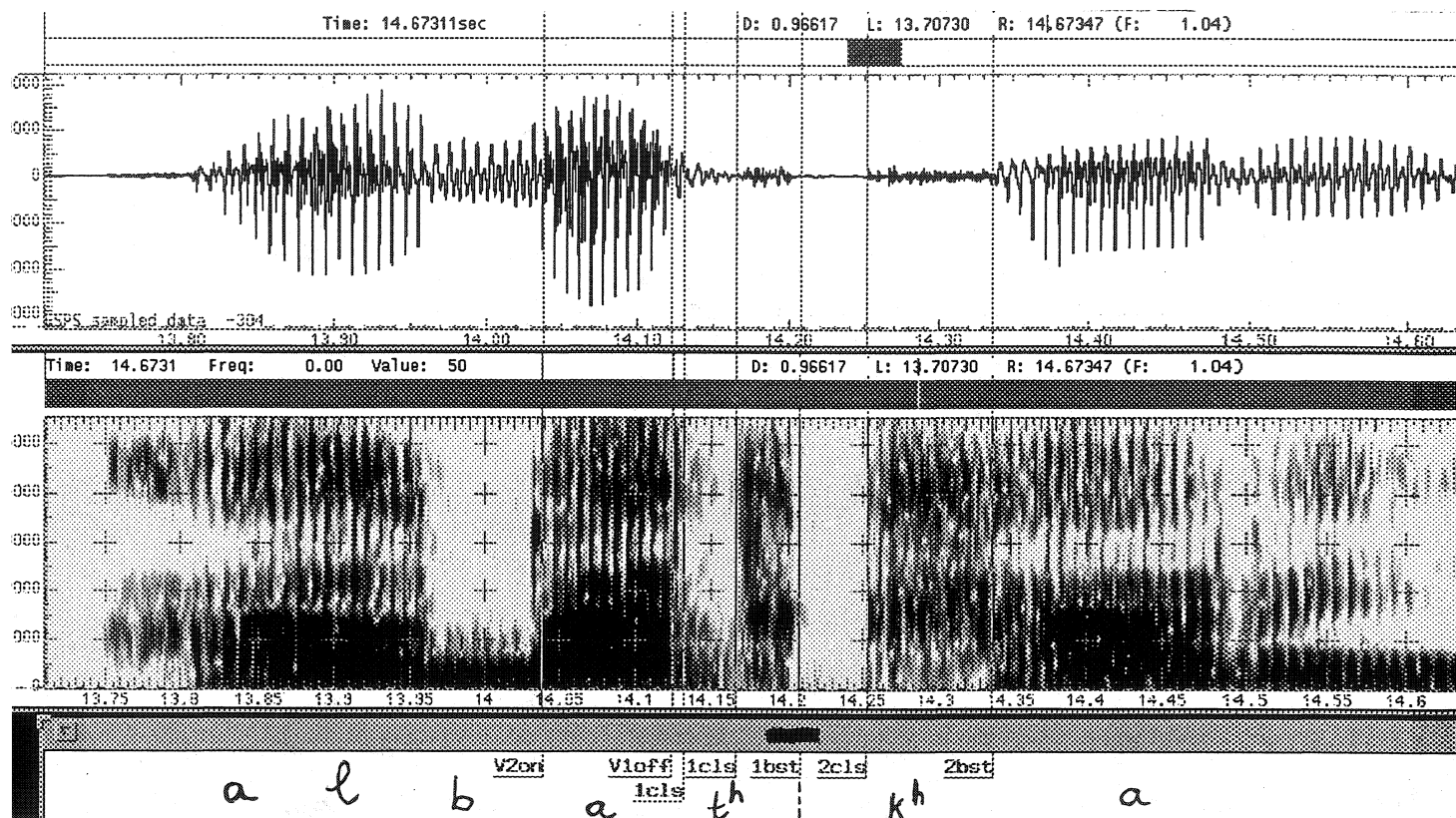


Figure 7. Waveform and spectrogram of the phrase /albat^h k^h ari/ (speaker Dim).

In section 3 an expectation was formulated concerning the duration of harmonic clusters: if they function as a unit, they are expected to be roughly half as long as a sequence of simple segments. However, when comparing the total duration of harmonic clusters and of consonant sequences, none of the clusters turned out to be shorter than the sequences, as previous studies of complex segments had suggested. I measured the voiced clusters and the aspirated clusters separately. I also separated the stop-final clusters ([dg], [bg], [t^hk^h], [ts^hk^h]) from the fricative-final ones ([dʏ], [bʏ], [t^hχ], [ts^hχ]). I then compared the average duration of word-medial clusters (means based on three repetitions) and sequences for all speakers. The results are shown in Figure 8.

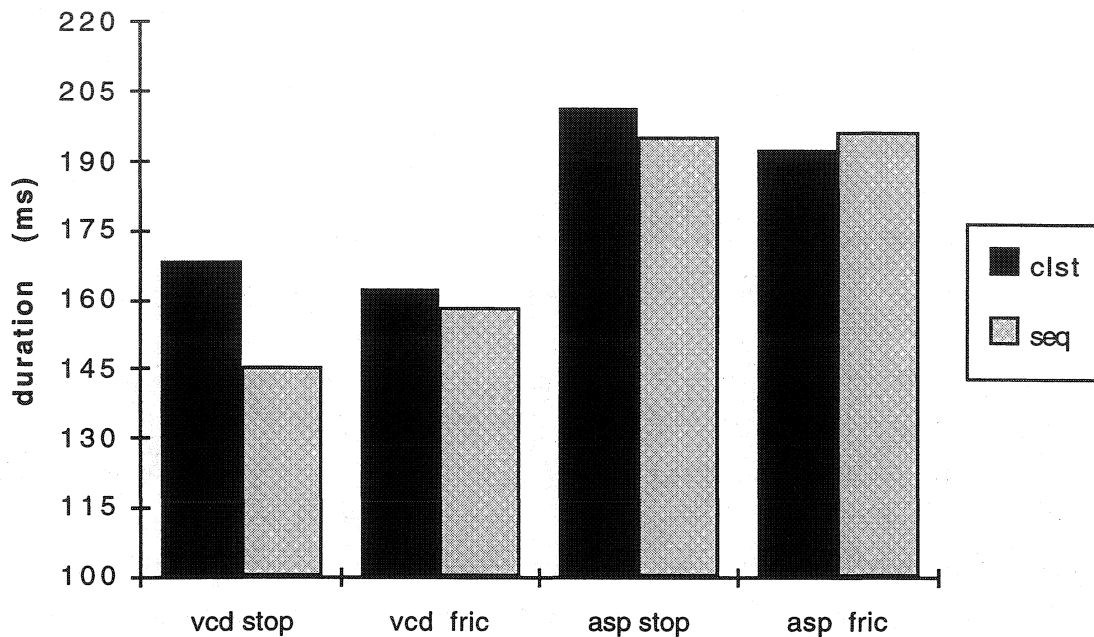


Figure 8. Average duration (ms) of clusters vs. sequences as a function of the manner of the second consonant.

