PHONETIC EXPLANATIONS FOR THE DEVELOPMENT OF TONES

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The development of contrastive tone because of the articulatory reinterpretation of segmentally-caused perturbations in intrinsic fundamental frequency is well attested in a number of unrelated languages. Considering the wide-spread character of this process, it is likely that its 'seeds' can be found in the functioning of the human articulatory and/or auditory mechanisms. This paper reviews what the authors consider promising explanations for well-attested tonal sound patterns, e.g. tone originating from the effect of prevocalic stop consonants or postvocalic glottal consonants, and tone rarely or never originating from the influence of postvocalic non-glottal consonants or from vowel height.*

Sound changes or sound patterns that are attested in diverse, widely-separated languages cry out for an explanation by reference to what is common to all speech communities: the physical apparatus which humans use to produce and perceive speech. One such sound change that reveals many striking common patterns is the development of tone (or 'tonogenesis', Matisoff 1973a), especially as documented in the East and Southeast Asian area (Maspéro 1912; Karlgren 1926; Haudricourt & Martinet 1946; Haudricourt 1954, 1961; Matisoff 1973a; Li 1977; Mazaudon 1977). We report here the results of our research aimed at providing phonetic explanations for tonal sound patterns (cf. Ewan 1975, 1976; Ewan & Krones 1974; Hombert 1974, 1975a,b, 1976a,b, 1977a,b; J. Hombert & S. Greenberg 1976; J. Ohala 1970, 1972, 1973a,b, 1976; J. Ohala & Ewan 1973).

BACKGROUND

1. The way the physical constraints of the speech mechanism leave their imprint on speech, particularly via sound change, has been discussed by J. Ohala 1974a, 1975: and earlier by Sweet 1888, Passy 1890, Paul 1891, Rousselot 1891, Haden 1938, Falc'hun 1943, Durand 1956, and Grammont 1965. Briefly, the pronunciation intended by the speaker may get distorted by the time it is perceived by the listener—either by the action of articulatory constraints which affect the way the sounds are uttered, or by the action of auditory constraints which affect the way the sounds are analysed by the listener's ear. Since the listener does not have independent access to the mind of the speaker, and thus may be unable to determine what parts of the received signal were intended and what were not, he may intentionally reproduce and probably exaggerate these distortions when he repeats the same utterances. Thus an intrinsic perturbation will come to be used extrinsically.

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The factors which could cause such sound change should thus be found in all human speakers, given the proper circumstances. For example, if articulatory constraints cause the postconsonantal fundamental frequency (F_0) variations which are implicated in the development of tones, it should be possible to find such variations in the speech of anyone producing the relevant consonant types, whether they speak a tone language or not. It also follows that there should be (or at least could be) independent development of the same sound pattern in unrelated languages.

Thus the 'case' for a particular sound pattern's being phonetically motivated, whether tonal or not, requires evidence of the following sort:

(a) It should be widely attested as an independently developed pattern in several languages.

(b) The phonetic 'seeds' of the sound pattern should be demonstrable in any speaker under appropriate conditions.

(c) These 'seeds' should be shown to be fortuitous, i.e. unintentional by-products (distortions or additions) of the intended speech signal.

(d) In the case of distortions caused by articulatory factors, it must be shown that they are detectable by listeners.

We will first, in §§2–5 below, consider tonal development through influence of neighboring consonants. The first step in showing that this process is caused by universal phonetic factors is to cite evidence that it is widely attested. Then, to provide a phonetic explanation for it, we need to demonstrate the following:

(i) The 'seeds' of this sound change, i.e. small consonantally-induced F_0 perturbations on vowels, should be present in the speech of all speakers having the relevant consonant contrasts, whether they speak a tone language or not.

(ii) These F_0 perturbations on vowels should be fortuitous, i.e. unintentional by-products of the consonants.

(iii) The F_0 perturbations should be detectable by listeners, so that in certain circumstances they may be exaggerated, and thus lead to the development of tone.

The effect of prevocalic voiced vs. voiceless stops

2.1. Historical data. The development of contrastive tones on vowels because of the loss of a voicing distinction on obstruents in prevocalic position is probably the best-documented type of tonogenesis. When such a development occurs, a relatively lower tone develops on vowels following a previously voiced series, and a relatively higher tone is found after a previously voiceless (or voiceless aspirated) series.

The correlation between initial consonant and tone was noted at the beginning of this century by Maspéro for Vietnamese and by Karlgren for Chinese, and was later extended to other East and Southeast Asian languages by Haudricourt 1954, 1961, Matisoff 1973a, and Mazaudon 1977. This correlation is also found in other linguistic groups, e.g. in Hottentot (Beach 1938:247–53). Although it did not give rise to tonal development, a similar synchronic correlation between consonant types and F_0 has been found in other African languages (Hyman 1973a,b, Hyman & Schuh 1974).

2.2. THE 'SEEDS' OF THE SOUND CHANGE: PHONETIC DATA. Phonetic studies by House & Fairbanks 1953, Lehiste & Peterson 1961, Mohr 1968, Lea 1973, and Löfqvist 1975—among others—show how a voicing distinction in prevocalic position can affect the F_0 of the following vowel. Some of the data from these studies are summarized in Table 1.

	p	*t*	*k*	*b*	*d*	*g*
House & Fairbanks 1953	127.9	127.1	127.2	120.9	120.6	122.8
Lehiste & Peterson 1961	175	176	176	165	163	163
Mohr 1968	130.7	129.8	131.1	125.1	124.8	125

TABLE 1. Fundamental frequency (in Hz) of vowels as a function of the preceding consonant, as determined by three studies.

Although the number of subjects and the methods used to measure and average the data differ in these studies, it is clear that the F_0 of a vowel is higher after voiceless (aspirated) than after voiced stops, and that it does not vary in any consistent way as a function of the place of articulation of the stops. Unfortunately, these data give only an averaged or peak value for F_0, making it impossible to deduce the time course of the perturbation caused by the preceding consonant.

