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Author
Vicenik, Chad

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An Acoustic Study of Georgian Stop Consonants

Chad Vicenik
cvicenik@humnet.ucla.edu

Abstract

This study investigates the acoustic properties of ejective, voiced and voiceless aspirated stops in Georgian, a Caucasian language, and seeks to answer two questions: (1) which acoustic features discriminate the three stop manners and (2) do Georgian stops undergo initial strengthening, and if so, is it syntagmatic or paradigmatic strengthening? Five female speakers were recorded reading words embedded into carrier phrases and stories. Acoustic measures include closure duration, voicing during the closure, voicing lag, relative burst intensity, spectral moment of bursts, phonation (H1-H2) and f0. Of these, voicing lag, voicing during the closure, mean burst frequency, H1-H2 and f0 could all be used to discriminate stop manner, but stop manners did not differ in closure duration or relative burst intensity. Georgian stops did show initial strengthening and showed only syntagmatic enhancement, not paradigmatic enhancement. Stops showed longer closure durations, longer voicing lags, less voicing during the closure and higher H1-H2 values in higher prosodic positions.

1. Introduction

Georgian, a Caucasian language spoken in Georgia, has three stop manners: voiceless aspirated, voiced and ejective (Shosted & Chikovani 2006). Its stop inventory is given below in Table 1. This study examines the stop consonants of Georgian and will look at a number of acoustic measures in order to describe the similarities and differences between ejectives and the other stop manners present in the language. This information will be used to make predictions about which acoustic features might best serve as perceptual cues. This study will also examine how the acoustic characteristics of the stop consonants change at different prosodic positions, or in other words, how they participate in the process of initial strengthening (Fougeron & Keating 1997).

	Bilabial	Alveolar	Velar	Uvular
Aspirated	p^h	t^h	k^h	
Ejective	p'	t'	k'	q'
Voiced	b	d	g	

Table 1. Stop inventory of Georgian.

1.1 Ejectives and Stop Systems with Ejectives

Ejective stops are produced quite differently from pulmonic stops. They are produced using simultaneous constrictions in the oral cavity and at the glottis and are often associated with loud bursts, caused by increased oral air pressures due to raising of the glottis during constriction. There has been considerable research into the phonetics of ejectives over the last few decades. Some of the acoustic characteristics of ejectives that have been explored include voice onset time (henceforth, VOT) (Hogan 1976, Lindau

1984, Ingram & Rigsby 1987, Sands et al. 1993, McDonough & Ladefoged 1993, Warner 1996, Maddieson et al. 2001, Wright et al. 2002, Billerey-Mosier 2003, Wysocki 2004, Gordon & Applebaum 2006), closure duration (Lindau 1984, McDonough & Ladefoged 1993, Warner 1996, Wysocki 2004, Gordon & Applebaum 2006), voicing jitter (Wright et al. 2002), f0 (Warner 1996, Wright et al. 2002) and amplitude measures, such as the amplitude of the burst or the amplitude rise time of the following vowel (Ingram & Rigsby 1987, Warner 1996, Wright et al. 2002).

A sizable percentage of this research has concentrated on the question of ejective typology, specifically the idea proposed by Kingston (1985) that ejectives could be classified into two types: fortis and lenis. However, it now seems that such a binary typology does not exist and instead, ejectives in different languages, and even within a single language produced by different speakers, cover a continuum of acoustic characteristics (Ingram & Rigsby 1987, Warner 1996, Wright et al. 2002). While most of the studies on ejectives have concentrated on the possibility of a fortis/lenis classification, the issues of which acoustic measures distinguish ejectives from other stop manners within a given language, and thus, which acoustic measures are likely to perceptually cue ejective stop manner, have gone largely unexplored. In particular, the similarities and differences between ejectives and voiced stops are relatively unknown. In fact, voiced stops have been left out of some studies entirely on the assumption that the two stop types were so different that no comparisons needed to be made. This is surprising considering that it has been pointed out that field workers often perceive ejectives as voiced stops (Ingram & Rigsby 1987, Fallon 2000), and there are proposals in historical linguistics, namely Glottalic Theory (Gamkrelidze & Ivanov 1972, Hopper 1973), that suggest ejectives have diachronically changed into voiced stops.

Many of the studies that have examined ejectives in comparison to the other stop manners in a language have looked at VOT (Ingram & Rigsby 1987; McDonough & Ladefoged 1993; Gordon 1996; Warner 1996; Maddieson et al. 2001; Wright et al. 2002; Billerey-Mosier 2003). In most languages, the VOT of ejectives is shorter than for aspirated stops and longer than either voiced or voiceless unaspirated stops. However, in Kiowa (Billerey-Mosier 2003), ejectives have VOTs nearly twice as long as aspirated stops. Other acoustic measures have shown less success in distinguishing ejectives from other stop manners. Closure duration does not reliably distinguish stop manner in Navajo (McDonough & Ladefoged 1993) or Ingush (Warner 1996), but does distinguish stop manner in Turkish Kabardian (Gordon & Applebaum 2006). Ejectives show slower vowel amplitude rise time than other stop manners in Witsuwit'en (Wright et al. 2002), but not in Gitksan (individual speakers showed consistent patterns, but there was no consistent pattern across speakers) (Ingram & Rigsby 1987). In both Gitksan and Witsuwit'en, ejectives were more likely to show jitter or aperiodicity than pulmonic stops, and there is some evidence suggesting f0 could be used to distinguish ejective stops from pulmonic stops in both languages. On the whole, in both languages, there was little difference in f0 following different stop manners, but in individuals, there were gender specific differences. Women showed falling f0 and men showed rising f0 following ejectives.

1.2 Georgian Stops

Georgian stops have been examined in a few previous studies. Robins & Waterson (1952) offered a descriptive analysis of Georgian phonology, and supported their observations with some kymographic data. In their study, they noted that, within the ejective stops, ejection was only heard word initially, but that glottalization could be heard coarticulated with the following vowel both word initially and intervocalically word medially. The aspirated and voiced stops had no noticeable glottalization. Intervocalic ejectives were heard with some voicing during the closure, an impression supported by their kymographic evidence. Voiced stops, they point out, really only show voicing when surrounded by vowels. Word initially and word finally, and in clusters, voiced stops often appeared as voiceless unaspirated stops.

Wysocki (2004) performed an acoustic study of Georgian stops located word initially and intervocalically in words read from a list. She measured VOT and closure duration and qualitatively described noise quality following stop release, burst amplitude and any fluctuations in amplitude and voicing pulses in the following vowel. She found that stop manner was not distinguished by closure duration, but that there was a three way distinction in manner by VOT. Aspirated stops had the longest VOT, around 90 ms, voiced stops had the shortest, around 20 ms, and ejectives had an intermediate VOT, around 50 ms. Wysocki observed that voiced stops tended to have the quietest bursts and ejectives had the loudest bursts, but there was considerable variation within each manner. She agrees with Robins & Waterson that the voiced stops are better characterized as voiceless unaspirated stops, and, unlike in their study, she does not even observe significant voicing during the closure in an intervocalic position. She points out that aspirated stops are followed by aspiration noise while ejectives are followed by periods of relative silence, and that vowel onsets following ejectives frequently show fluctuations in amplitude and voicing pulse cycle duration.

1.3 Initial Strengthening

The variability in the production of ejectives has mainly been studied in terms of interspeaker variability (for example, Ingram & Rigsby 1987 and Wright et al. 2002). Wysocki's (2004) study on Georgian is one of the very few studies that look at how the production of ejectives varies in different prosodic positions. She found that for all stops, VOT was shorter intervocalically than word initially, but the difference was the most dramatic for ejective stops. Aspirated and voiced stop VOT decreased around 5 ms, while ejective VOT decreased about 25 ms. She did not report any differences for the other acoustic features she examined.

It has been well established that speech segments are affected by their position in prosodic structure. Speech segments that appear at the beginning of a prosodic unit appear to be produced with stronger and longer articulations. For example, English /n/s show greater linguopalatal contact and longer seal durations when beginning higher prosodic domains, like intonational phrases, than when beginning lower prosodic domains, like words or syllables (Fougeron & Keating 1997). Similar effects have been demonstrated for French, Korean and Taiwanese /n/s and /t/s (Keating et al. 2003) and Tamil nasals (Byrd et al. 2000). In English, aspirated stops have longer VOT and /h/s are more consonant-like and phrase initially than phrase medially (Pierrehumbert & Talkin 1992).

It is not clear in which ways consonants are being strengthened. Hsu & Jun (1998) point out two types of possible strengthening: syntagmatic enhancement and paradigmatic enhancement. Syntagmatic enhancement is the enhancement of the contrast between the consonant and the following vowel. That is, consonants would become more obstruent-like. Paradigmatic enhancement would enhance the contrast between similar consonants, like stops of different manners, for example. In most languages, only syntagmatic enhancement has been observed at the beginnings of prosodic phrases. However, in their study, Hsu & Jun show that Taiwanese shows paradigmatic strengthening as well as syntagmatic strengthening. Taiwanese aspirated stops have longer VOT in higher prosodic positions and voiced stops are more voiced, while voiceless unaspirated stops show no differences.

1.4 Current Study

In this study, the similarities and differences between the Georgian stop manners will be examined with respect to seven acoustic measures:

- Voicing lag
- Closure duration
- Duration of voicing into the closure
- Phonation of the vowel onset (measured by H1-H2)
- Change in f0 between post-stop vowel onset and vowel midpoint
- Relative intensity of stop burst compared to the following vowel
- Burst spectral measures (mean, skew, and kurtosis)

Voicing lag, which is nearly equivalent to voice onset time (voicing lag can only be positive), closure duration and change in f0 are measured because these measures are common in previous acoustic studies of ejectives, and at least voicing lag and f0 have been shown to distinguish ejectives from other stop manners in other languages. If the voiced stops in Georgian are really voiced, the duration of voicing into the closure is expected to separate them from the aspirated and ejective stop manners. If, however, voiced stops in Georgian are in fact voiceless unaspirated stops, there might be little difference in the amount of voicing between them and the ejective and aspirated manners. This measure is also of interest because of the finding by Robins & Waterson (1952) about voicing into the closure of ejectives in Georgian, which is an unexpected characteristic of Georgian ejectives. Phonation is measured because ejectives in Georgian and other languages are associated with glottalization and irregular voicing, which might distinguish them from the pulmonic stops. Ejectives are commonly described as unique because of their sharp, popping bursts, and preliminary evidence from Wysocki (2004) suggests Georgian stop manners might be distinguished by their bursts. Therefore, the bursts are examined in intensity and spectral moments. It has been previously shown that spectral moments, specifically mean burst frequency, is useful in distinguishing voiced and voiceless stops in other languages (Sundara, 2005). Results of these acoustic measurements, in conjunction with a discriminant analysis, will be used to make hypotheses about which of the measures might serve as perceptual cues, and their robustness.