Paired two-tailed t-tests reveal a statistically significant difference between voiced word-medial stop-final clusters (168 ms) and sequences (145 ms), but it is the former which are significantly longer [$t(11)=5.99$, $p=.000$]. Fricative-final medial clusters (162 ms), are comparable to stop-fricative sequences (158 ms). Stop-final aspirated clusters (201 ms) are not significantly different from the sequences (195 ms). The same holds true of fricative-final clusters (192 ms) versus the sequences (196 ms). None of the results is the expected one. If the word-medial clusters were indeed complex segments, they were expected to be shorter than a sequence of two simple segments. None of the clusters was shorter than the sequences, suggesting that their treatment as complex segments is incorrect.

6. Discussion

Contrary to previous assumptions, the spectrograms and waveforms clearly show the presence of two bursts in the voiced clusters, one for each stop, and of two aspirated bursts in the aspirated clusters. The waveforms and spectrograms of these clusters show a clear sequence closure1 - burst1 - closure2 - burst2, although many grammars describe

them as consisting of one single closure, and one release. This finding contradicts the characterization of harmonic clusters as having simultaneous closures and only one release. Both stops are released, and for the aspirated series both are aspirated. The aspiration of the second stop is slightly longer than that of the first, which is not surprising, given that an aspirated release is impeded by an immediately following stop. Even if auditorily one might conclude that the first stop burst is missing, in the sense that it is almost not heard, the acoustic evidence for the presence of a burst is quite strong.

This result confirms the findings of other studies. The issue of the presence vs. absence of a burst in English is addressed by Henderson and Repp (1982). The oscillograms based on their recordings contradict the commonly held view that in a sequence of two stops the first one has no release. Henderson and Repp find clear bursts for both stops in word-internal sequences (*cactus*, *pigpen*), and in word-final ones (*act*, *sobbed*), thus contradicting an observation by Anderson (1974) that English stops lack a release when followed by another obstruent. Henderson and Repp find that in English words the release bursts are most common when the second stop is a velar. In an alveolar-velar sequence both stops are released, explained by the fact that the same articulator is involved (the tongue). The first closure must be released before the second one can be formed. At the same time, the results of a perception experiment reveal that the burst is so weak, that it is not heard. The authors therefore conclude that 'unreleased' is an auditory concept, but that a burst is acoustically and articulatorily present. Similarly, in Georgian the bursts of the first stop are not auditorily detectable, but they are clearly produced.

Similarly, Kim and Jongman (1994) find that Korean stops are released, contrary to traditional descriptions of the language, which claimed that stops are not released, in word-final or word-medial codas. For monosyllabic CVC words the authors found that a root-final /t/ followed by a suffix-initial /k/ was released 83% of the time.

The results of the present acoustic investigation, showing the presence of two clear bursts in the harmonic clusters would be even more convincing if supported by an articulatory EPG study. It would show whether the closures of the two consonants in the cluster are to any degree simultaneous in harmonic clusters vs. sequences. Should the EPG data also show the presence of two distinct bursts, the analysis suggested above would be further strengthened.

If coronal- and labio-dorsal clusters such as dg, tk, bg, pk were complex segments, they would be the mirror image of, for instance, labio-velars (/kp/). According to Maddieson (1990) the former are not attested as complex segments, a situation explained

by their articulation. Maddieson and Ladefoged (1989) claim that clicks are the only attested segments with simultaneous coronal and dorsal closures. They are, however, velaric ingressive sounds. In a pulmonic egressive airstream mechanism, a velar closure cannot be formed unless the first stop has been released (Maddieson 1990). In the case of /kp/ and /gb/, C1 can be released after the labial closure has been formed, because two different major articulators are involved: the tongue dorsum and the lips. Thus, in this case it is possible to produce two closures simultaneously. In the case of pk, tk, bg, dg, however, any C1 of any articulation must be released before the velar closure can be formed. The two closures cannot be simultaneous, with only one release. They are a sequence of two stops, allowed in a syllable onset, at least in word-initial position.

Such a case, where apparent complex consonants are found to be simply complex onsets is that of Shona (Maddieson 1990). Shona has a velarization rule by which a high vowel following a non-velar consonant becomes a velar consonant. The rule is formulated in (10):

(10) CV1V2 → CKV2

|
[+hi]

K = velar (/k/, /g/, /ŋ/)

monomorphemic

imbwa → imbga

‘dog’

uzutwe → uzútk^we

‘(mushroom sp.)’

Noun class prefix + root

mu+ana → mwana → mjana

‘child’

mu+edzi → mwedzi → mjedzi

‘moon’

tu+ana → twana → tk^wana

‘little children’

Doke (1931) refers to them as ‘velarized’ bilabials and coronals, implying that they are functionally single consonants. His studies show diagrams based on palatograms and linguagrams of the articulatory position of these clusters, suggesting that they have simultaneous closures. Maddieson's measurements of intraoral air pressure, as well as his waveforms, clearly show that the two closures are successive, and that each stop has its own release burst. Based on these results, and on the simple syllable structure of the language (Shona has only open syllables), he argues that the velarization rule is simply a glide strengthening rule which changes glides into velar consonants when they follow

non-velar consonants. Shona clusters resulting from velarization should be analyzed as complex onsets, rather than complex segments. If Georgian indeed allows the same complex onsets word-internally that it allows word-initially, it might constitute a case similar to Shona, in the sense that harmonic clusters are simply onset clusters, and not complex segments.

The presence of the two bursts justifies the phonetic notation of harmonic clusters used in this study. I represented each member of the cluster with its own aspiration or glottalization: $t^{h}k^{h}$, $t'k'$ as opposed to tk^{h} , tk' , which would be appropriate for a complex segment.

The second issue of interest was the comparison of the total duration of clusters and sequences. The results showed the following: for the voiced series the total duration of word-medial stop-final clusters was found to be longer than for stop sequences. The duration of the voiced fricative-final clusters was comparable to that of sequences. For the aspirated series, the duration of both stop- and fricative-final clusters was similar to that of sequences.

The results did not follow the predictions made by Maddieson and Ladefoged (1989) with respect to the duration of complex segments vs. sequences of simple segments. According to them complex segments have very similar durations to single segments, therefore they should be shorter than a sequence of two single segments. A Georgian word-medial cluster functioning as a complex segment should have roughly half the duration of a sequence of two single segments. Georgian clusters do not show this difference, suggesting that an analysis as complex segments is incorrect. Moreover, in one case in the voiced series the harmonic clusters are slightly longer than the sequences.

7.1 Effects of syllable structure

In the previous section a difference in duration was mentioned, between voiced stop-final harmonic clusters and sequences. The harmonic clusters were slightly longer, exactly the opposite of the predicted result. The tokens were further segmented into separate parts (namely burst and closure duration), and measured individually, in an attempt to see which portion contributed to the difference. These results, however, are not as robust as the ones presented in section 5. For one thing, the duration differences may have been affected by the lack of control for word duration. Secondly, in most cases, one or more speakers had to be left out because a burst was absent, and the relevant measurements could not be made.