Data gathered by Hombert 1975a remedy this. He recorded five adult male American English speakers' pronunciation of the sentence 'Say C[i] again', where C=[p t k b d g] (and for three of the speakers, [w m] as well). Each token was repeated ten times. For each token he sampled F_0 at 20 ms intervals from vowel onset to 100 ms after vowel onset. The results are given in Figures 1–2. Fig. 1 shows the frequency-normalized F_0 curves on the vowels following the voiced and voice-

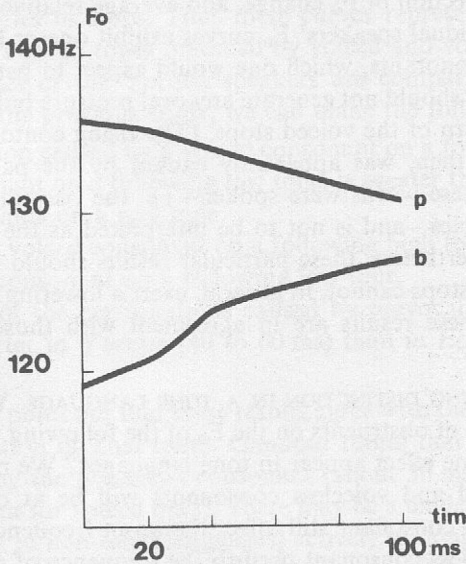

FIGURE 1. Average fundamental frequency values (in Hz) of vowels following English stops (data from five speakers). The curves labeled [p] and [b] represent the values associated with all voiceless and voiced stops, respectively—regardless of place of articulation. The zero point on the abscissa represents the moment of voice onset; with respect to stop release, this occurs later in real time in voiceless aspirated stops.

less stops, averaged over all speakers' samples; Fig. 2 shows the F_0 curves, including those for vowels following sonorants, for three individual speakers (each curve is the average of ten tokens). In both figures, the zero point on the abscissa represents the moment of voice onset; in the case of the voiceless aspirated stops, this occurs later in real time, with respect to stop release.

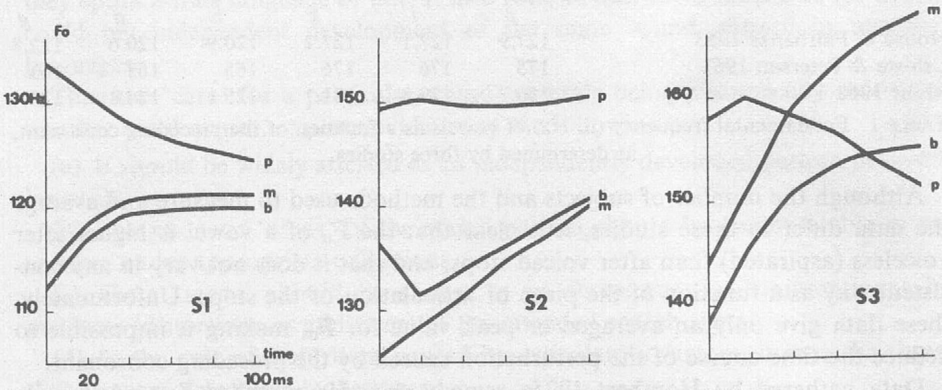

FIGURE 2. Average fundamental frequency values (in Hz) from three individual speakers of vowels following English voiced and voiceless stops and sonorants. (Data plotted as in Fig. 1.)

Although the greatest difference in the F_0 curves in Fig. 1 is at the vowel onset, statistical analysis of variance, followed by Duncan's test, reveals that they are still significantly different 100 ms after vowel onset. These two curves differ from each other in two ways: direction of F_0 change, and average relative value. The data in Fig. 2 show that individual speakers' F_0 curves exhibit one or both patterns.

The F_0 pattern of sonorants, which one would expect to perturb F_0 minimally or not at all (since they should not generate any oral pressure build-up), is generally similar to the F_0 pattern of the voiced stops. (The rising contour after the voiced stops and sonorants, then, was apparently caused by the particular intonation contour with which these words were spoken—i.e. the rise–fall contour typically used on stressed syllables—and is not to be interpreted as the lowering of F_0 by these consonants. Nevertheless, these particular results should not be taken as an indication that voiced stops cannot, in general, exert a lowering effect on following vowels: see below.) These results are in agreement with those reported by Lea 1973.

2.3. EFFECT OF VOICING DISTINCTION IN A TONE LANGUAGE. We have presented data showing the effect of obstruents on the F_0 of the following vowel in non-tonal languages. Will the same effect appear in tone languages? We need to know what the behavior of voiced and voiceless consonants will be at different frequency registers. Will a voiced consonant still affect the onset frequency of a vowel with low tone? Will a voiceless consonant perturb the frequency of a high tone?

To answer these questions, data on the time course of F_0 variation after voiced and voiceless stops (as reported above) were gathered by Hombert 1975a, 1977b from two Yoruba speakers. The results are given in Figure 3. Each data-point represents the average of 70 measurements. The broken lines represent F_0 of

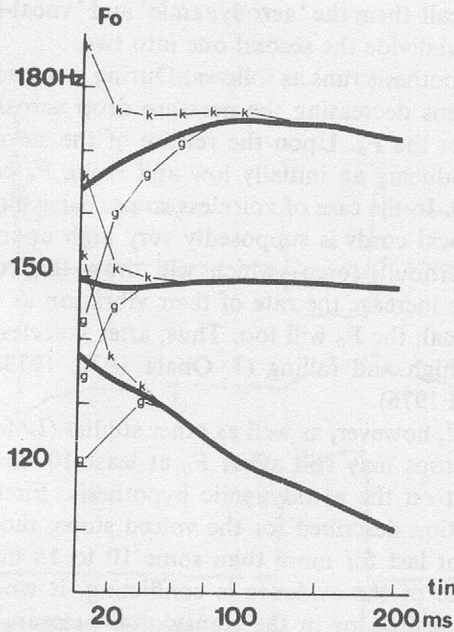

FIGURE 3. Average fundamental frequency values (in Hz) of vowels following voiced and voiceless velar stops after each of the three tones in Yoruba (data from two speakers). The thick lines give the average values for both stop types for each of the three tones. (Data plotted as in Fig. 1.)

vowels after each series of stops. Thus these curves represent the averaged frequency of the three Yoruba tones preceded by voiced and voiceless consonants.

Since the F_0 ranges of the Yoruba speakers are comparable to those of the English speakers of the previous study, we can make the following comparisons:

(a) The perturbation caused by a voiced consonant on a following high tone, or by a voiceless consonant on a following low tone, is greater than the effect of these two series of consonants on a mid tone.

(b) The effect of a voiced consonant on a following high tone is greater than the effect of a voiceless consonant on a following low tone.

(c) The duration of the perturbations caused by prevocalic consonants on the F_0 of vowels is shorter in Yoruba (40 to 60 ms) than in English (> 100 ms; cf. Fig. 2).