Georgian has at least two major prosodic domains – the accentual phrase (AP), which is about the size of a content word, and the intonational phrase (IP), which is about the size of a short sentence or major clause (Jun et al. 2007).[1] Each of the seven acoustic measures will be made for each stop manner at the beginning of each phrase type, as well as word medially, a prosodic position below the AP.

If initial strengthening in Georgian works to make segments syntagmatically more consonantal, then it is expected that all stops will show longer closure durations, longer voice lag times, and less voicing into the closure in higher prosodic positions than in lower prosodic positions. If initial strengthening works to enhance the paradigmatic contrast between stop manners, then it is expected that aspirated stops will show longer voice lag in higher prosodic positions while voiced stops will show reduced voice lag. Voiced stops should show increased voicing into the closure while ejective and aspirated stops should show less voicing. Phonation contrasts and f0 differences should likewise be enhanced in higher prosodic positions.

2. Methods

2.1 Procedure

This study looks at nine stops in Georgian that differ in place (labial, alveolar and velar) and manner (aspirated, voiced and ejective). The uvular ejective was excluded because its realization varies freely between a glottal stop, an ejective stop and an ejective fricative (Shosted & Chikovani 2006).

Five adult women were recorded. All participants were native, literate speakers of Georgian and were fluent L2 speakers of English. Recordings were made using a Shure head-mounted microphone in the UCLA sound attenuated booth. Its signal was run through an XAudioBox pre-amp and A-D device and recorded using PCQuirerX at a sampling rate of 44,100 Hz. Audio signals were segmented using a waveform display supplemented by a wide band spectrogram, and analyzed using Praat (Boersma 2001) and Pitchworks (Scion R&D).

2.2 Materials

Targeted stops were located in real Georgian words, which were found in a dictionary and confirmed with a consultant. Stops appeared either word-initially or intervocalically, beginning the second syllable, and were followed by the low vowel /a/.

[1] There is also evidence in Georgian for an intermediate phrase (ip), which is between an AP and IP in size, but it is not referenced in the current study.

Words were recorded in two different conditions: in two carrier phrases and in three short stories, which were written with the aid of a consultant. In the carrier phrase condition, the vowel preceding the targeted stop was always the low vowel /a/. In the story condition, the preceding vowel was not controlled. The two conditions were used in an attempt to elicit two styles of speech, more formal and less formal, in order to see if and how the significant acoustic correlates differ between speech styles. Tokens in the carrier phrase condition were presented in random order. Approximately one-fourth of the presented items were fillers.

Targeted stops appeared in three different prosodic positions: intonational phrase initial, accentual phrase initial and word-medially. In the carrier phrase condition, in order to appear in the intonational phrase initial position (henceforth IP-initial), words were placed in the carrier phrase *[XXX k□art□uli sit'q'vaa]*, "XXX is a Georgian word." For both the accentual phrase initial (henceforth AP initial) and word medial prosodic positions, words were placed in the phrase *[sit'q'va XXX davts'ere]*, "I wrote the word XXX."

The prosodic positions of the targeted words were confirmed after recording by identifying phrasal tone contours and by judging break strength. As reported in Jun et al. (2007), words in Georgian have stress on the initial syllable, which is marked tonally using pitch accents. In general, each word makes up one accentual phrase, which, in declarative sentences, is usually marked by a low tone on the stressed syllable and a high tone on the AP final syllable. The ending of an IP is marked by a boundary tone, usually with an increased pitch range compared to the APs. The break between two IPs is also considerably larger than between two APs. Cases where the exact prosodic phrasing could not be determined were removed from the analysis. The most common difference from what was predicted was the division of the sentences in the story condition into more phrases, resulting in the placement of a predicted AP initial word in an IP initial position. These tokens were recategorized in the analysis.

2.3 Analysis

Seven acoustic measures were made for each targeted sound, when possible. Closure duration and voicing into the closure were measured only for tokens appearing AP initially and word medially because there is no marking of the closure onset in IP initial position. Phonation at the vowel onset (H1-H2) and change in f0 (Δf0) were measured only for tokens read in the carrier phrase. This was done because many of the tokens in the story condition would have had to be excluded due to overly creaky, non-periodic phonation, where no reliable H1-H2 or f0 measure could be made. All other measures were made for all tokens.

Closure duration was taken to be the duration between the stop implosion and the stop burst. The stop implosion was marked by either a sharp fall in the waveform amplitude or the cutoff of higher energy in the spectrogram. The stop burst was marked by a sudden rise in the waveform amplitude.[2] Voicing lag (which can only be positive) was examined rather than voice onset time (which can be negative or positive) because voicing into the closure was also examined. There were no tokens that showed partial prevoicing, so tokens with negative VOT had voicing throughout the entire closure. This information is captured by the measure of voicing into the closure. Voicing lag was taken to be the duration between the stop burst and the subsequent onset of voicing, which was marked by the beginning of periodicity in the waveform and taken at the first zero-crossing. Tokens with negative VOT were recorded as having a value of zero voicing lag. Voicing into the closure was measured from the stop implosion to the last appearance of periodicity in the waveform. The ratio of voicing duration and total closure duration is used in the analysis. These measures are indicated in Figure 1 for a word medial /t'/, from the word *[sat'**a**xt'o]*.

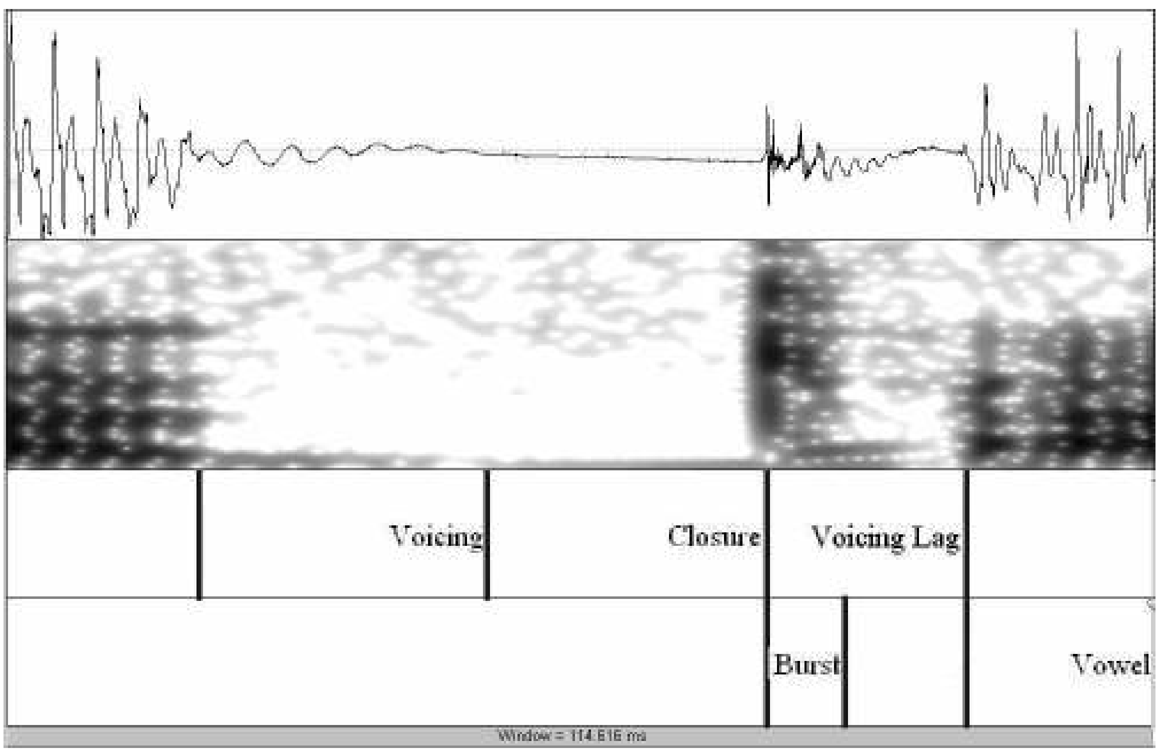

Figure 1. A token of word medial /t'/, from the word *[sat'axt'o]*, "capital," illustrating the portions of the stop segmented for analysis. The portion of the closure that showed voicing and the portion without voicing (labeled as 'closure') add to give the total closure duration. Voicing lag, burst and total duration of the following vowel (only the beginning portion is shown) are also labeled.

Burst intensity and the shape of the burst spectrum were calculated over the entire burst duration beginning at consonantal release. The size of the analysis window thus varied from token to token; it was determined by the duration of the burst. The period between the burst and the vowel onset (which included aspiration, as in the aspirated stops, or silence, as in some of the ejectives and voiced stops) was not included in the burst intensity measurement. Visual inspection of the spectrogram and waveform was used to

[2] Occasionally, the stop burst in the waveform and the spectrogram did not align. Stop bursts were marked using the waveform only.

distinguish the burst duration from any subsequent gap. The end of the burst was characterized by a sudden drop in intensity and reduced energy at lower frequencies. These portions of the stop are also indicated in Figure 1.

Relative burst intensity was calculated relative to the intensity of the following vowel to factor out the effect of differences in overall intensity across speakers. The maximum intensity of the burst (in dB) and was subtracted from the maximum intensity of the vowel (in dB) to obtain these measures (Stoel-Gammon et al. 1994).

The shape of the burst spectrum was characterized by three measures: mean, skew and kurtosis. Spectral moments were derived from the power spectra over the entire burst duration for frequencies up to 22,050 Hz. To make the procedure for calculating spectral moments consistent with that used by Forrest et al. (1988) and Sundara (2005), bursts were pre-emphasized prior to making spectral measurements; above 1000 Hz the slope was increased by 6 dB/oct. Stops were also filtered using a 200 Hz high-pass filter, making the procedure consistent with Jongman et al. (1985) and Sundara (2005).

Phonation was measured at the vowel onset by taking a 21 Hz-bandwidth FFT spectrum over a window of 40 ms, measuring the intensity of the first and second harmonics, and then taking the difference (H1-H2). If harmonics could not be resolved at the vowel onset, phonation was measured at the earliest place in the vowel where clear harmonics could be seen. Tokens where this measure could not be made within the first 10 ms of the vowel were excluded.