A significant difference was found in the duration of the first closure of voiced clusters. The closure of the first stop turned out to be longer in the voiced harmonic clusters than in sequences. Table 3 contains the average duration of the closure of the first stop in voiced word-medial clusters and in stop sequences. The difference between them is statistically significant for both stop-final and fricative-final clusters, showing that the closure duration is longer in word-medial clusters than in stop sequences.

	cluster	sequence		
stop-final	55	42	t(8)= -2.47	p=.039
fricative-final	56	42	t(8)= -3.31	p=.011

Table 3. Average duration (ms) of the closure of the first stop in voiced stop-final and fricative-final clusters and sequences.

In what follows I will argue that the duration difference in the first closure is not entirely unpredicted. I suggest that it constitutes evidence for the difference in syllabification between word-medial clusters and sequences: word-medial clusters are tautosyllabic, while the consonant sequences formed across word boundaries are not, as shown below:

- (11) word-medial sequences
 V1 . C1C2V2 V1C1 . C2V2

Although complex onsets would violate sonority, it could be that the homogeneity of laryngeal features is the only requirement for tautosyllabicity. The phonology of these onsets can be handled by the multiple-onset analysis presented in section 2, based on Gussmann (1992), with only one laryngeal feature per onset. The restriction on laryngeal features is not uncommon. English also requires one laryngeal gesture per onset. According to Browman and Goldstein (1986) this requirement is satisfied in English onsets where the voiced/voiceless contrast is neutralized following /s/. Thus a single glottal gesture is found for word-initial s-stop clusters. The phonological behavior of such clusters, like that of Georgian harmonic clusters, is ambiguous: they might be considered to act as single units, given the single glottal gesture, or as sequences of two units, given two oral gestures. Therefore, homogeneity of laryngeal features across a cluster is not necessarily associated with a clear behavior of that cluster as a complex segment, but rather with an ambiguous phonological status. The compatibility of laryngeal features in well-formed onsets is also explored by Steriade (1993). She relates

the well-formedness of an onset to the possibility of merging compatible laryngeal features in that particular articulatory sequence.

The location of the syllable boundary remains a controversial issue in Georgian. Although most descriptions of the language claim that harmonic clusters are syllabified in the onset, the intuitions of native speakers are very mixed. Arguments for tautosyllabicity can be based on such descriptions, on frequency of occurrence of bursts, and on the fact that all of the harmonic clusters are perfectly well-formed word-initial clusters, as shown in section 2.

The presence/absence of the first burst was discussed in section 6. The waveforms show a clear difference with respect to the release burst of the first stop. Word-initially and word-medially both stops are often released, whereas in sequences the first stop is less often released, or released with less aspiration in the aspirated series. It can be argued that the weaker aspiration or the absence of a burst occur in the coda, versus full burst and aspiration in the onset. The frequency of release bursts may serve as evidence for the different syllabification pattern. I show below the percentage of releases for each position in the token, and the position of the syllable boundary argued for:

<u>wd-initial cluster</u>	<u>wd-medial cluster</u>	<u>sequence</u>
C1 C2	C1 C2	C1 C2
94% 99%	94% 88%	70% 100%
. C1C2	(. C1C2)	C1 . C2

Table 4. Percentage of releases as a function of syllable boundary location.

The lowest frequency of bursts occurs in single coda consonants (70%), and the highest in single onset consonants (100%). Both consonants in the harmonic clusters have a higher burst frequency than the one coda consonant in the sequence, a result which supports the syllabification pattern illustrated above. Both consonants in the word-medial harmonic cluster have a lower frequency of burst occurrence than the single onset consonant, which may be caused by their clustering in the same onset. The second consonant in the word-initial clusters behaves very much like a single onset consonant. It is released more systematically (99%) than in the word-medial cluster (88%). The difference shows that in the clusters the second burst is more likely to be affected by the overall accumulation of segments in the word than the first burst. For the first consonant in the clusters there is no difference in release frequency. The identical values for the frequency of the first burst support the idea of a similar behavior with respect to syllable

structure: the first consonant of the word-medial cluster is also in the onset, like its counterpart in the word-initial cluster.

I tried to find further evidence for the syllabification pattern in the duration of the vowel preceding the cluster/sequence, based on earlier studies (Maddieson 1983, 1985) showing that vowels are longer in open than in closed syllables. In an investigation of the Chadic language Bura, Maddieson (1983) uses vowel duration as evidence that word-initial labial-alveolar consonant sequences are resyllabified word-internally, where possible:

- (12) tsa + bda → tsab . da
 person/aspect + 'to collect honey'
 tsa + mta → tsam . ta
 'to die'

A vowel preceding a coda consonant is found to be shorter than one preceding an onset consonant. In order to investigate this effect in Georgian, I measured the vowel duration of the original recordings. I first compared the duration of the vowels preceding the cluster and sequence [bg], and the cluster and sequence [t^hk^h]. In the words containing clusters the syllable boundary is reported to be before the entire cluster. In the sequence the syllable boundary is between its two members. The results are given in Table 5.

(V.C1C2V)	dat ^h k ^h ma	134		
VC1.C2V	albat ^h k ^h ari	83 (62%)	t(5)= -7.71	p=.001
(V.C1C2V)	dzibgiri	93		
VC1.C2V	eg e b gip'ovis	80 (86%)	t(5)= -2.28	p=.072

Table 5. Vowel duration (ms) for six speakers (means over 3 repetitions).

The /a/ in /dat^hk^hma/, presumably in an open syllable, is significantly longer than the /a/ in /albat^h k^hari/, clearly a closed syllable. The duration of /a/ in the sequence is 62% of the duration of /a/ in the cluster. The difference is less significant for /i/ in /dzibgiri/ vs. /e/ in /eg**e**b gip'ovis/, (the vowel in the sequence is 86% of the one in the cluster). However, the trend is quite strong in the right direction, especially considering the fact that low and mid vowels are longer than high vowels.

Nevertheless, we cannot safely say that vowel duration provides strong evidence for the two different syllabification patterns, because other factors which may have affected it were not controlled for: the number of segments and syllables in the tokens, vowel quality, position in the word, stress. The number of syllables and segments has an effect on segment duration. It is known that the larger the number of segments in a word, the shorter their individual durations. In one case we compared different vowels, but vowel height differences are in fact encoded in vowel duration; high vowels are found to be shorter than mid and low ones. We find the opposite effect (/i/ longer than /e/), but it could very well be due to the environment, which for /i/ consists of fewer segments than for /e/. The vowel's position in the word can also affect its duration. Stress is not expected to make much of a difference, as it is reported to be weak in Georgian. I conclude that the evidence from vowel duration shows a tendency in the right direction, but is not entirely reliable.

It is important to remember that the difference in duration was found for the voiced series only, but not for the aspirated clusters versus sequences. The difference could also be interpreted as simply related to voicing. We saw that sequences tend to lack the first burst 70% of the time, as opposed to clusters, whose first burst is more often released (94%). Whenever the first burst is not released, voicing has to be maintained over the entire duration of the two closures, which requires considerable articulatory effort. It may be that in such circumstances the duration of the sequence is reduced in order to maintain voicing comfortably throughout. The clusters don't need this adjustment, since each voiced closure is released, for each stop, without imposing additional pressure on the vocal cords.

