UNIVERSITY OF CALIFORNIA

Los Angeles

Tonal realization and Implementation of Accentual Phrase in Seoul Korean

A thesis submitted in partial satisfaction of the requirements for the degree Master of Arts in Linguistics

by

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1999

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1999

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ABSTRACT OF THE THESIS

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The aim of this paper is to provide implementation rules for the fundamental frequency (f0) of the Accentual Phrase (=AP) in Seoul Korean. To implement the Korean AP precisely, two aspects of f0 were considered: microprosody (consonantal effects), and speech rate effects.

Microprosody was investigated in terms of the influence of an AP-initial consonant on the fundamental frequency of the following syllables within the AP. It was found that Korean tense or aspirated onset consonants raised the f0 value of the following adjacent vowel, and when they were positioned in the onset of the first syllable of an AP, they continuously raised f0 values of the following non-adjacent vowels.

It was also found that speech rate affected the tonal realization of an AP. In fast speech, speakers showed narrower pitch ranges than in normal speech. In addition, the penultimate Low tone of the AP tonal pattern was undershot when the speaker reduced the duration of an AP more than 30% at fast rate. However, regardless of the change of speech rate, AP-initial consonant effects were found both at the fast rate and normal rate. This f0 raising after aspirated or tense consonants supports previous claims that the microprosody in Korean is phonologized in phrase initial position.

On the basis of these results, implementation rules for 4- or 5-syllable APs were provided by using linear regression. Finally, schematics of f0 targets and an interpolation model within the AP were suggested.

1. Introduction

1.1. F0 implementation

The study of the phonetic aspects of speech has advanced greatly over the past decade as a result of the rapid development of computer systems. With increasing linguistic knowledge, nowadays computer speech synthesis has reached a high level of performance: low error rate in text-to-speech conversion and high intelligibility in synthesis from phonemic input. However, though speech quality from these synthesizers has recently improved very much, there are still many problems to overcome. One such problem is that the intonation and rhythm of synthesized voices are often too monotonous. To synthesize more natural f0 contours for phrases or utterances, we need to implement tonal realization rules which demonstrate general characteristics of the f0 system. This is called f0 implementation.

It seems that there are three aspects of f0 implementation which should be considered in speech synthesis studies. The first is known as microprosody: consonantal effects, intrinsic vowel effects and stress effects (e.g., Kohler 1990), the second is rate effects and undershoot (e.g., Fougeron and Jun 1996) and the third is tone scaling and downstepping (e.g., Liberman and Pierrehumbert 1984, Pierrehumbert and Beckman 1988). Kohler (1990) showed that changes in f0 were caused by vowel height, preceding consonants, following consonants, and voicing. Fougeron and Jun (1996) showed that an increase in speech rate affected French intonation in that speakers reduced pitch range and the number of Accentual Phrase (=AP), a tonally marked prosodic unit, within an utterance by dephrasing prosodic boundaries. Pierrehumbert and Beckman (1988) showed that the scale of High and Low peaks of Japanese APs needed to be manipulated within an overall pitch range which was changed by tonal declination and downstepping.

These tone scaling, speech rate and microprosody effects have been considered in previous f0 implementation and speech synthesis studies. For example, tone scaling and pitch range normalization were used to predict f0 contours in English (Liberman and Pierrehumbert 1984), Japanese (Pierrehumbert and Beckman 1988) and German (Möhler 1998). Ohno, et al. (1998) showed speech rate dependency of parameters in f0 contour generation and Hirose and Kawanami (1996, 1998) showed that dialogue speech had a higher speech rate than read speech and provided prosodic rules for a text-to-dialogue speech system in Japanese. Vainio and Altosaar (1998) modeled microprosody variation triggered by different segments types and manners in Finnish.

However, the studies of f0 implementation on microprosody have usually been fairly scarce compared to the studies on tonal scaling and speech rate. Since microprosodic changes have been seen as the lowest level of prosodic system, they were usually not considered as a part of the main prosodic pattern of an utterance, but rather considered as segmentally conditioned perturbations. Thus, the microprosodic changes of the sounds have not received much attention, although most synthesis systems model the timing of f0 peaks and differences in f0 slopes.

Studies on f0 implementation of Korean usually focused on determining AP or IP boundary location and predicting syllable locations of High and Low tones (e.g., Lee, et al. 1998), and microprosody has not been considered much in Korean f0 implementation. However, in Korean, as we will see, the AP-initial onset raises f0 of all vowels in the AP, and therefore plays a significant role in determining the tonal pattern of APs. Thus, if this effect of microprosody is ignored in speech synthesis, consequently, the overall quality of the intonation of the synthesized utterances may not be high in Korean.

In this study, we will examine two aspects of f0 implementation in the Korean AP, microprosody and speech rate, in order to provide implementation rules of the tonal pattern of the Korean AP. The aspects of tonal scaling and downstepping will not be considered in this study since they occur in a domain larger than an AP (i.e., Intonational Phrase). Investigating these aspects of microprosody and speech rate will not only increase our knowledge of prosody in Korean, but also provide crucial f0 implementation rules for the improvement of speech synthesis study.

1.2. Microprosody and Korean AP

Cross-linguistically it has been generally accepted that a consonant influences the f0 of the following vowel onset. One example is that voiceless consonants raise the f0 of the following vowel more than voiced consonants and breathy consonants (House and Fairbanks 1953, Gandour 1974, Löqvist 1975, Hombert 1978, Hombert et al. 1979). House and Fairbanks (1953) tested English nonsense words and found that the f0 of vowels is higher after voiceless consonants than those after voiced consonants. The same pattern was found in Thai (Gandour 1974), and Swedish (Löfqvist 1975), Yoruba (Hombert 78, Hombert et al. 1979).

The influence of Korean obstruents on the following vowel has also long been known (Kim 1965, 1970, Han & Weitzman 1970, Hardcastle 1973 (for stops), Kagaya 1974 (for stops, affricates, and fricatives), Jun 1993, 1996, Cho 1996, Han 1998 (for stops)). Korean has three manners of voiceless obstruents: aspirated, tense (voiceless unaspirated) and lax (voiceless breathy). Studies show that a vowel has a higher f0 after voiceless aspirated obstruents and tense obstruents, and a lower f0 after voiceless lax obstruents. Previous f0 studies of Korean consonants are summarized in Table 1. "A" refers to aspirated obstruents (p^h, t^h, k^h, $tʃ^h$, s, h), "T" refers to tense obstruents (p', t', k', tʃ', s'), and "L" refers to lax obstruents (p, t, k, tʃ).

Prosodic Condition	F0 value of the following vowel	
Word in isolation	A > T > L	Han & Weitzman (1970)
		Kagaya (1974: 'KT')
		Cho (1996)
	T > A > L	Kim (1965)
		Hardcastle (1973)
	T > L	Kagaya (1971)
Word in sentence	A > T > L	Kagaya (1974: 'KT')
	A = T > L	Jun (1989, 1993, 1996)
	T > L	J.I. Han (1996)
	A = T > L	N.H Han (1998)

Table 1. Summary of previous studies on f0 at voice onset following obstruents in Korean (Han 1998)

As shown in Table 1, f0 after aspirated or tense obstruents was always higher than that after lax stops though the difference between aspirated and tense obstruents was not consistent across studies.[1] With regard to prosodic condition, the results of these previous studies seem to be less consistent in 'word in isolation' position.

These effects of Korean consonants on the following vowels have been claimed to play an important role in the Korean intonation model presented in Jun (1989, 1993, 1996a, to appear). She proposed that a phonological phrase in Korean is tonally marked, and is called an Accentual Phrase (henceforth AP). The underlying tonal pattern of the Seoul Korean AP is Low-High-Low-High (LHLH) or High-High-Low-High (HHLH), where the AP-initial tone is determined by the laryngeal feature of the phrase initial segment. When an AP-initial consonant is either aspirated or tensed, having [+stiff vocal cords] (Halle & Stevens 1971), the AP begins with a High tone; otherwise the AP begins with a Low tone, thus LHLH pattern.[2] Schematic representations of these two tonal patterns of Korean AP are shown in Figure 1.

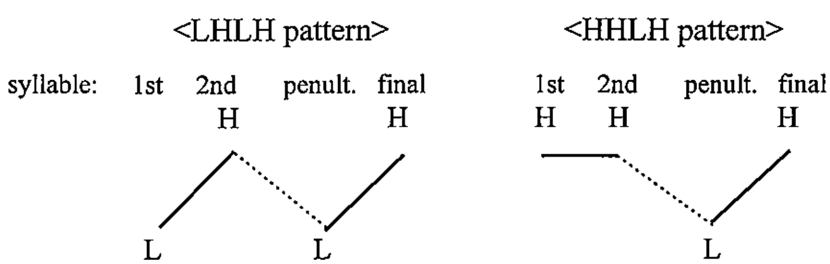


Figure 1. Schematics of two tonal patterns of a Korean AP described in Jun (1993, 1996b)

[1] Kagaya (1974: 'KZ') showed one exception (C' > C > C^h). In Kagaya (1974), the speaker KZ produced each of the stops four times in nonsense monosyllables and disyllables of the forms /Ce/ and /eCe/. In /eCe/ pattern, C is not word initial so that it would not show the consonant effect on the following vowel. However, a question remains: why did other speakers not show the same pattern? I will not consider this exceptional case here.
[2] That is, APs having an initial lax obstruents, sonorant onset or zero onset have initial L tone.

These four underlying tones are realized on the surface when an AP has more than three syllables: the two initial tones are associated with the two initial syllables of an AP and the two final tones are associated with the two final syllables of an AP (Jun 1996a, to appear). But when an AP has fewer than four syllables, either one or both of the two medial tones, the H tone in the second syllable and the following L tone, are undershot.

Recently Jun (1996b) showed that the initial f0 triggered by lax - tense or aspirated consonants (i.e., microprosody) in Korean was far more different from that triggered by voiced-voiceless consonants in other languages such as English and French, when the consonant was at the beginning of a phrase (i.e., Accentual Phrase). She further showed that unlike in English or French the difference persisted until the end of a syllable in Korean. That is, the f0 difference after voiced and voiceless consonants disappeared 40-60ms after the consonants in English and French as observed in previous studies, while the effect stayed until the end of the following vowel in Korean. She also showed that the f0 difference between two consonant types was substantially larger in Korean. These findings imply that microprosody is important in Korean f0 implementation.

Questions raised from Jun's study are the following: How far does this initial difference persist through an Accentual Phrase? Does it persist through the second syllable, or even farther away? And are these consonantal effects kept both in normal and fast rates? Previous studies of Korean consonant effects on f0 have mainly focused on the following *adjacent* vowel, but little have been known about the effect of a consonant on the following *non-adjacent* vowels within a word or a phrase. In this study, we will see experimental evidences for Korean which suggest that a *non-adjacent* consonant - the onset consonant of the AP-initial syllable - can affect the tonal realization of a whole AP.

Besides this segmental effect, we will also see how different speech rates affect the tonal realization of an AP. Based on these experimental results, implementation rules for 4- or 5-syllable APs will be provided by using linear regression. Finally new schematics of f0 targets and an implementation model within an AP in Seoul Korean will be proposed.

The organization of this paper is as follows. Section 1 introduces this study. In Section 2, Experiment 1 examines the consonant effects on f0 values in APs composed of *nonsense* words, with normal/fast rates. In Section 3, Experiment 2 shows consonant effects on f0 values in APs composed of *real* words, at normal/fast speed rates. It will be shown that the consonantal effects and rate effects found in nonsense word APs are also found in real word APs. Results are discussed in each section. Implementation rules for 4-or 5-syllable APs of Korean are provided in Section 4. In Section 5, conclusions are given.

2. Experiment 1: Consonantal and speech rate effects in APs composed of *nonsense* words

2.1. Methods

An AP in Korean is generally composed of one to six syllables (Kim et al., 1997[3]), and more than 80% of APs are composed of 2-5 syllables (Korea Telecom Report, 1996). In this study, however, to observe consonant effects on f0 values of the following syllables and the tonal realization of the Korean AP, 4- and 5-syllable APs were examined. These APs show the full realization of the 4 basic underlying tones (LHLH or HHLH) in Korean.

Target APs were composed of 4- or 5-syllable nonsense words (/CaCaCaka/(4-syllable AP) and /CaCaCaCaka/(5-syllable AP)) and each AP was placed at the beginning of a carrier sentence: "_______yəkiɛ issə" (___ is here.). Note that the last syllable of all APs is the subject marker /ka/; this /k/ is not a test consonant. To examine whether affricate consonants trigger different tonal patterns, if any, from stop consonants, two data sets were examined. All-lax-consonant set will be used as controls. That is, all consonants of control APs were either the lax stop /t/ or the lax affricate /tʃ/, e.g.,

[3] An AP can be composed of more than 6 syllables in Korean. However, in most cases, these 6-syllable APs are composed of two or more words. Also there is a tendency for speakers not to form APs consisting of more than 6 syllables in casual speech.

Mean number of syllables within an AP (Kim et.al, 1997).
speaker 1: 5.03 syllables when an AP has an initial H tone, 2.99 syllables when an AP has an initial L tone
speaker 2: 4.44 syllables when an AP has an initial H tone, 2.79 syllables when an AP has an initial L tone

/tatataka/ and /tʃatʃatʃaka/ for 4-syllable control APs, and /tatatataka/ and /tʃatʃatʃatʃaka/ for 5-syllable control APs. To form test APs, each C in the control AP was replaced by either a tense or an aspirated consonant at the same point of articulation; i.e., a tense stop /t'/ or an aspirated stop /tʰ/ replaced one of the 3 or 4 lax stops /t/, and a tense affricate /tʃ'/ or an aspirated affricate /tʃʰ/ replaced one of the 3 or 4 lax affricates /tʃ/ in the string. There were a total 16 target APs (2 control and 14 test APs). All these APs are shown in Table 2. For simplicity, a symbol 'L' is used for 'a lax obstruent +/a/', 'A' for 'an aspirated obstruent +/a/' and 'T' for 'a tense obstruent +/a/'.

	Types	symbol	APs(Stop)	APs(Affricate)
4-syllable AP	lax (control)	LLLL	tatataka	tʃatʃatʃaka
	aspirated	ALLL	tʰatataka	tʃʰatʃatʃaka
		LALL	tatʰataka	tʃatʃʰatʃaka
		LLAL	tatatʰaka	tʃatʃatʃʰaka
	tensed	TLLL	t'atataka	tʃ'atʃatʃaka
		LTLL	tat'ataka	tʃatʃ'atʃaka
		LLTL	tatat'aka	tʃatʃatʃ'aka
5-syllable AP	lax (control)	LLLLL	tatatataka	tʃatʃatʃatʃaka
	aspirated	ALLLL	tʰatatataka	tʃʰatʃatʃatʃaka
		LALLL	tatʰatataka	tʃatʃʰatʃatʃaka
		LLALL	tatatʰataka	tʃatʃatʃʰatʃaka
		LLLAL	tatatatʰaka	tʃatʃatʃatʃʰaka
	tensed	TLLLL	t'atatataka	tʃ'atʃatʃatʃaka
		LTLLL	tat'atataka	tʃatʃ'atʃatʃaka
		LLTLL	tatat'ataka	tʃatʃatʃ'atʃaka
		LLLTL	tatatat'aka	tʃatʃatʃatʃ'aka

Table 2. APs designed for Experiment 1(L: lax , A: aspirated, T: tense). *-ka* is a particle as a subject marker which attached to the end of the word in Korean.

Two male (DO and HJ) and two female (HA and HS) speakers of the Seoul dialect participated. To help speakers to produce nonsense words more naturally, 4- or 5-syllable APs with real words were added as foil items. Sentences were pseudorandomized so that the sentences having real word APs came at the beginning of each AP set and after every 3 or 4 sentences having target APs. All sentences were read six times each at normal rate and then six times at fast rate. The data were recorded in a sound booth in the UCLA phonetics lab using a head-worn microphone (SHURE 10A) and a DAT recorder (TASCAM DA-30). The speech was digitized at an 11,000Hz sampling rate.