F0 was measured using the cepstral method with a window of 35 ms and step size of 5 ms, at the vowel onset and the midpoint of the vowel and then subtracting. If there was no accurate pitch track at the vowel onset, the f0 at the earliest location within the vowel that did show an accurate pitch track was measured. Tokens which did not show a pitch track within the first 10 ms of the vowel were excluded. Tokens which showed greater than 10 Hz variation over the central 50% of the vowel were also excluded. This last criterion was meant to eliminate tokens with a rising or falling pitch accent.

Tokens which did not show a full closure or that were mispronounced were also excluded, as were tokens where the following vowel was whispered. These tokens made up about 1% of the data.

For each measure, a repeated measures (RM) ANOVA was run with the two within-subjects factors of prosodic position (3 levels – IP-initial, AP-initial & word-medial) and manner (3 levels – aspirated, ejective & voiced), with alpha set at 0.05. A separate ANOVA was run for each place of articulation (3 places – bilabial, alveolar & velar). These ANOVAs seek to avoid the possibility of type 1 error caused by inflated *n* by using each speaker's mean as the dependent variable. Sphericity violations were corrected by using the Huynh-Feldt correction, which adjusts the degrees of freedom downward in order to reach a more accurate significance value. Because post-hoc tests are not available for RM-ANOVAs, significant interactions and main effects were explored using paired t-tests.

RM-ANOVAs were also run with a 2-level factor of condition, either carrier phrase or story. However, the effect of condition was only significant for closure duration and voicing into the closure. Tokens embedded in a story showed shorter closure durations (8.9 ms) and more voicing into the closure (an additional 10% or 3.0 ms) than did tokens read in a carrier phrase. There was no effect of condition for any other measure, suggesting either that there is no difference between speaking styles for these measures, or that the effort to elicit two different speaking styles was not very successful. So, measurements for tokens from the two conditions have been averaged together and the factor has been left out of the final analysis.

3. Results

3.1 Closure Duration

Closure duration did not distinguish the three stop manners in Georgian. There was no main effect of manner at any place of articulation. This confirms the findings of Wysocki (2004) and suggests that closure duration would be a very poor cue for stop manner. Bilabial stops showed the longest average closure duration, as well as the most variation. Average durations are given in Table 2.

For closure duration, it is expected that stops in higher prosodic positions will have longer closures than stops in lower prosodic positions. This was observed for all places of articulation. On average, stops in an AP initial position had closure durations of 71 ms, while stops in a word medial position had closure durations of 56 ms. Durations for each place of articulation are given in Table 3. Statistical results for stop manner and prosodic position are given in Table 4.

	Labial	Alveolar	Velar
Aspirated	75.3 (sd 15.3)	59.4 (sd 7.2)	56.9 (sd 9.7)
Ejective	70.2 (sd 7.4)	65.0 (sd 11.0)	55.2 (sd 5.3)
Voiced	81.0 (sd 26.2)	57.3 (sd 11.8)	54.1 (sd 9.1)

Table 2. Average closure durations, given in milliseconds, for each stop manner at all places of articulation.

	Labial	Alveolar	Velar
AP Initial	86.5 (sd 18.6)	67.4 (sd 8.3)	59.9 (sd 7.2)
Word Med	64.5 (sd 7.6)	53.7 (sd 7.4)	51.0 (sd 6.3)

Table 3. Average closure durations, given in milliseconds, in each prosodic positions at all places of articulation.

	Labial	Alveolar	Velar
Manner	$F(1.710,6.842) = 2.027$; $p = 0.204$	$F(1.329,5.316) = 3.692$; $p = 0.106$	$F(1.436,5.745) = 0.517$; $p = 0.565$
Position	**$F(1,4) = 12.126$; $p = 0.025$**	**$F(1,4) = 76.739$; $p = 0.001$**	**$F(1,4) = 11.952$; $p = 0.026$**

Table 4. Results from the RM-ANOVA conducted for closure duration.

3.2 Voicing Into the Closure

In Georgian, all stop manners showed voicing into the closure as a continuation of the preceding voiced sound. This voicing usually died out before the stop release, but, for some voiced stops, it continued uninterrupted throughout the closure. There were no instances of stops in an intervocalic position (either AP-initial or word-medial) that showed prevoicing, where the voicing started during the middle of the closure and continued through the stop burst. There were a handful of IP initial tokens which showed prevoicing (9 of 223), but these were not included in the analysis.

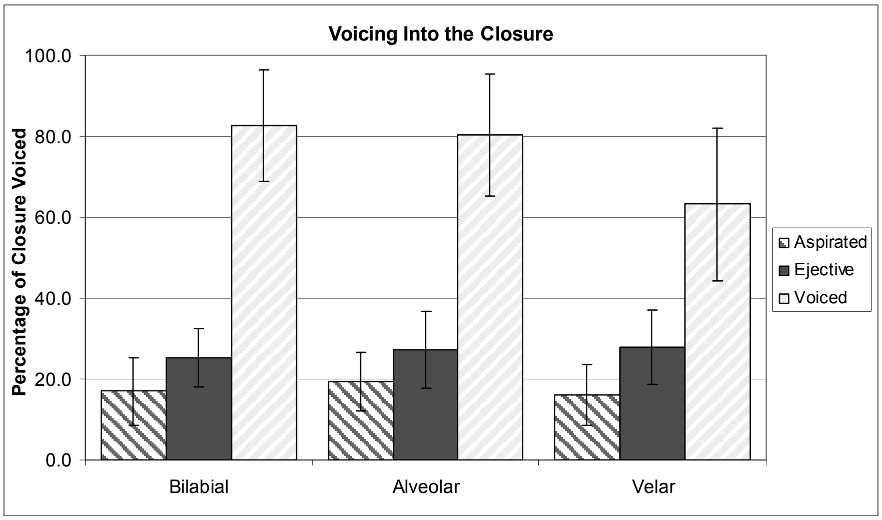

Figure 2. Average duration of voicing into the stop closure, given as a percentage of total closure duration, for each place of articulation and stop manner.

	Bilabial	Alveolar	Velar
Manner	**F(2,8) = 138.096; p < 0.001**	**F(1.161,4.643) = 102.594; p < 0.001**	**F(1.818,7.273) = 33.971; p < 0.001**
Position	F(1,4) = 0.285; p = 0.622	F(1,4) = 1.990; p = 0.231	**F(1,4) = 8.364; p = 0.044**
Manner x Position	F(1.195,4.780) = 0.885; p = 0.413	F(1.113,4.454) = 5.456; p = 0.072	**F(2,8) = 7.102; p = 0.017**

Table 5. Results of the RM-ANOVA conducted for voicing into the closure.

Voicing into the closure distinguished the voiced stops from the aspirated and ejective stop manners. On average, 75% of a voiced stop's closure was voiced, whereas only 17% of an aspirated stop's closure and 27% of an ejective stop's closure was voiced. But, some velar ejectives showed voicing for half of the closure. Statistically, there was a main effect of manner on closure voicing at each place of articulation. Voiced stops showed significantly more voicing than either aspirated or ejective stops. There was no significant difference between the aspirated and ejective stop voicing at either the bilabial or alveolar places of articulation. However, the velar stops showed an interaction between stop manner and prosodic position. In AP initial position, velar aspirated and velar ejective stops were significantly different, but not in word medial position.

Average percentages of the closure that was voiced for the three stop manners at different places of articulation are given in Figure 2.

It was expected that stops in lower prosodic positions would be more lenited than stops in higher prosodic positions and, thus, show more voicing into the closure, except for possibly voiced stops. Voiced stops might show increased voicing in higher prosodic positions in order to enhance the voicing contrast. However, Georgian stops showed no differences in the amount of voicing at different prosodic positions, except for voiced velar stops. Voiced velar stops, [g], showed significantly greater voicing in word medial position than in AP initial position (76.3% vs. 62.6%, respectively), which is contrary to paradigmatic enhancement, though consistent with medial lenition. Statistical results for stop manner and prosodic position are given in Table 5.

3.3 Voicing Lag

In general, voicing lag distinguished all three stop manners. Aspirated stops showed the longest voicing lag time, 58 ms on average, and voiced stops showed the shortest voicing lag time, 12 ms. Ejective stops showed an intermediate voice lag time of 33 ms. Voice lag time for all stop manners increased at more posterior places of articulation. Average voice lag times for the three stop manners at different places of articulation are given in Figure 3. These results agree with the general findings of Wysocki (2004), although these values are smaller than the values reported in that study. Because the voicing lag values are smaller for all manners, it is likely that the differences are due to rate of speech differences. The speakers in this study spoke more rapidly than the speakers in Wysocki (2004).

At every place of articulation, there was a significant interaction between stop manner and prosodic position. These statistical results are given in Table 6. Voicing lag distinguished all three stop manners in every prosodic position and at every place of articulation except in three cases. In IP-initial position, only bilabial aspirated and bilabial ejective stops showed significantly different voice lag times; alveolar and velar aspirated and ejective stops did not have significantly different voice lag times in IP initial position. In AP-initial position, alveolar ejective and alveolar voiced stops were not significantly different in voicing lag.

There was considerable overlap between the voice lag time of individual tokens of ejectives and the other two stop manners. This is illustrated in Figure 4 with alveolar stops. In IP-initial position, there was considerable overlap between the ejectives and the aspirated stops. In this position, ejectives were more likely to have a significant pause between the stop burst and the vowel onset, which was filled with relative silence, caused by a delay in glottal release. In lower prosodic positions, the ejective tokens overlap more with the voiced tokens in voicing lag. In these positions, the ejectives were more likely to have a (near) simultaneous oral and glottal release and did not show a silent gap.

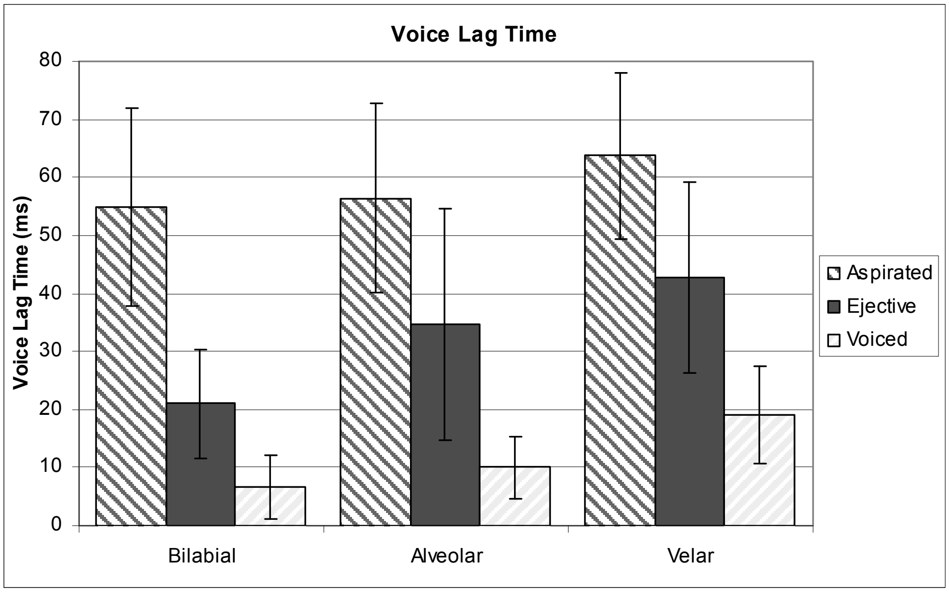

Figure 3. Average voice lag, given in milliseconds, for each place of articulation and stop manner.