The issue of the syllable boundary location might be clarified by an acoustic study of new tokens, this time contrasting different locations of syllable boundary with respect to the clusters: a clear open syllable, a clearly closed syllable, and a word-medial cluster preceded by a vowel, as shown in (13):

- | | | | |
|------|-------------------------------------|--|------------------------------------|
| (13) | da t ^h k ^h ma | albat ^h k ^h mari | dat ^h k ^h ma |
| | 'and saying' | 'probably husband' | 'to agree' |

The durations of consonants as well as preceding vowels would be relevant.

7.2 Summary

The preceding section focuses on the interpretation of additional results, trying to tie them in with the main issue addressed in this study: the presence/absence of consonant clusters functioning as a single unit in Georgian. It was found that the difference in duration in the stop-final voiced series is due to the duration of the first closure. None of the other parts measured (the second closure, the bursts, or the duration of the fricatives /ɣ/, /χ/) shows a significant difference. The difference in closure duration, along with the frequency of release-bursts and of aspiration, and differences in vowel duration, provide evidence for the syllabification of Georgian consonant clusters. I argue that word-medial consonant clusters are tautosyllabic, as opposed to sequences of consonants formed across word boundaries, which are heterosyllabic.

8. Conclusions

The present study has provided acoustic evidence for the nature of Georgian harmonic clusters. The results of the study do not support the phonological treatment of harmonic clusters as complex segments. Previous studies of complex segments have shown that their duration is comparable to that of single segments. Georgian word-medial consonant clusters turn out to be as long as consonant sequences, instead of shorter, as predicted if they had been complex segments. In one case they are even slightly longer. Descriptions of harmonic clusters claim also that they have simultaneous closures and only one release. The waveforms and spectrograms based on the recordings in this study contradict this description. I have argued instead that all obstruent clusters in Georgian are sequences of segments, articulated independently. The term 'harmonic cluster' implies only that the members of the cluster share the same laryngeal features.

In addition, a slight difference was found in the duration of the closure of the first stop, which is longer in word-medial clusters than in sequences. It was suggested that this difference could be attributed to the difference in syllabification: word-medial clusters are both in the syllable onset, while consonant sequences are separated by a syllable boundary. Evidence for the location of the syllable boundary was brought from Georgian phonotactics, from the duration of the vowel preceding the cluster/sequence, and from the more frequent absence of the first stop burst in sequences (syllable coda), than in word-medial clusters (syllable onset).

9. References

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Appendix 1

Ejective clusters

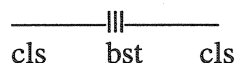
This appendix contains a description of the acoustic shape of single ejectives and ejective clusters in Georgian. I consider this appendix useful since very little acoustic data is available on Georgian ejectives. I compare the acoustics of Georgian ejectives to the results of previous studies by Robins and Waterson (1952) on Georgian, Lindau (1984) on Hausa and Navaho, Colarusso (1988) on Northwest Caucasian languages, and Flemming, Ladefoged and Thomason (1994) on Montana Salish. The harmonic ejective clusters are:

corono-dorsal: t'k', t'q', ts'k', ts'q', tʃ'k', tʃ'q'

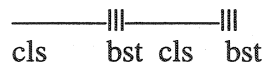
labio-dorsal: p'k', p'q'

As mentioned at the beginning of this study, for the ejective series no stop sequences could be found in the language, because no Georgian words end in ejectives. Therefore no relevant comparison can be made, as for the voiced and aspirated series, between word-medial harmonic clusters and stop sequences. In what follows I will discuss acoustic parameters for ejective stops and for ejective stop clusters, regardless of their position in the word.

The present study shows that ejective stops vary considerably in their acoustic shape. Two particular shapes are the most common: they often seem to have a second closure following their burst:



Sometimes, when the ejective is followed by a vowel, a second burst can be seen, released into the vowel:



Figures 9 and 10 show examples of Georgian single ejectives. In both cases the second closure following the burst can be clearly seen.

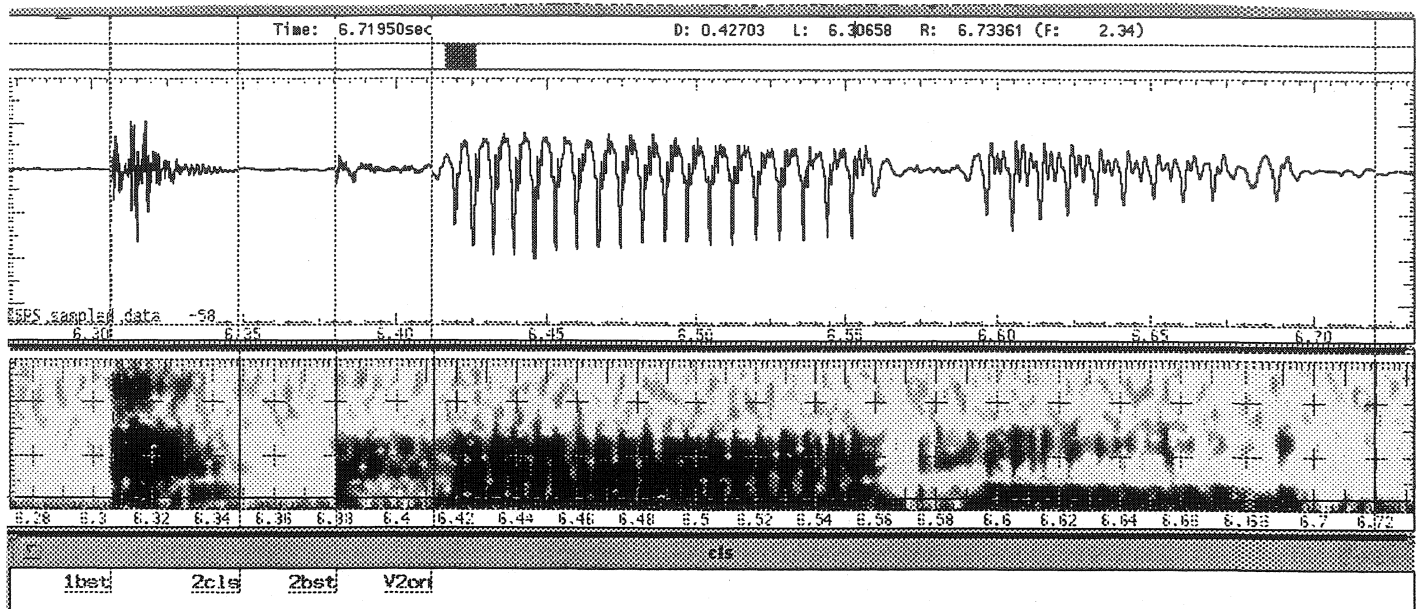


Figure 9. Waveform and spectrogram of the word /k'ari/ 'door' (speaker Gg).

