Closure Duration in the Classification of Stops:

A statistical analysis

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[Some thirty years ago, Ilse Lehiste and I were fellow students in Ann Arbor, working in the laboratory of the late Gordon E. Peterson, our teacher. After that, for several years we were colleagues in Columbus, laying the foundation for an embryonic Department of Linguistics. Through these decades, her friendship has always been a source of comfort for me, and her scholarship a standard for emulation. My co-authors and I are pleased to have this opportunity to honor her. This little essay is on phonetics, a field to which she has contributed so much. - WSYW]

Stop consonants have been traditionally described by the terms voiced-voiceless, aspirated-unaspirated and tense-lax (fortis/lenis). It has been suggested (Lisker & Abramson 1964) that all the acoustic properties of stops are consequences of a change in the timing relationship between the release of a closure and the onset of vocal fold vibration.

The technical term VOT (voice onset time) has been applied to this timing relationship. However, the VOT approach has difficulties in a number of languages, e.g., Korean (Kim 1965). It is obvious that if the contrast of stops does not exist along voice-voiceless and aspirated-unaspirated dimensions, the VOT method will be unable to capture the difference.

Another approach for classifying stops was proposed by Halle and Stevens in their 1971 article that fundamental frequency varies as a function of vocal fold tension. It has been shown (Lehiste & Peterson 1961) that a voicing distinction of stop sound in prevocalic position can affect the F0 of the following vowel. Further, although VOT was very similar for the initial voiced stops and the voiceless stops after an s, the F0 were very dissimilar (Reeds & Wang, 1961 and Ohde, 1984). It seems that this might provide us with an alternate method for classifying stop sounds which do not have the contrast in voicing and aspiration.

Are these two approches sufficient to classify stops in any language? Toward answering this question a dialect of Chinese is used. The Wu dialect is one of seven major dialects of Chinese. It has three types of stop sounds (traditionally they are described as voiceless unaspirated, voiceless aspirated and voiced). Y. R. Chao called this "tripartite division of initial stops" (1928). As early as in the 1920's F. Liu found that the voiced stops in Wu are actually not voiced. It was also noticed by Chao that when this sound occurs in an intervocalic position it is fully voiced.

In recent years there have been two acoustic studies of Wu stops by Cao (1982) and Shi (1983). Both of them show that the VOT does not differ significantly between the two unasp-rated stops. Here are the VOT values reported by Shi. (Cao did not supply any quantitative data)

b	p	d	t	g	k
7.5	6	7.5	7	20	16

Shi also measured the fundamental frequency of the following vowels to examine the effect the stops have on their following vowels. But this approach was not successful for two reasons: 1) Since Wu is a tone language the change in fundamental frequency is mainly a tonal phenomenon, and 2) The stops are in complementary distribution. As a result of historical change the so-called voiced stops never occur in the same tone with voiceless stops. Thus Shi was unable to determine if the F0 differences were due to the tone or due to the consonants.

Because of the problems discussed above, we need to find some other acoustic cues besides VOT and F0 to study the stop sounds in Wu. We know that stop sounds are produced with the vocal tract entirely occluded. When the vocal tract is occluded at some point within the oral cavity the air escaping from the lungs is trapped behind the constriction, thereby causing a build-up of oropharyngeal air pressure.

The following acoustical parameters appear to be important cues to identifying stop consonants:

1) Duration of the closure
2) Presence of the voicing during the closure phase
3) Voice onset time
4) Duration of the noise burst
5) The perturbation on the following vowels

The closure durations of voiceless stop sounds are greater than for their voiced counterparts. This fact was observed and studied by Lisker (1957), in a study to distinguish stop consonants in word-internal position.

But in initial position, the difficulty to get the duration of the closure is that if the stop sound is voiceless during the closure and at an initial position, it will result just as silence in the waveform. Although physically there is a starting point of the closure, we can not determine it from the waveform.

In order to get the starting point of the closure, we put the syllables with the stops we are interested in in a carrier phrase. Thus, we can use the end of the preceding syllable as a reference point to get the closure duration of the stop.

The data we use is taken from Shanghai speech, which belongs to the Wu dialect group. It is not the same variety of Wu studied by Shi and Cao, but the stop types are the same (Chao 1928). Some relevant phonological features of Shanghainese are introduced below.

