Publications corresponding to these sections:

1. "Consonant types and tone in Siamese" *Journal of Phonetics* (1974) 2:337-350.

2. "The features of the larynx: n-ary or binary?" *Phonetica* 32:241-253.

3. "The glottal stop in Siamese: predictability in phonological description" *Phasaa* 4.2:66-78.

4. "On the representation of tone in Siamese" In *Studies in Tai Linguistics*, edited by J. G. Harris and J. R. Chamberlain. Central Institute of English Language: Bangkok, Thailand.

5. "Evidence from Lue for contour tone features" *Phasaa* 5.2:39-52.

6. "Counterfeit tones in the speech of Southern Thai bidialectals" to appear in *Lingua*.

Phonetic explanation of the development of

tones from prevocalic consonants

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I. Introduction

The development of contrastive tones on vowels due to the loss of a voicing distinction on obstruents in prevocalic position is probably the most well documented type of tonogenesis. When such a development occurs a relatively lower pitch register develops on vowels following the previously voiced series and a relatively higher pitch is found after the previously voiceless or voiceless aspirated series. This process can lead to a multiplication by two of the number of tones. If the language was atonal it will have two tones after this development; an already existing two-tone system will be transformed into a four-tone system, and so on. The correlation between initial consonant and pitch register was noticed at the beginning of this century by Maspero (1912) and Karlgren (1926) for Chinese, and later extended to other East Asian languages by Haudricourt and Martinet (1946), Haudricourt (1954, 1961), Matisoff (1973a) and Mazaudon (1975). This correlation is also found in other linguistic groups, e.g., in Hottentot (South Africa) as described by Beach (1938). Although it did not give rise to tonal development, a similar correlation between consonant types and fundamental frequency height is found in certain African languages (Hyman 1973 a,b; Hyman and Schuh 1974).

I will assume that when similar sound changes occur in languages genetically, geographically and chronologically distant, these changes should be explained in terms of physiological constraints (articulatory and/or auditory). In order to show that the development of tones due to the loss of a voicing distinction in prevocalic position is phonetically motivated, I will present production and perception data and I will show to what extent they overlap.

II. Production data

a. Previous studies

Phonetic studies by House and Fairbanks (1953), Lehiste and Peterson (1961), Mohr (1968), Lea (1973), and Löfqvist (1975) among others, show how a voicing distinction in pre-vocalic position can affect the fundamental frequency (Fo) of the following vowel. Some of the data from these studies are summarized in Table 1.

	p	t	k	b	d	g
House and Fairbanks (1953)	127.9	127.1	127.2	120.9	120.6	122.8
Lehiste and Peterson (1961)	175	176	176	165	163	163
Mohr (1968)	130.7	129.8	131.1	125.1	124.8	125.0

Table 1. Fundamental frequencies (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 Fo values of vowels are higher after voiceless (aspirated) than after voiced stops and that these values do 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 a peak value for Fo, making it impossible to deduce the time course of the Fo perturbation caused by the preceding consonant.

b. Experimental conditions

In order to remedy this, the following data were collected. Five American subjects without speech disorders or history of hearing pathology, speaking some form of general American English dialect were used. They spoke 6 cv nonsense words where C = [p,t,k,b,d,g] (and for three subjects [w,m] as well),and V = $\{i\}$. The word list spoken consisted of ten tokens of each test word arranged in random order. Each test word was uttered in the frame "say ___ again". The recording was done in a sound treated room. Measurements were made on a mini-computer by means of a hardware pitch extractor (Krones, 1968), with a reference point at the onset of the vowel, Fo values were measured at onset and 20, 40, 60, 80 and 100 msec after this onset.

c. Results

The results are given in Figures 1 and 2, Figure 1 showing Fo curves on the vowels following the voiced and voiceless stops, averaged over all speakers' samples, and Figure 2, showing the Fo curves, including those for vowels following sonorants, for three individual speakers.