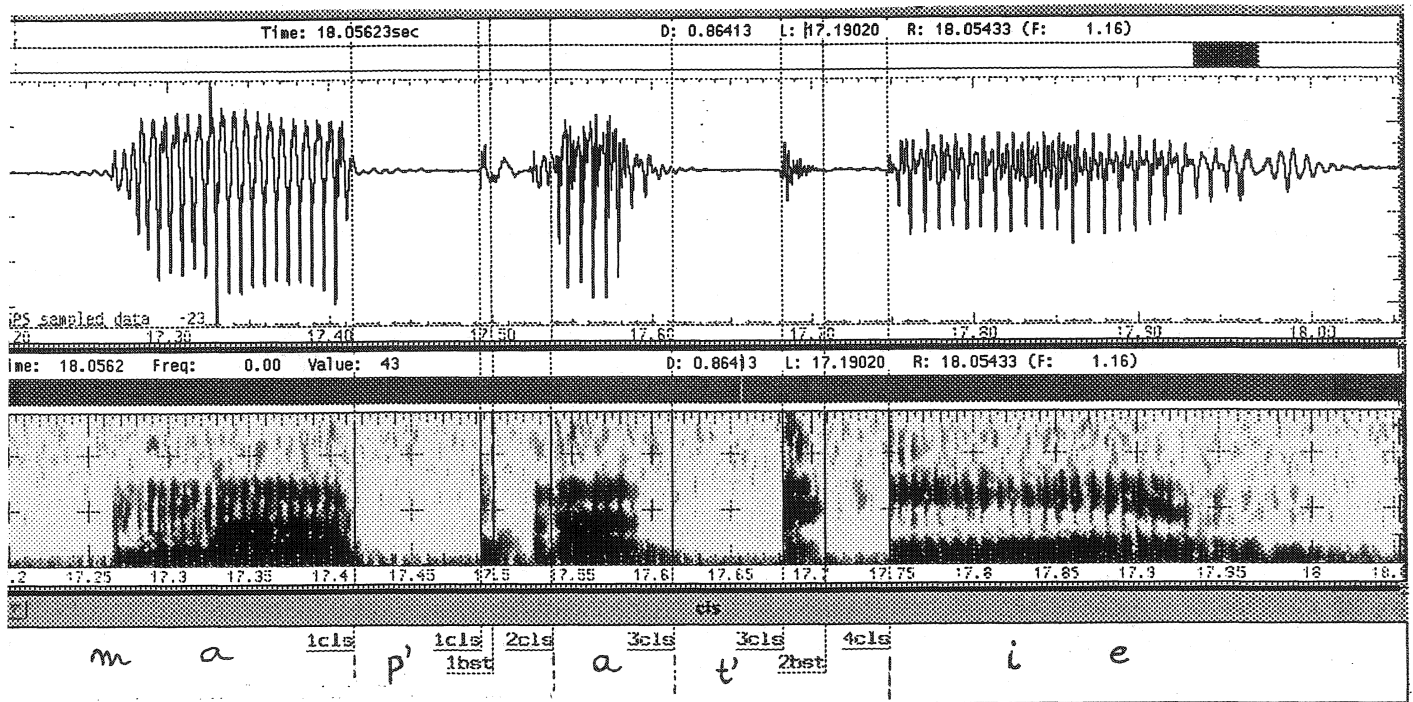


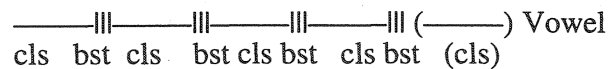
Figure 10. Waveform and spectrogram of the phrase /map'at'ie/ 'Forgive me' (speaker Gg).

Two closures are also found by Lindau (1984) in Hausa and Navaho intervocalic velar ejectives. Flemming et al. (1994) show aerodynamic tracings of Montana Salish ejectives, in which a considerable lag (of about 100 ms) is seen between the oral release and the release of the glottal closure, when the vocal cord vibrations begin. The ejective has a relatively small burst of oral air flow, followed by absence of airflow, showing that the glottal closure is maintained after the oral release. This phenomenon is visible on the waveforms of Georgian ejectives, in the closure following the ejective burst. Similarly, I interpret the first closure as corresponding to the closure produced in the oral cavity for the articulation of the stop, and the second one to the glottalic closure, which continues after the articulation of the stop. From their articulatory descriptions we know that ejective stops use glottalic airstream. This means that during their articulation the glottis is closed, and the larynx moves upward, acting like a piston which compresses the air in the mouth or pharynx, above the glottal closure. The opening of the glottis is delayed until after the articulation of the stop. Ladefoged (1993) gives the following instructions to the reader trying to produce a glottalized /k/, like the one in Hausa: "Release the [k] closure while still maintaining the glottal stop. Finally release the glottal stop and follow it with a vowel." (p. 122) The two closures visible on the waveform might correspond to those preceding the two releases in the articulatory description. Also, the second burst, corresponding to the glottal opening, is sometimes clear enough, at other times rather weak, and sometimes it is superimposed on the following vowel. A vowel onset simultaneous with the glottal release may explain the occasional squiggles or irregular pulses in it.

According to previous studies, the two closures are not unexpected. Jakobson, Fant and Halle (1951) show spectrograms of Circassian glottalized (checked) /p/ vs. simple voiceless (unchecked) /p/, followed by the vowel /a/. The spectrograms show that the ejective has an abrupt closure and is followed by a period of silence. The segments they refer to as 'checked' are marked by a sharper termination, and especially by an abrupt onset. Colarusso (1988) points out that 'checking', the abrupt onset, is a cue for intervocalic or prevocalic ejectives. Intervocalically the onset of the ejective (the beginning of its closure) can appear abrupt, because the preceding vowel has to stop abruptly for the glottis to close, in preparation for the ejective. Similarly, the termination of the ejective and the onset of a following vowel are going to be rather abrupt. The buildup of supraglottal air pressure by raising the larynx will be followed by an abrupt release. According to him, a more important cue for all positions is the strong intensity of the bursts. They appear very dark on the spectrogram.

Chomsky and Halle's (1968) description of ejectives in *The Sound Pattern of English* also suggests that two closures and two releases are to be expected, since ejectives involve supplementary motions. Chomsky and Halle argue that the closures must be released in a specific order, for the auditory effects to be clear. More precisely, "the closures are released in order of increasing distance from the lips." (p. 324) Thus, the first closure and release should correspond to the articulation of the sound in the oral cavity, and the second closure and release correspond to the glottal closure and opening. Catford (1977) confirms the fact that the glottal closure is released only after the release of the articulatory oral closure (p. 69). Georgian single ejectives, word-initial and intervocalic, confirm these observations.

Georgian ejective clusters confirm the result obtained for their voiced and aspirated counterparts: each member of the cluster has a visible burst (or bursts), showing that the cluster consists of a sequence of two ejectives, and is not a doubly articulated stop. Based on the description of a single ejective given above, a cluster of two ejectives is predicted to consist of four closures and four releases, sometimes with a fifth closure immediately preceding the vowel:



What I find, however, is that in a cluster not all four bursts are realized. Most clusters have only two or three. The second stop, the one immediately preceding the vowel, sometimes has an additional closure before the vowel onset.

A series of spectrograms and waveforms of ejective clusters are shown in Figures 11-15. The /t'/ burst is followed by a closure, then a strong /k'/ burst, and another closure before the vowel onset.