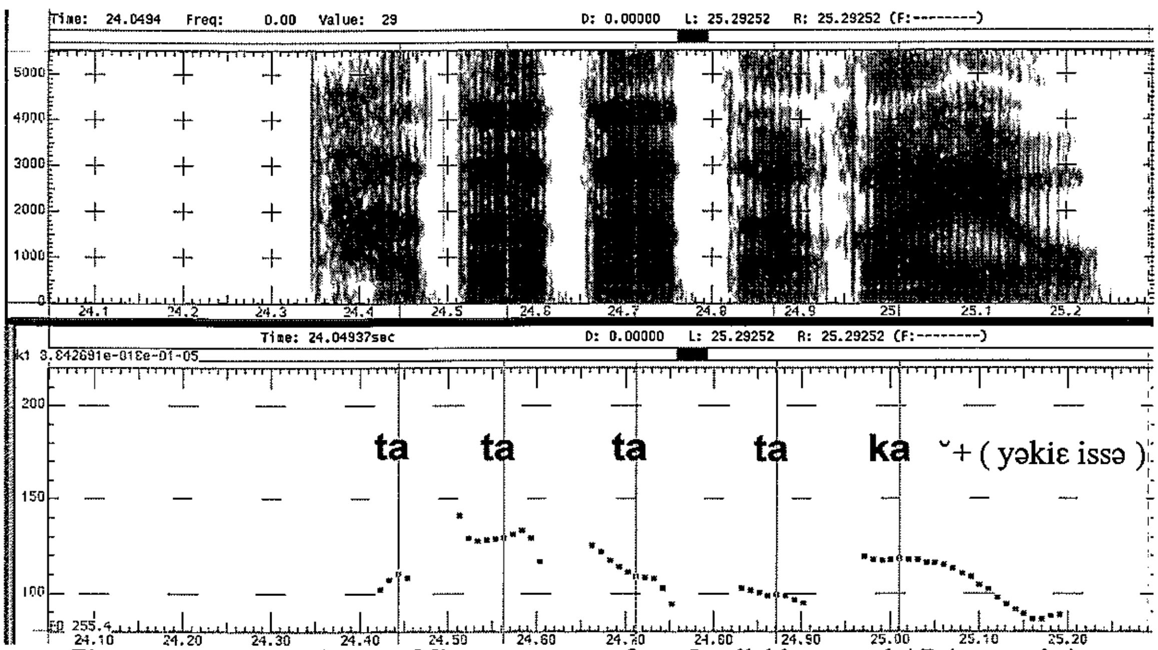


Figure 2. A sample picture of f0 measurement for a 5-syllable control AP (tatatataka).

Acoustic measurements were made by using XWAVES+ (Entropic Research Laboratory). A sample spectrogram and a f0 track are shown in Figure 2. F0 values at the mid point of each vowel, and durations of target APs were measured from spectrograms. Since f0s were always measured at the mid point of each vowel, there is no guarantee that f0 peaks and valleys were recorded in these measurements: sometimes peaks and valleys were found at the end of the vowel. All data were statistically analyzed by using one-way ANOVA[4] and Fisher's PLSD *posthoc* pairwise comparison with 95% significance level ($p<0.05$) in StatView 5.0 (SAS Institute Inc.).

2.2. Normal speech: results and discussion

F0 measurements showed that stops and affricates have similar tonal patterns, and they were not consistently different across speakers. Sometimes the f0 of the following vowel after stops was slightly higher than the f0 after affricates but sometimes vice versa.[5] The results of two-way ANOVA with factors of consonant manner and syllable position are shown in Table 3 (Also see Appendix 1 for all mean f0 contours of stops and affricates, respectively).

[4] The data were submitted to one-way ANOVA with a factor of AP type, described in Table 2, separated for each speaker and syllable. 16 separate one-way ANOVAs were generated for 4-syllable APs (4 speakers * 4 syllables), and 20 separate one-way ANOVAs were generated for 5-syllable APs (4 speakers * 5 syllables).

[5] In Kagaya(1971) the average value of f0 of stops (S) was slightly higher than that of affricates (A). (tense: 160(S) >157(A), lax: 148(S) >144(A), aspirated: 162(S) >157(A) in CV position and tense:159(S) >149(A), lax:141(S) >138(A), aspirated: 150(S) >147(A) in VCV position) However, since the f0 ranges were the same or largely overlapped between them, it is hard to say that the f0 of the vowel after stops are higher than the f0 after affricates.

		M1		**M2**		**F1**		**F2**		**ALL**	
			P		P		P		P		P
4-syl	**Syl**	√	<.0001	√	<.0001	√	<.0001	√	<.0001	√	<.0043
	Man		=.15		=.75		=.55	√	**=.0105**		.77
	Syl*Man		=.46		=.54		=.97		=.40		.99
			P		P		P		P		P
5-syl	**Syl**	√	<.0001	√	<.0001	√	<.0001	√	<.0001	√	<.0001
	Man		=.09	√	**<.0001**		=.10		=.50		.34
	Syl*Man		=.39	√	**=.0115**		=.61		=.88		.97

Table 3. A summary of 10 two-way ANOVAs on f0 for the factors of syllable position and consonant manner in nonsense word APs at normal rate. 'Syl' represents syllable position and 'Man' represents consonant manner. √ represents that there are significant effects (95%) of this factor.

Though Speaker F2 showed a slightly significant difference between affricates and stops in 4-syllable APs (p=.0105) and Speaker M2 showed a significant difference between affricates and stops in 5-syllable APs (p<.0001) and a slight interaction between consonant manner and syllable position (p=.011), speakers generally showed no significant effects or consistent differences for consonant manner and no interaction between consonant manner and syllable position. Thus, data from stops and affricates were pooled together in the following graphs.

We will first examine the initial aspirated or tense consonants' effect on the following syllables, syllable by syllable. And then we will consider the positional effects on the f0 of each syllable, focusing on consonant types (aspirated/tense).

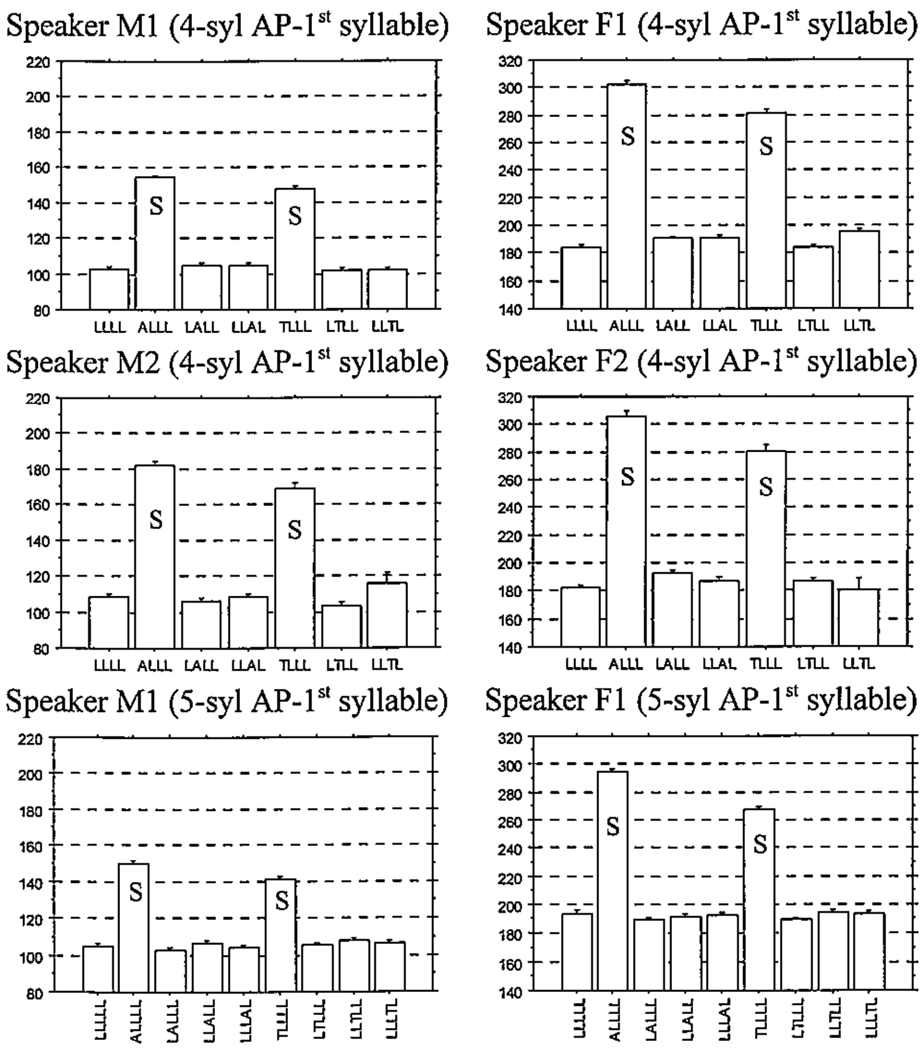
From the statistical analysis, differences due to AP types described in Table 2 were found in each syllable. Table 4 shows F values and P values from 36 ANOVAs (4 speakers * 4 syllables (for 4-syllable APs) + 4 speakers * 5 syllables (for 5-syllable APs)). The difference between AP types in each syllable was tested with Fisher's PLSD *posthoc* pairwise comparison with 95% significance level ($p<.05$).

		M1		**M2**		**F1**		**F2**	
		F(6,77)	P	F(6,77)	P	F(6,77)	P	F(6,77)	P
4-syl	**1st**	254.7	<.0001	306.0	<.0001	773.9	<.0001	393.5	<.0001
	2nd	146.7	<.0001	121.4	<.0001	78.0	<.0001	193.4	<.0001
	penu.	16.1	<.0001	18.1	<.0001	9.5	<.0001	7.0	<.0001
	final	1.5	**=.1766**	8.5	<.0001	8.9	<.0001	5.5	<.0001
		F(8,99)	P	F(8,99)	P	F(8,99)	P	F(8,99)	P
5-syl	**1st**	160.8	<.0001	299.4	<.0001	466.4	<.0001	396.7	<.0001
	2nd	68.0	<.0001	37.1	<.0001	50.3	<.0001	249.1	<.0001
	3rd	8.3	<.0001	20.7	<.0001	17.3	<.0001	43.9	<.0001
	penu.	10.9	<.0001	6.2	<.0001	20.1	<.0001	7.1	<.0001
	final	5.9	<.0001	1.8	**=.07**	1.4	**=.20**	3.4	<.05

Table 4. A summary of 36 one-way ANOVAs on f0 for the factor of each syllable in nonsense word APs at normal rate.

As shown above, the first syllable showed the largest F-value and the final syllable showed the smallest F-value. This means that the effects, whatever they are, are largest in the first syllable. There were significant differences among AP types in the first, second, third and penultimate syllables of 4- or 5-syllable APs ($p<.0001$). As for the final syllable, though Speaker F2 showed significance for both 4- and 5-syllable APs, other speakers showed significant differences, either 4- or 5- syllable APs: M1 did not show significance in 4-syllable APs ($F(6,77)=1.5$, $p=.17$) and M2 ($F(6,77)=1.8$, $p=.07$) and F1 ($F(6,77)=1.4$, $p=.20$) did not show significance in 5-syllable APs. Thus, we can see that the f0 of the final syllable, which does not contain a test consonant, is not quite as variable as in other syllables but is relatively constant, regardless of the AP type. However, these F-values cannot tell what kind of f0 differences there are. We will see what contributes to f0 differences in detail in the following graphs.

Figure 3 shows average f0 values of the first syllable in 4- or 5 syllable APs. In the graphs, a symbol 'S' indicates that the value is significantly higher (p<.05) than the control value (LLLL and LLLLL :these are always the first bar in the graphs).



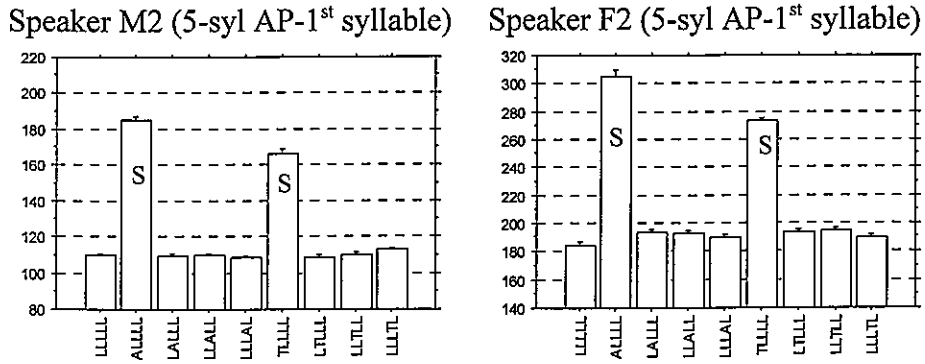


Figure 3. Average f0 value of the 1st syllable in 4- or 5-syllable APs. Y-axis represents f0 value and X-axis represents the APs by syllable sequence described in Table 2, error bars = standard error, 'S' represents the f0 value is significantly higher than the control f0 value (Fisher's *posthoc* pairwise comparison with 95% significance level): the same formats are used in the following graphs.

As shown in Figure 3, in the first syllable of the AP, the f0 value of the vowels after the phrase initial aspirated or tense consonant (**A**LLL, **T**LLL, **A**LLLL and **T**LLLL) was significantly higher ($p>0.001$) than that after lax consonants (**L**LLL and **L**LLLL), confirming the previous results in Jun (1993, 1996b). Also note that vowels with an aspirated onset (**A**LLL and **A**LLLL) have higher f0 values than the vowels with a tense onset (**T**LLL and **T**LLLL).

Other results, shown in Figure 4, show the second syllables. For all speakers, the f0 of the vowel in the second syllable was significantly higher than that of the control syllable (L**L**LL and L**L**LLL) when the AP began with either aspirated or tense consonant (A**L**LL, T**L**LL, A**L**LLL and T**L**LLL). In addition, the f0 of the second syllable was significantly higher than that of the control syllable when the onset of the second syllable had an aspirated or tense onset consonants(LALL, LTLL, LALLL and LTLLL). Figure 4 shows the f0 value of the second syllable in 4- or 5-syllable APs.

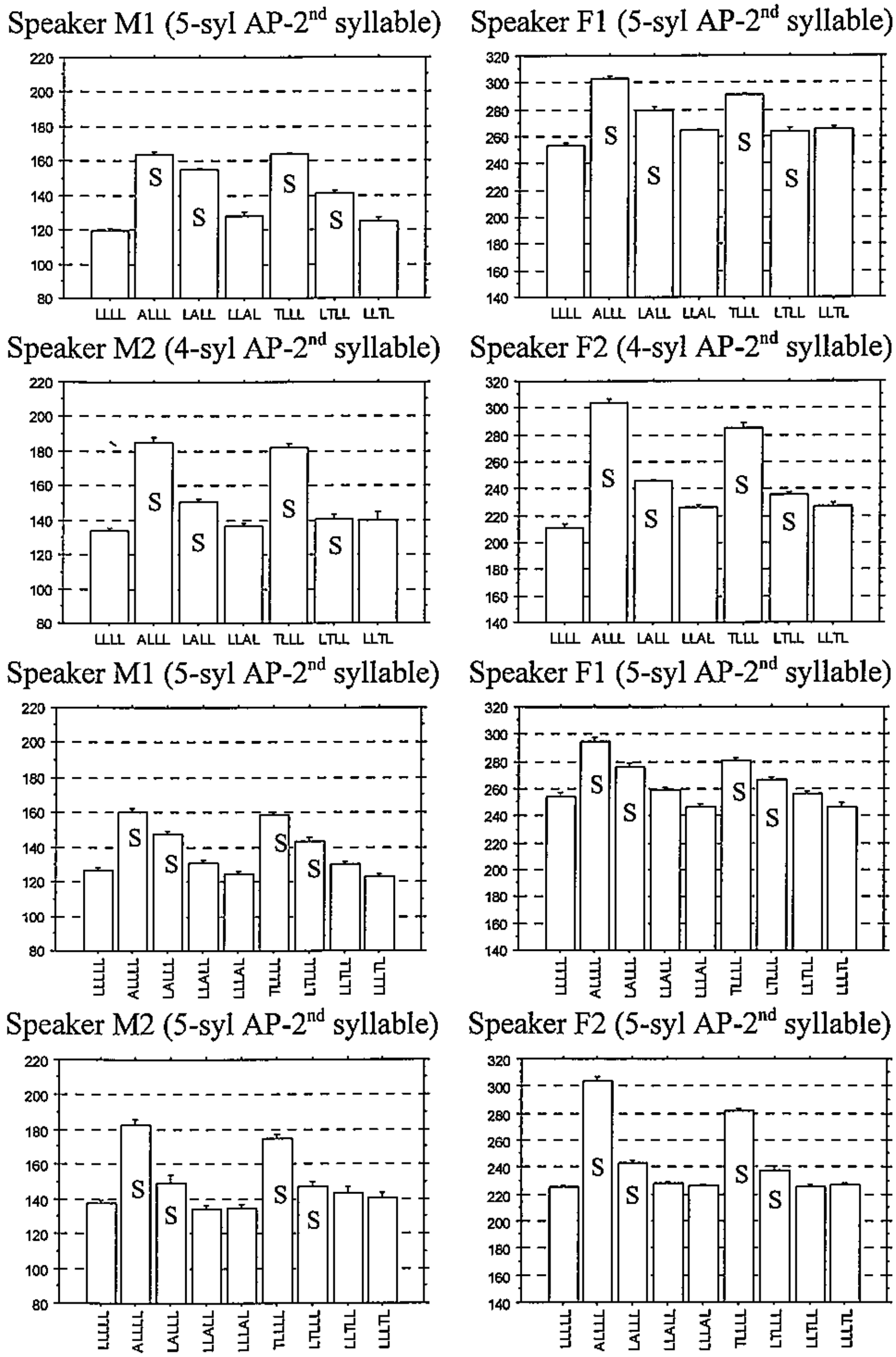


Figure 4. Average f0 value of the 2nd syllable in 4- or 5-syllable APs as a function of the location and type of test consonant in each.