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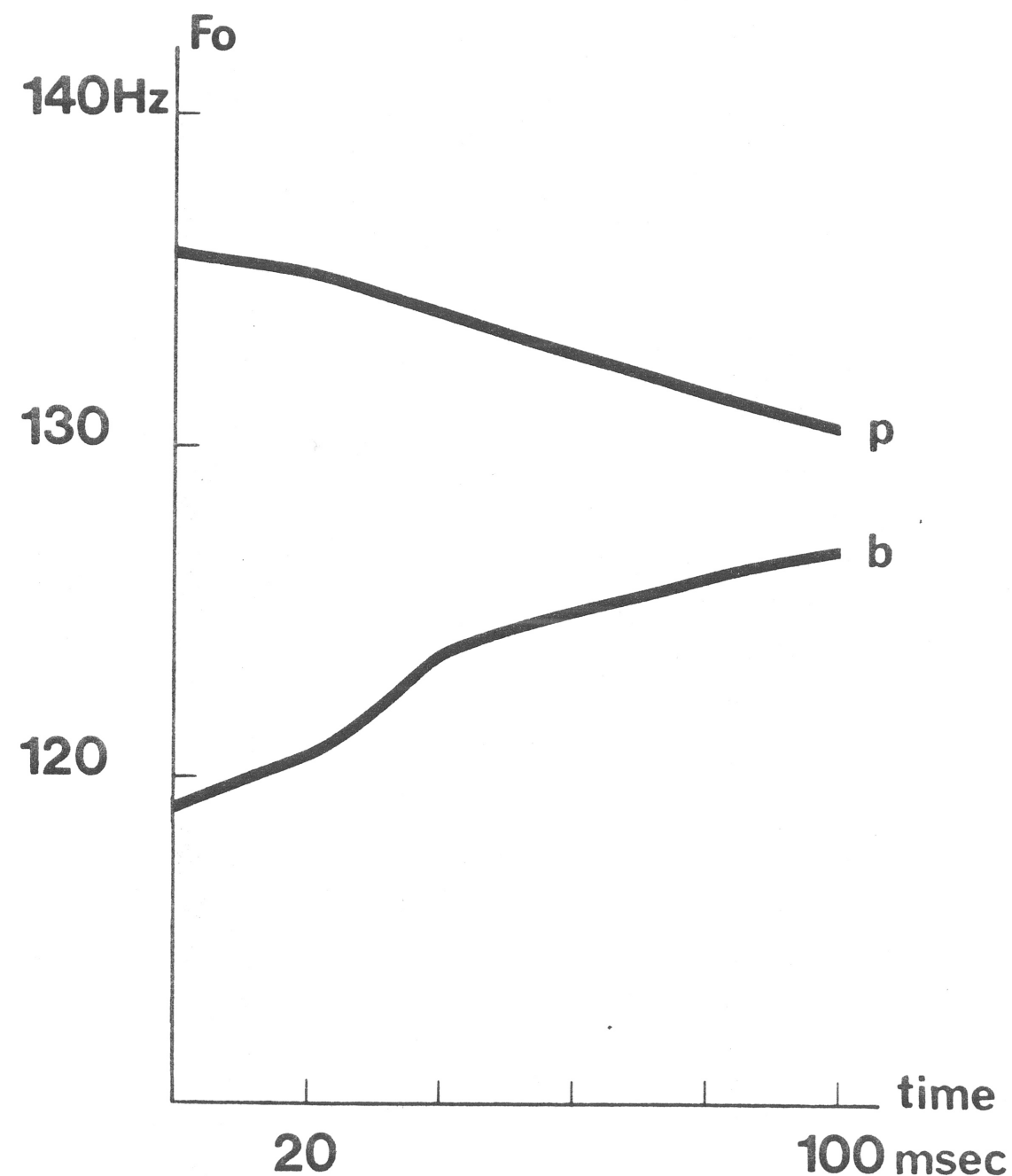