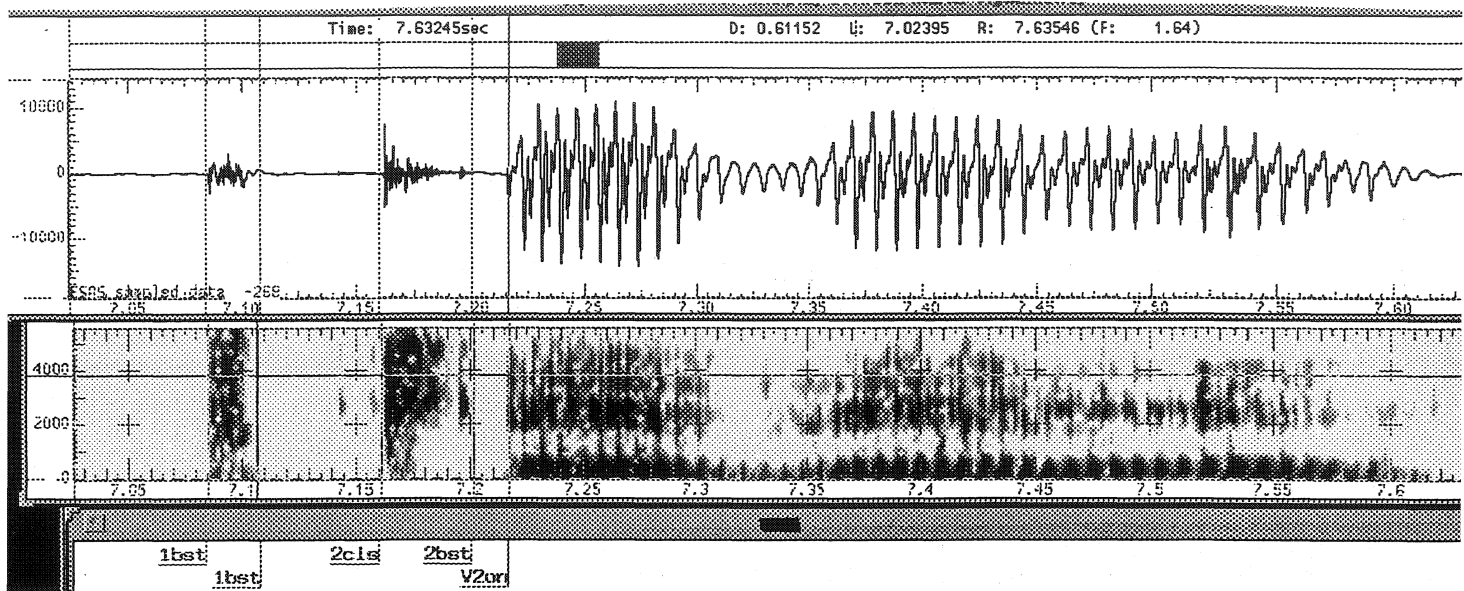


Figure 11. [t'k'] /t'k'ivili/ (speaker Gg).

The /k'/ burst is particularly clear, and followed by a second closure. Sometimes a second burst can be seen right in the vowel onset.

In their articulatory and auditory study of Georgian sounds, Robins and Waterson (1952) perceive a marked ejective articulation in word-initial ejectives, and in members of word-initial clusters. We would expect, therefore, that acoustic cues for ejectives will be stronger in word-initial position. All we have noticed in the clusters above is that the /k'/ burst is quite strong and clear, but not necessarily more so in initial position than word-medially.

/q'/ has the largest variety of acoustic shapes. In Figure 12 its burst is preceded by aspiration, while in Figure 13 it has three bursts and three closures.

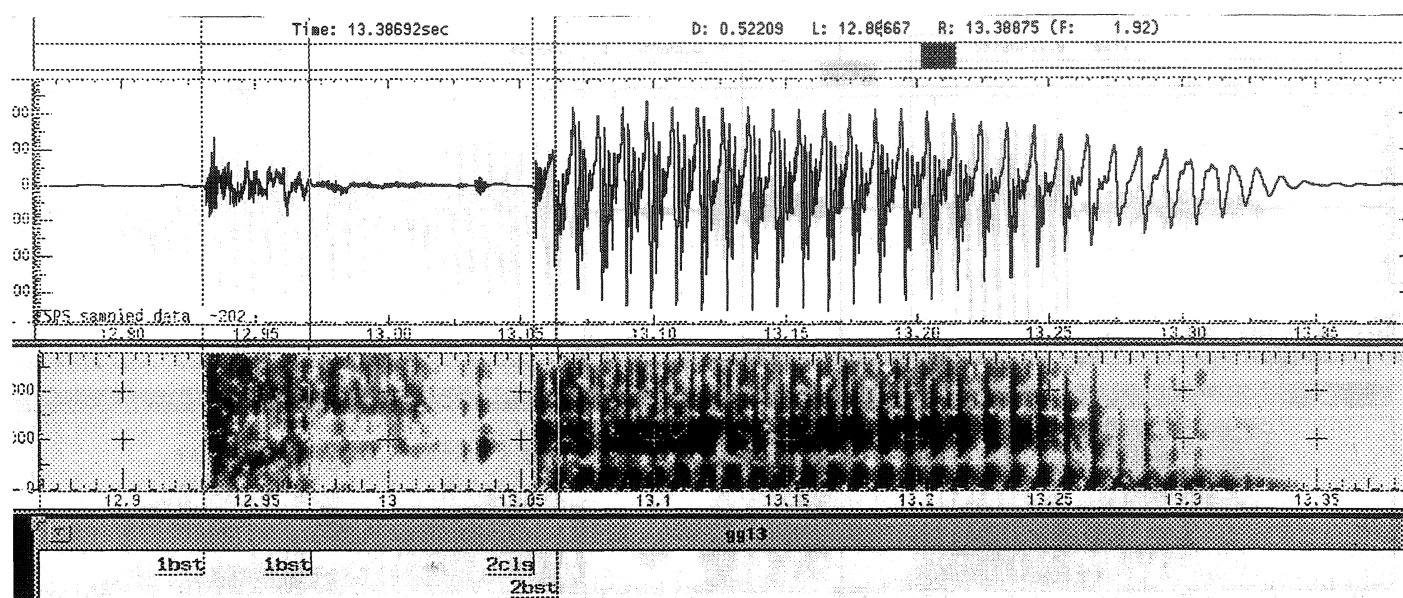


Figure 12. Waveform and spectrogram of the cluster [t'q'] in /t'q'e/ (speaker Nat).