It is worthwhile to point out that these results agree with the findings of Gandour 1974 in his investigation of Thai tones. Gandour found that a shorter part of the vowel was affected by the preceding consonant (about 30 ms for voiceless consonants and about 50 ms for voiced ones). There may be a tendency in tone languages (which does not exist in non-tonal languages) actively to minimize the intrinsic F_0-perturbing effect of prevocalic consonants—probably so that the different tones will be maximally distinct perceptually.

2.4. HYPOTHESES ON THE PHONETIC BASIS OF THE PITCH PERTURBATIONS. There are two types of hypotheses currently entertained to account for these pitch perturbations: we will call them the 'aerodynamic' and 'vocal-cord tension' hypotheses, and will later subdivide the second one into two.

The aerodynamic hypothesis runs as follows: During a voiced stop, oral pressure gradually builds up, thus decreasing the pressure drop across the vocal cords—which in turn decreases the F_0. Upon the release of the stop, the pressure drop returns to normal, producing an initially low and rising F_0 contour after voiced stops (Ladefoged 1967). In the case of voiceless stops (particularly aspirated ones), the airflow past the vocal cords is supposedly very high upon release, creating a higher-than-normal Bernoulli force—which will draw the vocal cords together more rapidly, and thus increase the rate of their vibration at vowel onset. As the airflow returns to normal, the F_0 will too. Thus, after voiceless stops, the F_0 contour will be initially high and falling (J. Ohala 1970, 1973a, Abramson 1975, Hombert & Ladefoged 1976).

The data in Figs. 1–2, however, as well as other studies (Löfqvist), show that the voiced and voiceless stops may still affect F_0 at least 100 ms after vowel onset. This casts some doubt on the aerodynamic hypothesis. First, it is clear that the aerodynamic perturbation described for the voiced stops, though certainly a real one, probably does not last for more than some 10 to 15 ms after stop release. Second, although some of the evidence is conflicting, it would appear that the differences in rate of airflow, or in the transglottal pressure drop following the release of voiced and voiceless stops, also does not last very long after vowel onset. In fact, J. Ohala 1974b, 1976, presenting subglottal pressure data and the predictions of a mathematical model of speech aerodynamics, has shown that glottal airflow and subglottal pressure (and thus the transglottal pressure drop) may be LESS at vowel onset after voiceless aspirated stops than after voiced stops (see Figure 4)—just the opposite of what is assumed by the aerodynamic hypothesis. (See Hombert 1975a and J. Ohala 1976 for a more detailed discussion of these points.)

Moreover, some doubt has been expressed that there can be an appreciable effect on F_0 by glottal airflow, insofar as this is independent of subglottal pressure (D. Klatt and K. N. Stevens, p.c.)

The basic assumption of the vocal-cord tension hypothesis is that, in the course of making the voiced vs. voiceless distinction on stops, vocal-cord tension is changed so as to affect the F_0 of adjacent vowels. Halle & Stevens 1971 suggest that these intrinsic variations are the result of horizontal vocal-cord tension: the vocal cords are presumably slack in order to facilitate voicing during voiced stops, and stiff in order to inhibit voicing during voiceless stops; and these vocal-cord states spread to adjacent vowels, affecting their F_0. Halle & Stevens claim that the F_0 should be perturbed on the preconsonantal as well as postconsonantal vowels.

Another variant of the vocal cord tension hypothesis is that which suggests that it is the vertical tension of the vocal cords which is affected by the voiced vs. voiceless distinction (J. Ohala 1973b, Ewan 1976, Stevens 1975). In principle, both variants of this hypothesis are capable of explaining the relatively long-term effects of the prevocalic consonants on F_0. However, counter to Halle & Stevens' hypothesis, there seems to be no significant tendency for the voicing distinction in consonants to affect differentially the F_0 of PRECEDING vowels. Evidence on this point is discussed in §4.2, below.

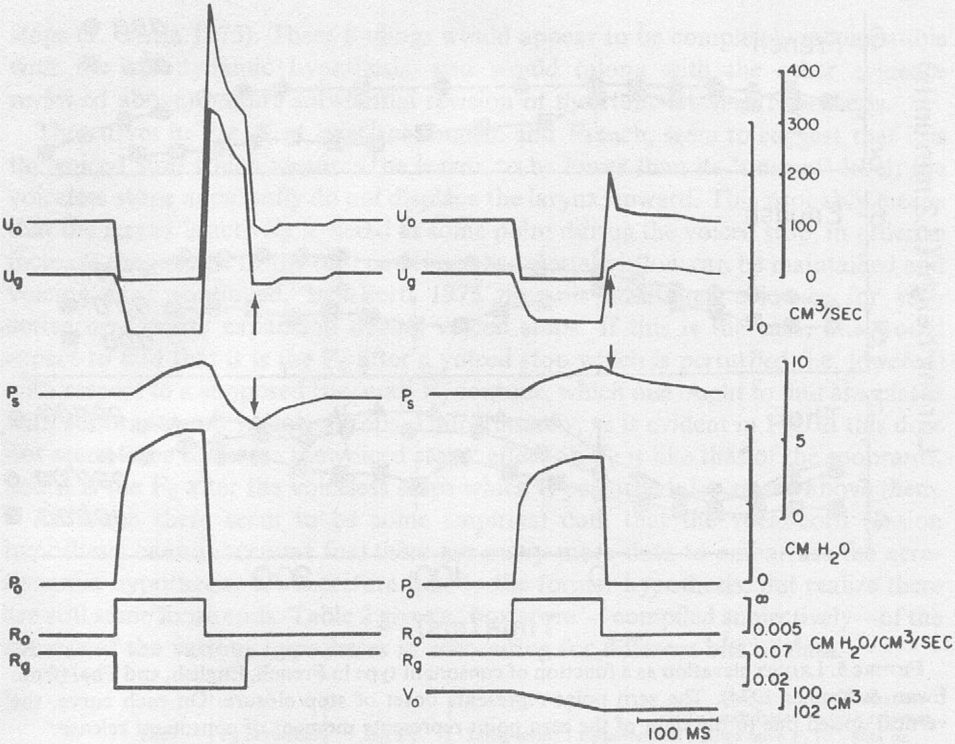

FIGURE 4. Results of computer simulation of aerodynamic events during two VCV utterances. On the left, C = voiceless aspirated stop; on the right, C = voiced stop. Upper four output parameters: oral airflow (U_o), glottal airflow (U_g), subglottalair pressure (P_s), and oral air pressure (P_o). Lower three input parameters: oral constriction air resistance (R_o), glottal resistance (R_g), oral volume (V_o). Arrows point to differences in glottal flow and subglottal pressure at moment of vowel onset following the two stop types. (From Ohala 1974b.)