Figure 1. Fundamental Frequency values of vowels after voiced and voiceless aspirated stops - [p] and [b] represent the voiceless aspirated and the voiced series respectively. Fundamental frequency (vertical axis) is measured as a function of time (horizontal axis) -(5 subjects).
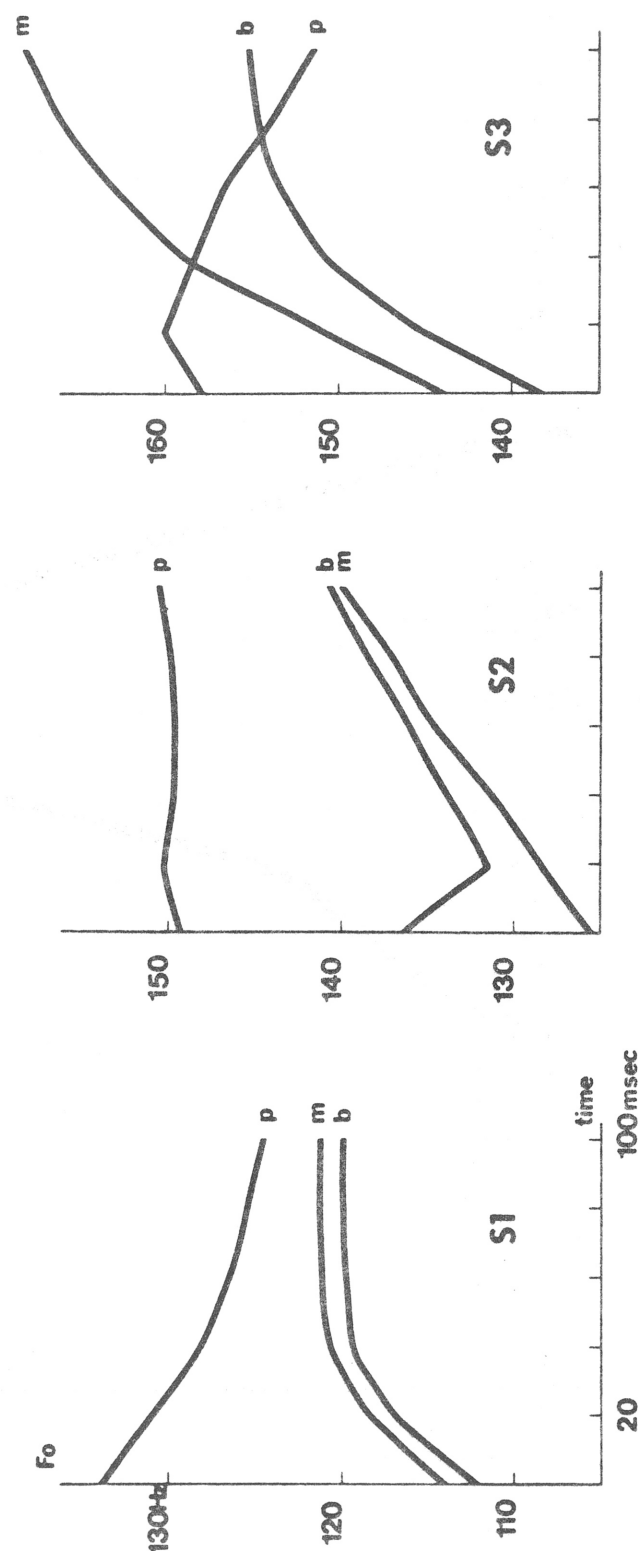
Figure 2. Individual Fo patterns after voiced, voiceless aspirated stops and sonorants (3 subjects).

The explanations proposed to explain these facts (Fo raising after voiceless consonants vs Fo lowering after voiced consonants)can be divided into two categories. The first attributes these Fo perturbations to aerodynamic effects and the second to differences in vocal cord tension.

Researchers following the first theory (i.e. aerodynamic) would explain the phenomenon in the following terms. After the closure of a voiced consonant, voicing continues, but since the oral pressure increases (because of the closure), the pressure drop decreases, leading to a lower frequency. The fundamental frequency then rises after the release until it reaches the "normal" value of the vowel which is being realized. In the case of a voiceless consonant, since the rate of air flow is supposed to be high, a strong Bernoulli effect will draw the vocal folds together very rapidly; they will be pushed apart very rapidly as well because the subglottal pressure is still high. Consequently, the rate of vibration of the vocal folds will be high at the onset of the vowel and will return gradually to the intrinsic value of the vowel being realized.