Some phonological features of Shanghainese:

There are three different types of stops: one is voiceless and aspirated, and two are phonetically unvoiced and unaspirated. But traditionally one is called voiceless and the other one is called voiced. All three types of stops appear at three articulatory places: bilabial, alveolar and velar. Here we will not consider the aspirated ones, since they do not pose a problem for traditional methods of classification. For convenience, we use the symbols p, t and k for the voiceless stops and b, d and g for the so-called voiced stops.

There are five tones, three of them are long and two of them are short. Their phonetic values in a five height system (5 is the highest and 1 is the lowest) are: 1. 51 2. 334 3. 113 4. 5(short) 5. 23(short). The two serios of unaspirated stops are distributed in different tones. P, t and k's only occur with tone 1,2, and 4 (high register), and b, d and g's only occur with tone 3 and 5 (low register).

Experiment 1:

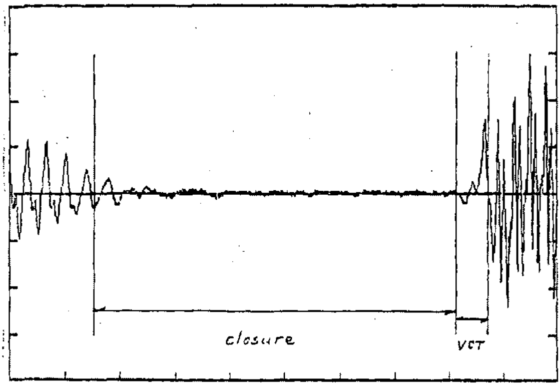
The two types of stops at three articulatory positions with a vowel, [e] for long tones and [ə] for short tones, are selected for each of the five tones. All the syllables are real words in Shanghainese.

Tone	1	2	3	4	5
bilabial	pe 班	pe 板	be 倍	pə 拨	bə 拔
alveolar	te 堆	te 对	de 队	tə 答	də 达
velar	ke 间	ke 拣	ge [ ]	kə 革	gə 轧

Each word is pronounced ten times. The total number of tokens is 3x5x10=150. The recordings were made in a sound booth. The experimental utterances were displayed on a IBM PC-AT screen by using the ILS (Interactive Laboratory Systems) software made by Signal Technology Inc.

In order to get the closure time of the articulator, the tokens are placed in carrier phrases /do? __ i? pi/ (which means "Say __ once." in English). Three measurements are made for each stop, as shown in Figure 1 below. Each division on the x-axis marks off 20 msc.

The starting point of closure in the waveform was determined on the basis of both a sudden decrease in amplitude, and a loss of high frequency components. As we can see from Figure 1, the voicing containing energy at the fundamental frequency and F1 continues past the start point of closure for several periods. The end point of the closure was determined on the appearance of the noise type waveform. And the voice onset point was determined on the appearance of periodic waveform, from the starting point to the end point of the closure is taken to be the closure of articulator. The duration from the end point of the closure to the voice onset point is the traditional VOT. After the voice onset point the durations of five successive periods were also measured.



All the calculations are done by using the Statistical Analysis System (SAS). The results for monosyllabic word in a carrier phrase, listed by tones, are shown below:

TONE 1

variable	n	mean	S.D.	min-value	max-value
clo	30	157.80	15.26	128.00	191.50
VOT	30	16.27	11.94	5.90	48.00
F01	30	5.86	0.70	4.50	7.10
F02	30	6.42	0.38	5.70	7.10
F03	30	6.31	0.41	5.60	6.90
F04	30	6.35	0.36	5.70	7.00
F05	30	6.38	0.36	5.80	7.10

TONE 2

variable	n	mean	S.D.	min-value	max-value
clo	30	150.60	15.39	116.60	178.50
VOT	30	19.45	9.25	7.20	42.30
F01	30	7.35	0.80	6.00	8.80
F02	30	8.13	0.63	7.00	9.20
F03	30	8.23	0.64	6.60	9.30
F04	30	8.33	0.63	7.10	9.40
F05	30	8.45	0.58	7.20	9.80

TONE 3

variable	n	mean	S.D.	min-value	max-value
clo	30	126.01	19.92	82.80	166.10
VOT	30	24.33	10.70	11.50	45.70
F01	30	8.58	0.92	7.20	11.40

F02	30	9.84	0.55	8.90	11.20
F03	30	10.18	0.47	9.50	11.40
F04	30	10.29	0.37	9.60	11.30
F05	30	10.31	0.36	9.60	11.20

TONE 4

variable	n	mean	S.D.	min-value	max-value
clo	30	156.26	14.15	132.40	179.70
VOT	30	15.52	9.02	7.90	34.00
F01	30	6.03	0.36	5.30	6.60
F02	30	6.78	0.34	6.10	7.40
F03	30	6.73	0.22	6.30	7.20
F04	30	6.78	0.23	6.20	7.20
F05	30	6.81	0.23	6.20	7.20