	Bilabial	Alveolar	Velar
Manner	**F(2,8) = 77.834; p < 0.001**	**F(2,8) = 46.522; p < 0.001**	**F(1.569,6.276) = 57.110; p < 0.001**
Position	**F(2,8) = 14.466; p = 0.002**	**F(2,8) = 9.094; p = 0.009**	**F(2,8) = 11.701; p = 0.004**
Manner x Position	**F(3.315,13.262) = 7.932; p = 0.002**	**F(4,16) = 5.115; p = 0.008**	**F(4,16) = 6.016; p = 0.004**

Table 6. Results from the RM-ANOVA conducted for voice lag.

Bilabial			
	IP Initial	AP Initial	Word Med
Aspirated	59.6 (sd 15.8)	64.8 (sd 16.4)	40.4 (sd 8.7)
Ejective	26.3 (sd 9.3)	20.9 (sd 11.6)	15.7 (sd 4.2)
Voiced	11.4 (sd 5.1)	6.5 (sd 4.4)	1.9 (sd 2.0)
Alveolar			
	IP Initial	AP Initial	Word Med
Aspirated	61.7 (sd 13.9)	64.0 (sd 19.2)	43.5 (sd 7.2)
Ejective	49.0 (sd 18.4)	34.1 (sd 22.7)	21.4 (sd 7.7)
Voiced	13.7 (sd 3.4)	10.1 (sd 5.8)	6.3 (sd 4.7)
Velar			
	IP Initial	AP Initial	Word Med
Aspirated	69.6 (sd 15.0)	70.5 (sd 13.6)	51.2 (sd 3.3)
Ejective	59.1 (sd 15.4)	39.4 (sd 11.7)	29.8 (sd 4.0)
Voiced	24.7 (sd 7.3)	16.8 (sd 7.4)	15.8 (sd 8.6)

Table 7. Average voice lag, given in milliseconds, for each stop manner at every prosodic position, separated by place of articulation.

It was expected that, if initial strengthening served to make all stops more consonantal, then voicing lag would increase in higher prosodic positions for all stop manners. On the other hand, if initial strengthening enhanced the paradigmatic contrast between stop manners, only aspirated stops should show longer voicing lag in higher positions. Voiced stops should show no change, or reduced lag. For aspirated stops, there was no difference in voicing lag between IP-initial and AP-initial positions, but voicing lag decreased significantly in word-medial position, by nearly 20 ms. This was true for all places of articulation. Contrary to the expectations of paradigmatic enhancement, voiced stops showed a general trend of longer voicing lag times in higher prosodic positions. At the bilabial and alveolar places of articulation, voicing lag time was significantly shorter for word-medial voiced stops than either IP-initial or AP-initial voiced stops. However, the difference in voicing lag time between the two higher prosodic positions was not significant. At the velar place of articulation, there was no significant difference in the voicing lag time of voiced stops between any of the prosodic positions, although the difference between IP-initial and AP-initial position approached significance. Like voiced stops, ejectives also showed the general trend of longer voicing lag times in higher prosodic position. At all places of articulation, ejective stops showed significantly shorter voicing lag time in word-medial position than in IP-initial position, but the difference between AP-initial and word-medial position was not significant. At the bilabial and alveolar places of articulation, the difference between IP-initial and AP-initial ejectives approached significance, but at the velar place of articulation, ejective voicing lag time was significantly shorter in AP-initial position than in IP-initial position. These results are given in Table 7.

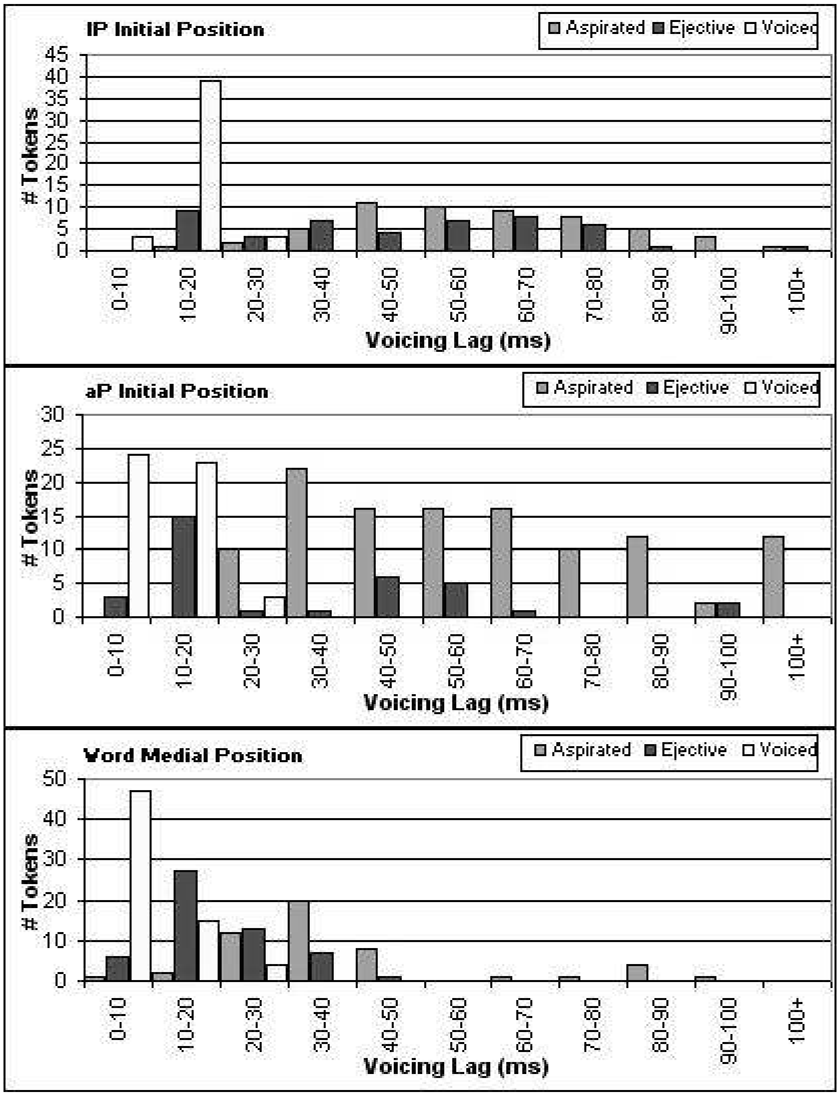

Figure 4. Histograms of voice lag for alveolar stops in a) IP initial position, b) AP initial position and c) word medial position.

3.4 Relative Burst Intensity

Of over two thousand tokens measured, 7.5% had no detectable burst. The majority of these tokens were voiced stops (58.1%), 31.7% were aspirated and 10.1% were ejective stops. Of all the tokens measured, only 17 ejectives showed no burst. Stops that had no burst were also more likely be produced at a more anterior place of articulation: 49.1% of the burstless stops were bilabial, 31.1% were alveolar and 19.8% were velar.

Burst intensity relative to the intensity of the following vowel did not distinguish stop manner in Georgian; there was no main effect at any place of articulation. There was also no main effect of prosodic position, indicating that, in general, relative burst intensity does not show any effect of initial strengthening, though, this might simply mean that intensity of the stop bursts and the vowel both increased. However, there was a significant interaction between stop manner and prosodic position at the alveolar and velar places of articulation. There was no obvious pattern behind these interactions. The main observation of note was that ejective stops showed a significantly stronger burst, relative to the following vowel, in word medial position than in AP initial position. The difference in intensity between IP initial ejectives and word medial ejectives approached significance. Average relative burst intensities for different stop manners are presented in Table 8 and for different prosodic positions in Table 9. Statistical tests are presented in Table 10.

	Labial	Alveolar	Velar
Aspirated	10.1 (sd 2.4)	11.8 (sd 2.4)	9.2 (sd 2.8)
Ejective	9.5 (sd 3.5)	11.5 (sd 3.1)	8.2 (sd 2.9)
Voiced	8.9 (sd 2.5)	11.3 (sd 2.9)	8.2 (sd 2.8)

Table 8. Average relative burst intensity, given in dB, for each stop manner at all places of articulation.

	Labial	Alveolar	Velar
IP Initial	10.0 (sd 3.6)	12.2 (sd 2.5)	8.7 (sd 3.0)
AP Initial	10.2 (sd 2.5)	12.0 (sd 3.3)	9.8 (sd 2.1)
Word Med	8.2 (sd 1.8)	10.4 (sd 2.2)	7.1 (sd 2.8)

Table 9. Average relative burst intensity, given in dB, for each prosodic position at all places of articulation.

	Bilabial	Alveolar	Velar
Manner	$F(2,8) = 0.783$; $p = 0.489$	$F(2,8) = 0.220$; $p = 0.807$	$F(1.383,5.532) = 0.497$; $p = 0.568$
Position	$F(1.383,5.532) = 1.781$; $p = 0.245$	$F(2,8) = 1.923$; $p = 0.208$	$F(1.137,4.548) = 4.417$; $p = 0.94$
Manner x Position	$F(3.717,14.870) = 2.507$; $p = 0.090$	**$F(2.790,11.159) = 14.047$; $p < 0.001$**	**$F(4,16) = 3.090$; $p = 0.046$**

Table 10. Results from the RM-ANOVA conducted for relative burst intensity.