The experimental data presented earlier as well as earlier studies (Löfqvist 1975), show that a consonant still affects the fundamental frequency of the following vowel at least 100 msec after vowel onset. Proponents of the second theory (vocal cord tension) claim that this perturbatory effect is too long to be attributed to aerodynamic factors. Halle and Stevens (1971) suggest that these intrinsic variations are the result of horizontal vocal cord tension and they propose the features [stiff] and [slack] vocal cords to capture the relationship between low tone and voiced consonants (where the vocal cords are supposed to be slack in order to facilitate voicing) on the one hand, and high tone and voiceless consonants on the other hand. Studies by Ohala (1972), Ewan and Krones (1974), as well as more recent work in progress by Ewan suggest that the Fo perturbation is caused at least partially by vertical tension (i.e. larynx height).

Both of these explanations (horizontal and vertical tension) fail to account for the fact that postvocalic consonants do not have the same effect on F_0 as prevocalic consonants do (however see below). Lea (1972, 1973) suggests that both voiced and voiceless consonants lower the Fo of the preceding vowel. Other studies (Mohr 1971, Slis 1966) indicate that postvocalic consonants have a similar effect on Fo as prevocalic consonants but with a much smaller magnitude. The counterargument I just presented based on different influences of pre- and post-vocalic consonants can be weakened if one considers that postvocalic consonants are less "strongly" articulated than their prevocalic counterparts (Slis 1967, Fromkin 1969).

Nevertheless, Halle and Stevens' position is not supported by experimental data; electromyographic recordings by Hirose, Lisker and Abramson (1973) and Hirose and Gay (1972)do not show obvious differences in the tension of the laryngeal muscles during the production of voiced/voiceless distinctions. Ewan and Krones' claim however, is in agreement with experimental

data showing a correlation between F̄o and larynx height (Ohala 1972, Ohala and Ewan 1972). Ewan and Krones (1974) also show a correlation between voiced sounds and low larynx position as opposed to voiceless sounds and high larynx position. It was also indicated that the larynx was in lower position at the end than at the beginning of a voiced consonant. This suggests that the larynx is actively lowered during a voiced consonant in order to increase the volume of the oral cavity. Warren and Hall (1973) and Bell-Berti (1975) show that this is, at least partially, an active process. If this is the case one would expect to find a perturbed (lowered) Fo after voiced consonants as opposed to a nonperturbed Fo after sonorants and voiceless consonants. Unfortunately this does not seem to be the case in the data presented in Figure 2, where it is shown that sonorants pattern similarly to voiced obstruents. Although it seems that theories based on muscular tension cannot account for some empirical data, we are in an even more difficult situation with theories based only on aerodynamic factors.

Klatt, Stevens and Mead (1968) present air flow data in which a high rate of air flow lasts only about 50-60 msec into the vowel; comparable but uncalibrated data are presented by Frøkjkær-Jensen, Ludvigsen and Rischel (1971). Moreover, van Hattum and Worth (1967) as well as Isshiki and Ringel (1964) show that oral airflow is momentarily lower after voiceless aspirated consonants than it is after voiced consonants. These data are in agreement with the results of a mathematical model of aerodynamics proposed by Ohala (1975a). All these results seem to favor the theories based on muscular tension.

III. Perceptual data

a. Previous studies

There is evidence from experiments using synthesized speech that small fundamental frequency perturbations can be used as cues to discriminate between sonorants and voiced obstruents and between voiced and voiceless obstruents (Chistovitch 1969, Haggard et al 1970, Fujimura 1971, Abramson 1974). The perception of stimuli with changing frequency contours has been investigated for pure tones (Brady et al 1961; Heinz et al 1968, Nabelek and Hirsh 1969; Nabelek et al 1970; Pollack 1968; Sergeant and Harris 1962; Tsumura 1973) as well as for vowels (Klatt 1973; Rossi 1971). From these studies it is difficult to conclude to what extent the perception of a changing frequency contour would be affected by a steady-state frequency immediately following the contour.

b. Experimental conditions

In order to get these data, the following study was carried out.[1] Ten subjects, native speakers of American English, with normal hearing, participated. Acoustic stimuli consisting of 10 instances of the vowel [i] were synthesized with different fundamental frequency patterns.