As shown in Figures 3 and 4, all speakers showed f0 raising in the first and second syllables. Crucially, as seen in Figure 4, it should be noted that when the first syllable onset is a tense or aspirated consonant, the f0 of the *second* syllable, with a lax onset (ALLL, TLLL, ALLLL and TLLLL), is substantially higher than the control vowel f0 (LLLL and LLLLL). Furthermore, it is still higher than the f0 of the second syllable vowels with a tense or aspirated onset (LALL, LTLL, LALLL and LTLLL): the f0 of the second syllable of ALLL, TLLL, ALLLL and TLLL is as high as, or sometimes even higher than, that of the first syllable (see Figure 3 and 4 or Appendix 2). This means that AP-initial aspirated or tense obstruents substantially raise the f0 of the second syllable as well as that of the first syllable, and the second H tone in the HHLH pattern does not have the same f0 value as the first H tone in the LHLH pattern in Seoul Korean. That is, the second H tone of HHLH is significantly higher ($p < .001$) than the first H tone of LHLH in Seoul Korean even if the onset consonant of the second syllable (first H of LHLH) has an aspirated or tense onset. Figure 5 shows simplified schematics of the f0s of the first and second syllable of APs.

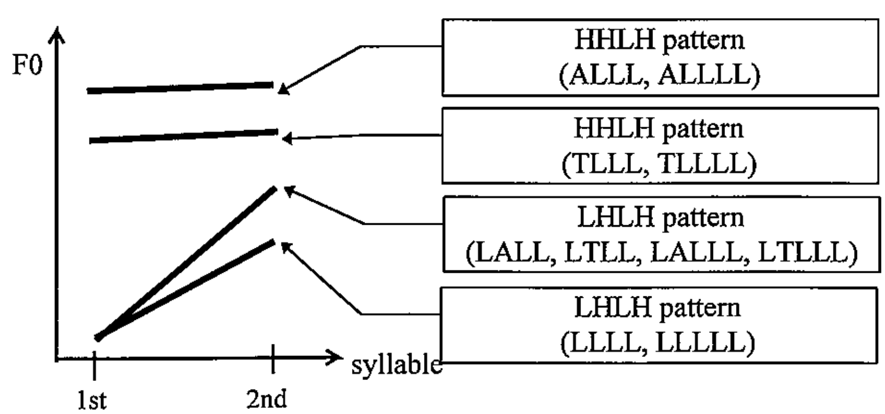


Figure 5. Schematics of f0 targets of the first and second syllables in APs.

As for the difference between APs with an initial aspirated onset and with an initial tense onset, for all speakers, syllables with an aspirated onset (ALLL, ALLLL) had significantly higher f0 values ($p<.05$) than syllables with an tense onset (TLLL, TLLLL) in the first syllable. Also for two out of four speakers, the second syllable of an AP having an initial aspirated onset (A**L**LL, A**L**LLL) was significantly higher ($p<0.05$) than that of an AP having an initial tense onset (T**L**LL, T**L**LLL). Thus, in Section 4, two different implementation rules will be provided for these types (ALLL and TLLL, ALLLL and TLLLL).

In the third syllable of 5-syllable APs, for three out of four speakers (M1, M2, and F2), when the first syllable onset was an aspirated or tense consonant, the f0 of the third syllable vowel with a lax onset (TL**L**LL and AL**L**LL) was still significantly higher than the control vowel f0 (LL**L**LL) and sometimes slightly higher than that of vowels with a tense or aspirated onset consonant (LL**A**LL and LLTLL) (see M1 and F2). The results from each speaker are shown in Figure 6.

However, unlike in the first and the second syllables, the f0 of the third syllable having an aspirated or tense onset consonant (LL**A**LL and LL**T**LL) was not always higher than the control case (LL**L**LL) across speakers. Two speakers (M2 and F2) showed higher f0 after tense or aspirated onset consonants than after lax onset consonants ($p < .05$). M1 and F1 had f0 raising after an aspirated onset consonant but not after a tense onset.

This weakened effect of AP-initial consonant on the third syllable may be due to its position within an AP. In 5-syllable APs of Seoul Korean, a H tone is generally[6] realized on the second syllable and a L tone is realized on the penultimate syllable of an AP (Jun 1996a, to appear), and there is tonal interpolation between those H and L tones. Since the third syllable in a 5-syllable AP is positioned on the interpolation line between the second and the penultimate syllable, the influence of AP-initial consonants on the third syllable f0 seems to be weakened when the consonant is tense consonant. (see F1-5 in Figure 6 where LLTLL (227Hz) is lower than LLLLL (243Hz) and M1-5 where LLTLL is not significantly higher than LLLLL (p = 0.07)).

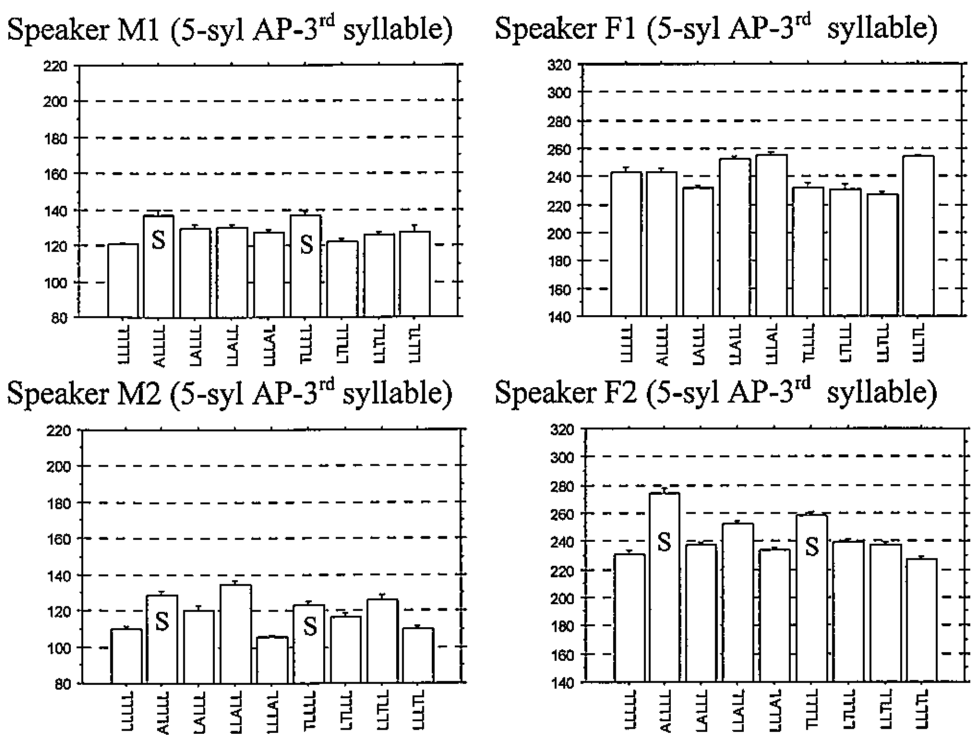


Figure 6. Average f0 value of the 3rd syllable in 5-syllable APs.

[6] Some people realize the initial H tone on the third syllable. In this experiment, the speaker HS displays this pattern in the control AP. See Appendix 2.

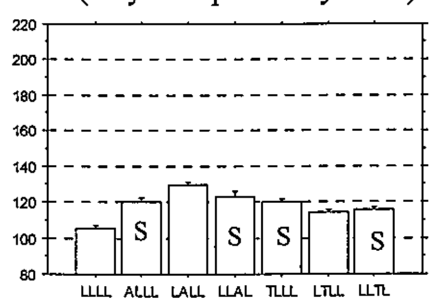
It should also be noted that when the second syllable onset consonant of the AP is an aspirated or tense consonant, the f0 of the third syllable vowel (LA**L**LL and LT**L**LL) is not always significantly higher than the control f0 (LL**L**LL). That is, LA**L**LL and LT**L**LL was not higher than LL**L**LL in Speaker F1-5, LA**L**LL was not significantly higher than LL**L**LL in Speaker F2-5 (p=.08), and LT**L**LL was not significantly higher than LL**L**LL in Speaker M1-5 (p=.07). In addition, even if the third vowel in LA**L**LL or LT**L**LL was higher than the third vowel in the control LL**L**LL in some cases, the f0 difference between them was much smaller than the f0 difference between the second vowel in A**L**LLL or T**L**LLL and the second vowel in the control L**L**LLL. (See Figure 5, where the first syllable onset consonant influenced the second syllable vowel.)

The graphs in Figures 3, 4 and 6 show that raising of f0 values triggered by aspirated and tense consonants in phrase initial, but not phrase medial, position has a consistent and strong effect, especially on the second syllable in 4- and 5-syllable APs. The effect was still present in the third syllable in 5-syllable APs, though not as strong as in the first and second syllables. This f0 raising by aspirated or tense obstruents in Korean seems to confirm Jun (1996b)'s claim that the f0 difference triggered by AP-initial consonants is not due to segmental perturbation as in English and French, but is phonologized, i.e., a phonological aspect of Korean intonational phonology. In other words, aspiration or tenseness at the left edge of a prosodic unit (i.e., AP) influences the tonal realization of the phrase.

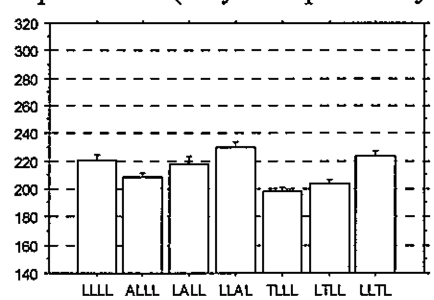
Let us return to the syllable-by-syllable examination. In the penultimate syllable where L tone is realized for both HHLH and LHLH tonal patterns in Seoul Korean, all speakers showed significantly higher ($p<.05$) average f0 for a vowel having an aspirated onset (LLL**A**L) than for a vowel having a lax onset (LLL**L**L) except Speaker F1-4, while the average f0 for a vowel having a tense onset (LLL**T**L) was not always significantly higher than for a vowel having a lax onset (LLL**L**L), shown in Figure 6 below. Thus, a tendency was found that an aspirated onset raises the f0 of the vowel in the penultimate syllable more than a tense onset.

Interestingly, for three of four speakers, the f0 of the penultimate vowel in AL**L**L, TL**L**L, ALL**L**L and TLL**L**L was higher than the control vowel f0 (LLL**L**L). This confirms that aspirated and tense consonants in phrase initial position have a strong effect on the following syllables up to the penultimate, with the effect decreasing after the second syllable of an AP. Mean f0 contours of all syllables are shown in Appendix 2.

Speaker M1 (4-syl AP-penult. syllable)



Speaker F1 (4-syl AP-penult. syllable)



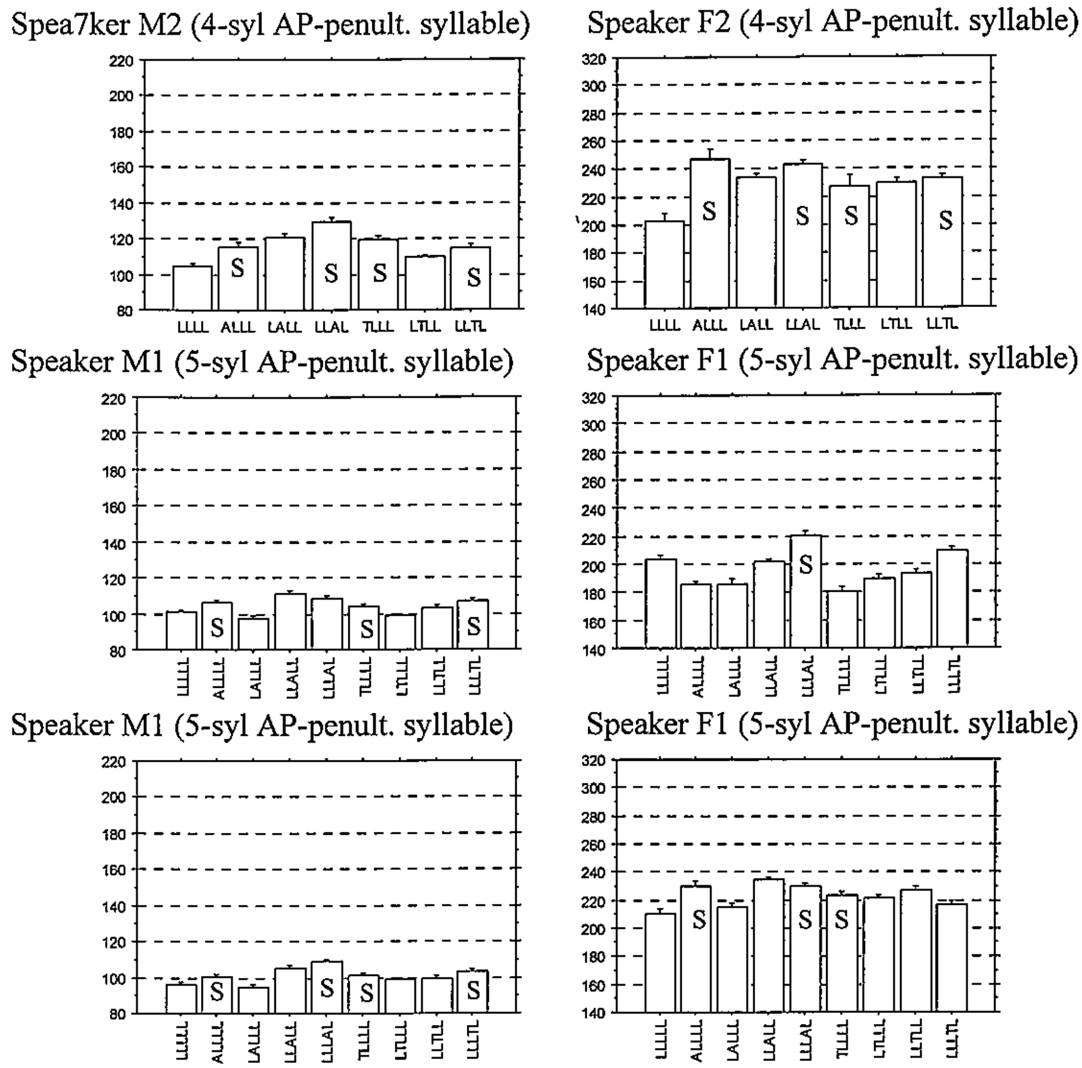


Figure 7. Average f0 value of the penultimate syllable in 4- or 5-syllable APs.

Finally, as for the AP-final syllable, all speakers showed rather consistent f0 values regardless of the differences in the preceding consonant types. Since the final syllable was a particle *-ka,* no aspirated or tense onset was tested for the final syllable as shown in Table 2. However, f0 values were not always significantly different regardless of the types of the preceding consonant (See Table 3, the result from ANOVA): f0 variations were less than 20Hz. (See Appendix 2). Some examples are shown in Figure 8.

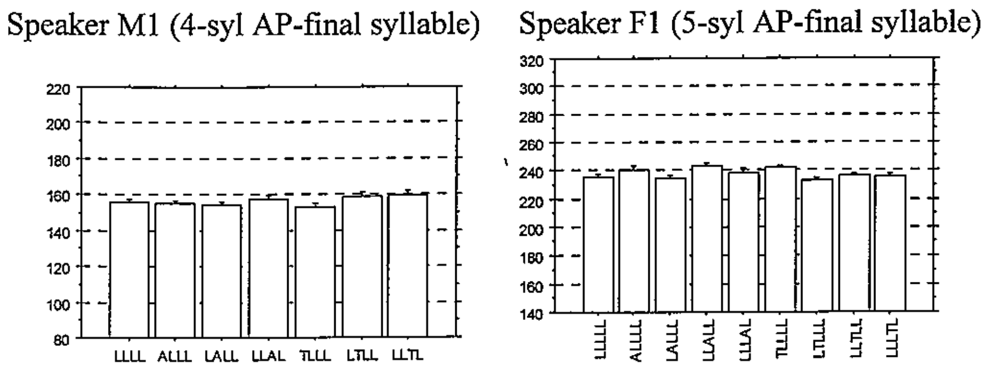


Figure 8. Average f0 value of the final syllable vowel in 4- or 5-syllable APs.