Also troublesome for Halle & Stevens' hypothesis is the fact that electromyographic studies of the laryngeal muscles' activity during the production of voiced and voiceless stops do not uniformly show any significant difference in the activity of those muscles that might be expected to affect F_0 (Hirose et al. 1972; Hirose, Lisker & Abramson 1973; D. Erickson 1976). Dixit 1975 did find consistently higher activity in the cricothyroid muscle during the production of Hindi voiceless (as opposed to voiced) stops; however, this finding was not wholly replicated by Kagaya & Hirose 1975, who found slightly higher activity in the cricothyroid muscle of their Hindi-speaking subject only at the onset of the voiceless unaspirated stop, but not the voiceless aspirated stop.

In agreement with the hypothesis that the voiced/voiceless articulations affect the VERTICAL tension of the vocal cords (and, indeed, the motivation for proposing the hypothesis in the first place) is the finding by Ewan & Krones—in accord with the earlier observation made by Jespersen 1889 and Hudgins & Stetson 1935—that the vertical position of the larynx differs for voiced and voiceless stops.

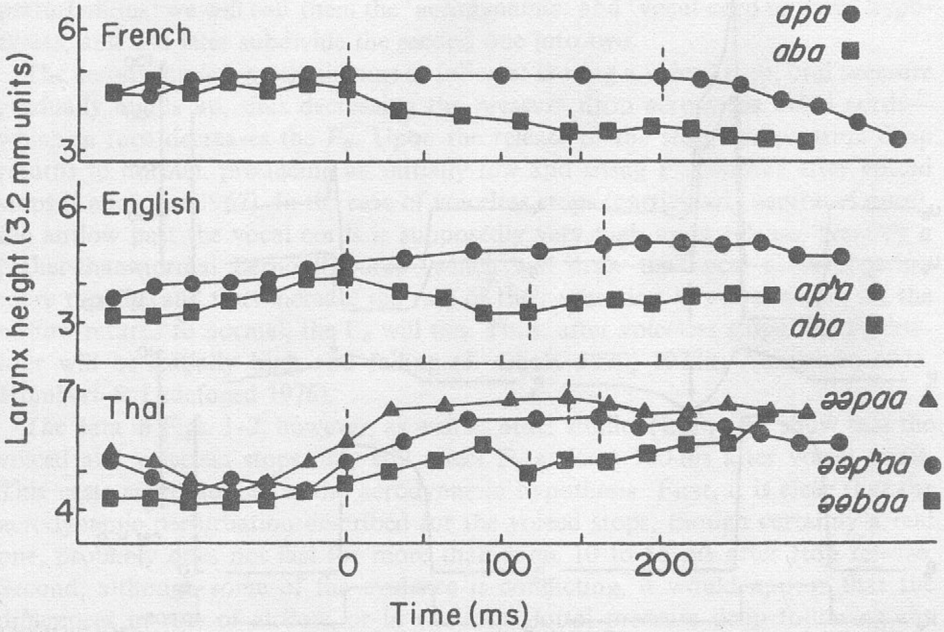

FIGURE 5. Larynx elevation as a function of consonant type in French, English, and Thai (from Ewan & Krones 1974). The zero point represents onset of stop closure. On each curve, the vertical dotted line to the right of the zero point represents moment of consonant release.

Figure 5 shows some averaged larynx-height curves for intervocalic stops spoken by individual speakers of French, English, and Thai. (These data were obtained by a special photo-electric device called the 'thyroumbrometer', invented by Ewan & Krones, which tracks larynx elevation during speech.) Their finding of higher larynx position for voiceless as opposed to voiced stops—coupled with the well-documented fact that in normal speech, other things being equal, F_0 is positively correlated with larynx elevation (J. Ohala 1972, 1973b; J. Ohala & Ewan 1973)—is compatible with the 'vertical tension' hypothesis. (It is still a matter of speculation, however, exactly how the variations in the vertical position of the larynx can be translated into variations in the vertical tension of the vocal cords; but see Stevens.)

Additional evidence in favor of this hypothesis is the fact that, in general, the difference in larynx elevation between the two stop types is greatest at the end of the consonant closure, and that this difference persists well into the following vowel. This effect is apparent in the data given in Fig. 5. This accounts for the effect of consonants being evident only on the F_0 of the following, not the preceding, vowel; and it accounts for the persistence of F_0 perturbation for 100 ms or more into the following vowel. In addition, Hombert & Ladefoged have recently shown that the F_0 pitch perturbation caused by the French voiceless unaspirated stops is of the same order of magnitude (and lasts about as long) as that after the English voiceless aspirated stops. This pattern holds even though the aerodynamic parameters of glottal airflow and transglottal pressure drop at vowel onset are probably more similar after voiced and voiceless unaspirated as opposed to voiceless aspirated stops (J. Ohala 1975). These findings would appear to be completely incompatible with the aerodynamic hypothesis, and would (along with the other evidence reviewed above) require substantial revision of the Halle–Stevens hypothesis.

The curves in Fig. 5, at least for English and French, seem to suggest that it is the voiced stop which requires the larynx to be lower than its 'normal' level; the voiceless stops apparently do not displace the larynx upward. This probably means that the larynx is actively lowered at some point during the voiced stop, in order to increase the volume of the oral cavity so that glottal airflow can be maintained and voicing thus continued. Bell-Berti 1975 presents additional evidence for such active oral cavity expansion during voiced stops. If this is the case, one would expect to find that it is the F_0 after a voiced stop which is perturbed (i.e. lowered) with respect to a supposed 'normal' F_0 contour, which one ought to find associated with sonorants and voiceless stops. Unfortunately, as is evident in Fig. 2, this does not seem to be the case: the voiced stops' effect on F_0 is like that of the sonorants, and it is the F_0 after the voiceless stops which is perturbed, i.e. raised above them.

Although there seem to be some empirical data that the vocal-cord tension hypothesis cannot account for, there are many more data to embarrass the aerodynamic hypothesis. We therefore lean to the former hypothesis, but realize there are still some loose ends. Table 2 gives a 'box score'—compiled subjectively—of the success of the various hypotheses in accounting for different bits of data.