As shown in Figure 3, each stimulus was composed of a slope followed by a level tone maintained constant at 120 Hz. The onset frequency was either 110 or 130 Hz (i.e. Fo = +10 Hz). The duration of the slope was varied at 40, 60, 100, 150 and 250 ms. In other words, 5 stimuli (with Fo onset = 130 Hz) had a falling fundamental frequency and 5 stimuli (with Fo onset = 110 Hz) had a rising fundamental frequency. The overall 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 fundamental frequency. The duration of this vowel was also 250 ms. The level of its fundamental frequency 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 one of the 10 stimuli was presented 3 times in a randomized order. The subjects heard the stimuli through earphones at a comfortable level (about 70 dB). The parameter values were chosen in order to simulate the effects of consonants on neighboring vowels.

c. Results

The results[2] are presented in Figure 4, subjects' responses are plotted as a function of the duration of the slope. Responses to stimuli with a falling Fo at the onset (from 130 Hz to 120 Hz) are indicated by a circle ("O"), responses to stimuli with a rising Fo (from 110 to 120 Hz) are indicated by a cross ("X"). A statistical analysis of these data (analysis of variance followed by Duncan's test) indicates that the two curves are already perceived as significantly different when the onset slope (from Fo onset to level Fo) is 60 ms long.[3]

This graph suggests that 1) falling patterns (i.e. vowels with fundamental frequency onset above 120 Hz) are perceived more accurately than rising patterns (i.e. vowels with fundamental frequency onset below 120 Hz; 2) the longer the slope, the more accurate the matching, but correlation between slope duration and accuracy of matching is not linear.