Besides the f0 raising due to the AP-initial consonant, positional f0 differences were found. The measurement showed that the f0 of the vowel was influenced by not only the laryngeal feature of the onset consonant but also by its position in the AP. That is, f0 values of vowels largely varyed along with their syllable position within a prosodic unit (AP).[7] [8] For three out of four speakers (M2, F1, and F2), the f0 values of vowels with an aspirated or tense onset in the second syllable (LA**LL**, LA**LLL**, LT**LL** and LT**LLL**) (partially shown in Figure 4) were significantly lower ($p < .05$) then those with an aspirated onset in the first syllable (**A**LLL, **A**LLLL, **T**LLL and **T**LLLL) (partially shown in Figure 3). Also, for all speakers, the f0 values of vowels after an aspirated or tense onset in the third syllable in 5 syllable APs (shown in Figure 6) and the penultimate syllable in 4 syllable APs (LLAL, LLALL, LLTL and LLTLL) were significantly lower ($p < .05$) then

[7] The influence of the prosodic context on the realization of f0 of a segment (macroprosody) has been shown in previous works (e.g., Silverman (1986), Steele (1986))
[8] Steele (1986: 93) claimed that:

> In a careful consideration of segmental f0, the possibility arises that segmental effects may in some measure interact with the overall prosodic context. That is, not only do the segments affect the overall prosody, but the prosodic context may also affect the segments.

those after an aspirated or tense onset in the first syllable (ALLL, ALLLL, TLLL and TLLLL). This suggests that the consonantal effect on f0 of the vowel in the second, third and penultimate syllables is weaker than that found in the first syllable of 4- or 5-syllable APs. Figure 9 shows f0 values after aspirated and tense consonants in all non-final syllables of an AP. Positional f0 differences for all syllable positions are shown below.

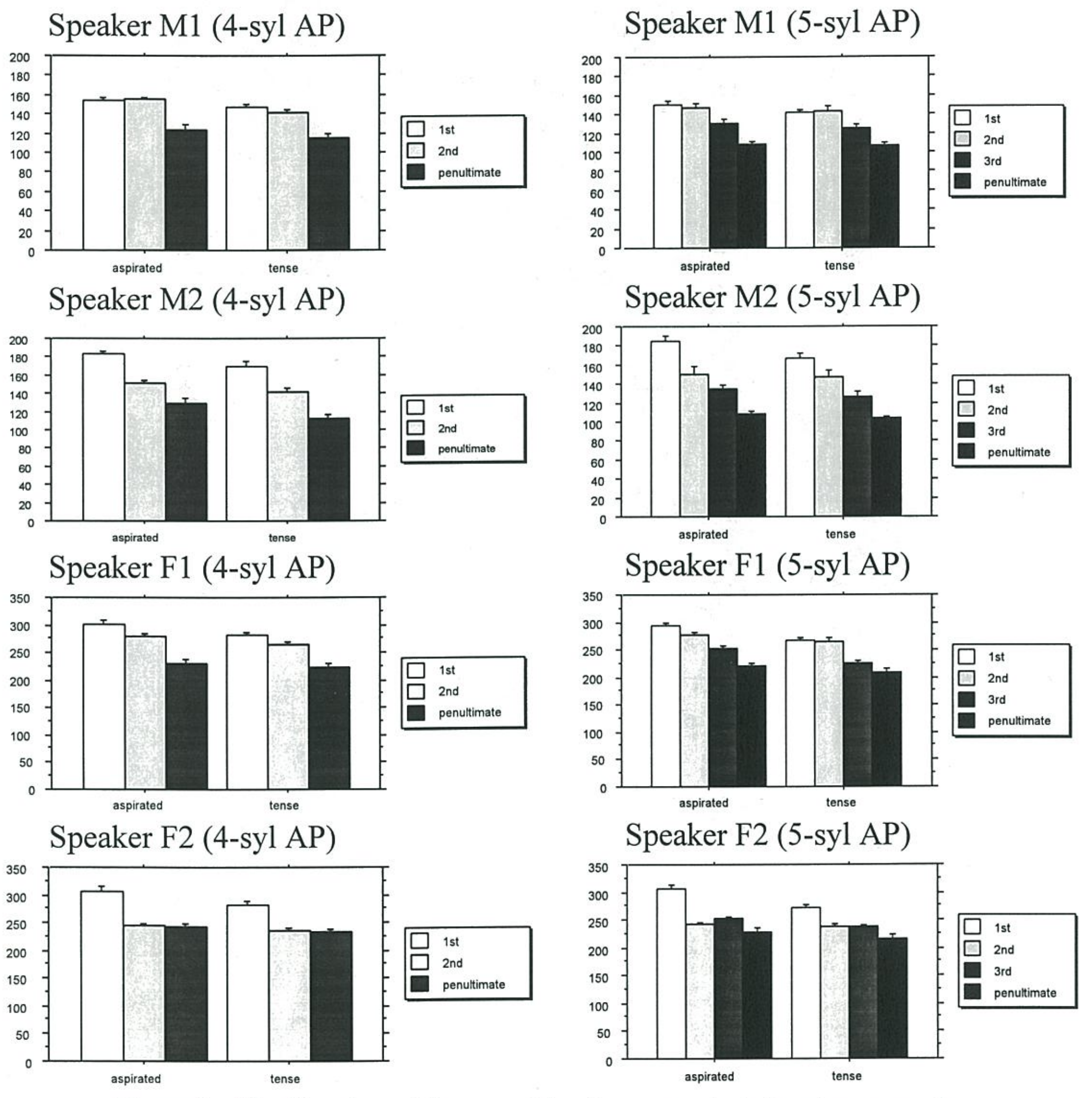


Figure 9. The f0 value of the vowel having an aspirated or tense onset in each syllable position in an AP.

Finally, the average f0 of a vowel having an aspirated onset was always higher than that of a vowel having a tense onset in any syllable position. This may be due to the fact that aspirated consonants have greater subglottal pressure than tense consonants. In previous studies, however, f0 values for aspirated and tense onsets were not always higher than those for tense onsets, as shown in Table 1. Since this study controlled prosodic structure and number of syllables better than previous ones, it is very likely that the f0 of the vowel after aspirated consonants is substantially higher than that after tense consonant.

2.3. Fast speech: results and discussion

In order to observe relative speaking rate, within and across speakers, the duration of the target AP was measured both at normal and fast rates. Table 4 shows the difference between the two rates for all speakers. Speaker F2 showed a smaller difference between normal and fast rates and speaker M2 showed a bigger difference. In general, speakers reduced the duration of target APs approximately 25% at fast rate.

	4-syl			5-syl		
	normal	fast	ratio f/n	normal	fast	ratio f/n
M1	530	436	82%	652	490	75%
M2	647	423	65%	776	529	68%
F1	656	462	70%	718	574	79%
F2	688	520	75%	806	678	84%

Table 5. Mean durations (ms) of target APs in normal and fast speech.

Table 5 shows the maximum and the minimum f0 values of APs to assess the f0 range difference between normal and fast rates. The difference in Hz between the maximum and the minimum will be hereafter called pitch *displacement* (following Fougeron and Jun 1998). In the measurements, the maximum value was usually found at the first or second syllable of a HHLH pattern AP and the minimum value was found at the first or penultimate syllable. This means that for a LHLH pattern AP, the lowest value was found in the first syllable, and for a HHLH pattern AP, the lowest f0 value was found in the penultimate syllable. However, sometimes the lowest value was found in the penultimate syllable for LHLH pattern and the first L tone was not always lower than the second L tone.

For three of four speakers (M1, M2, and F1), the pitch displacement values of 4- or 5-syllable APs were smaller at fast rate than at normal rate.[9] The pitch range was considerably reduced for speaker M2 (21% for 4-syllable APs and 28% for 5-syllable APs) and Speaker F1 (about 15%) at fast rate. Speaker M1 showed about a 16% reduction for 4-syllable APs and about a 4% reduction for 5-syllable APs. On the contrary, speaker F2 showed larger displacement values at fast rate in 5-syllable APs, though she showed smaller displacement values at fast rate in 4-syllable APs. Pitch range reduction at fast rate has also been found in other languages. Fougeron and Jun (1998) showed global lowering of both maxima and minima for two out of three speakers for

[9] For male speakers, all minimum f0 values are slightly raised while maximum f0s are not consistently lowered at fast rate. For female speakers, all maximum and minimum f0 values are lowered at fast rate..

French and Caspers (1994) showed global rising of both maxima and minima at fast rate for Dutch. A reduction of pitch displacement at fast rate was also found in German (Kohler, 1983). The pitch displacements for all speakers are shown in Table 6 below.

		M1		M2		F1		F2	
		normal	fast	normal	fast	normal	fast	normal	fast
4-syl	max	164	165	186	183	303	280	306	284
	min	101	111	104	118	184	181	182	177
	displ.	**63**	**53**	**82**	**65**	**119**	**99**	**124**	**107**
5-syl	Max	160	171	185	171	295	278	304	302
	min	98	111	96	107	186	180	184	151
	displ.	**62**	**60**	**89**	**64**	**109**	**98**	**120**	**151**

Table 6. Maximum and minimum f0 values of 4- or 5-syllable APs.

It can be inferred from the two tables above that speakers show different pitch patterns at the fast rate. At normal rate, APs showed a High-High-Low-High (HHLH) pattern when the AP-initial consonant was a tense or aspirated consonant, or Low-High-Low-High (LHLH) when the AP-initial tone was lax consonant, confirming Jun's proposals about tonal structure of the AP (1993, 1996a,b, to appear). At fast rate, for two of four speakers (M2 and F1), the penultimate L tone was undershot in 4-syllable APs: the pitch differences between the penultimate L tone and adjacent H tones were greatly reduced at fast rate so that the penultimate L tone was positioned between two H tones and had a much higher f0 than that of the penultimate L tone in APs at normal rate. However, for the other two speakers (M1 and F2), the pitch differences between the penultimate L tone and adjacent H tones were not changed at fast rate. Speaker M1 showed almost the same penultimate L tone values both at normal and fast rates and speaker F2 showed the same or lower L tone values at fast rate.

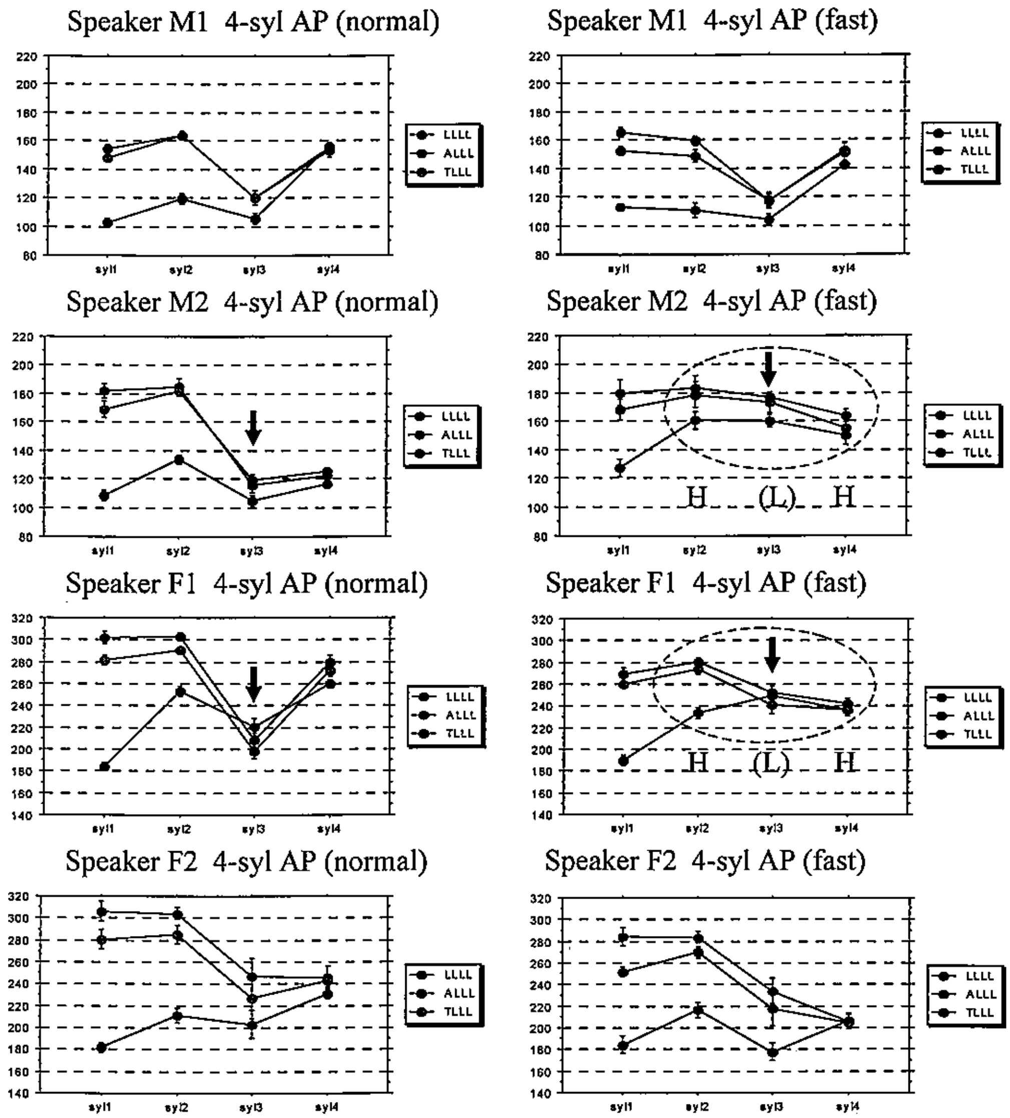


Figure 10. Tonal patterns of 4-syllable APs at normal rate and at fast rate.

For all speakers, final H became less apparent at fast rate. That is, the difference between penultimate L tone and the final H tone was reduced at fast rate compared to normal rate. Speakers M2 and F1 showed the penultimate L tone undershoot; the final H tone was raised in M2 4-syl AP and the final H tone in F1 4-syl AP was lowered at fast rate, so that their tonal patterns look quite similar at fast rate (LHH).

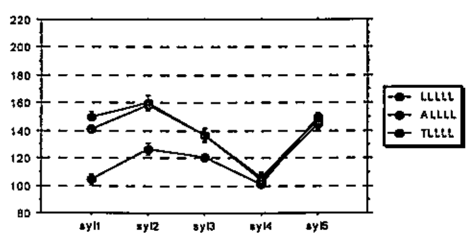
Speaker F2 did not show the penultimate L tone undershoot in control AP (LLLL), while the penultimate L tone in APs with an aspirated or tense onset (ALLL and TLLL) seemed to be undershot. However, actually the APs with an aspirated or tense onset (ALLL and TLLL) in F2 4-syl AP were dephrased, and they formed a new AP with following AP(s). Thus, ALLL and TLLL in F2 4-syl AP could not be considered as undershoot cases, since the test AP did not form a whole AP, but a part of the new AP composed of the test AP and the following AP(s), and the L tone was assigned to the penultimate syllable of the new AP. In f0 implementation, these dephrased test APs should be excluded in undershoot counting.

Here a question may be raised: why do Speaker M2 and F1 show the penultimate L tone undershoot while speaker M1 and F2 do not? One possibility is the durational difference between the speakers: the shorter duration, the more undershoot. Speaker F1 showed shorter APs than speaker F2. However, Table 3 shows nearly the same duration of APs at fast rate for speakers M1 and M2 (436ms for speaker M1 and 423ms for speaker M2). Thus, it seems that duration is not a critical factor which determines the penultimate L tone undershoot.

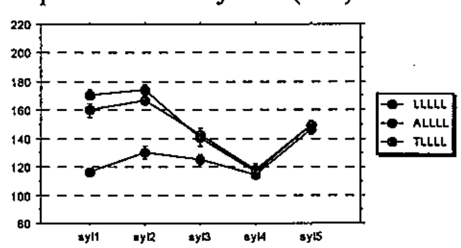
Instead of considering the absolute value of duration, if we consider the relative duration of APs at normal and fast rates, we can see that penultimate L tone undershoot is closely related to the proportional increase in speed. Speaker M2 reduced the duration about 35 % at fast rate and speaker F1 reduced about 30%, while speaker M1 and F2 reduced just 18% and 25%, respectively. Thus, we hypothesize that the penultimate L tone is undershot only for speakers showing more than 30% reduction at fast rate. It should be noted that speaker M2 (35% reduction) showed more undershoot - three tones in the circle were more flat - than for the speaker F1 (30% reduction), while speaker F2 (25% reduction) showed no undershoot for control APs (LLLL) and dephrasing for APs with an aspirated or tense onset (ALLL and TLLL) and speaker M1 (18% reduction) showed no undershoot for any APs.

As for 5-syllable APs, only one speaker, M2, showed the penultimate L tone undershoot at fast rate. Note that speaker M2 was the only person who showed more than 30% of pitch reduction (32%) at fast rate while speaker F1 reduced about 21% and showed virtually no undershoot in 5-syllable APs. This confirms that the penultimate L tone undershoot is closely related to the ratio of speech rate change rather than the absolute speed.

