In this table slack voiced stops are represented by the regular voiced symbols with an added subscript [,]

ASPIRATED	$p^h6?$	'to strike'	t^hi	'heaven'	$k^hA?$	'competence'
UNASPIRATED	PA?	'hundred'	ti?	(particle)	ko?	'corner'
SLACK VOICE	bX?	'white'	d 1	'earth'	ga?	(possessive marker)

acoustic difference between these two sounds is manifested at the release. After detailed acoustic analysis, Fagan concludes that the systematic acoustic difference between the pairs of stops lies in the frequency of the first formant, and in the phonation type at the onset of the following vowel (Fagan 1988:194-5). Our own investigations have also shown that the stops with slack voice exhibit a lowered Fl, indicating that larynx lowering occurs. In vowels following these stops, there is a lower FO, and a reduction of energy in the upper frequency range of the spectrum, a notable acoustic property of vowels with slack or breathy voice (see chapter 9). Hayward (personal communication) also noted a slightly longer VOT for the slack voiced stops, reflecting the greater opening between the vocal folds.

Slack voice also occurs in the so-called lenis consonants in Wu dialects of Chinese, such as Shanghai, where the plosives occur at the bilabial, dental and velar places of articulation. As shown in table 3.9, there are three series of stops in this language. One series is plainly aspirated. The difference between the other two series has been the subject of some debate. Some accounts view one series as voiceless unaspirated and the other as voiced during closure and release, but with the release accompanied by weak voiced aspiration; other accounts regard the latter series as voiceless during closure with some voiced breathiness following. We follow Cao and Maddieson (1992), who indicate that the latter account is more appropriate, in that the issue is determined not so much by whether the stops are voiced or voiceless during closure, but rather by a phonation difference at the release of the stops. The so-called voiced stops have slack voice offsets, a quality detectable in the onset of the following vowel, whereas the other voiceless stops are not at all breathy in the comparable portion. Figure 3.9 shows the contrast for the bilabial stops. The spectrograms in the lower part of the figure indicate that neither of these stops

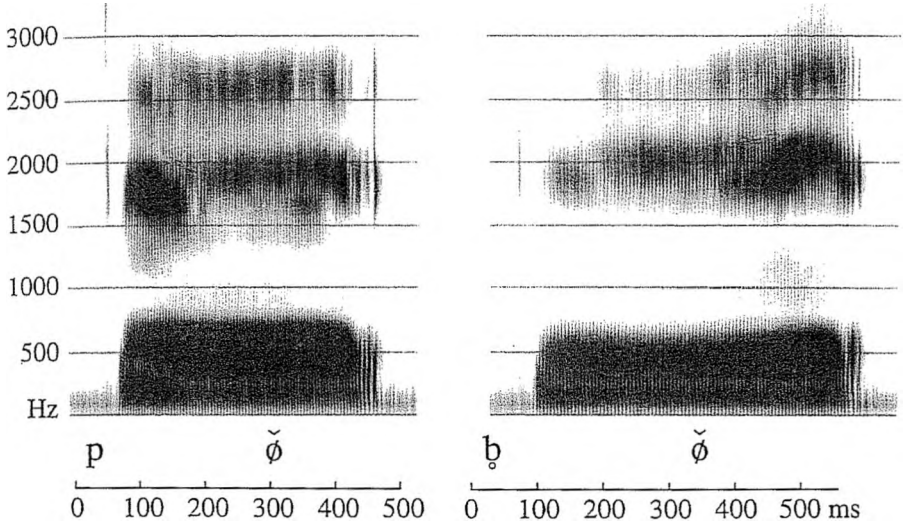

Figure 3.9 Spectrograms and power spectra illustrating the difference between Wu Chinese unaspirated stops. The words are pil 'half' and bb 'bowl' spoken by a female speaker from Shanghai.

is voiced; in both words vocal fold vibration starts 20-30 ms after the stop release. The power spectra (0-4 kHz) of the first few periods (50 ms) of the vowel in the upper part of the figure show that the difference in amplitude between the second formant and the fundamental is greater for the lenis stop, indicating that it has a more breathy voice. Breathy voice is typically marked by a relative decrease in the amplitude of the harmonics in the middle and upper parts of the spectrum. While the phonological contrast may be thought of as inherent in the consonants, the clearest manifestation is in the following vowel. There is also a greater random noise component in the breathy spectrum.