3.5 Spectral Moments of Bursts

3.5.1 Mean Frequency

Mean burst frequency did not distinguish stop manners at all places of articulation. There was a main effect of manner only for alveolar stops and bilabial stops; however, for bilabial stops there was also an interaction between stop manner and prosodic position. Bilabial and alveolar voiced stops had a lower mean burst frequency than either ejective or aspirated stops produced at the same place of articulation. For alveolar stops, this difference approached significance and for bilabial stops, the difference was significant, but only in word-medial prosodic position. Different velar stop manners showed no difference in mean burst frequency. These results are partially consistent with Sundara (2005), who found that voiced stops had lower mean burst frequencies than voiceless stops. Again, this is found in Georgian, but only for bilabial and alveolar stops. Average mean burst frequencies for the three stop manners at alveolar and velar places of articulation are given in Figure 5 and for bilabial stops in each prosodic position in Figure 7a.

For alveolar stops, mean burst frequency did not differ across prosodic positions. There was a main effect of prosodic position, however, for velar stops, and again, there was an interaction between manner and position for bilabial stops. Velar stops, all manners, showed significantly lower mean burst frequencies in word medial position than in higher prosodic positions. This was also true of bilabial voiced stops. Bilabial aspirated and ejective stops, on the other hand, showed higher mean burst frequencies in lower prosodic positions, but the differences were only significant for ejectives in IP initial position. Mean burst frequencies for alveolar and velar stops in different prosodic positions are given in Figure 6. Statistical results are given in Table 11.

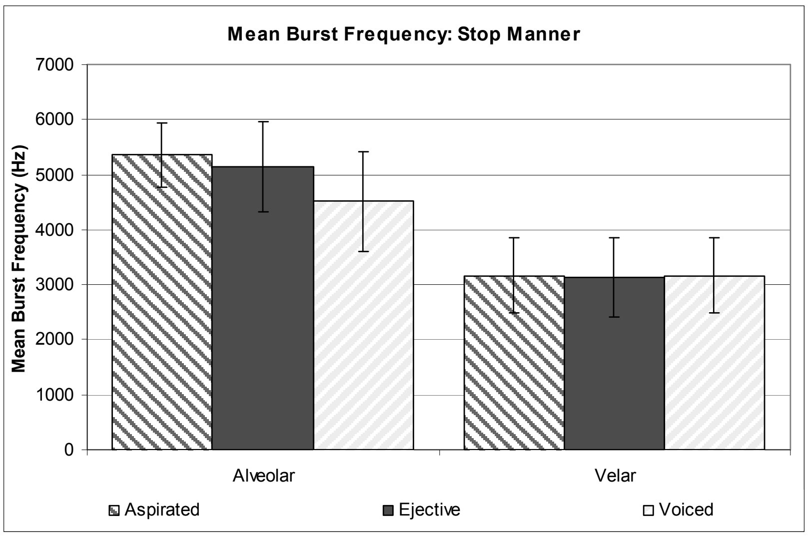

Figure 5. Average mean burst frequency, given in Hz, for each stop manner at alveolar and velar places of articulation.

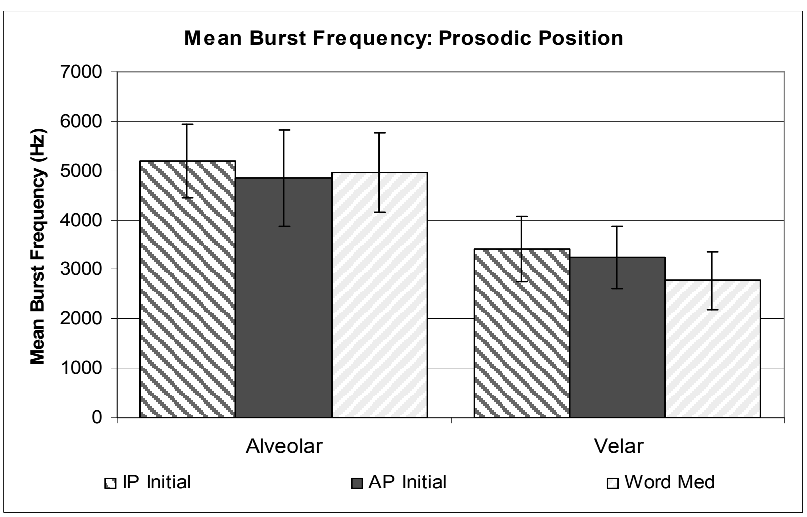

Figure 6. Average mean burst frequency, given in Hz, in each prosodic position for alveolar and velar places of articulation.

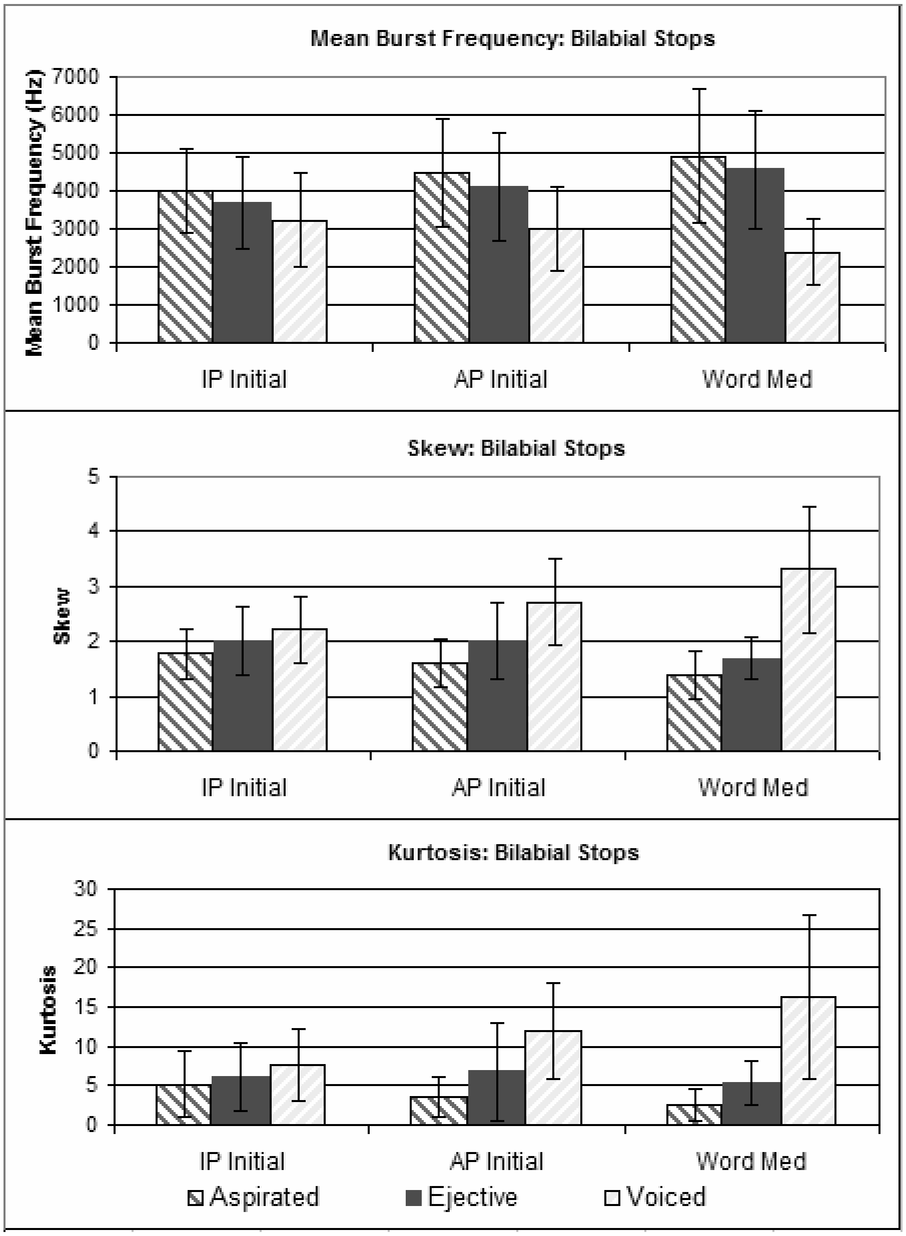

Figure 7. Spectral moments of the burst of bilabial stops for each stop manner at each place of articulation. A) gives the mean burst frequency, in Hz. B) gives the skewness values and C) gives kurtosis values.

	Bilabial	Alveolar	Velar
Manner	**F(2,8) = 9.426; p = 0.008**	**F(2,8) = 5.214; p = 0.036**	F(1.485,5.939) = 0.069; p = 0.887
Position	F(1.570,6.279) = 0.848; p = 0.445	F(2,8) = 1.948; p = 0.205	**F(1.670,6.681) = 17.503; p = 0.003**
Manner x Position	**F(3.467,13.869) = 3.553; p = 0.038**	F(4,16) = 1.341; p = 0.298	F(4,16) = 1.591; p = 0.225

Table 11. Results from the RM-ANOVA conducted for mean frequency of the stop burst.

3.5.2 Skewness

Skewness is a measure of the symmetry of a distribution. Negative skew refers to a distribution whose mass is concentrated in the higher values and has a mean that is lower than the median. Positive skew refers to a distribution whose mass is concentrated in the lower values and has a mean that is larger than the median. In terms of burst frequency, a negative skew would imply more energy in higher frequencies than in lower frequencies, and a positive skew would imply the opposite.

	Alveolar	Velar
Aspirated	0.9 (sd 0.4)	2.4 (sd 0.7)
Ejective	0.9 (sd 0.5)	2.4 (sd 0.6)
Voiced	1.1 (sd 0.6)	2.5 (sd 0.7)

Table 12. Average skewness for each stop manner at alveolar and velar places of articulation.

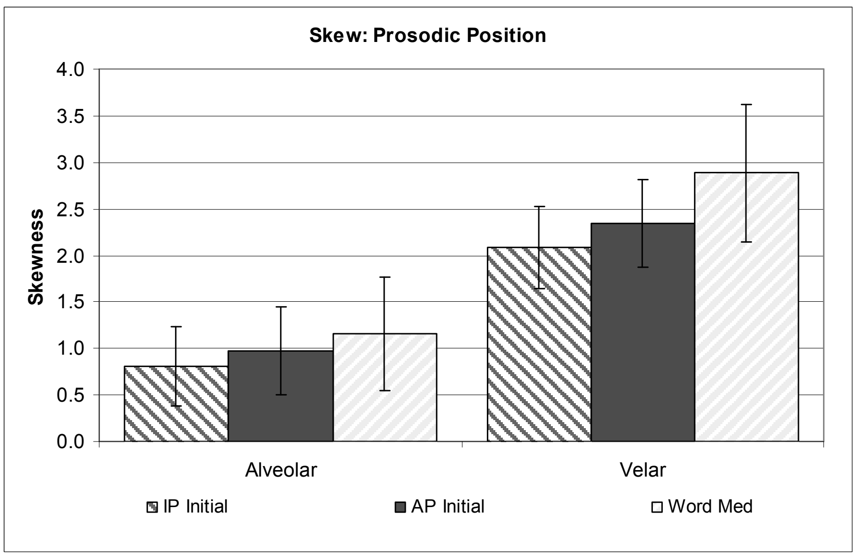

Figure 8. Average skewness for each stop manner at alveolar and velar places of articulation.