TONE 5

variable	n	mean	S.D.	min-value	max-value
clo	30	125.98	13.65	99.60	149.80
VOT	30	21.43	12.24	6.90	59.40
F01	30	7.89	0.66	6.00	9.50
F02	30	9.05	0.43	8.30	10.10
F03	30	9.23	0.38	8.60	9.80
F04	30	9.19	0.38	8.30	10.20
F05	30	9.17	0.33	8.50	9.80

From these results above we can see that:

1) The average value of closure durations of p, t, and k in tone 1,2 and 4 are longer than those of b, d and g in tone 3 and 5. In descending values, these are: 157.8(1), 156.3(4), 150.6(2), 126.0(3) and 126.0(5). The difference between these two types of stops is approximately 30 milliseconds.

2) All the VOT values are positive. The average value of VOT values in five tones from shortest to longest are 15.52 (4), 16.27(1), 19.45(2), 21.43(5) and 24.33.(3) separately. It means that these two types stops are both voiceless stops. On the average, the b, d and g have a longer VOT value than the p,t and k, but the difference is relatively small. The difference is about 6 milliseconds ((21.43+24.33) / 2-(15.52+16.27+19.45)/3=5.8).

3) The duration of the five periods are longer for b,d and g.

4) Although the averages are different, from the ranges of each variable we can see that they overlap with each other.

The maximum value of a variable with a smaller average is always above the minimum value of a corresponding variable with a larger average. For example: The closure duration in tone 2 is 150.6, it is longer than the average closure duration in tone 3, which 126.0. But the minimum value in tone 2 (116.6) is smaller than the maximum value in tone 3 (166.1). There is no clear boundary between these variables. By looking at average and range, we would not be able to determine how many types of stop sounds there are.

In order to tell the statistical significance of these numbers, a multivariate statistical method Hotelling's T-square is applied to test the differences between all 10 possible pairs (nx(n-1)/2, n=5). The formula we used is:

$$T^2 = [N_1 N_2 / (N_1 + N_2)] (\bar{X}_1 - \bar{X}_2)' S_c^{-1} (\bar{X}_1 - \bar{X}_2)$$

The corresponding F value is calculated in the following way:

$$F = (N_1 + N_2 - p - 1) T^2 / [p(N_1 + N_2 - 2)]$$

with p and $N_1 + N_2 - p - 1$ df $\quad p = 7, \; N_1 = N_2 = 30$

The result is shown below:

	1	2	3	4
2	40.82			
3	277.79	36.38		
4	6.72	30.06	332.02	
5	144.64	16.36	29.26	159.96

$F(7,50) = 3.02 \; (\alpha = 0.01)$

All the F values indicate that none of them is the same, since all the F values are larger than 3.02. It cannot be the right result since there are only two types of stops. We are using three different measurements here, the closure duration, VOT and F0. In order to determine which paramter contribute to the difference shown by the F values, a post-hoc T-square test is applied.

$$F_{sub} = n \frac{(\bar{X}_n)^2}{S_{nn}}$$

Here are the results:

Tones	12	13	14	15	23
clo	0.42	6.16	0.02	9.28	3.67
VOT	0.17	0.97	0.01	0.35	0.46
F01	7.68	21.40	0.18	17.18	3.19
F02	20.78	102.07	1.94	81.23	16.09
F03	24.38	148.09	3.12	105.41	22.95
F04	28.77	224.40	3.96	114.11	27.35
F05	34.98	228.01	3.97	125.72	28.49

Tones	24	25	34	35	45
clo	0.28	5.50	5.88	0.00	9.12
VOT	0.35	0.06	1.52	0.12	0.58
F01	8.89	1.02	25.79	1.44	23.69
F02	13.51	5.59	86.37	4.91	65.27
F03	18.74	6.89	168.95	9.39	124.46
F04	20.47	5.24	244.71	16.10	111.96
F05	20.15	4.54	257.95	20.97	133.37

The first row are the F values of the closure durations. It tells us that there is no significant difference between the pairs 12, 14, 24 and 35 (<3.02). But the differences are significant for the 13, 15, 23, 25, 34 and 45 pairs. We have mentioned that traditionally the stops in tone 1, 2 and 4 are called voiceless and the stops in tone 3 and 5 are called voiced (although they are voiceless also). Here, the F values for the closure duration clearly indicate the same classification that the stops in tone 1, 2 and 4 are one type which significantly differ from the other type of stops that occur with tone 3 and 5. The question whether the two types of unaspirated stops are the same is answered.