Speaker M1 5-syl AP (normal)



Speaker M1 5-syl AP (fast)



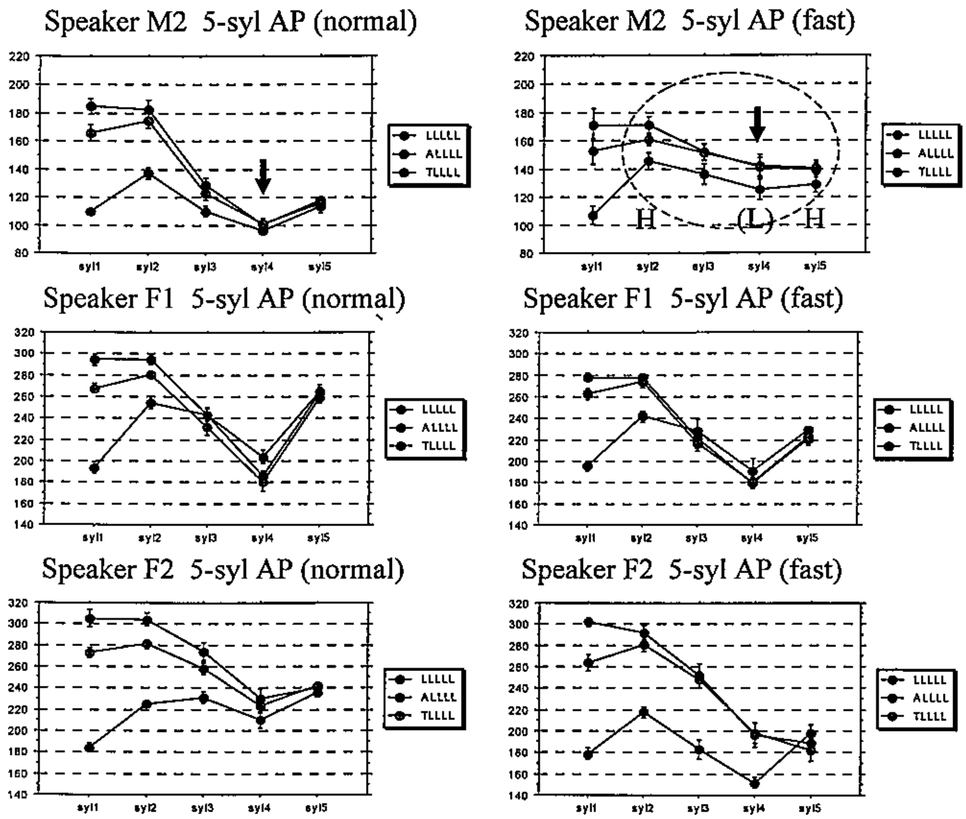


Figure 11. Tonal patterns of 5-syllable APs at normal rate and at fast rate.

Strictly speaking, the penultimate L tone was slightly raised for speaker M1 who showed 25% reduction at fast rate; thus the penultimate L tone seems to be undershot. However, unlike M2 5-syl AP where the penultimate L tone was much higher than the first L tone at fast rate, the first L tone in M1-5 was also slightly raised at fast rate and their values were almost the same. Therefore, we do not want to regard this M1 case as real undershoot. In addition, since speaker F2 also showed dephrasing for APs having an aspirated or tense onset (ALLLL and TLLLL) in 5-syllable APs, these APs were not considered as undershoot cases, as we discussed in 4-syllable APs.

From Figures 10 and 11, we can see that as the AP becomes longer, the tendency for the penultimate L tone to be undershot at fast rate is weakened. Speaker M2 showed 35% reduced duration in 4-syllable APs at fast rate and the penultimate L tone was undershot with a slightly higher value than the final H tone. However, in 5-syllable APs, although this speaker showed 32% reduced duration, the penultimate L tone was undershot to a lesser degree and still lower than the preceding H tone. This proves that the H tone preceding the penultimate L tone is substantially associated with the second syllable, thus giving enough time for the penultimate L tone to reach the target, where there is an extra syllable (the third syllable) in the 5-syllable AP. That is, there is a longer transition time between the H tone in the second syllable and the L tone in the penultimate syllable in 5-syllable APs than 4-syllable APs. Thus, the penultimate L tone is not easily undershot as found in 4-syllable APs, even when the speech rate is faster.

Now let us discuss the f0 raising of following vowels triggered by an AP-initial aspirated or tense consonant, at fast rate. All speakers showed almost the same results as those found at normal rate, though there was a slight difference in the penultimate syllable of 5-syllable APs. Measurements showed that initial tense or aspirated consonants not only raised the f0 of the immediately following vowel, but also the f0 of the vowels in the following non-adjacent syllables, as noticed in the APs spoken at normal rate. That is, a tense or aspirated onset consonant in the first syllable raised f0 values of the following adjacent segment and this effect persisted through the following non-adjacent syllables spoken at fast rate.

For all speakers, the f0 of the vowel in a first syllable with a tense or aspirated onset (ALLL, TLLL, ALLLL and TLLLL) was slightly higher in a second syllable than the vowel with a lax onset consonant (LLLL and LLLLL). The f0 raising effect was so strong that the f0 of the following syllable having a lax onset (ALLL, TLLL, ALLLL and TLLLL) was still higher than the second syllable of the control AP (LLLL and LLLLL) and APs having an aspirated or tense onset in the second syllable (LALL, LTLL, LALLL and LTLLL). Some examples of the speaker M1 and F1 are shown in Figure 12 below. [10]

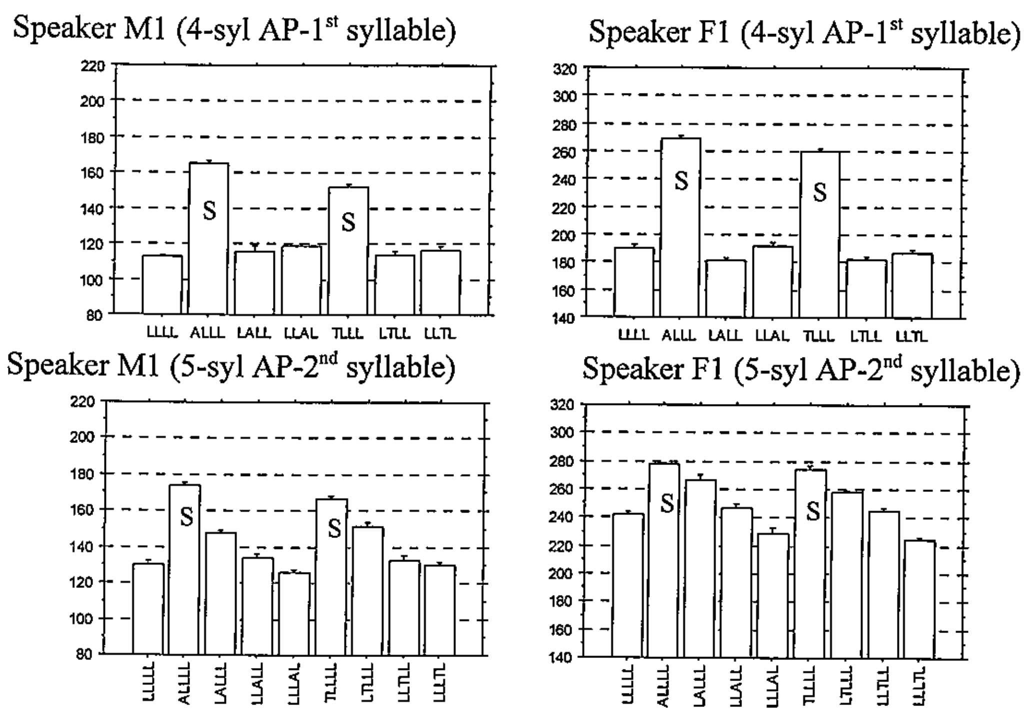


Figure 12. Some average f0 value of the 1st and 2nd syllable vowels in 4- or 5-syllable APs at fast rate.

[10] Like graphs in section 2.1, data from stops + affricates are also pooled together in the following graphs since all speakers show similar tonal patterns triggered by stops and affricates and do not show consistent differences at fast rate.

In the third syllable of 5-syllable APs, for three out of four speakers (M1, M2, and F2), when the first syllable onset is an aspirated or tense consonant, the f0 of the third syllable vowel with a lax onset (TL**L**LL and AL**L**LL) was still significantly higher than the control vowel f0 (LL**L**LL). However, the f0 of the third syllable vowel with a lax onset (TL**L**LL and AL**L**LL) was not always higher than that of third syllable vowels with a tense or aspirated onset (LL**A**LL and LL**T**LL). The results from each speaker are shown in Figure 13.

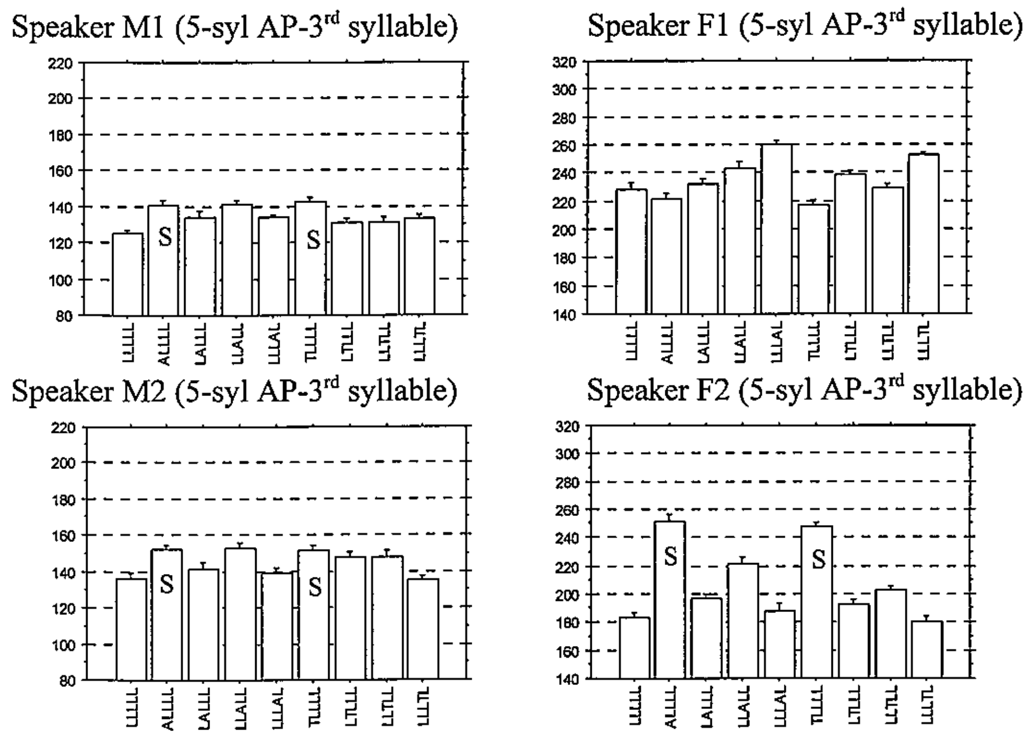
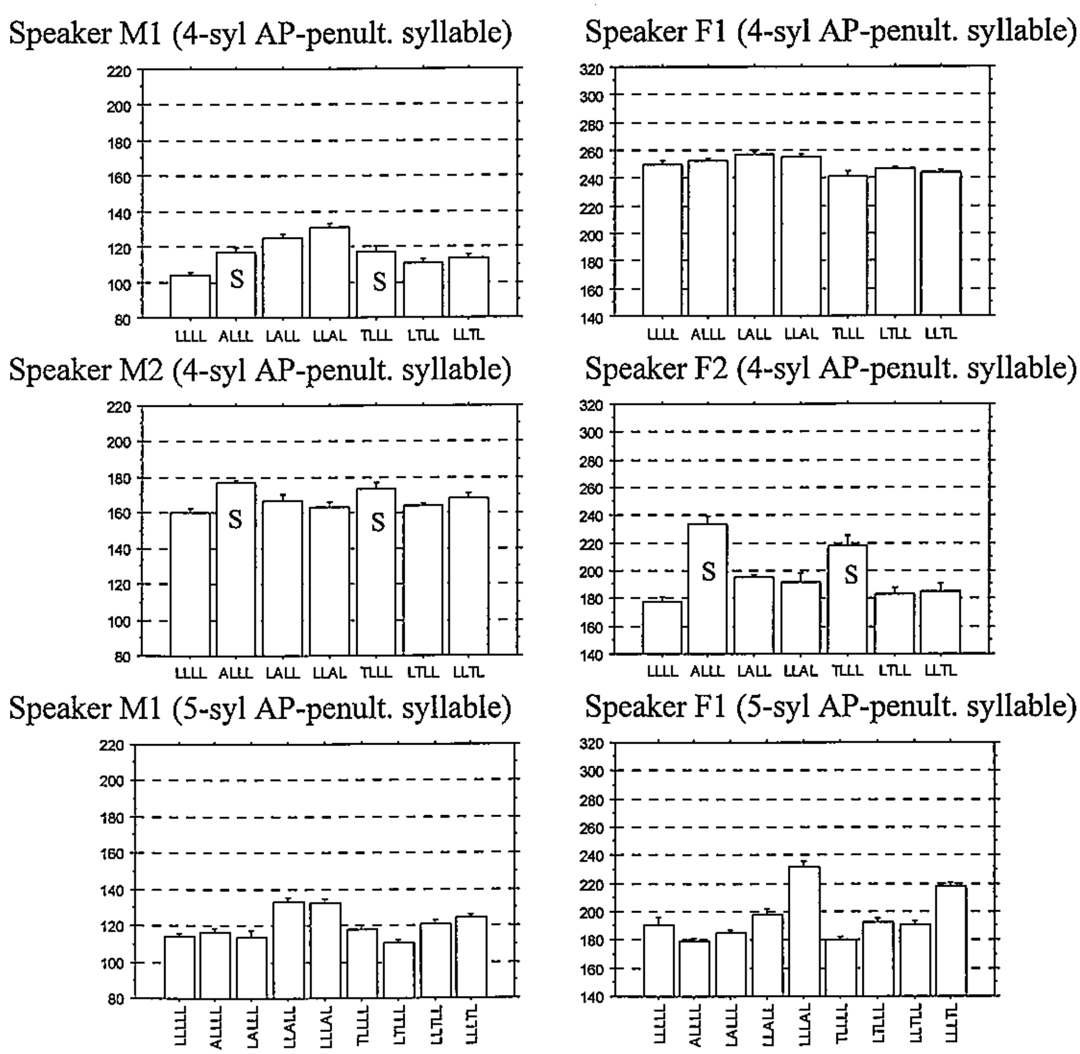


Figure 13. Average f0 value of the 3rd syllable vowel in 5-syllable APs at fast rate.

In the penultimate syllable, for three out of four speakers (M1, M2 and F2), the f0 of the penultimate vowel in AL**L**L, TL**L**L, ALL**L**L and TLL**L**L was significantly higher than the control vowel f0 (LLLLL) in 4-syllable APs. And for two out of four speakers

(M2 and F2), the f0 of the penultimate vowel in ALLL, TLLL, ALLLL and TLLLL was significantly higher than the control vowel f0 in 5-syllable APs. Speaker M1 did not show significant f0 raising in the penultimate syllable in 5-syllble APs at fast rate, while he showed a significant effect at normal rate (See Figure 7). Thus it seems clear that the AP-initial consonants affect non-adjacent following syllables, up to the penultimate with lesser degree, at fast rate.



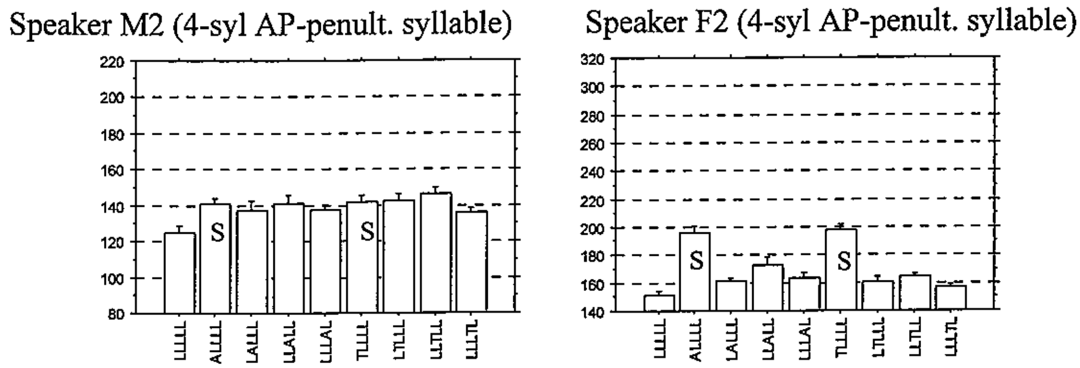


Figure 14. Average f0 value of the penultimate syllable vowel in 4- or 5-syllable APs at fast rate.

Finally, as for the AP final syllable, all speakers also showed consistent f0 values regardless of differences in preceding consonant types at fast rate, as shown in normal rate (cf. Figure 8).

In summary, speakers showed f0 raising after an AP-initial aspirated or tense consonant at fast rate as well as at normal rate. This means that AP-initial aspirated and tense consonants have a strong effect on the following syllables up to the penultimate at fast rate, with the effect decreasing after the second syllable of an AP.