d. Discussion

These results can be explained by forward masking. If we extrapolate the results obtained with steady state tones to contours, (i.e. masking a higher frequency by relatively lower frequency) we can understand why the onset region of the rising ramp was not accurately perceived, since each frequency was masked by the previous lower frequency (since the frequency is going up). This is not the case for the falling tone in which each frequency is followed by a lower frequency. Data from the psychoacoustic literature (Brady et al 1961, Heinz et al 1968, Pollack 1968, Nabelek and Hirsh 1969, Nabelek et al 1970, Tsumura 1973) can be interpreted as supporting my claim concerning the role of masking in the perception of changing frequency contours.
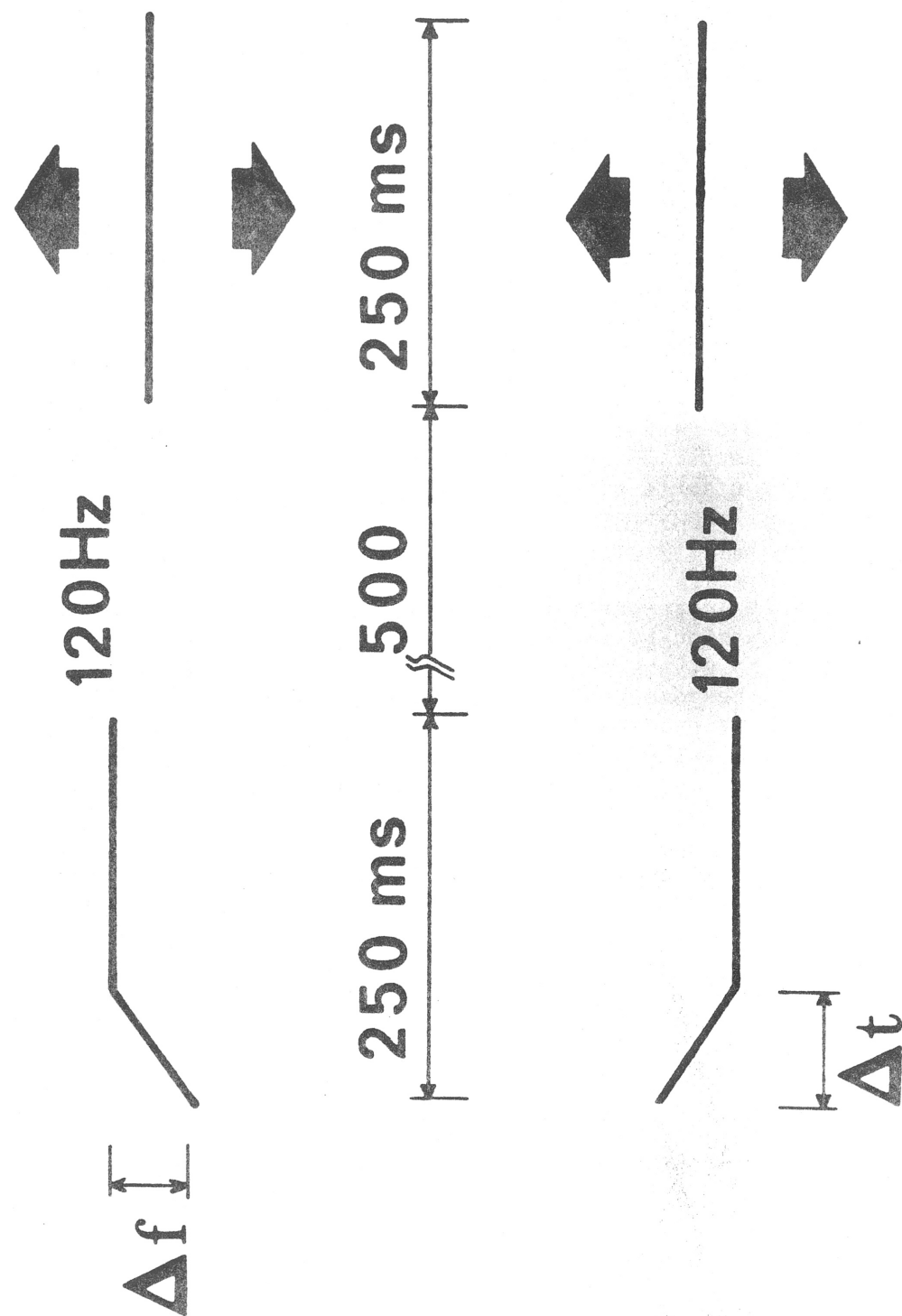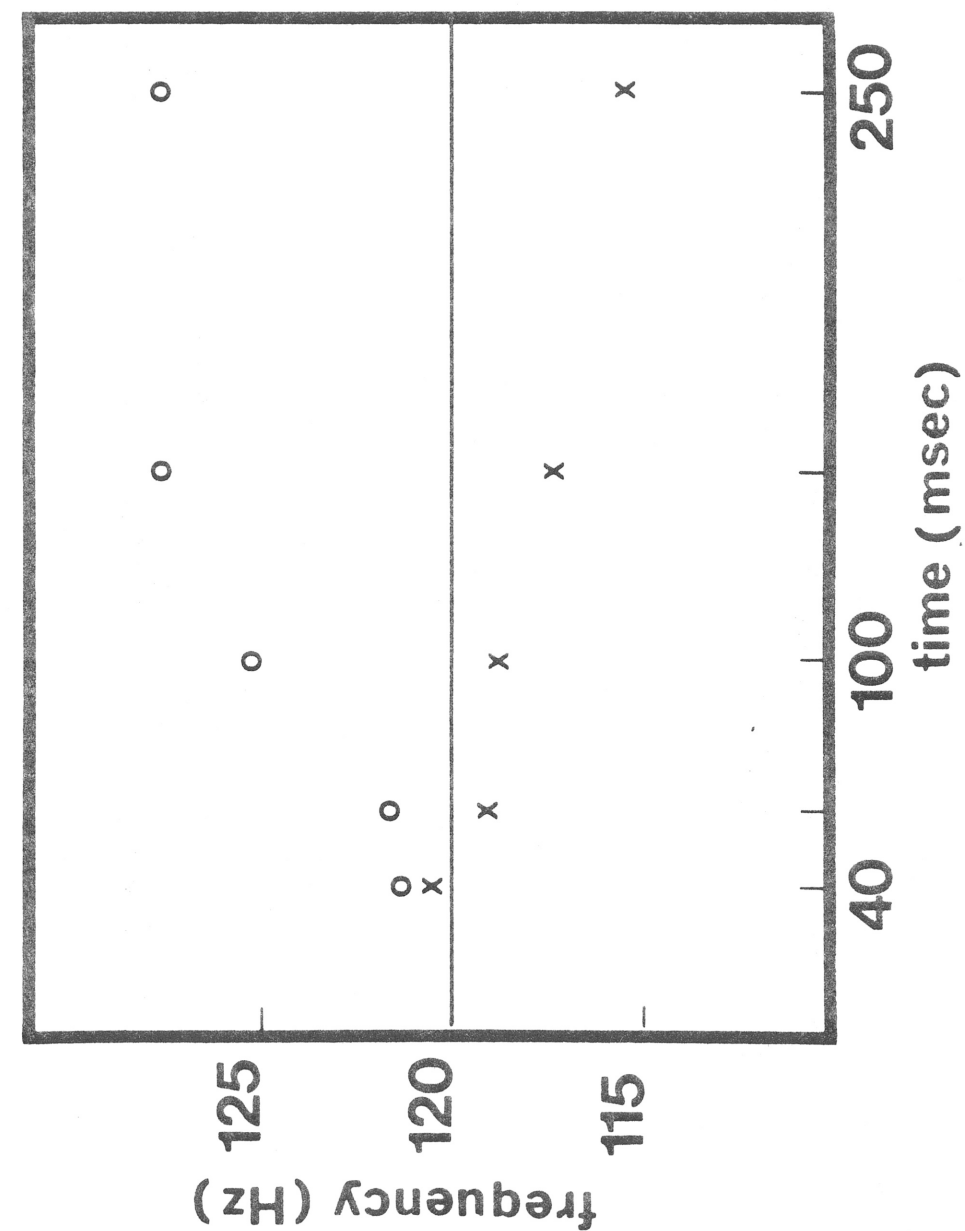
Figure 3.   Stimulus presentation.