<table>
<tr><th colspan="2">FACT / HYPOTHESIS</th><th>F_0 perturbation exists on post-consonantal vowel</th><th>No F_0 perturbation on pre-consonantal vowel</th><th>Long-term persistence (> 100 ms) of F_0 perturbation</th><th>F_0 pattern of voiced stops in English like that of sonorants</th><th>Voiceless unaspirated stops have F_0 perturbation similar to voiceless aspirated</th><th>Compatible with relevant data on laryngeal physiology (EMG, airflow etc.)</th></tr>
<tr><td colspan="2">Aerodynamic Hypothesis</td><td>yes</td><td>yes</td><td>no</td><td>possible</td><td>no</td><td>no</td></tr>
<tr><td rowspan="2">Vocal-Cord Tension Hypothesis</td><td>Halle–Stevens</td><td rowspan="2">yes</td><td>no, unless modified</td><td rowspan="2">yes</td><td rowspan="2">no, unless modified</td><td>no, unless modified</td><td>mixed</td></tr>
<tr><td>Vertical Tension</td><td>yes</td><td>yes</td><td>yes</td></tr>
</table>

TABLE 2. 'Box score' of the three hypotheses offered for phonetic basis of consonant-related F_0 perturbation on vowels. An entry in a particular cell indicates an assessment of whether the hypothesis (leftmost column) accounts for a particular fact (top row).

2.5. PERCEPTIBILITY OF THE F_0 PERTURBATIONS. There is evidence, from experiments using synthesized speech, that small F_0 perturbations can be used as cues to discriminate between sonorants and voiced obstruents (Chistovich 1969), and between voiced and voiceless obstruents (Chistovich 1969; Haggard, Ambler & Callow 1970; Fujimura 1971; Abramson 1975; Massaro & Cohen 1976). But there is little information on minimal perceptible F_0 perturbations.

To get these data, the following study was carried out. Ten subjects with normal hearing, native speakers of English, participated. Acoustic stimuli consisting of ten instances of the vowel [i] were synthesized, with different F_0 patterns chosen to simulate the effects of consonants on neighboring vowels.

As shown in Figure 6, each stimulus was composed of a slope followed by a level tone maintained constant at 120 Hz. The onset frequency of the slope was either 110 or 130 Hz (i.e. $\Delta F_0 = \pm 10$ Hz). The duration of the slope was varied at 40, 60, 100, 150, and 250 ms. In other words, five stimuli (with F_0 onset = 130 Hz) had a falling F_0, and five stimuli (with F_0 onset = 110 Hz) had a rising F_0. The

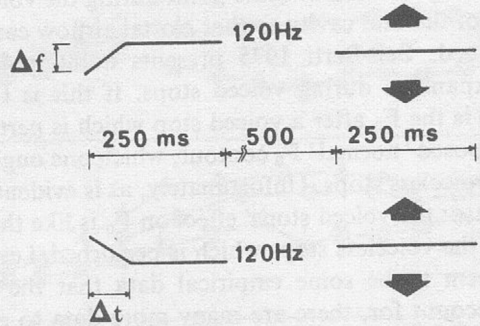

FIGURE 6. Schematic representation of manner of stimulus presentation. See text for details.

over-all duration of each stimulus was fixed at 250 ms. Each time a stimulus was presented, it was followed by a 500 ms pause and a second vowel [i] with a steady-state F_0. The duration of this second vowel was also 250 ms. The level of its F_0 was adjustable by a knob, controlled by the subject. The task was to match the pitch of the second vowel to the pitch of the BEGINNING of the first vowel. The rate of stimulus presentation, as well as the number of trials for a given presentation, were controlled by the subject. Each of the ten stimuli was presented three times in randomized order. The subjects heard the stimuli through earphones at a comfortable level (about 70 db). The results are presented in Figure 7; subjects' responses are plotted as a function of the duration of the slope; and each curve represents one

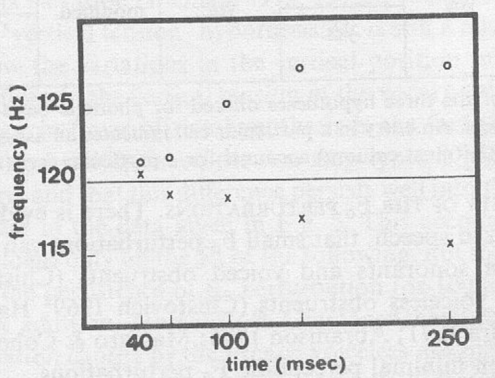

FIGURE 7. Results of psychophysical test described in text. Subjects' responses (i.e. their estimates of starting pitch of tone with initial ramp) are plotted as a function of the duration of the ramp. Open circles plot subjects' response to the stimuli with initial falling ramp (130 to 120 Hz); the crosses plot their responses to the stimuli with the initial rising ramp (110 to 120 Hz).

level of F_0 onset. A statistical analysis of variance, followed by Duncan's test, indicates that the two curves are significantly different when the onset slope (from F_0 onset to level F_0) is 60 ms long.

We showed above that the consonantally-induced F_0 perturbations on vowels in such non-tonal languages as English, or marginally tonal languages like Swedish, persist for some 100 ms after vowel onset. The perceptual data just presented show that listeners start hearing significant differences in the F_0 onset of our synthesized stimuli when the slope of the F_0 contour is 60 ms long. Thus there is at least 40 ms between the time we start hearing the differences and the time the real consonant-related F_0 variations cease to be significantly different. (As mentioned above, the consonantally-induced F_0 perturbations in Yoruba were shorter than those in non-tonal languages; but they were also of greater magnitude. Other perceptual data, not presented here, suggest that F_0 ramps having the same magnitude as the F_0 perturbations in Yoruba are perceptually different when they are 40 ms long; cf. Hombert 1975a.)

These data, then, allow us to define the narrow limits,[1] both perceptual and articulatory, within which the development of tones from a former voiced/voiceless stop contrast is likely to occur.

2.6. SUMMARY OF EVIDENCE ON TONOGENESIS FROM PREVOCALIC CONSONANTS. In this section we have reviewed evidence that the development of tone on vowels after voiced and voiceless obstruents can be explained by reference to articulatory and auditory facts—and, specifically, that the voicing distinction in prevocalic position causes small F_0 perturbations which are perceptible and whose physiological origin can (to a large extent) be accounted for.

THE ROLE OF OTHER CONSONANT TYPES IN TONE DEVELOPMENT

3. Although the data are not as extensive as they are for the role of voiced vs. voiceless obstruents in tone development, there are strong indications that other types of consonants may also give rise to tone.