As is apparent from the preceding discussion, there are many differences in

Voiceless aspirated stops are too well known to need much discussion here; and, indeed, they have already been illustrated in the tables of contrasting stops in Thai, Korean, Hindi and Igbo, and in figures 3.5 and 3.7. In Hindi, as Dixit and others have shown, voiceless aspirated stops are produced with a glottal opening gesture that begins at about the moment that the oral closure is made and reaches its maximum at about the moment that the oral closure is released. This is in contrast to the unaspirated voiceless stops. In these the glottal opening begins at about the same time, but the maximum is reached at about the mid-point of the oral closure duration and the vocal folds return to a voicing position again at about the moment of release. In the aspirated case the maximum width of the glottal opening is also much greater than in the unaspirated voiceless stops. There are two ways of interpreting this greater width; it can be seen as the essential aspect of the production of voiceless aspiration, that is, aspiration is an extra-wide opening of the vocal folds (Kim 1965), or it can be seen as a by-product of the mechanism by which a delay between the offset of the oral and glottal gestures is achieved, that is, aspiration is essentially a matter of the timing between speech movements controlling laryngeal setting and oral articulation (Goldstein and Browman 1986). We will discuss this issue further below. Voiceless aspirated stops are often characterized as having a long VOT, the length of time after the release of a stop closure before the start of modal voicing for the following sound. The extensive work of Lisker and Abramson (1964,1967) has shown that VOT is a highly effective measure for differentiating stops with different laryngeal actions in a wide variety of languages.

As all the examples above are of stops in initial position, it is worth noting that contrasts between voiced, voiceless unaspirated and aspirated stops also occur in final position. Examples in Eastern Armenian are given in table 3.10. The differences between the minimal pairs in the first two rows of the table is principally a matter of voicing. Waveforms of words with final velar stops of these three types are shown in figure 3.10. The g is voiced throughout the closure and vocal fold vibrations continue after the closure is released, whereas k has voicing for only a few periods immediately after the beginning of the closure. As is often the case, the voiceless closure is longer. In this particular

			'phrase'	'under'
VOICELESS ASPIRATED	kap^{h} 'dub'	barts^{h} 'high'	votj^{h} 'no'	tak^{h} 'hot'

pair, there is virtually no difference between the lengths of the vowels before voiced and voiceless stops, although, taking our data as a whole, vowels before voiceless stops are usually a few milliseconds shorter than those before voiced stops.

For this speaker, the difference between the voiceless aspirated and unaspirated stops (the lower pair of words in figure 3.10) is in the strength of the release. The voiceless unaspirated stops are weakly released or (in other data from this speaker) not released at all, whereas the aspirated stop has a shorter closure and a noticeable burst followed by noisy airflow that is sustained for some considerable time. Several of our speakers of Eastern Armenian probably have a glottal closure accompanying final unaspirated stops, and in some cases these sounds are weakly ejective. It should be noted that this three way contrast exists only in Eastern and not in Western Armenian.

It has been suggested that "heightened subglottal pressure is a necessary but not sufficient condition for aspiration" (Chomsky and Halle 1968: 326). This suggestion was somewhat over-energetically decried when it first appeared (e.g. by Ladefoged 1971). At that time there was evidence that heightened subglottal pressure occurred on stressed syllables, but no evidence that it ever characterized a single segment. But Chomsky and Halle were right to invoke increased subglottal pressure - for some instances of aspiration. In the case of Owerri Igbo discussed above, the voiceless aspirated stops had a heightened subglottal pressure, despite being shorter than their unaspirated counterparts. One might have expected that the stops with the longer closures (the voiceless unaspirated stops) might have had a higher peak pressure; if the subglottal pressure is produced by a constant decrease in lung cavity size, then the longer the closure the more the pressure would increase. Nevertheless, at least for some speakers, the pressure is significantly higher during the aspirated sounds, and there must be greater respiratory activity to account for it. There is there-