3. Experiment 2: Consonantal and speech rate effects in APs composed of *real* words

3.1. Methods

To confirm that AP-initial consonant effects on f0 values of the following syllables and the tonal realization of the Korean AP are not limited to the nonsense words, 4- and 5-syllable APs composed of *real* words were examined in Experiment 2. Each target AP was placed at the beginning of a carrier sentence: "_______ tʃəkiɛ issə" (___ is there.). Since Experiment 1 showed no significant difference between affricates and stops, affricates and stops were randomly used in the target APs. Only one syllable in an AP had a tense or aspirated onset consonant and other syllables had lax onsets or no onset. The target APs are shown in Table 7.

	Types	symbol	APs(Stop + Affricate)	
4-syllable AP	aspirated	asp1	tʰa.i.ə.ka	'a tire'
		asp2	kyo.tʃʰa.ro.ka	'a cross-section'
		asp3	tʃa.doŋ. tʃʰa.ka	'a car'
	tensed	tns1	t'a.o.ki.ka	'a crested ibis (bird)'
		tns2	po.t'a.ri.ka	'a sack'
		tns3	ka.ip.tʃ'a.ka	'a member'
5-syllable AP	aspirated	asp1	tʃʰa.dʒən.no.ri.ka	'a group sport'
		asp2	ki.tʃʰa.no.ri.ka	'a train-like playing'
		asp3	ki.ne.tʰa.ki.ka	'a swing'
		asp4	pul.tʃ a.toŋ.tʃʰa.ka	'a fire engine'
	tensed	tns1	t'a.ra.o.ki.ka	'following'
		tns2	pæ.t'a.ra.ki.ka	'the name of a novel'
		tns3	man.won.tʃ'a.ri.ka	'10,000 won cash'
		tns4	yaŋ.tʃo.əp.tʃ'a.ka	'a brewer'

Table 7. 4- and 5-syllable real word APs where one of the syllables has either an aspirated or tense onset and the rest syllables have lax or sonorant or zero onsets. 'aspX' refers to the AP having an aspirated onset in the Xth syllable and 'tnsX' refers to the AP having a tense onset in the Xth syllable. *-ka* is a particle as a subject marker which attaches to the end of the word in Korean.

As shown in Table 5 above, the target APs are not fully controlled since it is impossible to find real word APs which have only one aspirated/tense onset in one syllable and lax onsets in all other syllables.

The speakers who participated in Experiment 1 (two male (DO and HJ) and two female (HA and HS)) were recorded. The data were recorded, measured and statistically analyzed in the same way as described in Experiment 1.

3.2. Results and discussion

Measurements showed that AP-initial tense or aspirated onset consonants also raised f0 values of the following adjacent vowel, and when they were positioned in the first syllable onset of an accentual phrase, they continuously raised f0 values of the following non-adjacent vowels. That is, at normal rates, for all speakers, when the first syllable onset was an aspirated or tense consonant, the f0 of the second vowel with a lax onset (asp1 and tns1) was significantly higher than the vowel having a lax onset and still higher than that of vowels with a tense or aspirated onset consonant (asp2, tns2). Figure 15 shows average f0 values of 4- and 5-syllable real word APs at normal rate.

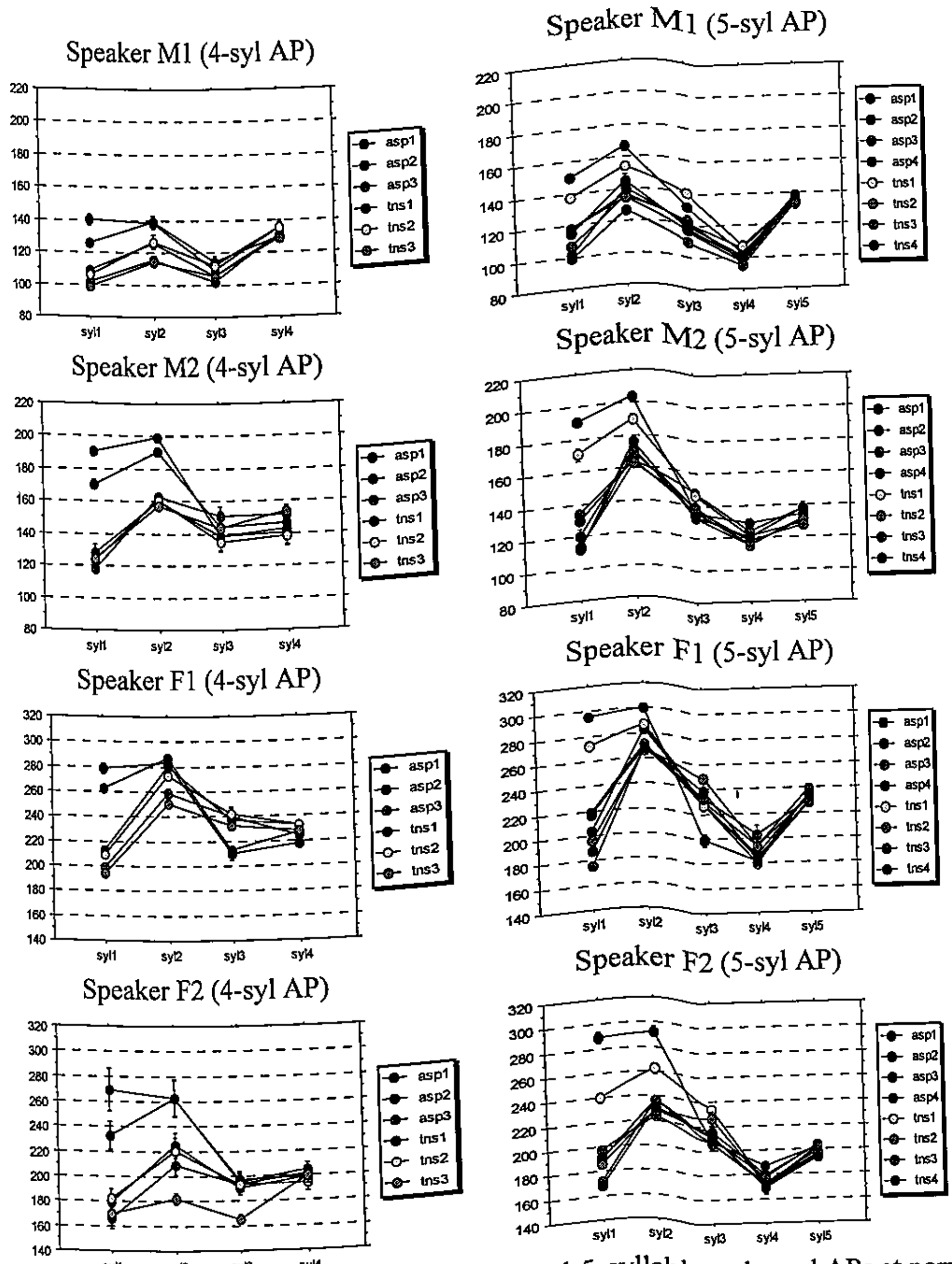


Figure 15. Average f0 values of each syllable in 4- and 5-syllable real word APs at normal rate.

However, unlike the results in Experiment 1, the initial consonant effect was rather weak after the second syllable. As for the third and penultimate syllables, speakers generally did not show f0 raising when the AP begins with an aspirated or tense consonant, except for one case, M1 5-syl AP. In Figure 15, the third and penultimate syllables show that the f0 values of the vowels having an AP-initial aspirated or tense consonant (asp1 and tns1) are not significantly higher than others. In experiment 1, we saw the AP-initial consonantal effects are weakened after the second syllable, though three out of four speakers showed significant f0 raising in the third and penultimate syllables. The difference between the two experiments may be due to differences in how carefully word structure is controlled[11]. However, the results shown above still confirm that AP-initial consonant effects on the following non-adjacent syllables are general characteristics of Korean APs, and not limited to the nonsense word APs.

Next, let us consider real word APs at fast rate. All speakers showed that f0 of a first syllable having an aspirated or tense onset is significantly higher than that of a first syllable having a lax onset. Also when the first syllable onset was an aspirated or tense consonant, the f0 of the second vowel with a lax onset (asp1 and tns1) was significantly higher than the vowel having a lax onset (asp3, tns3, asp4 and tns4). However, when the first syllable onset is an aspirated or tense consonant, the f0 of the second vowel with a lax onset (asp1 and tns1) was not always higher than that of vowels with a tense or aspirated onset consonant (asp2, tns2) (See M1 4-syl AP, M1 5-syl AP). In addition, for three of four speakers (M1, M2, F1), AP-initial consonant effects almost disappeared after the second syllable. Thus, similar trend was found in APs at both normal and fast rates.

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[11] Or, there may be a nonsense word effect. More experiment is needed.

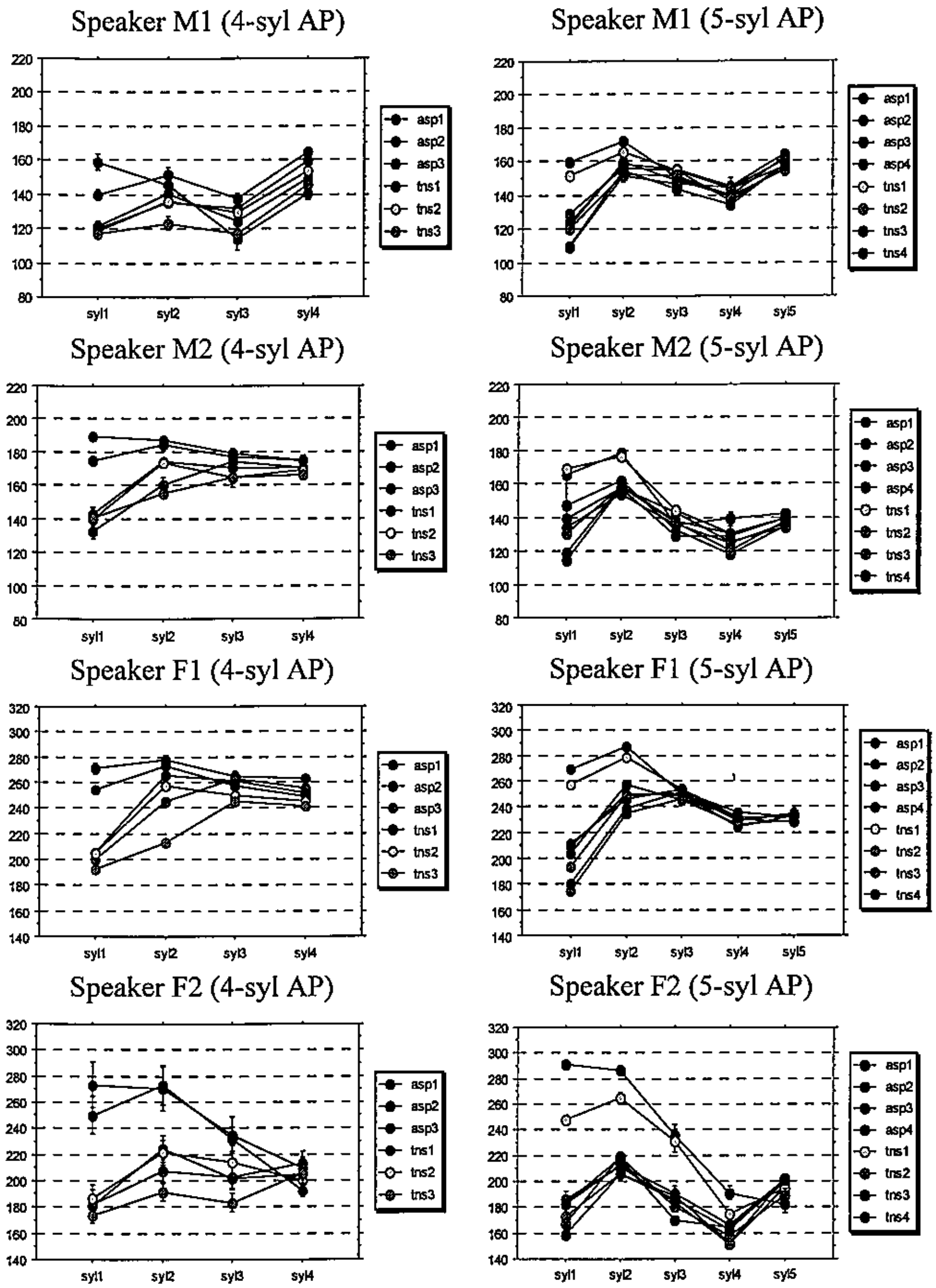


Figure 16. Average f0 values of each syllable in 4- and 5-syllable real word APs at fast rate.

As for penultimate L tone undershoot, we saw in Experiment 1 that there was a tendency for the penultimate L tone to be undershot when the speaker reduced the duration of an AP about 30% at fast rate (section 2.3.). Table 8 shows durations of target APs.

	4-syl			5-syl		
	normal	fast	ratio f/n	normal	fast	ratio f/n
M1	530	381	72%	610	447	73%
M2	535	379	70%	654	454	69%
F1	632	382	60%	708	476	67%
F2	642	452	70%	816	565	69%

Table 8. Mean durations (ms) of target APs in normal and fast speech.

For three out of four speakers (M2, F1, F2), the duration of an AP is reduced more than 30% at fast rates and the penultimate L tone was undershot. Speaker F1 showed great reduction in 4-syllable APs (40%) and 5-syllable APs (33%). All speakers showed the penultimate L tone undershoot, except F2 5-syl AP.

It is interesting to see the pitch range change of real-word APs. In Experiment 1, three out of four speakers showed pitch range reduction. In Experiment 2, only two speakers (M2, F1) showed pitch range reduction in both 4- and 5-syllable APs: speaker M1 showed pitch range reduction in Experiment 1 whereas he showed pitch range extension in Experiment 2.

		M1		**M2**		**F1**		**F2**	
		normal	fast	normal	fast	normal	fast	normal	fast
4-syl	**max**	140	164	199	189	287	277	262	273
	min	99	114	118	132	194	192	166	174
	displ.	**41**	**50**	**81**	**57**	**93**	**85**	**96**	**99**
5-syl	**Max**	160	172	203	178	300	287	292	290
	min	99	109	112	114	176	174	170	167
	displ.	**61**	**63**	**91**	**64**	**124**	**113**	**122**	**123**

Table 9. Maximum and minimum f0 values of 4- or 5-syllable APs.

To summarize, initial consonant effects were found in real word APs, especially in the first and second syllables. That is, AP-initial tense or aspirated onset consonants raised f0 values of the following adjacent vowel, and when they were positioned in the first syllable onset of an accentual phrase, they continuously raised f0 values of the non-adjacent vowels in the second syllable. Though some results were different from the previous results and initial consonantal effects were not as strong as in Experiment 1, in general, the data in Experiment 2 confirmed the results in Experiment 1.

4. Implementation of 4- and 5-syllable APs in Korean

So far we have seen that f0 raising triggered by aspirated and tense consonants in phrase initial position had a consistent and strong effect through the second syllable and even the third and penultimate syllables in 4- or 5-syllable APs. But the influence of an aspirated or tense consonants was found to be limited to its own syllable when the consonant was in the middle of an AP. These segmental effects on f0 were rather clearly shown in the nonsense corpus, but were somewhat inconsistent after the second syllable in real word corpus probably due to uncontrolled segmental contexts. Therefore, we will use the nonsense word data rather than the real word data as the basis for implementing the f0 of the Korean AP.

To provide f0 implementation rules for Korean APs, we will use linear regression analysis. Regression analysis describes the way in which one variable is related to the other. That is, regression analysis derives an equation which can be used to estimate the unknown value of one variable (e.g., f0 of the second syllable) on the basis of the known value of the other (e.g., f0 of the first syllable). Linear regression analysis has been used in various implementation studies. Liberman and Pierrehumbert (1984) used linear regression to predict f0 peaks among downstepped phrases in English, Pierrehumbert and Beckman (1988) used linear regression with pitch range normalization to predict f0 targets in Japanese, and Black and Hunt (1996) used linear regression to predict three f0 targets (at the beginning, mid, and end) of each syllable of a word in Japanese.

The data presented in section 2 give useful cues for the implementation of the AP in Korean. It was shown that, at normal rate, the f0 of the first syllable having a lax onset (LALL, LTLL, LLAL, LLTL, LALLL, LTLLL, LLALL, LLTLL, LLLAL, and LLLTL) was very consistent compared to f0 variation in the second (and the third in 5-syllable APs) syllable. The f0 of the final syllable was also consistent, but will not be considered as a basis of implementation since no segmental variation was given to the final syllable. Thus, we will use the f0 of the initial syllable with a lax onset consonant as a starting point. Knowing the initial vowel f0 with a lax onset consonant, the remainder of the intonation pattern seems to be predictable by linear regression. An example of regression plot between the first and the second syllables of control APs is shown in Figure 17.