Stop manners did not differ in burst skewness at either alveolar or velar place of articulation. There was a main effect on skewness for bilabial stops, as well as a significant interaction between manner and prosodic position. Voiced bilabial stops had more positive skew than either bilabial ejective or bilabial aspirated stops in all prosodic positions, although the difference was only significant AP-initially and word-medially. This implies more energy in frequencies below the mean than in frequencies above the mean. Average skewness for bilabial stops in each prosodic position is given in Figure 7b. Skew values for each stop manner at alveolar and velar places of articulation are given in Table 12.

Both alveolar and velar stops showed more positive skew in lower prosodic positions, which suggests increased energy in frequencies below the mean relative to frequencies above the mean in lower prosodic positions. Both places of articulation showed a main effect, although only the difference between IP-initial stops and word-medial stops was significant. Skewness at each prosodic position for alveolar and velar stops is given in Figure 8. Statistical results are given in Table 13.

	Bilabial	Alveolar	Velar
Manner	**F(2,8) = 8.856; p = 0.009**	F(1.492,5.967) = 3.074; p = 0.126	F(2,8) = 0.325; p = 0.731
Position	F(1.991,7.963) = 0.268; p = 0.771	**F(2,8) = 5.716; p = 0.29**	**F(1.407,5.627) = 8.980; p = 0.22**
Manner x Position	**F(4, 16) = 6.885; p = 0.002**	F(3,12) = 1.120; p = 0.380	F(4,16) = 0.758; p = 0.568

Table 13. Results from the RM-ANOVA conducted for skewness.

3.5.3 Kurtosis

Kurtosis is a measure of the 'peakedness' of a distribution. In terms of burst frequency, higher kurtosis implies more energy in frequencies far from the mean. Lower kurtosis implies more energy in frequencies near the mean.

Results for kurtosis of burst spectra were similar to results for skewness. Stop manners did not differ in kurtosis at either alveolar or velar place of articulation. There was, though, a main effect of manner for bilabial stops, as well as a significant interaction between manner and prosodic position. Voiced bilabial stops had greater kurtosis than either bilabial ejective or bilabial aspirated stops in all prosodic positions, although the difference was only significant AP-initially and word-medially. Average kurtosis for bilabial stops in each prosodic position is given in Figure 7c. Kurtosis values for each stop manner at alveolar and velar places of articulation are given in Table 14.

Both alveolar and velar stops showed increasing kurtosis of burst spectra in lower prosodic positions. Both places of articulation showed a main effect, although only velar IP-initial stops were significantly different. Kurtosis at each prosodic position for alveolar and velar stops is given in Figure 9. Statistical results are given in Table 15.

	Alveolar	Velar
Aspirated	2.1 (sd 1.7)	8.3 (sd 5.2)
Ejective	1.9 (sd 1.6)	8.4 (sd 4.4)
Voiced	2.4 (sd 2.3)	9.1 (sd 4.8)

Table 14. Average kurtosis for each stop manner at alveolar and velar places of articulation.

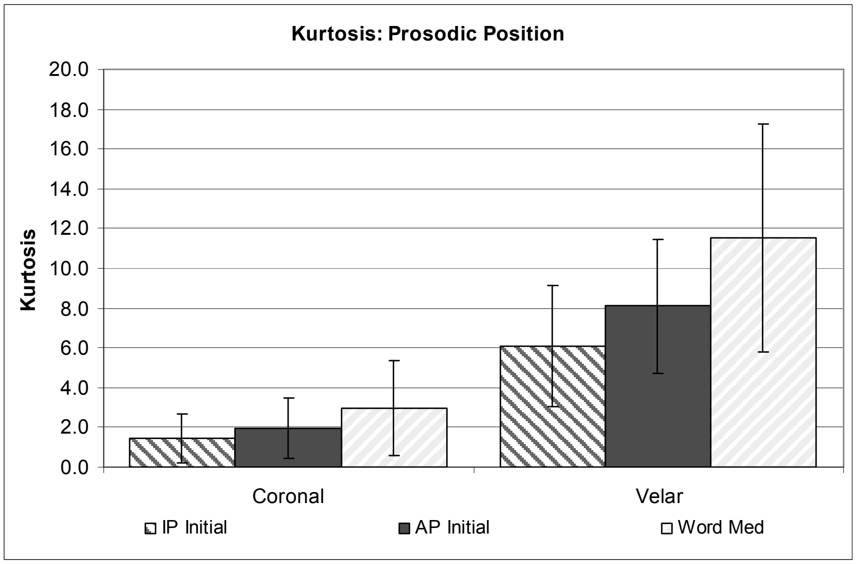

Figure 9. Average kurtosis for each stop manner at alveolar and velar places of articulation.

	Bilabial	Alveolar	Velar
Manner	**F(2,8) = 7.902; p = 0.013**	F(1.120,4.480) = 0.836; p = 0.422	F(2,8) = 0.350; p = 0.715
Position	F(2,8) = 0.469; p = 0.642	**F(1.913,7.653) = 5.017; p = 0.042**	**F(1.376,5.502) = 7.526; p = 0.032**
Manner x Position	**F(4,16) = 3.710; p = 0.025**	F(2.395,9.579) = 0.793; p = 0.501	F(3.440,13.762) = 0.866; p = 0.495

Table 15. Results from the RM-ANOVA conducted for kurtosis.

3.6 Phonation

Overall, the phonation used by the speakers was quite creaky and irregular. As a result, it was difficult to get reliable measures of H1-H2 or f0. In general, phonation was more creaky in the story condition than in the carrier phrase condition, so only tokens recorded in a carrier phrase were measured.

Phonation was expected to distinguish stop manners in Georgian. In particular, ejectives were expected to be followed by relatively creaky phonation, based on the glottalization heard by Robins & Waterson (1952) and the fluctuations in voice pulse frequency observed by Wysocki (2004). Voiced and aspirated stops, on the other hand, are expected to be followed by vowels with modal phonation. Indeed, there was a main effect of manner at every place of articulation and the results generally fit the expected pattern, as can be seen in Figure 10. For bilabial and velar stops, ejectives had significantly lower H1-H2, and thus, were followed by creakier phonation than either the aspirated or voiced stops. Aspirated stops were associated with higher H1-H2 values, more breathy phonation, compared to voiced stops, but this difference was not significant at the bilabial and velar places of articulation. Vowels following alveolar aspirated stops were significantly more breathy than after either voiced or ejective alveolar stops. Vowels following alveolar ejectives were creakier than after voiced stops, but the difference was not significant at this place of articulation.

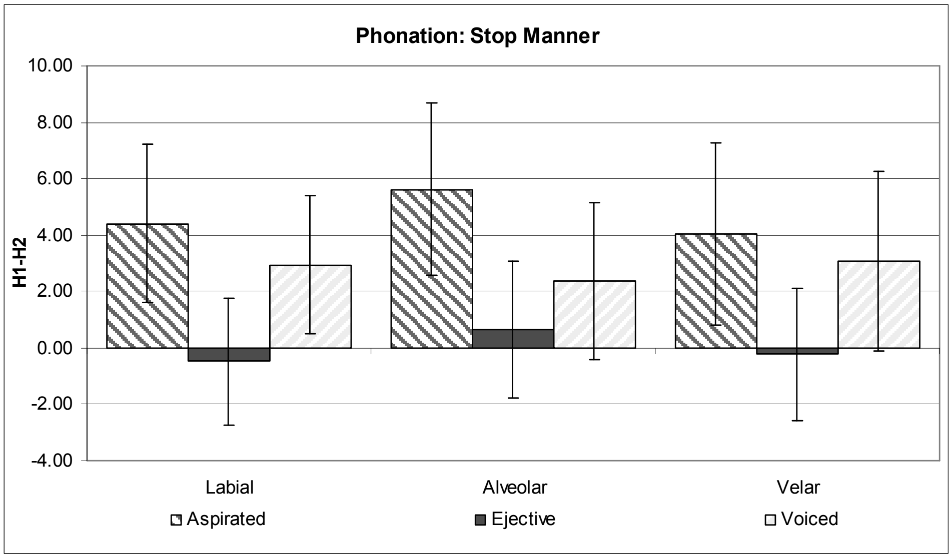

Figure 10. Average H1-H2 values for each place of articulation and stop manner.

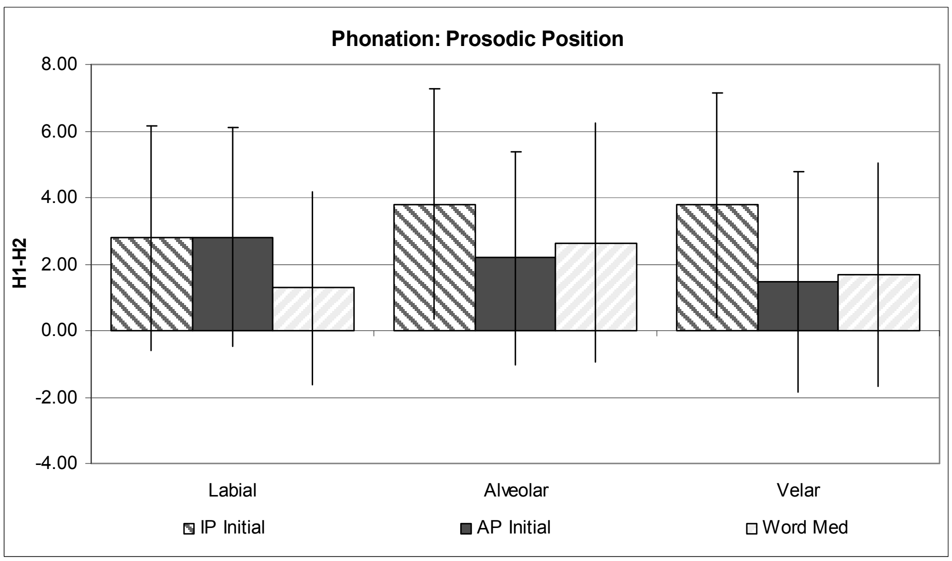

Figure 11. Average H1-H2 values for each place of articulation at each prosodic position.