3.1. BREATHY VOICED CONSONANTS. In Punjabi, breathy voiced consonants became voiceless unaspirated, leaving a low tone on the following vowel (Gill & Gleason 1969, 1972; Haudricourt 1972a,b). Data presented by Glover 1970 on Tibeto-Burman languages indicate that breathy voiced consonants are stronger F_0 depressors than (simple) voiced obstruents. In Ndebele, breathy voiced consonants pattern with voiced obstruents in lowering the pitch on following vowels (Ladefoged 1971).

The 'seeds' of this phenomenon can be found in Hindi, a non-tonal language, in that the onset F_0 of a vowel after a breathy voiced consonant is markedly lower than that after any other consonant type (J. Ohala 1974a, Kagaya & Hirose 1975).

The physiological cause of this phenomenon requires more investigation;

[1] The limits may not be as 'narrow' as we imply; 60 ms was the average duration of the slopes that subjects could reliably differentiate. Some subjects naturally did better than the average—i.e. could differentiate shorter F_0 slopes. Are sound changes initiated by 'average' hearers, or by better-than-average hearers? If the latter, then there is even greater overlap between the F_0 perturbations that occur in natural speech and what the human listener can detect.

however, some of the contributing factors can be guessed at. Although the rate of airflow through the glottis is high upon the release of breathy voiced consonants, the vocal cords are not closely adducted; thus the Bernoulli force should be weak. The subglottal pressure is also markedly lower upon their release (because of the high rate of airflow), and this by itself would lead to a somewhat lower F_0 (M. Ohala & J. Ohala 1972). In addition, breathy voice involves less forceful contraction of the laryngeal adductor muscles (J. Ohala 1973a; Hirose, Lisker & Abramson; Dixit; Kagaya & Hirose); these not only act to bring the vocal cords together, but also are known to participate in F_0 regulation (Hirano & J. Ohala 1969, J. Ohala 1970, Atkinson 1973).

3.2. IMPLOSIVES. J. Greenberg (1970:133) indicates that implosives 'are always less productive of tone lowering than the corresponding plain voiced stops'. In the Loloish group of Lolo-Burmese, the 'glottalized' series has led to the development of higher tones than the voiceless or voiced series, as attested in modern dialects such as Lahu, Lisu, and Sari (Matisoff 1972, Mazaudon 1977).

D. Erickson 1975, in a preliminary study of Sindhi stops, found in the speech of one native speaker that the F_0 at vowel onset after the implosive [ɓ] was as high as the F_0 after the voiceless unaspirated [p], and both were much higher than the onset F_0 after the voiced [b]. However, there was little difference in the onset F_0 following [ɓ] and [b] as spoken by an English-speaking phonetician. Further phonetic data are badly needed on this class of consonants.

Whether implosives actually are tone raisers, or just fail to lower tone, these are puzzling—given the evidence cited above that voiced obstruents tend to be tone depressors, and given the phonetic similarity between fully-voiced stops and implosives (the difference between them lies primarily in the rate of oral-cavity expansion; cf. Ladefoged 1971). J. Ohala 1976 presents data from a mathematical model of speech aerodynamics that support the plausibility of a claim (attributed to Ladefoged) that the rapid lowering of the larynx during implosives can generate such a high rate of glottal airflow that the F_0 can be raised above the normal level. However, if true, this process can account only for higher F_0 during the implosive consonant closure itself, not on the following vowel. Also, this mechanism would presumably contradict (or at least override) the effect on F_0 of lower vocal-cord tension which is hypothesized to result from a lowered larynx.

EFFECT OF VOICED/VOICELESS CONSONANTS ON F_0 OF PRECEDING VOWEL

4.1. HISTORICAL DATA. As seen in §2 above, we have a respectable number of historical cases illustrating tonal development from the loss of some voicing contrast in prevocalic position. Tonal development from the loss of a voicing distinction in the postvocalic position seems to be extremely rare, if it exists at all. Maran 1971, 1973 claims that, in certain dialects of Jinghpaw, tones are completely predictable from the voicing of the final consonant; and he even goes further, predicting the tones from the final segment even when the voicing distinction has disappeared in the surface form. However, Matisoff 1973c offers a different analysis of Maran's data, in which the voicing of the final consonants does not affect the tone of the preceding vowel.

4.2. Phonetic data. Some studies (Mohr 1968, Slis 1966) indicate that postvocalic consonants have an effect on F_0 similar to that of prevocalic consonants (i.e., voiced consonants lower, and voiceless consonants raise, the F_0 of the following vowel), but with a much smaller magnitude. Other studies (Lea 1972, 1973, Hanson 1975, Jeel 1975) suggest that both voiced and voiceless consonants lower the F_0 of the preceding vowel (but see §2.4 above). Thus, if the intrinsic perturbations caused by postvocalic voiced and voiceless consonants on F_0 of preceding vowels are so similar, it is not surprising that they cannot be reinterpreted as tonal contrasts by speakers.

It is possible, under certain circumstances, for voiced and voiceless final stops indirectly to affect the tonal contour of the preceding vowel. It is well known that vowels are shorter before voiceless than before voiced consonants (Delattre 1962, M. Chen 1970). Thus if a tonal contour appears on a vowel which is followed by a voiceless consonant, it may be 'cut short' and have a different terminal F_0 than if it appears before a voiced consonant (Y. Erickson & Alstermark 1972, Löfqvist 1975, Bannert & Bredvad-Jensen 1975); see Figure 8. Such an effect has led to detectably different intonation patterns in Jeh (Thomas 1966), but apparently has not yet been reinterpreted in such a way as to produce a lexical tone distinction.

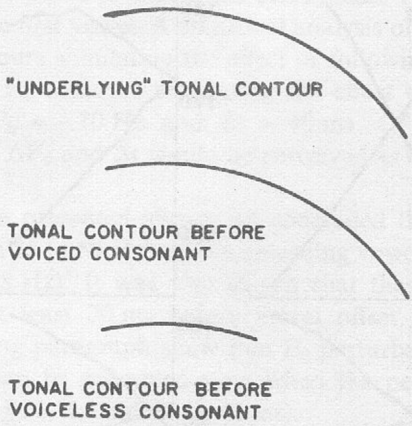

Figure 8. Idealized representation of how the same 'underlying' tonal contour (top) could have two different phonetic manifestations before voiced (middle) and voiceless (bottom) final consonants. The effect of the final voiceless consonant (by shortening the vowel) is to truncate the contour, so that the terminal pitch level would be different from that before a final voiced consonant.