The second row is the F values of VOT. None of these values reached a significant level. From the average data, we know that the p, t and k's have a shorter VOT than their counterparts. It indicates that VOT is not a significant parameter for distinguishing these two types of stops. It proves that the difference of these two types of stops in Wu is neither a voiced-voiceless nor a aspirated-unaspirated contrast.

From row 3 to row 7, are five periods after the release of the closure. Except four of them, first and second periods in pair 17 and the first period in pairs 58 and 68, all the other forty-six (92%) F values show that they are significantly different. These F values show that fundamental frequencies are not good variable which can be used to distinguish the stop types in tone languages like Wu. The F0 basically is a tonal phenomenon. Here we cannot be sure of how much the F0 difference is due to the tonal difference and how much due to the difference of stop types. We say this difference basically is a tonal difference simply because that they fit the traditional description of the tonal values well. Let us look at the table below:

tone	value	average duration of five periods
1	51	6.26 (160 Hz)
2	334	8.10 (123 Hz)
3	113	9.84 (102 Hz)
4	4(short)	6.63 (151 Hz)
5	23(short)	8.91 (112 Hz)

It is obvious that when the duration of the period is shorter, the rate of vibration is higher. Although there may exist some perturbations on the vowels caused by the stop sounds, we will not be able to distinguish them because they are dominated by much stronger tonal affects. And this also explains why the F values are all different in the tests with all 7 variables, because the results are strongly influenced by five F0 variables which basically are the tonal differences.

Experiment 2:

The two types of unaspirated stops also can occur in word-internal position in a disyllabic words. Because of the rules of tone sandhi, two unaspirated stops can and only appear in the same disyllabic tones. All the tones lose their contrast in the second syllabic position. Thus, five monosyllabic tones yield five corresponding disyllabic tones. The tonal values in five level system are:

tone	value
1	55 + 31
2	33 + 44
3	11 + 44
4	4(short) + 55
5	2(short) + 23

In these disyllabic words, the two types of unaspirated stops clearly contrast in voicing. The comparisons we make here apply to stops within the same tone only. The first syllables of these disyllabic words are /se/, /tciu/, /liang/, /tchi/ and /lo/. All of them are number words, they are 'three', 'nine', 'two', 'seven' and 'six' separately. Each of them is used to represent a different tone. Three pairs of words with the stops in question at three articulatory places are chosen for the second syllable. They are: /pe/vs./be/, /te/vs./de/ and /kwe/vs/gwe/. The total number of tokens for this experiment is 5x2x3x10=300.

From the waveforms, it is clear that most of the word-internal b, d and g's have voicing during the entire closure, but not the p, t and k's. Thus, in this word-internal position the difference of two stop types also appears as a voice-voiceless contrast. This is the reason for many previous studies to call them "real voiced stops"(Chao, Cao, Shi). But the word-internal voiced-voiceless contrast is not consistent in all tonal environments. The interesting thing is that in disyllabic words with tone 5 (11 + 23), neither stop shows any voicing.

This is not difficult to understand. Although stress contrasts have not been described in Wu dialects, in fact they exist and correlate well with tones within words. The contour of intensity has a similar change as the pitch contour. So the independence of the stress usually will be ignored. But here the relationship between the pattern of stress and voicing causes our attention. In all five disyllabic tones only tone 5 has the weak+strong pattern, while others have the strong+weak pattern instead. The lack of voicing in tone 5 indicates that if the second syllable is stressed the contrast between these two stops is still pretty much like that found at initial position. Thus it is necessary to measure the closure duration and F0 in order to classify these stops.

In the word-internal position, if there is voicing for b, d and g's, the duration of voicing equals the duration of closure duration and equals the VOT duration. So here we only measure the closure duration for both p, t and k's and b, d and g's. The durations of five periods after the burst are also measured like what we did in monosyllabic words. The results are shown below:

	p.t.k			b.d.g		
Tone 1	mean	s.d.	range	mean	s.d.	range
clo	123.18	12.98	97.5-146.9	70.61	11.01	53.4- 92.5
F01	12.54	1.22	9.6- 14.6	12.75	1.22	10.6- 15.4
F02	13.76	0.82	12.2- 16.0	13.74	1.08	11.8- 16.4
F03	14.40	0.98	13.0- 17.0	14.16	0.96	12.2- 16.4
F04	14.90	1.22	13.0- 18.0	14.58	1.06	12.8- 16.8
F05	15.60	1.28	14.0- 18.8	15.16	1.22	13.2- 17.4