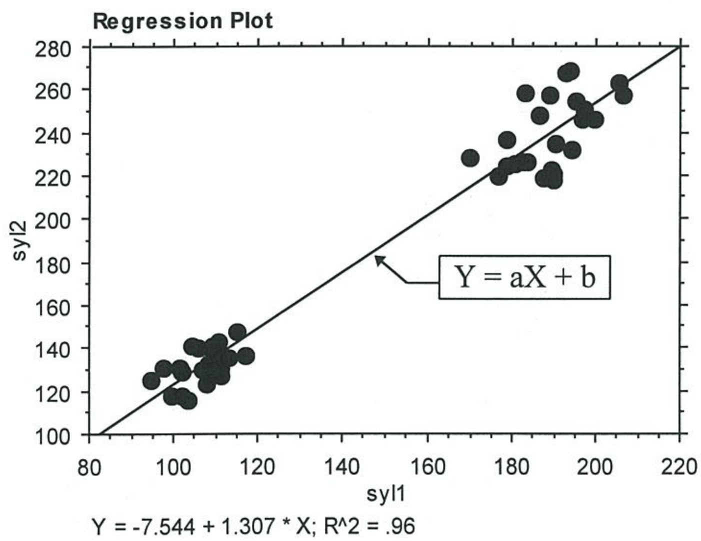


Figure 17. An example of linear regression plot. X-axis represents the f0 of the first syllable and Y-axis represents the f0 of the second syllable in the control APs (LLLL). The straight line represents the predicted relationship between two variables.

The same method has been applied to the other syllables in the control APs. That is, in each two-dimensional plot, the initial syllable f0 values of default APs (LLLL, LLLLL) were plotted on the X-axis and the f0 values of the third, penultimate or final syllable were plotted on the Y-axis. The predicted relationship was a straight line (as shown in Figure 17). Since this line showed 'predicted' values, the value of actual data was not always on the line but scattered on the plot. The formula of this line is in (1).

(1) $Y = aX + b$

Y : predicted f0 value of the second (or third, penultimate, final) syllable
X : f0 value of the first syllable of default APs
a : slope
b : intercept

Linear regression also gives R squared value (R^2) which means the proportion of the explained variance ($0 \leq R^2 \leq 1$) in the predicted values that is accounted for by the straight line (1). We can see f0 variances predicted by the straight line are very small since all R squared values in Table 10 are around 0.9.

	4-syl			5-syl			
	2nd	penult.	Final	2nd	3rd	penult.	final
slope	1.35	1.34	1.37	1.30	1.44	1.27	1.41
intercept	-15.46	-36.15	-7.67	-7.54	-37.68	-35.46	-17.8
R^2	.907	.925	.873	.960	.951	.931	.898

Table 10. A summary of slope and intercept values of correlation between the f0 value of the first syllable and that of other syllables in control APs (LLLL, LLLLL).

To test how successfully this model predicts f0 values of non-initial syllables, given the f0 value of the first syllable of a control AP, the slope and intercept values (in Table

10) were inserted into the formula (1). The results are shown in Table 11, with the f0 value of the first syllable given as 110Hz.

4-syllable AP (LLLL)		5-syllable AP (LLLLL)	
1st syl: (given)	**110** (Hz)	1st syl: (given)	**110** (Hz)
2nd syl: 1.35 * 110 - 15.46 =	**133** (Hz)	2nd syl: 1.30 * 110 - 7.54 =	**135** (Hz)
penult. syl: 1.34 * 110 - 36.15 =	**111** (Hz)	3rd syl: 1.44 * 110 - 37.6 =	**120** (Hz)
final syl: 1.37 * 110 - 7.67 =	**143** (Hz)	penult. syl: 1.27 * 110 - 35.4 =	**104** (Hz)
		final syl: 1.41 *110 -17.8 =	**137** (Hz)

Table 11. Examples of the f0 prediction calculated by the regression formula.

Now we have all f0 values of the default AP. The next step is to predict the f0 values of APs having an initial aspirated or tense onset (ALLL, TLLL, ALLLL, and TLLLL). There are two possible ways to implement HHLH pattern APs. One way is the f0 prediction of a HHLH pattern AP from a LHLH pattern AP (control AP) and the other way is the f0 prediction of other syllables of a HHLH pattern AP from the initial f0 of a HHLH pattern AP. we will try the former way first and then try the latter way.

In each two-dimensional plot, the average f0 values of a syllable in default APs (LLLL and LLLLL) were plotted on the X-axis and the f0 values of the same syllable of the APs having an initial aspirated or tense onset (ALLL, TLLL, ALLLL and TLLLL) were plotted on the Y-axis. The results of linear regressions are summarized in Table 12.

		4-syl			5-syl			
		1st	2nd	penult.	1st	2nd	3rd	penult.
asp	slope	1.76	1.13	.83	1.60	1.13	1.01	.974
	intercept	-17.89	35.5	33.35	-4.16	24.6	17.512	6.71
	R^2	.989	.922	.894	.963	.939	.943	.941
tns	slope	1.58	1.02	.99	1.41	1.02	.93	.92
	intercept	-9.36	46.99	15.81	2.46	33.87	23.12	11.37
	R^2	.994	.944	.878	.977	.962	.949	.937

Table 12. A summary of slope and intercept values of correlation between the f0 value of the default APs (LLLL, LLLLL) and APs having an initial aspirated or tense onset (ALLL,TLLL,ALLLL, TLLLL).

Since, as shown in Section 2, all speakers showed that f0 of APs having an initial aspirated onset was significantly higher than that of APs having an initial tense onset at the first syllable ($p<.001$) and average f0 of each syllable of APs having an initial aspirated onset was always higher than APs having an initial tense onset, these APs were plotted separately.

To implement APs having an initial aspirated or tense onset, we need another formula. The formula in (2) is basically the same as the formula in (1), but with different slope and intercept values (seen in Table 12).

(2) $Y' = cX' + d$

Y': predicted f0 value of the syllable having AP initial aspirated/tense onset
X': default f0 value (LLLL, LLLLL) calculated by formula (1)
c : slope
d : intercept

In Table 10, we already got all f0 values of default (LLLL, LLLLL) APs. With these f0 values of a control AP, we can predict f0 of each syllable in APs having an initial aspirated or tense onset. The f0 of each syllable in APs having an initial aspirated or tense onset was calculated by Formula (2). Table 13 shows predicted f0 values of APs having an initial aspirated or tense onset.

LLLL: 110(1st), 133(2nd), 111(penult.), 143(final) ← From Table 11

4-syllable AP (ALLL)		4-syllable AP (TLLL)	
1st syl: 1.76 * 110 - 17.89 =	**175** (Hz)	1st syl: 1.58 * 110 - 9.36 =	**164** (Hz)
2nd syl: 1.13 * 133 + 35.5 =	**185** (Hz)	2nd syl: 1.02 * 133 + 46.99 =	**182** (Hz)
penult. syl: .99 * 111 + 15.81 =	**125** (Hz)	penult. syl: .83 * 111 + 33.35 =	**125**(Hz)
final : (the same as default) =	**143** (Hz)	final : (the same as default) =	**143** (Hz)

LLLLL: 110(1st), 135(2nd), 120(3rd), 104 (penult.), 137(final) ← From Table 11

5-syllable AP (ALLLL)		5-syllable AP (TLLLL)	
1st syl: 1.60 * 110 - 4.16 =	**171** (Hz)	1st syl: 1.41 * 110 - 2.46 =	**152** (Hz)
2nd syl: 1.13 * 135 + 24.6 =	**177** (Hz)	2nd syl: 1.02 * 135 + 33.87 =	**171** (Hz)
3rd syl: 1.01 * 120 + 17.51=	**138** (Hz)	3rd syl: .93 * 120 + 23.12 =	**134** (Hz)
penult. syl: .97* 104 +6.71 =	**107** (Hz)	penult. syl: .92 * 104 +11.37 =	**107** (Hz)
final : (the same as default) =	**137** (Hz)	final : (the same as default) =	**137** (Hz)

Table 13. Examples of f0 values of syllables in APs having an initial aspirated or tense onset (ALLL, TLLL, ALLLL, and TLLLL) predicted by formula (2).

Note that the same value was used for the final syllable of all APs since speakers did not show consistent f0 difference at the final syllable in Experiment 1.

Figure 18 shows tonal patterns of APs predicted in Tables 11 and 13. The control APs (LLLL and LLLLL) show LHLH patterns and APs having an initial aspirated or tense onset show HHLH patterns. That is, the predicted f0 contours show the actual tonal patterns of Korean APs.

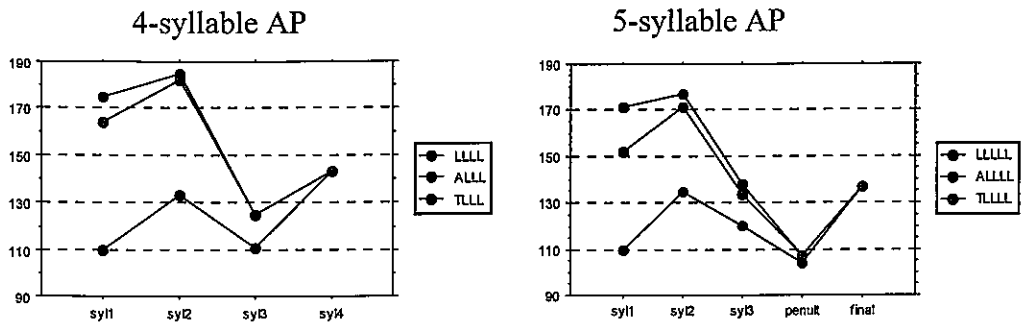


Figure 18 : Predicted f0s of 4- and 5-syllable APs by formulas (1) and (2).

Here, we will see the second way to implement HHLH pattern APs. In Table 13, we predicted the f0 values of the syllables in a HHLH pattern AP from the f0 values of the corresponding syllables in a LHLH pattern AP. However, sometimes we just know the f0 of the initial syllable in a HHLH pattern AP, instead of the f0 value of the LHLH pattern. Thus, we need formula (3) having different slope and intercept values to predict f0 values of other syllables from the f0 of the initial syllable in a HHLH pattern AP.

(3) $Y'' = eX'' + f$

Y”: predicted f0 value of the syllable having AP initial aspirated/tense onset
X”: f0 value of the first syllable in APs having aspirated or tense onsets (ALLL, ALLLL, TLLL, and TLLLL)
e : slope
f : intercept

As the same way we did for control APs, in each two-dimensional plot, the initial syllable f0 values of each HHLH pattern AP (ALLL, ALLLL, TLLL and TLLLL) were plotted on the X-axis and the f0 values of the third, penultimate or final syllable were plotted on the Y-axis. The results of linear regressions are summarized in Table 14.

		4-syl			5-syl			
		2nd	penult.	final	2nd	3rd	penult.	final
asp	slope	.94	.78	.86	.95	.90	.75	.82
	intercept	16.8	-13.5	-2.4	13.4	-15.0	-20.4	.82
	R^2	.99	.87	.83	.98	.90	.86	.82
tns	slope	.92	.74	.93	.96	.95	.82	.96
	intercept	26.7	3.5	-6.5	18,6	-13.9	-22.6	-14.5
	R^2	.98	.85	.87	.98	.90	.87	.87

Table 14. A summary of slope and intercept values of correlation between the f0 value of the first syllable and that of other syllables in APs having an aspirated or tense onset (ALLL,ALLLL, TLLL and TLLLL).

Figure 19 shows tonal patterns of APs predicted by (3) with slope and intercept values in Table 13. To compare the results from formulas (2) and (3), the same initial f0 values for APs having initial aspirated or tense onsets were used (175 Hz for ALLL, 164 Hz for TLLL, 171 Hz for ALLLL, and 152Hz for TLLLL). Since these f0 values were predicted values, though R^2 values were quite high (over 0.8), there were some mismatches, naturally. For example, note that the penultimate syllable of TLLLL is lower than that of LLLLL in Figure 19

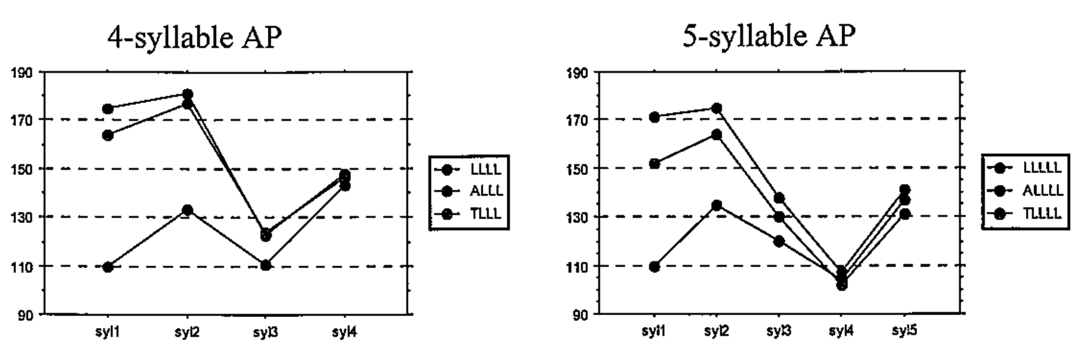


Figure 19 : Predicted f0s of 4- and 5-syllable APs by formula (3).

Then, let us compare these two ways of f0 implementation: the first way which predicts f0s of a HHLH pattern AP from f0s of a LHLH pattern AP and the second way which predicts f0s of other syllables of a HHLH pattern AP from the initial f0s of a LHLH pattern AP. Which way is better to implement HHLH pattern APs? It seems that the second way is more powerful since it is independent from f0s of a LHLH pattern. However, formula (2) is still useful when you just know the f0s of a LHLH pattern AP since it is based on the relation of f0 between LHLH and HHLH pattern APs while formulas (1) and (3) are based on the relation between the first syllable and other syllables. Therefore formula (2) can be used as a supplementary rule for formula (3).

Figures 18 and 19 show almost the same patterns and these predicted f0 values show AP patterns very similar to those found in Experiment 1. The first 2 syllables of APs with a H-H tone have significantly higher f0s than APs with a L-H tone in both Figures 18 and 19. Also the f0 of the third syllable in 5-syllable AP is almost on the interpolation line between the second H and the penultimate L tones. Therefore, we can predict the f0 values of the intervening syllables by knowing the second H and the penultimate L tones. Figure 20 shows schematics of f0 targets and interpolation within an AP at normal rate.

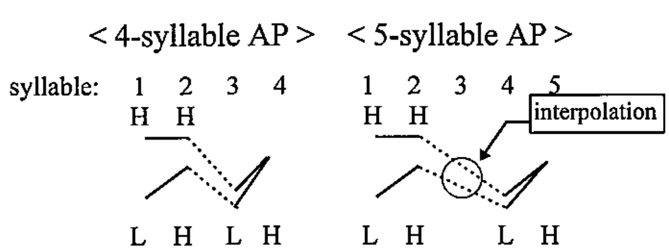


Figure 20. Schematics of f0 targets and interpolation within an AP at normal rate (simplified)

As for the APs at fast rate, we need some modification of the schematics shown above. Besides the pitch range reduction (pitch displacement), speakers also showed the penultimate L tone undershoot when the duration was reduced more than 30% compared to the duration of APs at normal rate. Otherwise speakers showed the same tonal pattern regardless of rate changes. Thus, if the reduction rate is less than 30% at fast rate, then the schematics of f0 targets and interpolation at fast rate are the same as the normal rate APs, shown in Figure 20 above. If the reduction rate is over 30%, than we need modified schematics shown in Figure 21.

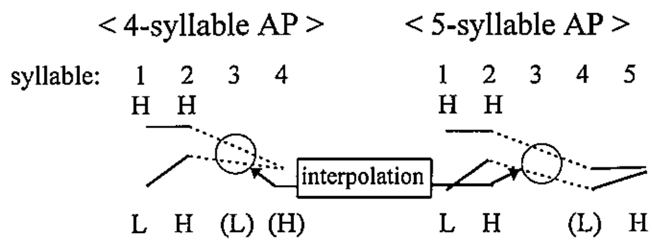


Figure 21. Schematics of f0 targets and interpolation within an AP at fast rate (over 30% reduction).

For 4-syllable APs, since the penultimate L tone is fully undershoot, there is interpolation between the second H tone and the final H tone (also the final H tone is undershot, thus not as high as that in normal rate). For 5-syllable APs, the degree of undershoot for the penultimate L tone is weaker than that in 4-syllable APs. Thus, we will maintain the interpolation between the second and the penultimate L tones. In Experiment 1, two speakers showed undershoot in 4-syllable APs at fast rate and one speaker showed undershoot in 5-syllable APs. Slope and intercept values of control APs at fast rate are summarized in Table 15.

	4-syl			5-syl			
	2nd	penult.	final	2nd	3rd	penult.	final
slope	1.34	1.26	1.09	1.17	1.00	.70	.99
intercept	-25.80	-21.85	16.16	8.09	18.0	40.8	26.4
R^2	.923	.716	.922	.928	.84	.746	.90

Table 15. A summary of slope and intercept values of correlation between the f0 value of the first syllable and that of other syllables in default APs (LLLL, LLLLL) at fast rate.