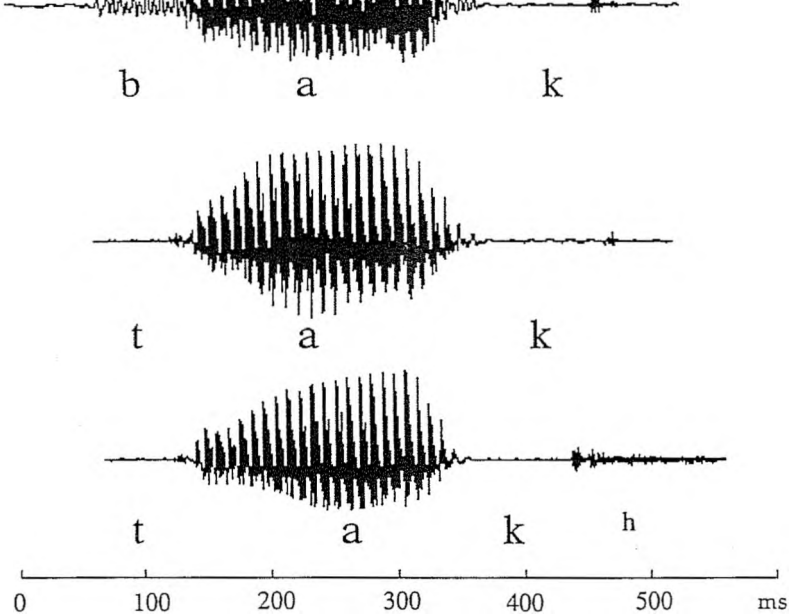

Figure 3.10 Waveforms illustrating contrasts among final velar stops in Eastern Armenian. The words are those in the final column of table 3.10.

fore some support for the suggestion that aspirated sounds are in some languages consistently produced with a heightened subglottal pressure. The pattern of increased oral pressure during the breathy voiced stops of Owerri Igbo might also indicate that these have the same characteristics. However this phonetic attribute is probably never the major distinguishing property in a phonological contrast. It is a secondary mechanism that can be called on to enhance (Stevens and Keyser 1989) the high level of trans glottal airflow which a wide open glottal aperture already ensures.

We are now ready to consider further the possible alternative meanings of the term aspiration. We have suggested above that aspiration is one end of a continuum of degrees of opening of the vocal folds during speech. This is similar to the proposal by Kim (1965). Another definition equates aspiration with a period of voicelessness after the release of an articulation, and before the vocal folds start vibrating. The first definition says nothing about the timing; the second nothing about any specific glottal aperture. There are some rather interesting consequences of selecting one or the other of these definitions. The first provides for the occurrence of aspirated segments with no delay of voice onset; all that is required is that the glottal aperture should be wide. Burmese has many pairs of verbs and adjectives that show a morphological alternation between simplex forms with voiceless unaspirated stops and causative forms with voiceless aspirated stops. The parallel alternation in nasals and laterals is usually described as being between voiced and voiceless counterparts. Examples of these alternations are given in table 3.11.

Patterns such as these have suggested to a number of phenologists that aspirated stops and voiceless sonorants share a common feature of aspiration (or [spread glottis]) (Cho 1990, Steriade 1993a). The Burmese voiceless nasals and laterals do not have a voiceless period after their release (see the descriptions in chapters 4 and 6) but what they could have in common with aspirated plosives and affricates is a wider glottal opening. Unfortunately we do not know if this is true as there is no data on glottal aperture in this language. However, we do have some data on airflow in the voiceless nasals and know that it may be well over 500 ml/s (Bhaskararao and Ladefoged 1991). This is very high for airflow through the nose and would be compatible with a relatively wide glottal aperture.