Tone 2	mean	s.d.	range	mean	s.d.	range
clo	129.33	15.92	110.7-154.6	82.39	11.15	59.7-106.9
F01	4.86	0.54	3.8- 6.0	5.48	0.76	4.0- 6.8
F02	5.32	0.52	4.2- 6.0	5.88	0.54	4.6- 6.8
F03	5.40	0.52	4.4- 6.4	5.88	0.52	4.6- 6.6
F04	5.40	0.50	4.4- 6.0	5.84	0.56	4.6- 6.6
F05	5.42	0.52	4.6- 6.2	5.80	0.48	4.6- 6.6
Tone 3	mean	s.d.	range	mean	s.d.	range
clo	133.49	17.38	90.9-163.2	105.86	22.85	72.1-130.2
F01	5.08	0.74	3.4- 6.2	6.46	1.38	5.0- 7.6
F02	5.80	0.66	4.4- 7.0	6.76	1.42	5.4- 7.8
F03	5.82	0.68	4.6- 6.8	6.78	1.46	5.4- 7.8
F04	5.82	0.64	4.6- 7.0	6.82	1.46	5.6- 7.8
F05	5.82	0.68	4.6- 7.0	6.78	1.44	5.6- 7.8
Tone 4	mean	s.d.	range	mean	s.d.	range
clo	186.60	26.39	143.0-240.2	143.04	26.45	90.7-169.8
F01	4.93	0.60	3.6- 5.8	5.67	0.71	4.2- 6.8
F02	5.56	0.57	4.2- 6.4	6.2	0.65	4.8- 6.8
F03	5.71	0.58	4.2- 6.4	6.15	0.59	4.8- 6.8
F04	5.68	0.56	4.6- 6.4	6.11	0.55	4.8- 6.6
F05	5.69	0.55	4.4- 6.4	6.08	0.58	4.8- 6.8
Tone 5	mean	s.d.	range	mean	s.d.	range
clo	217.81	18.80	189.6-268.8	136.64	18.22	110.0-181.0
F01	6.83	0.73	5.4- 8.0	7.60	0.94	5.8- 9.4
F02	7.13	0.64	5.8- 3.9	8.02	0.89	6.4- 10.0
F03	7.18	0.69	5.8- 8.2	8.11	0.84	6.2- 9.6
F04	7.25	0.70	5.8- 8.0	8.12	0.87	6.4- 9.2
F05	7.31	0.72	5.6- 8.4	8.04	0.78	6.4- 9.2

N = 30

The results can be summarized as follows: 1) The average value of closure duration for p, t and k's are longer than [illegible] for b, d and g's in the same tones. 2) The difference is relative not absolute. It means that the p, t and k's has a longer duration than b, d and gs only in the same tonal environment, not all the closure durations for p, t and k's are longer than b, d and g's. For example, the closure duration for p, t and k's in tone 3 is 109.5 msec. which is shorter than the closure duration for b, d and g's in tone 4 which is 143.0 msec.. Here we do not wish to explain these compensatory lengthening of the closure duration caused by the duration of preceding syllables, because the comparisons we interested in are only within each tonal category.

3) The durations of five periods on the average are shorter for the p, t and k's in tone 2, 3, 4 and 5, but it is in the opposite way in tone 1. 4) like what we see in monosyllabic tones, the phenomenon of overlapping is also in the data of disyllabic words.

In order to explain these numbers, the same Hotelling's T-square test is applied to the differences of two types of stops within the same tone. The results (F values) are listed below:

Tones	1	2	3	4	5
F-value	44.78	28.77	24.40	11.52	54.50

$F(6.50) = 3.19$ ($\alpha = 0.01$)

These F values tell us that in all the disyllabic tones the p, t and k's are significantly different (> 3.19) from the b, d and g's in the same tone. Here we like to know the contribution of closure duration and F0 to the total differences. The post-hoc test shows the F values below:

	1	2	3	4	5
clo.	43.55	26.65	4.23	6.21	43.93
F01	0.02	1.89	3.51	2.88	1.90
F02	0.11	2.58	1.72	2.49	3.01
F03	0.25	1.96	1.64	1.24	3.32
F04	0.28	1.52	1.82	1.32	2.79
F05	0.34	1.33	1.63	1.11	2.14

The first row is the F value of the closure durations which show s us that the closure duration of two different stops are significantly different(> 3.19) in all five disyllabic tones. From second row to sixth row are the F values for five periods after the release of the closure. Except the F01 in tone 3, all the F values shows that the difference caused by the different stops are not significantly different(< 3.19), although the average value suggests that F0 after p, t and k's are higher than b, d and g's. Again, from another angle it shows that, as we had found in monosyllabic words, the tonal influence is dominant.