	Bilabial	Alveolar	Velar
Manner	**F(1.860,7.439) = 13.359; p = 0.004**	**F(2,8) = 15.601; p = 0.002**	**F(2,8) = 6.718; p = 0.019**
Position	**F(1.528,6.110) = 5.367; p = 0.050**	F(1.528,6.111) = 3.602; p = 0.098	**F(1.354,5.414) = 41.908; p = 0.001**
Manner x Position	F(4,16) = 0.385; p = 0.816	F(4,16) = 0.631; p = 0.647	F(2.606,10.423) = 0.865; p = 0.476

Table 16. Results from the RM-ANOVA conducted for H1-H2.

Vowel phonation following stops tended to be more breathy in higher prosodic positions than in lower prosodic positions, but there was only a main effect of prosodic position for bilabial and velar stops. Vowels following IP-initial stops showed significantly higher H1-H2 values than vowels following stops in lower prosodic positions at bilabial and velar places of articulation. Average H1-H2 values at different prosodic positions are given in Figure 11. Statistical tests are presented in Table 16.

3.7 F0

As stated above, only tokens recorded in the carrier phrase condition were measured for f0. Despite the better voice quality used in this condition, there were still too few tokens where reliable pitch measurements could be made to perform a RM-ANOVA analysis. Instead, a simple ANOVA with two factors, manner and prosodic position, was run on the data. Like in the RM-ANOVAs, each speaker's mean was used at the dependent variable. Statistical results are given in Table 17.

In general, f0 following ejectives was flat or rose, while f0 following aspirated and voiced stops fell after the stop (Δf0 = f0 at vowel onset – f0 at mid-vowel), as can be seen in Figure 12. Despite this trend, there was a main effect of stop manner only at the alveolar place of articulation, where there was also a significant interaction with prosodic position. There was no effect of manner for bilabial or velar stops. Change in f0 significantly differentiated alveolar ejective stops from the other two stop manners at AP-initial and word-medial position; there was no difference between stop manners in IP-initial position. Alveolar aspirated and voiced stops were only different in AP-initial position; aspirated stops were followed by greater falling f0 than voiced stops. The trend observed is somewhat surprising considering the f0 results reported for other languages. In Gitksan (Ingram & Rigsby 1987) and Witsuwit'en (Wright et al. 2002), only men showed rising f0 following ejectives. Women showed falling f0. In Georgian, women show rising f0 following ejectives.

There were no significant effects of prosodic position on f0 at any place of articulation. However, in general f0 fell after stops in an AP-initial position, more so than after stops in either IP-initial or word-medial position, as can be seen in Figure 13. This is more likely due to the broad intonation patterns of the language than to any segmental effects. Georgian typically shows a rising intonation contour over the course of an accentual phrase. At a phrase boundary, the pitch quickly falls from a high target at the end of the first AP to a low target at the beginning of the second AP. However, the low target is typically not reached until the middle or end of the first syllable of the second AP. Thus, any of the stop tokens measured at the beginning of a sentence medial accentual phrase will tend to show falling f0.

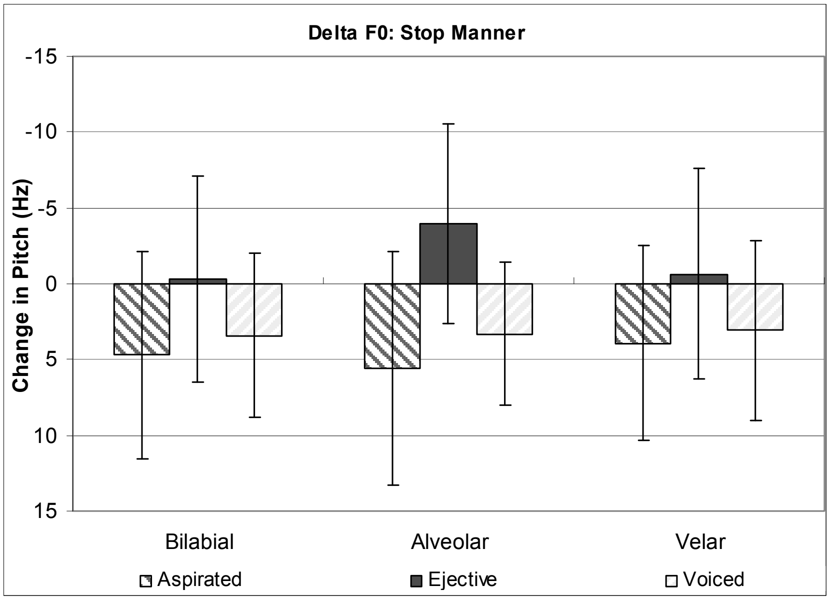

Figure 12. Average change in pitch, given in Hz, for each place of articulation and stop manner.

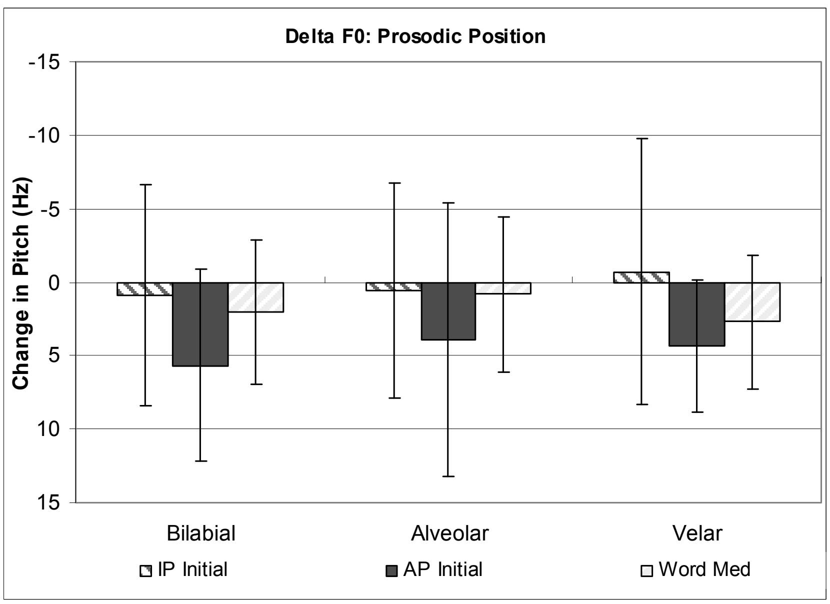

Figure 13. Average change in pitch, given in Hz, for each place of articulation at each prosodic position.

	Bilabial	Alveolar	Velar
Manner	F(2,36) = 2.196; p = 0.126	**F(2,36) = 10.802; p = < 0.001**	F(2,36) = 2.362; p = 0.110
Position	F(2,36) = 2.474; p = 0.098	F(2,36) = 1.691; p = 0.199	F(2.36) = 1.912; p = 0.164
Manner x Position	F(4,36) = 0.515; p = 0.725	**F(4,36) = 3.283; p = 0.022**	F(4,36) = 0.546; p = 0.703

Table 17. Results from the two-factor ANOVA conducted for change in pitch.

3.8 Evaluating the Importance of Acoustic Measures for Distinguishing Manner using Discriminant Analysis.

Many of the acoustic measures examined in this study can be used to some degree to distinguish stop manner, specifically, voicing lag, duration of voicing into the closure, H1-H2, f0 and burst spectral measures. A discriminant function analysis can be used to estimate the value of each acoustic measure for classifying the manner of a given stop token. Discriminant analysis uses a set of cases for which group membership is known to generate a set of functions that use a set of predictor variables to provide the best discrimination between groups. Once a set of functions is created, they can be used to classify new cases.

A discriminant analysis was conducted using the acoustic analysis results for 388 stop tokens in either AP-initial or word-medial position. IP-initial stops were excluded because they have no % Voicing measure. 37% were aspirated stops, 24% were ejectives, and 38% were voiced stops. These same tokens were then used as a test set for classification. All acoustic measures described above were input as predictor variables except for closure duration and relative burst intensity, which showed no differences in manner. All measures were input together.

Results of the discriminant analysis are given in Table 18, and the scores of each token for the two functions is given in Figure 14. It can be seen that the first function generally serves to discriminate voiced stops from ejective and aspirated stops. Duration of voicing into the closure and voicing lag are the best measures for this task; they have the highest correlation with function 1. The second function generally serves to discriminate aspirated and ejective stops. For this task, H1-H2 and Δf0 have the highest correlations, although voicing lag also has high correlation. Burst spectral measures show the lowest correlations for both measures, although they are best used to discriminate voiced stops from aspirated or ejectives. Mean burst frequency is the most useful of the spectral moments.

Acoustic Feature	Correlation with Discriminant Functions		Wilks' Lambda	F-value	Significance
	Function 1	Function 2			
% Voicing in Closure	0.916*	0.158	0.348	320.556	0.000
Voicing Lag	-0.655*	0.479	0.482	207.096	0.000
H1-H2	0.005	0.728*	0.772	56.717	0.000
Delta f0	-0.003	0.615*	0.826	40.456	0.000
Mean	-0.142*	0.024	0.957	8.618	0.000
Skew	0.093*	-0.014	0.981	3.725	0.025
Kurtosis	0.079*	0.016	0.986	2.685	0.070

Table 18. Statistical results for the discriminant analysis. Largest absolute correlations between each variable and discriminant function are marked with an asterisk.

Classification results are presented in Table 19. 83% of the original cases were correctly classified. Ejective stops are the hardest to classify correctly. Only 69.5% were classified correctly, most were misclassified as aspirated stops. Classification was better for aspirated and voiced stops. When aspirated stops were misclassified, they were misclassified as ejectives, not voiced stops. On the other hand, voiced stops were misclassified as both ejectives and aspirated stops.