Effect of glottal consonants on vowels

5.1. Historical data. The effect of a glottal stop on the tone of the preceding vowel is widely attested. By the 6th century, glottal stop disappeared in Vietnamese and was replaced by a rising tone (Haudricourt 1954, Matisoff 1973a). In the Lolo-Burmese family, Burmese high tone corresponds to Jinghpaw glottal stop (Maran 1971) and Lahu high-rising tone developed through what Matisoff 1970 calls 'glottal dissimilation'. Mei 1970 has shown that Middle Chinese *shang sheng* (rising tone) comes from a final glottal stop. Burling 1959 has reported that Kachari [ʔ] has the synchronic effect of raising the tone of the following syllable. The development of a falling tone from a postvocalic [h] has been observed in two cases: Middle Chinese *qu sheng* (falling tone) comes from postvocalic [h] (Pulleyblank 1962), and the same origin has been reported for Vietnamese falling tone (Haudricourt 1954, Matisoff 1973a).

5.2. PHONETIC DATA. Hombert 1976b gathered data on the time course of F_0 variation on the vowel immediately preceding [h] and [ʔ] in the speech of four Arabic speakers; the results are given in Figure 9. As can be seen, F_0 goes up a minimum of 9 Hz before [ʔ], and down 25 Hz before [h]. The two sets of curves are significantly different at least 70 ms before vowel offset. The parameter chosen for the statistical analysis (i.e. the interval between vowel offset and intersection of F_0 values) yields the most conservative estimate of statistical significance of the difference between the two sets of curves. If slope of the curves had been chosen as the parameter, the statistical significance would have been improved.

In order to determine the extent to which such F_0 variations can be perceived, a

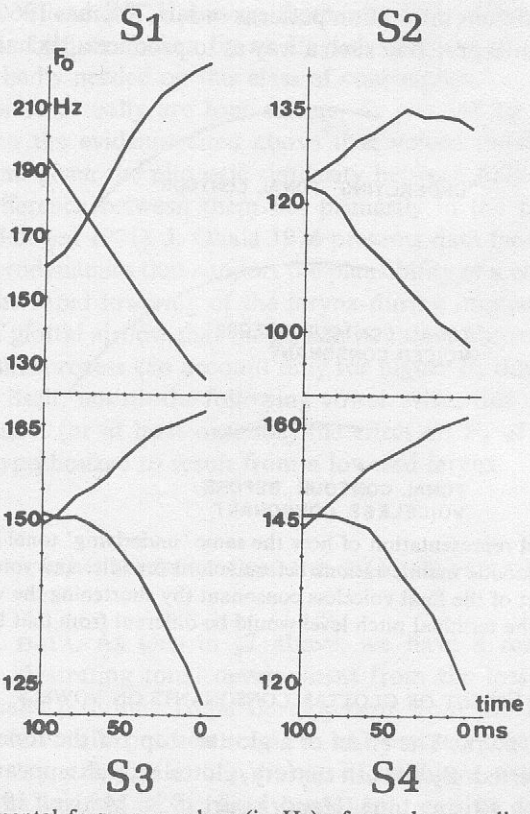

FIGURE 9. Fundamental frequency values (in Hz) of vowels preceding Arabic [ʔ] (curves with positive slope) and [h] (curves with negative slope), for four individual speakers. The zero point on the abscissa represents moment of postvocalic consonant onset.

study similar to that in §2.5 was conducted. Ten subjects, native speakers of American English, participated. The acoustic stimuli consisted of 30 instances of the vowel [i] synthesized with different F_0 patterns. As shown in Figure 10, the

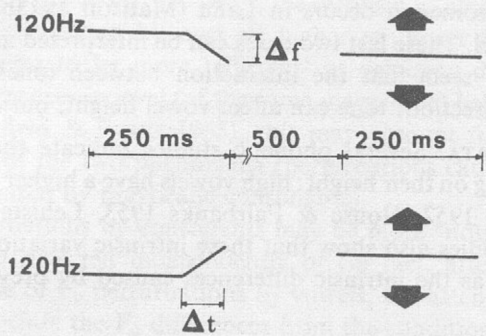

FIGURE 10. Schematic representation of manner of stimulus presentation. See text for details.

stimuli were mirror images of those used in the perceptual experiment described above; i.e., instead of the F_0 slope appearing at the beginning of the stimuli, it appeared at the end. Manner of presentation was identical to the previous test, except that subjects were asked to match the steady-state F_0 of the second vowel with the F_0 OFFSET of the first vowel. A statistical analysis of the results shows that the synthesized F_0 contours simulating the effect of following [ʔ] are perceptually differentiable from the F_0 contours simulating the effect of following [h] when $\Delta F_{ʔ} = +10$ Hz and $\Delta F_h = -10$ Hz and $\Delta t = 40$ ms. Of course, all contours having greater values of ΔF_0 and Δt would be perceived as different (see Hombert 1975b for details).

From the Arabic data presented above, we concluded that an [h] produces a drop in F_0 (varying from 25 to 50 Hz) on the preceding vowel, while [ʔ] produces a rise in F_0 (from 9 to 48 Hz). It was also shown that these two curves became significantly different at least 70 ms before vowel offset. The perceptual data presented in the preceding paragraph show that F_0 perturbations similar to those caused by [h] and [ʔ] can be perceived even when the perturbations are much smaller that this ($\Delta F = \pm 10$ Hz and $\Delta t = 40$ ms).

There are also reliable reports of glottal stops lowering pitch (e.g. in Mohawk; W. Chafe, p.c.) But Ladefoged (p.c.) has suggested that this may be attributed not to the glottal stop per se, but to creaky voice—a common variant of glottal stop.

DEVELOPMENT OF TONES FROM VOWEL HEIGHT

6.1. HISTORICAL DATA. It is difficult to find convincing cases or a consistent pattern of the historical development of tones from vowel quality. From the synchronic viewpoint, Pilszcsikowa-Chodak 1972 suggests that tone assignment of verb and noun plurals in Hausa is largely predictable from the height of the final vowel: a high (vs. low) final vowel predicting a high (vs. low) tone. This analysis, however, has been criticized by Hausa scholars (Newman 1975; W. Leben, p.c.; R. Schuh, p.c.) In another case, Schuh 1971 indicates that the tone pattern of Ngizim verbs is partially predictable from the vowel of the first syllable: if the vowel is [a], the verb will have a high tone. A similar case of an inverse correlation between tone height and tongue height was reported by Spears 1968 in Maninka. In Foochow (Yuan et al. 1960, L. Chen & J. Norman 1965, Maddieson 1974) the vowel is raised if the tone of some lexical items is replaced by a higher tone. A similar phenomenon occurs in Lahu (Matisoff 1973b), where the rising tone can raise a vowel. These last two cases can be interpreted as the effect of tones on vowels. It would seem that the interaction between tones and vowel height works in only one direction: tone can affect vowel height, but not vice-versa.