To sum up, implementation rules with different slope and intercept values were provided for APs having an initial lax, aspirated and tense onset by using linear regression. If we know the f0 of the first syllable of an AP, the remaining f0 values are predictable by using formulas (1) and (3). And, if we know the f0 values of a control AP, the f0 values of HHLH pattern APs are predictable by using formula (2).

5. Conclusion

We have seen that implementation of Seoul Korean was successful by considering microprosody and speech rate effects on the realization of the underlying tone patterns. As a microprosody effect, we have seen that Korean tense or aspirated onset consonants raised f0 values of the following vowel. When the consonant was located in the onset of the first syllable of an AP, it raised f0 values of following vowels, even non-adjacent ones, up to the penultimate syllable, with a lesser degree after the second syllable. That is, Korean AP-initial aspirated and tense consonants strongly and consistently affect the f0 of the second syllable, and the third and fourth syllables in 4 and 5 syllable of nonsense word APs.

This study showed that the initial consonant at the left edge, but not the consonant in the middle of an AP determined the tonal realization of a whole phrase, confirming previous claim (Jun 1996b) that f0 difference triggered by the AP-initial consonant is a phonological aspect of Korean intonational phonology. Also, data showed that, especially in the first and the second syllable positions of 4-5 syllable APs, vowels with an aspirated onset had higher f0 than vowels with a tense onset.

The results also confirmed the interpolation hypothesis. The tonal interpolation between the second syllable H tone and the penultimate L tone at normal rate made the f0 of the third syllable in 5-syllable APs predictable. At fast rate, however, the penultimate

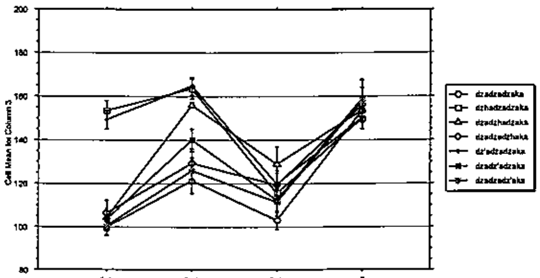
L tone was undershot depending on the reduction rate: speakers showed complete undershoot when the duration of the target AP was reduced more than 30% at fast rate. When the penultimate L tone was fully undershot, in 4-syllable APs, the f0 value of the penultimate vowel was achieved by interpolating between two adjacent H tones (the second H and the final H tones).

Finally, f0 implementation rules for 4- and 5-syllable APs in Korean were provided, on the basis of nonsense word data, by using linear regression analysis. Segmental effects and speech rate effects were carefully considered and reflected into the different implementation rules for APs having an initial lax, aspirated and tense onsets. If we know the f0 of the initial syllable of an AP, we can predict f0 values of other syllables of an AP. In addition, on the basis of results in Experiment 1 and 2, two types of schematics of tonal realization were also suggested. Most of all, this study provided crucial data for tonal realization and implementation of Accentual Phrase in Seoul Korean.

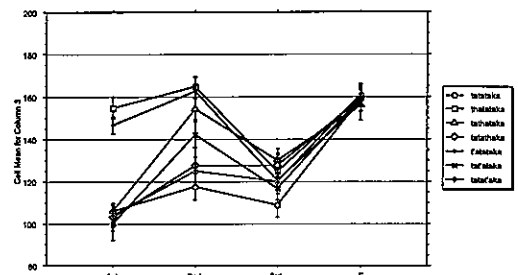
Appendix 1

Mean f0 contours (error bars = ±1 standard deviation) for 4 and 5 syllabel APs at normal rate.

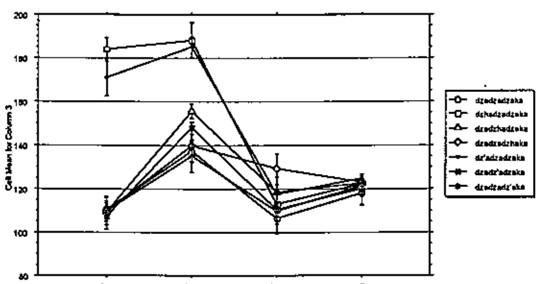
M1-4(affricate)



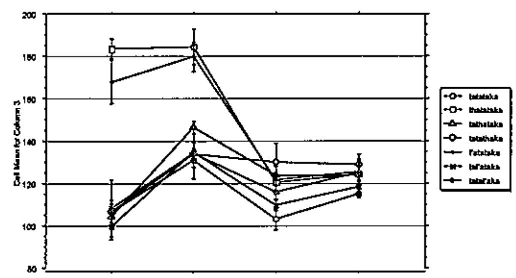
M1-4(stop)



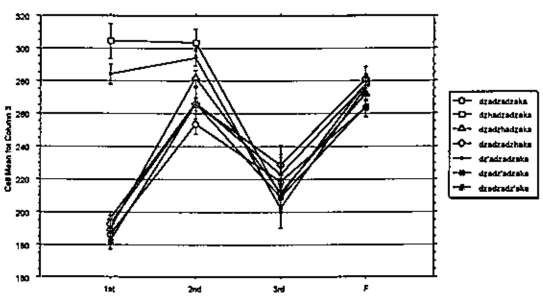
M2-4(affricate)



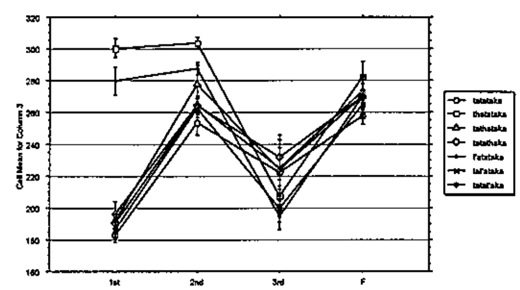
M2-4(stop)



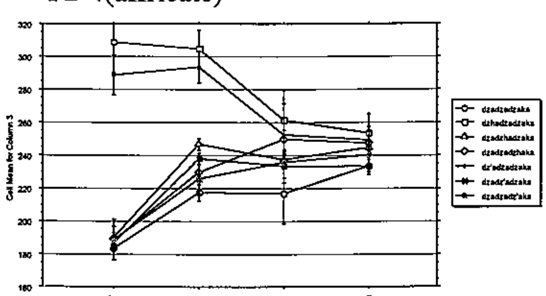
F1-4(affricate)



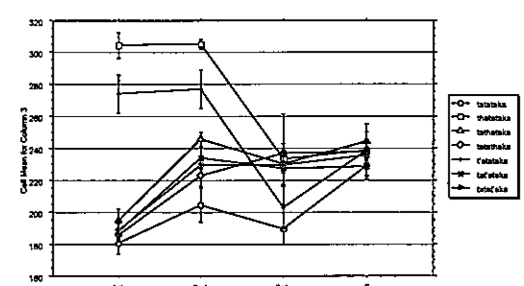
F1-4(stop)



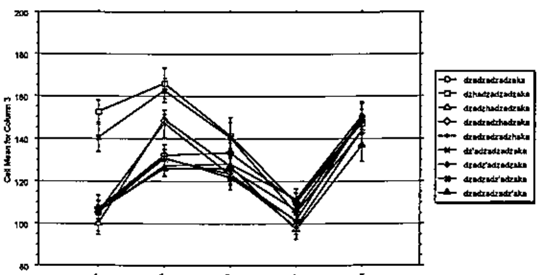
F2-4(affricate)



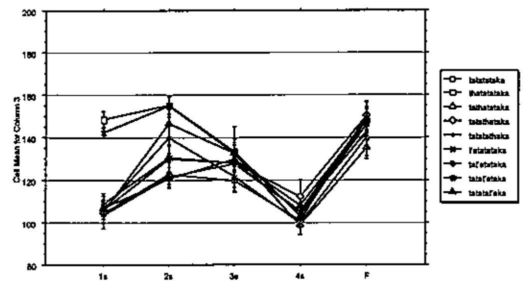
F2-4(stop)



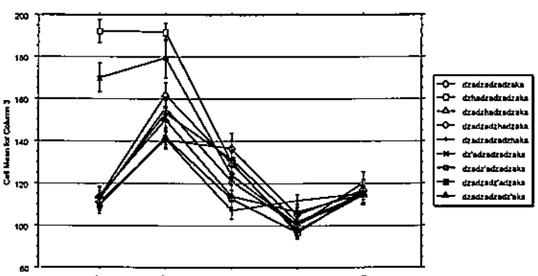
M1-5(affricate)



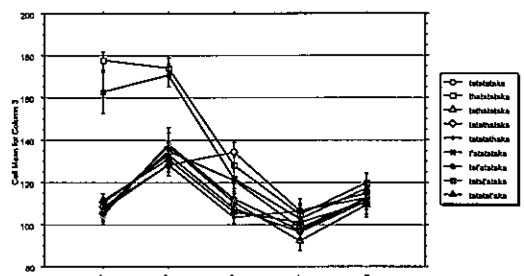
M1-5(stop)



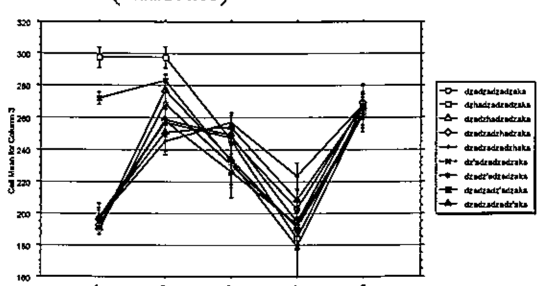
M2-5(affricate)



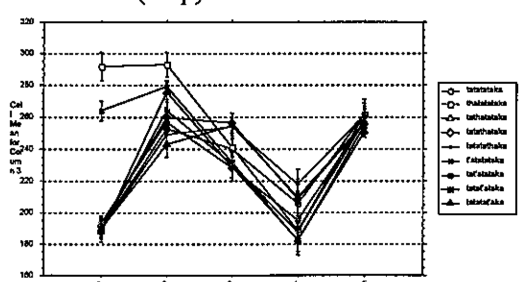
M2-5(stop)



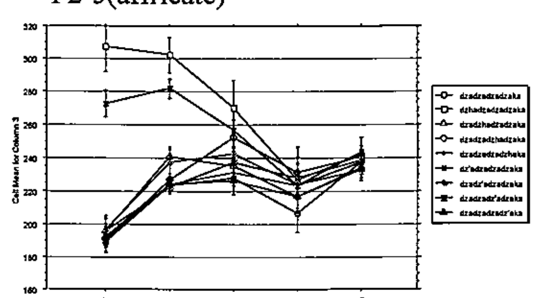
F1-5(affricate)



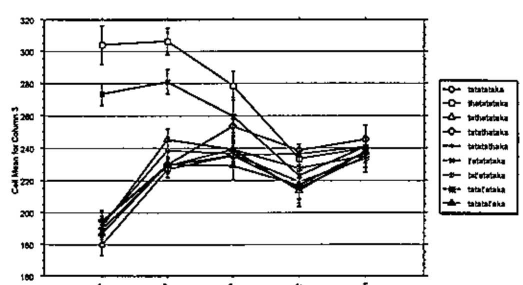
F1-5(stop)



F2-5(affricate)



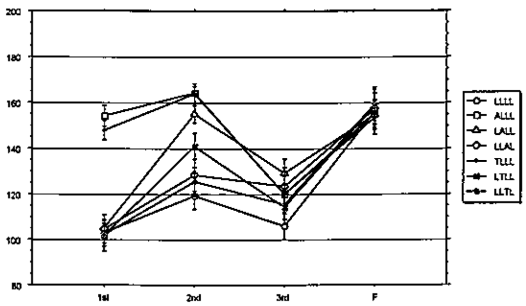
F2-5(stop)



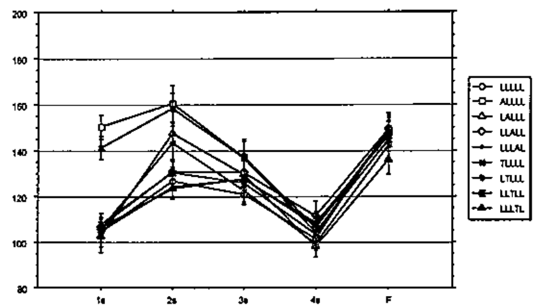
Appendix 2

Mean f0 contours (error bars = ±1 standard deviation) for 4 and 5 syllabel APs at normal rate.

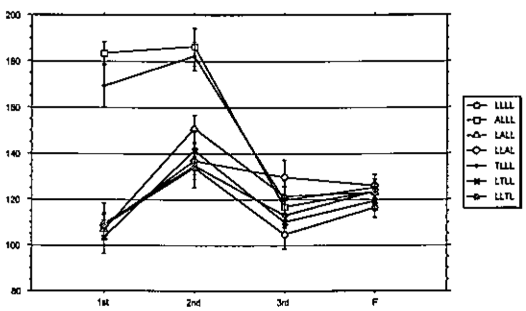
M1-4



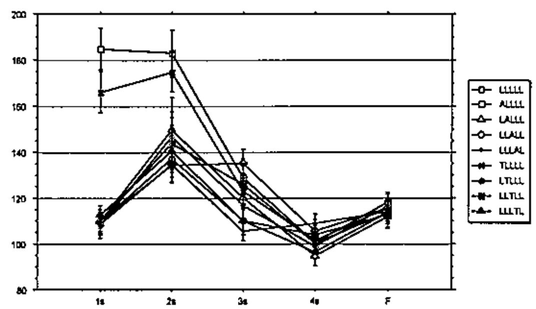
M1-5



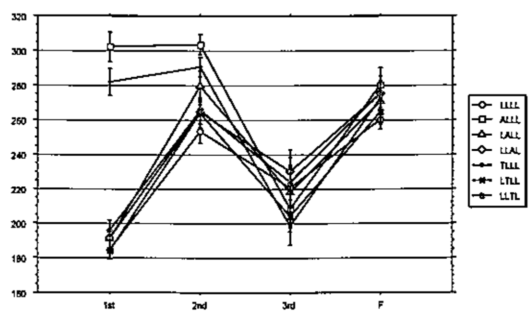
M2-4



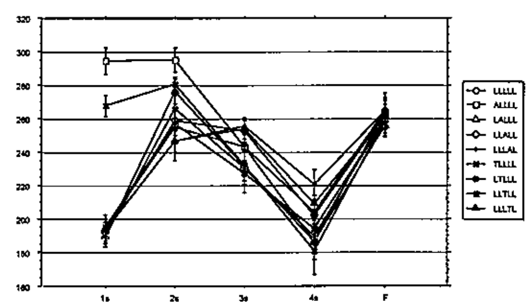
M2-5



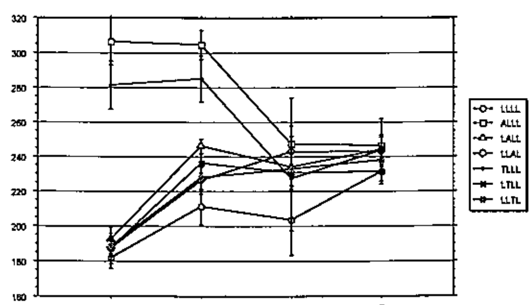
F1-4



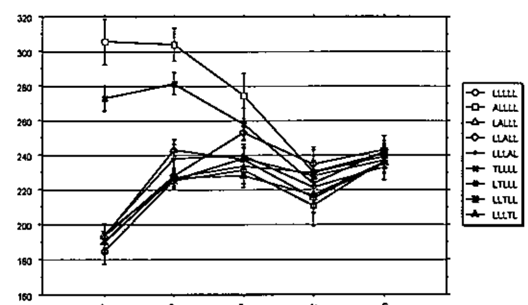
F2-5



F2-4



F2-5



Appendix 3

A summary of 36 one-way ANOVAs on f0 for the factor of syllable position in nonsense word APs at fast rate.

		M1		M2		F1		F2	
		F(6,77)	P	F(6,77)	P	F(6,77)	P	F(6,77)	P
4-syl	**1st**	119.2	<.0001	67.1	<.0001	376.2	<.0001	247.1	<.0001
	2nd	77.7	<.0001	9.1	<.0001	62.8	<.0001	129.1	<.0001
	penu.	17.2	<.0001	5.1	<.05	5.8	<.0001	16.5	<.0001
	final	4.9	<.05	3.2	<.05	6.2	<.0001	1.1	=.35
5-syl	**1st**	227.7	<.0001	49.5	<.0001	317.6	<.0001	357.6	<.0001
	2nd	100.2	<.0001	12.7	<.0001	52.9	<.0001	137.8	<.0001
	3rd	5.88	<.0001	5.7	<.0001	16.6	<.0001	42.5	<.0001
	penu.	14.2	<.0001	2.7	<.05	28.7	<.0001	19.8	<.0001
	final	2.6	<.05	2.4	<.05	1.9	=.06	2.9	<.05

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