Figure 4.   Perceived fundamental frequency (vertical axis) as a function of the duration of the slope (horizontal axis) - (0) indicates responses to falling Fo stimuli (Fo onset = 130 Hz).   (X) indicates responses to stimuli with risingFo (Fo onset = 110 Hz).

In these experiments, subjects were asked to match the pitch of a steady state signal with a changing frequency signal. They consistently adjusted their steady state tone closer to the final point of the contour. This fact already shows the role of masking which attenuates the effect of the onset region in favor of the offset region, but furthermore there is a tendency to match closer to the final point when the stimulus is a rising contour (as opposed to a falling contour). This indicates, as I have suggested, that the masking of the onset is more effective in the case of rising contours (as opposed to falling contours), and consequently, this leads to the perception of an averaged pitch closer to the offset frequency.

These data are also in agreement with the study of Brady et al (1961) with respect to the role of the rate of frequency change. They found that the matching of a steady state frequency with a contour frequency is closer to the end point of the contour when the rate of change is high; in other words, the onset region is less salient at high glide rates. This is shown on Figure 4 by responses close to 120 Hz when the slope duration of the stimulus is short (i.e. the rate of frequency change is high). This is also in agreement with Pollack (1968) and Nabelek and Hirsh (1969), whose results indicate that optimum discriminability of relatively small frequency changes is obtained at relatively slow glide rates.

Finally, it should be pointed out that this study was limited to the comparison of Fo differences vowels following voiced and voiceless obstruents. Further research should investigate the perceptual role of Fo during voiced consonant immediately preceding vowels vs. the absence of Fo during voiceless consonants.

IV. Conclusion

In the first part of this paper, I showed that the consonantally-induced Fo perturbations on vowels in such non-tone languages as English and Swedish persist for some 100 ms after vowel onset. The perceptual data just presented show that listeners start hearing significant differences in the Fo onset of our synthesized stimuli when the slope of the Fo 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 Fo variations cease to be significantly different.

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

Footnotes

[1] For a more complete description of this experiment, see Hombert 1975b.

[2] The fact that a linear scale is used does not distort the results within this narrow portion of the frequency range (see Stevens, Volkman, and Newman 1957). In any case my claim about the asymmetry between rising and falling contours would have been even more obvious with a logarithmic scale.

[3] In reporting the results of the perceptual experiments we have given those values of ΔFo and Δt of the pitch ramps which were detectably different *on the average*. It is an open question whether for the purpose of explaining how these differences could be detected in order to give rise to a sound change we should report instead those minimum differences detected by the best, not the average listener. If so, the values given above should be regarded as very conservative estimates of minimal detectable pitch perturbations (Hombert, in preparation).

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