6.2. PHONETIC DATA. Several phonetic studies indicate that vowels have an intrinsic F_0 depending on their height: high vowels have a higher F_0 than low vowels (Peterson & Barney 1952, House & Fairbanks 1953, Lehiste & Peterson 1961, Lea 1972). These studies also show that these intrinsic variations are of the same order of magnitude as the intrinsic differences caused by prevocalic consonants; see Table 3.

		i	*ɛ*	*æ*	*a*	*ɔ*	*u*
Peterson & Barney 1952	men	136	130	127	124	129	141
	women	235	223	210	212	216	231
	children	272	260	251	256	263	274
Lehiste & Peterson 1961	(1)	129	127	125	120	116	134
	(2)	183	166	162	163	165	182
House & Fairbanks 1953		127.9		119.8	118		129.9
Mohr 1971		128.8			124.2		129.9

TABLE 3. Intrinsic pitch of vowels (in Hz).

Since vowel height and prevocalic consonants seem to cause similar perturbations, one could expect tonal development resulting from vowel merging to be as frequent as tonal development resulting from the loss of some voicing contrast in prevocalic position; one would expect the development to show that high vowels give rise to high tones, and low vowels to low tones. As mentioned, however, the historical data are scanty on this point.

Moreover, the reverse pattern—low vowels giving rise to high tone, as in Ngizim—although equally rare, is not without a possible, if improbable, phonetic explanation. We have mentioned in §2.4, above, the evidence that larynx height varies directly with the F_0 of the voice. Raising or lowering the larynx also shortens or lengthens, respectively, the vocal tract; and this in turn affects the formant frequencies, especially the first formant. Since perceived vowel 'height' varies inversely with the first formant, it is possible that a higher F_0 of voice would, other things being equal, lead to a somewhat lower vowel quality. However, this effect is probably very small: e.g., a 1 cm variation in larynx height (about the average in conversational speech) would vary the first formant of [a] by a mere 50 Hz; with all other vowels the variation would be less (Lindblom & Sundberg 1971).

It would seem reasonable, then, to seek an explanation for the infrequency of the development of tones caused by the interaction of tones and vowels. One possible hypothesis is that, although intrinsic perturbations caused by consonantal influences and vowel height have similar absolute values, they are perceived differently. This possibility is currently being investigated (Hombert 1977a). Essentially two points are being tested:

(a) A voiced (vs. voiceless) consonant causes a relatively rising F_0 contour at the onset of the following vowel. However, the intrinsic F_0 associated with different vowel qualities is manifested by over-all higher vs. lower F_0 levels. Since our auditory system seems to be more 'efficient' at detecting dynamic CHANGES in F_0, rather than differences in level (of the same magnitude) between two F_0 signals (Møller 1973, Whitfield & Evans 1965), this may account for the differences in perceptual saliency of the two phenomena (perturbations caused by vowel height vs. perturbations caused by prevocalic consonants).

(b) The F_0 perturbations by consonants may be more 'noticeable' to listeners, in that they can be detected independently of (in fact, after) the conditioning segments. In the case of F_0 perturbations by vowels, the listeners may not be able perceptually to dissociate the F_0 differences from the conditioning segments, since they are both present simultaneously.

THE ASYMMETRY BETWEEN FALLING AND RISING TONES

7. Surveys providing accurate data on the incidence of tone shapes in various linguistic areas are rare. One study, done by Cheng 1973 for 737 Chinese dialect locations, shows that falling tone occurs more frequently than any other tonal contour. Probably related to this is the fact that speakers have a tendency to reduce the frequency interval between adjacent tones when a low tone is followed by a non-low tone. This can be achieved by lowering a high tone after a low tone. This phenomenon is very common among African languages, and is referred to as 'downdrift'. Thus in Igbo (cf. Hombert 1974), a sentence like 'It is his house',

ọ bụ ụlọ ya
H L H L H
/‾ _ ‾ _ ‾/

has the tones realized phonetically as follows:

[‾ _ ‾ _ ‾]

This decrease in interval between a low and a following non-low can also be achieved by raising the low tone—which, in some languages like Mbui-Bamileke (Hyman & Schuh), can reach the level of a mid tone.

All these data indicate that speakers have a tendency to avoid going up in frequency when producing tones. Phonetic studies by J. Ohala & Ewan 1973 and by Sundberg 1973 suggest that such asymmetries may be caused by laryngeal constraints. However, the experimental data in Hombert 1975b suggest that the onset of a falling tone is more accurately perceived than that of a rising tone. These data indicate a perceptual constraint which reinforces (i.e. coincides with) a possible articulatory constraint.

Conclusion

8. We have reviewed what we consider to be promising phonetic explanations for well-attested tonal sound patterns—e.g., tone originating from the effect of prevocalic stop consonants or postvocalic glottal consonants, and tone rarely or never originating from the influence of postvocalic non-glottal consonants or from vowel height. We are aware of some historical developments of tone which do not follow our predictions. Consider two examples: the occasional correlation between higher tone and original preceding voiced consonant (vs. lower tone and voiceless consonant), where just the reverse would be expected, and the development of a falling tone after loss of a postvocalic [ʔ], where a rising tone would be expected—as in a number of Chinese dialects (Cheng). Before abandoning or revising our predictions, we would want to make sure that the phonetic description of the segments involved in the tonal development is accurate. If the postvocalic [ʔ] implicated in the development of a falling tone was actually creaky voice at the time of the tonal development, the falling tone would not be exceptional. Again, if the prevocalic [b] implicated in the origin of higher tone had changed to an implosive [ɓ] by the time of the tonal development, this would no longer be an exceptional pattern either. We would also want to make sure that other factors had not modified the tones after their development along predicted lines. Hombert 1978 suggests, e.g., that tones can redistribute themselves in the available tone space in order to maximize the perceptual distance between the tones—much as vowels are presumed to distribute themselves in the vowel space (Liljencrants & Lindblom 1972).

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