On the other hand, if the definition emphasizes timing, rather than a specific glottal aperture then pairs of sounds such as p^h and b^s in Hindi, Igbo and many other languages can be grouped together as aspirated. At least in Hindi (Maddieson and Gandour 1977, Ohala 1983) and certain other Indic languages such sounds have shared phonological behavior. However, sounds such as b^{fi} do not have a period of voicelessness after the release of the closure, so aspiration cannot be defined in terms of such a period. Instead, if we want to

Pre-aspiration

Before we conclude our discussion of aspiration we should examine pre-aspiration. In pre-aspirated stops there is a period of voicelessness at the end of the vowel, nasal, or liquid preceding the onset of the stop closure. The best-known examples of these sounds occur in Scottish Gaelic, and in Icelandic and Faroese. In Gaelic the pre-aspirated stops occur only in medial and final position, where they are the counterparts of the aspirated stops which occur in initial position. In Icelandic and Faroese, where pre-aspirated stops also occur only in medial and final position, they are realizations of long (geminate) voiceless aspirated stops. All these languages have a contrast between voiceless unaspirated and voiceless aspirated stops in initial position. The unaspirated stops are unchanged in medial position, yielding a surface contrast between pre-aspirated and unaspirated stops. The pattern in Lule Sami (Engstrand 1987) is somewhat similar to that in Icelandic, except that there is no contrast between two series of stops in initial position.

Examples of surface phonetic contrasts involving pre-aspiration in Icelandic are given in table 3.12. Following Thrainsson (1978), we have used h rather than ^{h} to indicate pre-aspiration because pre-aspiration is longer than the aspiration after a stop release. We have also given the underlying forms according to Thrainsson's analysis. Figure 3.11 shows the patterns of changes over time in the volume of airflow and the width of the glottis which differentiate intervocalic aspirated, unaspirated and pre-aspirated voiceless stops in Icelandic (adapted from nl Chasaide 1985). Thrainsson, surveying the aerodynamic data in Petursson (1976) and Games (1974), notes that "pre-aspiration typically has a normal segment length in Icelandic, whereas postaspiration is much shorter.... This suggests that pre-aspiration is not simply the inverse of postaspiration, as its name and some phonetic descriptions might lead us to believe." In all instrumental studies of Icelandic, the duration of the pre-aspiration and stop closure together in hp, ht, etc. is about equal to the duration of the stop closure itself in unaspirated geminate stops (Thrainsson's phonemic /bb, dd/, etc.). The glottal opening gesture for a pre-aspirated voiceless stop is wider than for the unaspirated voiceless geminate, but does not take longer. In the pre-aspirated stop, the oral closure occurs when the glottal aperture is near

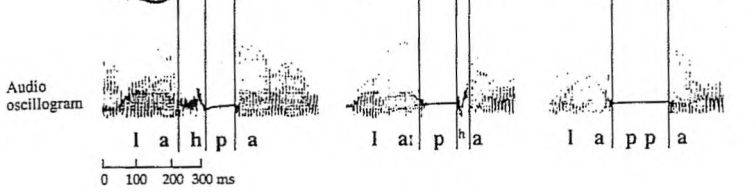

Figure 3.11 Intra-oral air pressure and glottal aperture records illustrating pre-aspirated, aspirated, and unaspirated bilabial voiceless stops in Icelandic (from data provided by nf Chasaide). The pre-aspirated and unaspirated stops are phonologically geminate and have a shorter preceding vowel.

Table 3.12 Contrasts illustrating pre-aspirated and unaspirated long voiceless stops in medial and final position in Icelandic As vowel length plays a part in distinguishing these stops, contrasts between long and short vowels are also illustrated. (Phonological interpretation in accordance with Thrainsson, 1978)

BILABIAL	ALVEOLAR	VELAR
k^{h}ohpar /koppar/ "small pot" [n.pl.]	maihtir /msettir/ 'may' [2s pt.sub.]	sahka /sakka/ 'sinkstone'
k^{h}oppor /kobbar/ 'young seal' [n.pl.]	moittir /meeddir/ 'distressed' [m.n.pl.]	sakka /sagga/ 'dampness' [ob.sg.]
k^{h}3ipar /kopar/ "copper"	mai:tir /maetir/ 'meet' [2s pr.sub.]	saika /saka/ "to blame'
	maihtnir /maetnir/ 'meet' [3p pr.ind.]	sahkna /sakna/ 'to regret'
k^{h}ahp /kapp/ "zeal"	viht /vitt/ 'wide'	t0hk /dokk/ 'dark' [f.n.sg.]
k^{Q}pp /gabb/ 'hoax'	vitt /vidd/ 'breadth'	t0kk / dogg/ 'dew'
kaip /gap/ "opening"	pilt /bit/ 'bite' [Ispr.]	t^{h}0:k /tok/ 'grasps' [n.pl.]