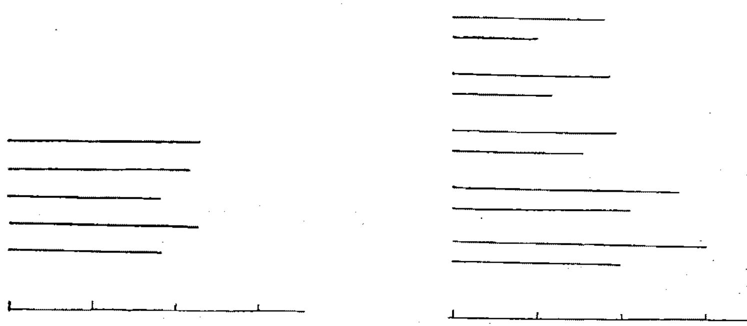
Discussion:

From the data and statistical results, we see that the closure duration efficiently classifies between p, t and k's and b, d and g's. On the other hand, the traditionally used acoustic cues VOT and F0 are not satisfactory here. From an articulatory point of view, both methods paid attention only to the glottal gesture, VOT refers to the relationship between the supraglottal closure release (the end point of closure duration) and the onset time of vocal folds vibration. And the F0 is also only concerned with the rate of vibration of the vocal folds after the closure release.

A complete account of stop sounds the closure period must also be taken into account. But in many acoustic studies this main part of stop sound production has been ignored.

Speech sounds differ from each other along several dimensions. This means that in some languages the stop sounds can be classified in more than one way. In English, for instance, the stops differ not only along the voiced-voiceless dimension, but along the tense-lax dimension as well. We have no reason to say that voice-voiceless or tense-lax is the only or the best way to do the classification in all the languages. But, as shown in Figure 2 below, whether the stops have voice-voiceless distinction or not and no matter what phonological positions they occur in, closure duration is always a reliable indicator.

Figure 2 has two displays. The length of the lines in Figure 2 shows the closure durations of the stops, each line showing the average over 30 samples. The divisions on the base line marks off increments of 50 msc. In the left display of monosyllabic samples, the top line shows that the average closure duration for p, t, and k with tone 1 is 157.8 msc, as reported in Experiment 1 earlier. Since both types of stops occur in the second syllable, the right display shows the line in pairs, as reported in Experiment 2 earlier. The upper line in the top pair shows that the average closure duration for p, t, and k with tone 1 is 123.2 msc.; the lower line in the top pair shows that the average duration for b, d, and g with tone 1 is 70.6 msc.



Here we used closure duration to study the stop sound in a tone language and got a clear classification between the two types of unaspirated stop sounds. Since the stops at initial positions are all voiceless, the name "voiced", strictly speaking, is a misnomer. The contradiction between the conventional name of a sound and phonetic reality of a sound is clear in this case. The right result from the measurements of closure duration does not necessarily indicate that the contrast between these stops only exists in one variable. Rather, it is a multidimensional phenomenon. But the importance of each variable is different. This was evalueated by the means of the statistical tests discussed above.

Conclusion:

It turns out that the term "stop" was aptly chosen, since the most effective classifier of stop sounds is the duration for which the sound is stopped. A recent study on the aerodynamics of Korean stops (Dart, 1987) reports that the fortis stops show a higher intraoral pressure. But the fortis stops are produced with longer closure durations as well. If we assume that the amount of air flow from the lungs to the speech tract remains approximately constant, then the higher pressure is simply a consequence of the longer closure duration.

Although the b, d, g discussed here are sometimes voiced, in word-internal positions, they are not voiced in general. Even though both types of stops are unvoiced and unaspirated, the b, d, and g have a significantly shorter closure duration.

Another central aspect of this study is that we tried to take fully into account that fact that a contrast is typically implemented multi-dimensionally, that is, simultaneously along several phonetic parameters. The situation is more complex in tone languages, such as the Shanghainese reported here, where one parameter, in this case F0, has many uses (Wang, 1972). In such situations, statistical procedures are especially necessary for evaluating the relative importance of the various parameters for different contrasts.

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