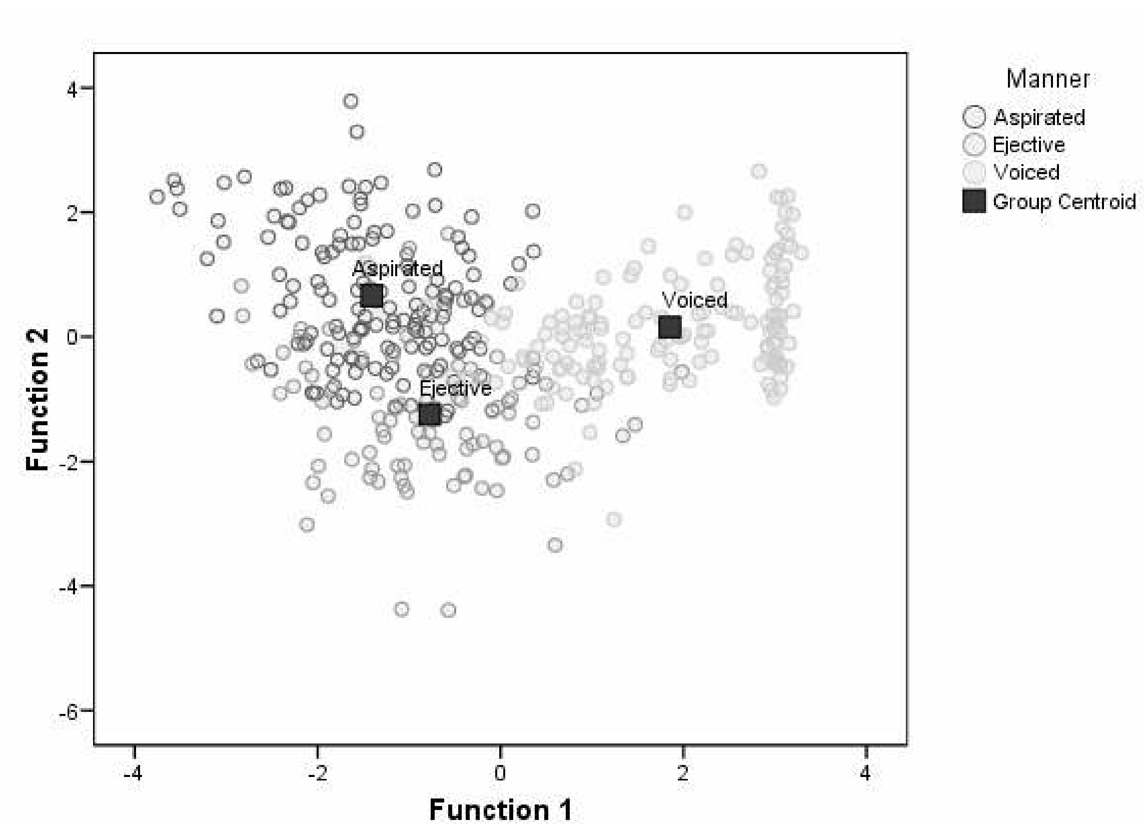

Figure 14. Scores of each token for the two discriminant functions.

Actual Manner	Predicted Manner (%)			Total Cases
	Aspirated	Ejective	Voiced	
Aspirated	86.1	13.9	0	144
Ejective	22.1	69.5	8.4	95
Voiced	4.7	6.7	88.6	149

Table 19. Classification results using discriminant functions.

4. Discussion

Georgian has three stop manners: voiceless aspirated, ejective and voiced. This study examined a number of acoustic features for each stop manner in order to determine which acoustic features might best serve as a perceptual cue distinguishing stop manner. Also, acoustic measures were made for each stop manner in three prosodic positions in order to examine the effects of initial strengthening on Georgian stops.

4.1 Possible Cues to Stop Manner

Of the seven acoustic measures examined in this study, five are possible cues to stop manner in Georgian. Georgian stop manners were not different in closure duration or burst intensity, but did differ to some degree in voicing lag, voicing during the closure, burst spectral moments, phonation and pitch. Wysocki (2004) also showed that closure duration did not vary for different stop manners in Georgian. She also observed that Georgian ejectives had louder bursts than voiced stops, but this observation is contradicted by the measurements made in this study. There was no statistical difference in relative burst intensity for any stop manner.

Voicing lag was the only acoustic measure that significantly differentiated all three stop manners, and was highly correlated with both functions of the discriminant analysis. Aspirated stops showed the most voicing lag, ejectives showed an intermediate voicing lag and voiced stops showed the least voicing lag. These results fit with the results from Wysocki (2004) and fit with the typologically common pattern seen in other languages. However, it seems unlikely that voicing lag could serve as a cue to stop manner by itself. In higher prosodic positions, though statistically different, ejectives and aspirated stops showed very similar voicing lags, with average differences sometimes as small as 10 ms. Both fall within the aspirated stop VOT category in Keating (1984). Word medially, ejectives and voiced stops showed very similar voicing lags, with average differences sometimes less than 15 ms. Both fall within the unaspirated stop VOT category in Keating (1984). Thus, it seems more likely that listeners might use voicing lag to distinguish one stop manner from the other two, but not to distinguish all three.

Voicing into the closure showed a strong trend in differentiating all manners, but only the voiced stops were significantly different at all places of articulation and showed significantly more voicing than either ejectives or aspirated stops. Both aspirated and ejective stops did show some voicing into the closure, confirming the observations in Robin & Waterson (1952). Ejectives showed about 6-7 ms more voicing than aspirated stops. Stops only showed voicing into the closure when surrounded by vowels. In an IP initial position, there was no voicing during the closure, except for a handful of voiced stops. Robin & Waterson also point this out. This suggests that the voiced stops in Georgian are probably phonemically voiced and likely become phonetically voiceless IP-initially due to the reduced subglottal pressure characteristic of that position. Such devoicing is common cross-linguistically and is observed in, for example, English (Keating 1984). Intervocalically, voicing into the closure would be a good perceptual cue for discriminating voiced stops from either aspirated or ejective stops, as indicated by the results of the discriminant analysis. This cue would fail, however, IP-initially, where voicing during the closure rarely occurs.

Bilabial voiced stops were distinguished from other bilabial stops in the spectral moments of their burst. Bilabial voiced stops had a lower mean burst frequency, and higher skewness and kurtosis values, especially in lower prosodic positions. Alveolar voiced stops also showed lower mean burst frequency, however velar voiced stops do not. Neither alveolar nor velar stops showed any differences in skewness or kurtosis for different manners. Because of these inconsistencies in place of articulation, burst spectral moments would likely serve as poor perceptual cues to stop manner. Burst spectral moments were the lowest performing predictor variables in the discriminant analysis.

Ejectives appear to be best differentiated from aspirated and voiced stops in terms of the phonation and f0 on the following vowel. Ejectives were immediately followed by creaky phonation, marked by low or negative H1-H2 values, and flat or rising f0. Aspirated and voiced stops, on the other hand, were followed by more modal or breathy phonation and falling f0. Creaky or irregular phonation has been associated with ejectives in Georgian (Robins & Waterson 1952; Wysocki 2004) as well as a number of languages, like Gitksan (Ingram & Rigsby 1987) and Witsuwit'en (Wright et al. 2002). However, in Gitksan and Witsuwit'en, f0 fell following ejectives for female speakers. In Georgian, women showed flat or rising f0 following ejectives. Men showed the opposite pattern in Gitksan and Witsuwit'en, however men were not measured in this study. It would be interesting to see how male Georgian speakers pattern with regards to f0 following ejectives.

Phonation and f0 seem to be promising cues in distinguishing ejective stops from aspirated and voiced stops. They would likely serve as second-step cues, as they did in the discriminant analysis. That is, listeners might discriminate one pulmonic stop manner, voiced stops, for example, from the other two manners using some cue, like voicing lag, and then discriminate ejectives from the remaining pulmonic manner using f0 and/or phonation. Although pitch and phonation seem to be promising potential cues, there was considerable overlap with the other two manners. This might make ejectives hard to perceive, as they might be easily confused with either the aspirated or voiced manners. Indeed, ejectives were the hardest stops to classify in the discriminant analysis using acoustic measures examined here.

4.2 Initial Strengthening

This study has shown that Georgian stops do show effects of initial strengthening. Two possible types of strengthening were proposed – paradigmatic enhancement, which would enhance the differences between stop manners in higher prosodic positions, and syntagmatic enhancement, which would simply make the stops more consonant-like and less similar to the following vowel. Only syntagmatic enhancement was found.

All stop manners showed longer closure durations and longer voicing lags in higher prosodic positions. If Georgian showed paradigmatic enhancement in its initial strengthening, voiced stops should show shorter or unchanged voicing lags in higher prosodic positions, but this was not the case. Nor was there any increase in the amount of voicing during the closure for voiced stops in higher prosodic positions. In fact, the only stop that showed any change in percent voicing was /g/, which showed less voicing during the closure in AP-initial position than it did in word-medial position, making it more like a voiceless stop than enhancing the voicing contrast. Paradigmatic enhancement might also predict that manner contrasts in f0 and H1-H2 should be enhanced in higher prosodic positions. However, there was no effect of prosodic position on f0 following stops, and although phonation was affected by prosodic position, all stop manners were affected in the same way. All stop manners were produced with breathier phonation in higher prosodic positions than in lower positions, including ejectives, even though it seems that the creakier phonation following ejectives might serve as a good cue to manner.

The effects of initial strengthening on burst features were less clear than on other acoustic measures. There was little effect of prosodic position on the burst intensity of aspirated and voiced stops. However, for ejectives, the burst was more intense in lower prosodic positions. This seems to be the opposite of initial strengthening. Stops are expected to be more strongly articulated in higher prosodic positions, which suggests, for ejectives, that oral air pressure should be higher phrase initially than phrase medially. A higher pressure should produce a louder burst. Instead, ejectives showed a louder burst phrase medially. This is not due to the fact that burst intensity in this study is a relative measure. Absolute intensities were checked against these results and ejectives did indeed show more intense bursts word-medially. It is unclear what would cause this effect.

Different places of articulation showed varying patterns in how spectral moments of bursts were affected by prosodic position. Georgian alveolar stops showed no change in mean burst frequency, but they did show lower skewness and kurtosis values in higher prosodic positions. Velar stops showed higher mean frequencies, and also showed lower skewness and lower kurtosis values in higher prosodic positions. Bilabial voiced stops pattern with the velar stops. Bilabial voiced stops showed higher mean frequencies, lower skew and lower kurtosis in higher prosodic positions, while bilabial aspirated and ejective stops showed lower mean burst frequencies in higher prosodic positions and no changes in skew or kurtosis.

5. Conclusion

Georgian stops are affected by initial strengthening, and, in general, show a syntagmantic, rather than paradigmatic, strengthening pattern, that serves to make the stops more consonantal and more distinct from the following vowel rather than enhancing the manner contrast. All stops show longer closure durations, longer voicing lags, less voicing during the closure and higher H1-H2 values in higher prosodic position.

There is no obvious acoustic correlate that would serve to distinguish all three stop manners in Georgian. Instead, it seems more likely that listeners must depend heavily on at least two cues to identify manner. The most likely cues include voicing lag, voicing during the closure, H1-H2 and f0. Ejectives were the hardest stop manner to classify, which suggests that they would be relatively easily confusable and the hardest to perceive. Which acoustic features listeners actually attend to, the relative importance of each, and their accuracy, can only be answered through perceptual studies. Identification and confusability studies are planned and should provide valuable information regarding the discrimination of ejectives and other stops in Georgian.

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