its maximum, about halfway through the voiceless period, whereas in the unaspirated voiceless geminate the oral closure occurs as the glottal opening gestures starts. Note also that the glottal aperture is no greater for the aspirated than for the unaspirated stop, again suggesting that greater glottal opening is not the defining characteristic of aspiration.

Scottish Gaelic pre-aspirated stops are illustrated in table 3.13. It should be noted that the extent of pre-aspiration varies in different dialects of this language; in Skye Gaelic pre-aspirated stops are comparable in length to those in Icelandic even though there is no reason to analyze them as geminates in Gaelic, whereas in Lewis Gaelic they are as short as other stops (ni Chasaide 1985).

Although pre-aspirated and (post-) aspirated stops are phonologically related in both Gaelic and Icelandic, it is obvious that the glottal gestures in these two categories differ in their timing relationships with the associated oral gestures. Further, at least in Icelandic, the glottal aperture in post-aspirated stops does not seem to be wider than that in voiceless unaspirated stops, although pre-aspirated stops show a wider aperture than either of the others (figure 3.11, also ni Chasaide 1985, Petursson 1976). Pre- and post-aspiration share the characteristic that a substantial part of the time during which the glottis is open is not aligned with the oral closure.

We also note that pre-aspiration is said to occur in Amerindian languages, such as the Algonquian language Ojibwa (Bloomfield, 1956: 8), and the Arawakan language Guajiro (Holmer 1949). We have not been able to investigate Ojibwa, but it is clear from Bloomfield's account that, much as in Icelandic, the pre-aspiration occurs only before the 'fortis' (long) consonants pp, tt, cc, kk, and that these consonants occur only in medial position. We have ourselves analyzed a single recording of Guajiro. In his account of this language, Holmer (1949: 49) states that, at the time of his investigations, many speakers did not use pre-aspiration in medial positions (again, the only position in which it may occur). In a recording of one speaker made approximately 30 years after Holmer's study, we found that the speaker sometimes used a breathy voiced offset to a vowel that was followed by a long stop, but he did

? may follow as well as precede other consonants in clusters.

Despite its importance in specifying the phonetic characteristics of some languages, we do not know of any language in which it is necessary to regard pre-aspiration as a feature required for distinguishing underlying forms. Stops of this kind always occur intervocalically or finally; there are no occurrences of initial pre-aspirated stops that we are aware of.

Glottal closure

At the opposite end of the continuum of glottal aperture from the kinds of gestures used in voiceless aspirated stops is a full closure of the vocal folds, as in a glottal stop. We will begin by discussing oral stops in which there is an accompanying glottal closure. These can be broadly divided into two types, depending on whether or not the glottal stop serves as the initiator of an airstream. We will discuss the glottalic airstream mechanism below, after we have exemplified stops with simultaneous glottal closure. These are familar as syllable-final variants of phonologically voiceless stops in various, mostly British, dialects of English. Figure 3.12 shows this variation in two utterances of the word *pack*, spoken by Ian Maddieson. In the spectrogram on the left the final velar stop is released and there is no accompanying glottal stop. In the one on the right, the entire velar closure is overlapped by a glottal stop, resulting in the suppression of any audible burst or frication when it is released. In such productions it is often possible to see the occurrence of creaky voiced phonation at the end of the vowel. The movement of the second and third formants towards each other typical of a velar closure is very apparent in this token, indicating that the velar gesture is well under way by the time the vocal folds close, but, in comparison with the other token of this word, the transitional movement of the formants is truncated a little by the supervention of the glottal closure.

There are other ways of combining a glottal closure with an oral articulation. In some of the languages described in the literature as having 'globalized' voiceless stops, a somewhat similar overlapping production of a glottal stop with the oral closure is what occurs. We have heard this phenomenon in