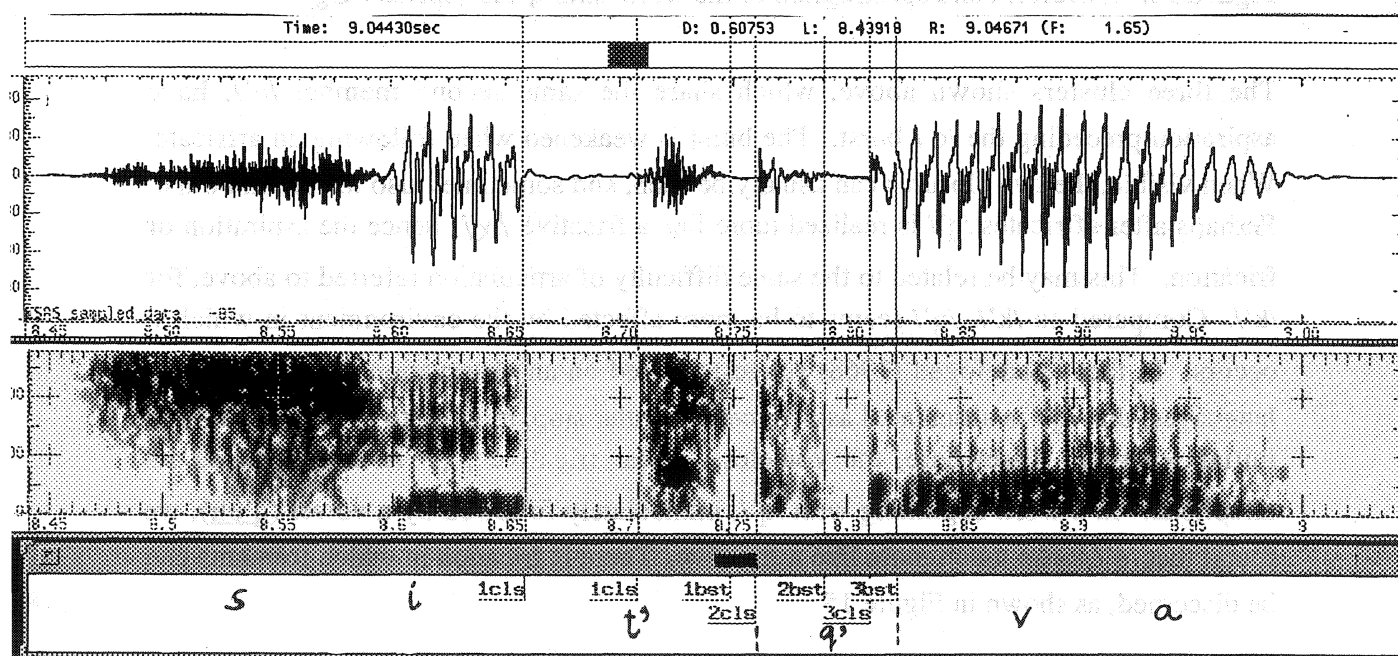


Figure 13. Waveform and spectrogram of the word /sit'q'va/ (speaker Gg).

In some cases the /q'/ burst immediately follows the affricate.

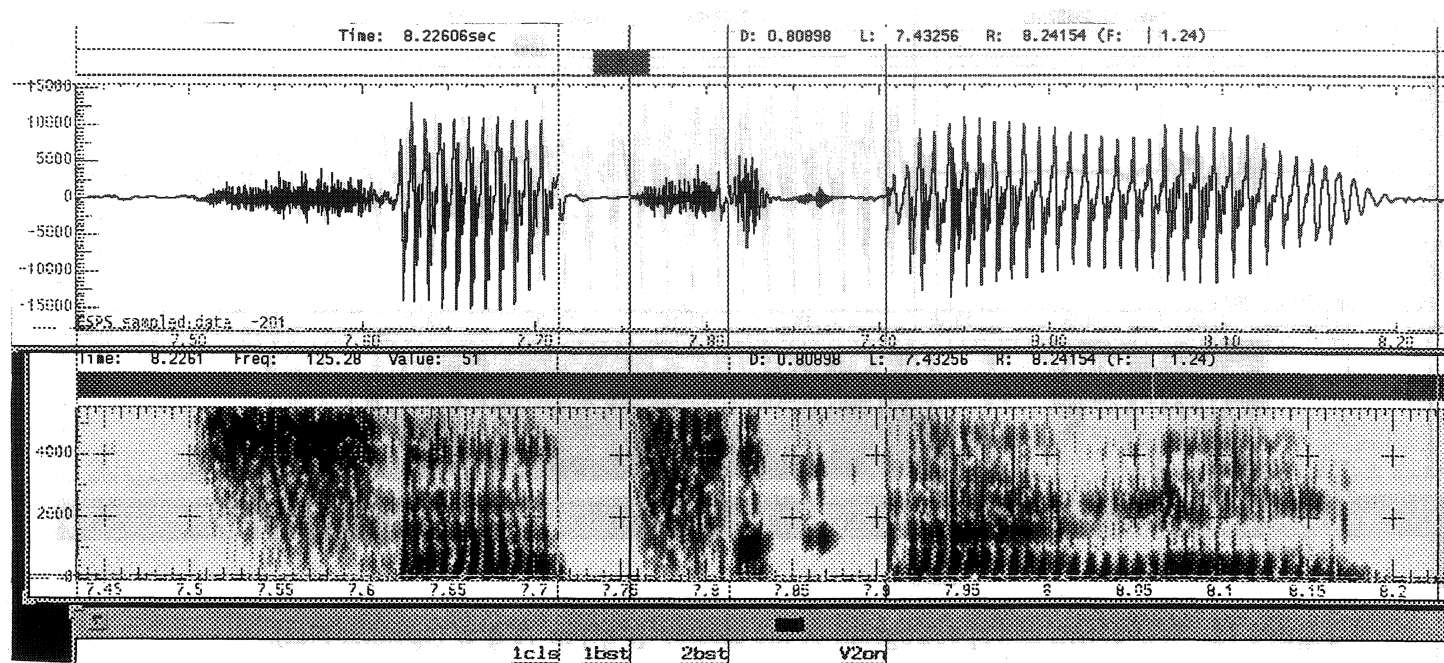


Figure 14. Waveform and spectrogram of the word /sats'q'ali/ (speaker Gg).

The three clusters shown above, which share the same second member /q'/, have aspiration preceding the /q'/ burst. The burst is weakened when following an affricate. When visible, the two closures can usually be seen, and sometimes also the second burst. Perhaps after affricates /q'/ is realized more like a fricative /χ/, hence the aspiration or frication. This may be related to the same difficulty of articulation referred to above, for /k'/. Compared to /k'/, /q'/ seems to be more affected by the environment in which it occurs. In fact, Ladefoged (1968) suggests, based on an observation of West African languages, that /q'/ is articulated as a voiceless uvular stop, referred to as 'fortis', only in initial position. Elsewhere, the voiceless uvular fricative /χ/ is classified as its allophone. In a word beginning with /q'/, immediately followed by a vowel (q'eli), we found that /q'/ looks much more like a fricative. There is frication in which formants can be discerned, as shown in Figure 15.

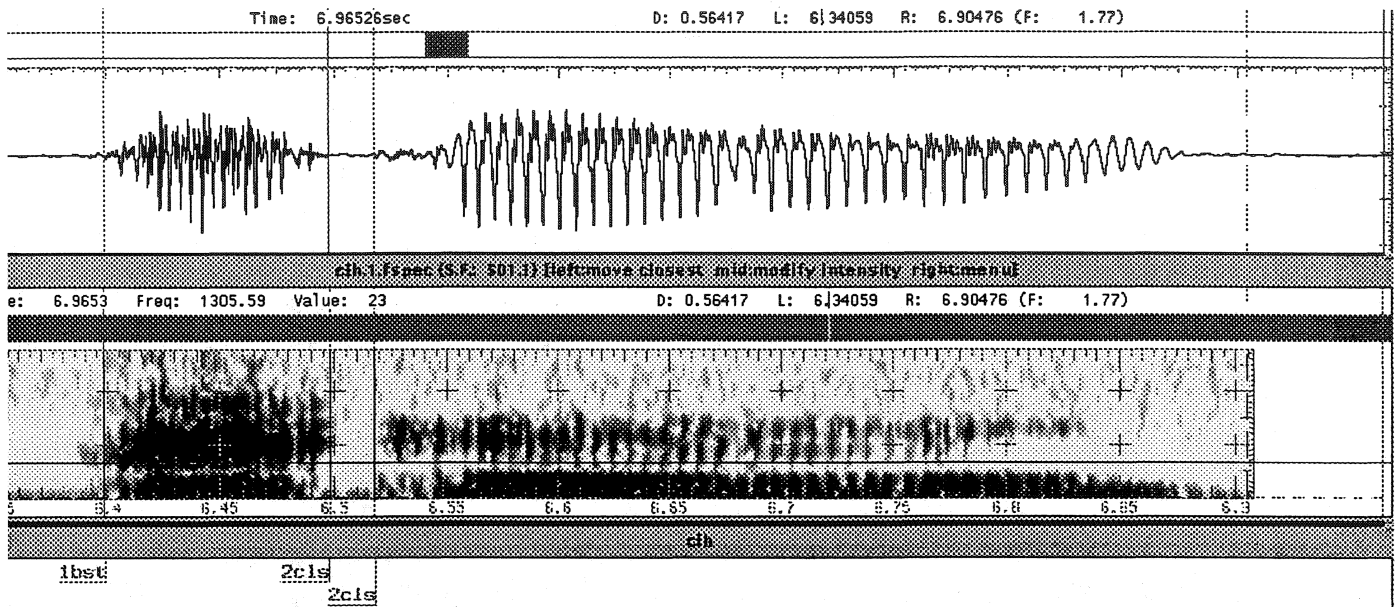


Figure 15. Waveform and spectrogram of the word /q'eli/ 'throat' (speaker Gg).

Figure 16 shows the waveform and spectrogram of the word /baq'aq'i/ 'frog'. Interestingly, in a word containing two intervocalic uvular stops, the first one has more of a stop release, while the second one more of a fricated release. The realization of /q'/ can also be a matter of adjacent vowel quality.

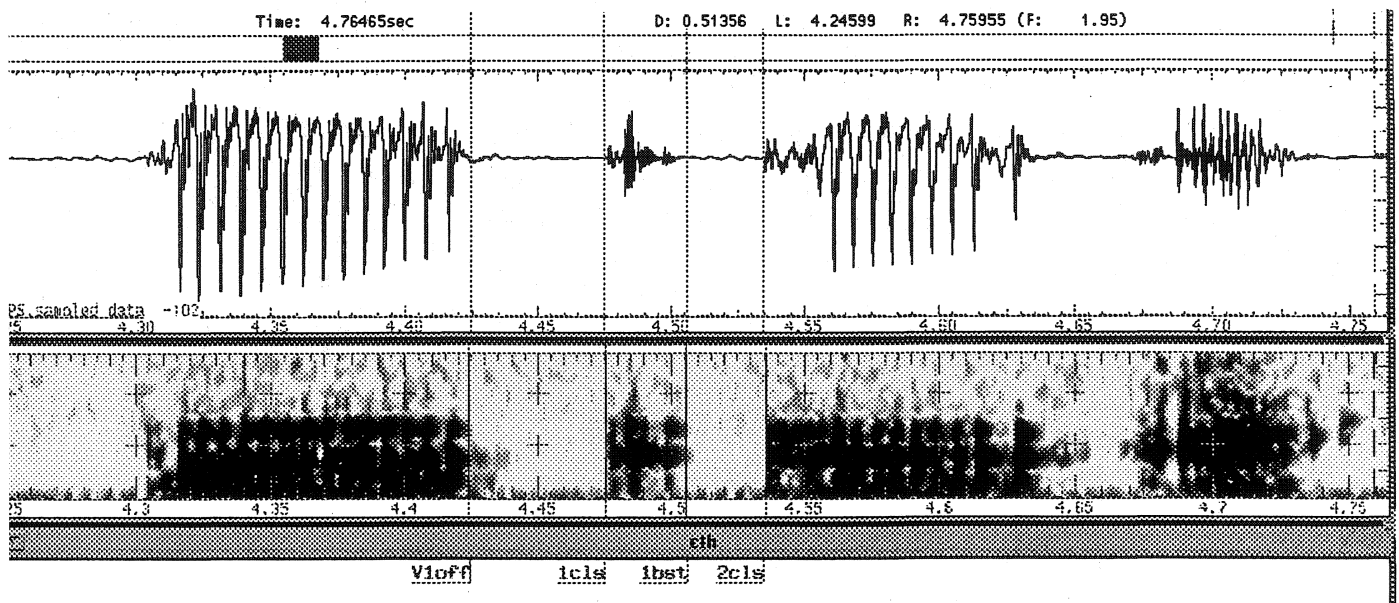


Figure 16. Waveform and spectrogram of the word /baq'aq'i/ 'frog' (speaker Gg).

Tschenkeli (1958, p. 45, 56), based on purely impressionistic observations, considers /q'/ an affricate rather than a stop, namely a /k'χ/ cluster, consisting of an ejective velar and a uvular fricative. He also says that the pronunciation of this particular segment is strongly affected by the environment in which it occurs. According to Aronson (1991) /q'/ is often realized as /q'χ/. Kuipers (1960) treats pulmonic (but not ejective) /q'/ as a full affricate, but regards the affrication as 'affricated homorganic aspiration'. Catford (1977) shows that /q'/ can be pronounced with a glottal stop. In this case it has no aspiration, and may be reduced to a fricative /χ/. Our findings support the evidence of the 'chameleon' nature of /q'/.

Appendix 2

Georgian wordlist

Harmonic clusters

<u>Word-initial:</u>	dgoma	'standing'
	dye	'day'
	bgera	'sound'
	byavili	'crying'
	t ^h k ^h ma	'saying'
	ts ^h k ^h era	'to stare'
	t ^h χa	'goat'
	ts ^h χeli	'hot'
<u>Word-medial:</u>	aYdgoma	'resurrection'
	asdyiani	'100 days long'
	dzibgiri	'hooligan'
	gabvverili	'blown up'
	dat ^h k ^h ma	'to agree'
	jevats ^h k ^h erdi	'to stare for long'
	gat ^h χoveba	'to get married'
	sits ^h χe	'heat'
<u>Sequences</u>	sad gip'ovo	'where can I find you?'
	rad yirs	expression of evaluation
	egeb gip'ovis	'perhaps he will find you'
	egeb yoria	'what if it is a pig?'

albat ^h k ^h ari	'probably wind'
mets ^h k ^h ali var	'I am a woman, too'
albat ^h χari	'probably ox'
mets ^h χari var	'I am an ox, too'
