Multiple acoustic cues of three-way phonemic contrast in stop consonants*

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Sun-Hoi Kim. 1999. **Multiple Acoustic Cues of Three-way Phonemic Contrast in Stop Consonants.** *Studies in Phonetics, Phonology and Morphology* 5, 79-103. In this paper, I argue that the three-way phonemic contrasting stop consonants should be characterized by the combination of multiple acoustic cues. This paper, presenting several types of acoustic cues, shows evidence of this argument from phonetic and acoustic experiments of Korean stop consonants. I measure physical values of Voice Onset Time (VOT), Stop Closure Duration (SCD), and Harmonic Amplitude (HA) in four native Korean adults in age from 30 to 34 years and four native Korean children in age from 5 to 7 years. The experimental results show that the L-value representing the [Constricted Glottis] feature distinguishes tense stops from lax and aspirated stops, and that the short SCD characterizes lax stops, differentiating them from tense and aspirated stops. **(University of Delaware)**

Keywords: Voice Onset Time, Stop Closure Duration, Harmonic Amplitude, Constricted Glottis, Spread Glottis.

1. Introduction

Since Lisker and Abramson (1964), it has been generally assumed that Voice Onset Time (VOT), which is roughly defined as the duration from the beginning of stop release to the voicing onset of the following vowel, is the single most reliable feature to differentiate among stop consonants with respect to both voicing (voiced and voiceless) and aspiration (unaspirated and aspirated). In some literature (C.-W. Kim 1965; Han and Weitzman 1970), however, it has been pointed out that VOT cannot be a cue to distinguish Korean tense stops from lax stops in that these two types of stops share a portion of their range in terms of VOT values (see

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Figure 1 in C.-W. Kim 1965: 347). As an alternative to the VOT analysis, J.-I. Han (1996) reported that Stop Closure Duration (SCD), which is roughly defined as the duration from the beginning of stop closure to the beginning of stop release, is a sufficient cue to distinguish Korean tense stops from the other stops.[1] In this paper, I argue that the three-way phonemic contrasting voiceless stop consonants in Korean cannot be characterized by a single acoustic cue, such as VOT or SCD, and that they should be differentiated by the combination of multiple acoustic cues. This paper, presenting several types of acoustic cues, shows evidence of this argument from phonetic and acoustic experiments of Korean stop consonants exhibiting three-way phonemic contrast.[2] I measure physical values of VOT and SCD in four Korean adults in age from 30 to 34 years and four Korean children in age from 5 to 7 years. In addition, in order to investigate the laryngeal property of each phonation type, I measure Harmonic Amplitude (HA) representing the acoustic properties of the vowels adjacent to stop consonants.

2. Perception Test

According to previous studies on child phonology (Macken and Barton 1979, 1980; Gandour *et al* 1986), children acquire the phonemic contrast of stop consonants in the production of their language under 5;0. In order to investigate whether the selected Korean child subjects are able to produce the phonemic contrast of Korean stop consonants, I took the perception test of Korean stop consonants produced by adult and child subjects participating in the production test. Eighteen Korean adult

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[1]J.-I. Han (1996) argues that Korean tense stops are underlyingly characterized as geminates of lax stops, and that they are assigned the feature [Constricted Glottis] by Geminate Reinforcement in the surface representation (J.-I. Han 1996: 2..). Accordingly, in Han's framework, Korean tense stops can be differentiated from the other stops by timing units in the underlying representation, and further by the presence of the feature [Constricted Glottis] assigned to the tense stops in the surface representation (see J.-I. Han 1996: 185 for discussion).

[2]Lisker and Abramson (1964) examined the VOTs of stop consonants in 11 languages including Korean. Korean, among these languages, is the only one where voicing contrast and aspiration contrast, either singly or conjunctively, cannot separate stop phonemes because Korean stop phonemes are all voiceless and these phonemes cannot be separately categorized by aspiration.

listeners, 10 males and 8 females, who did not participate in the production test, participated in this perception test. None of the listeners had any hearing disorders. For this perception test, six words consisting of two minimal triplets were produced with the carrier sentence by the adult and child subjects, as shown in (1).

(1) a. Test Words
pal 'foot' : p'al.le 'laundry' : p^hal 'hand'
tal 'moon' : t'al 'daughter' : t^hal 'mask'
b. Carrier Sentence
iken ___ -(i)ta. 'This is ___'
e.g. iken pal-ita 'This is a foot'

Recordings were made in a sound-proof room, and recorded sentences were saved into a computer. Sentences were digitized, and test words were extracted from the sentences using *Signalyze* version 3.12. Test words were re-recorded. The Sony digital audio tape-recorder (DAT) *TCD-D8* was used for both recordings. The 48 stimuli ((2) groups × (4) subjects × (6) words × (1) token) were presented to the listeners. Only the test words were played from the digital tape over the *Sony MDR-009* headphone to each listener in a sound-proof room.

Results of this test show that the percent correct performance in each stop phoneme of each speaker is above 60% that is significantly different from chance level 33%, as shown in (2).

(2) Mean identification scores (in percent) for Korean stop consonants (Correct responses are underlined, and chance level is at 33 %.)

Child Group/ Adult Group

Stimulus Phonemes	Response					
	p	p'	p^h	t	t'	t^h
/p/	74/86	0/0	26/14			
/p'/	3/1	97/99	0/0			
/p^h/	19/14	0/0	81/86			
/t/				78/86	0/0	22/14
/t'/				3/1	97/99	0/0
/t^h/				25/13	0/0	75/87

The results in (2) further show that the overall pattern of percent correct performance in perception does not exhibit any significant difference between adult stop consonants and child stop consonants. What this test shows, therefore, is that the adult subjects and the child subjects produce the phonemic contrast of Korean stop consonants in the same manner, in that the Korean adult listeners can identify phonemic difference in child stop consonants, as well as in adult stop consonants. This result does not mean that no physical values of acoustic properties characterizing stop consonants should be significantly different between adult group and child group. However, if an acoustic property is the single cue to characterize Korean three-way phonemic contrasting stops, its physical value of a phoneme should not be significantly different between adult group and child group producing the same phonemic contrast, and its physical values of different phonemes should be significantly different between adult group and child group, as well as within each group. For instance, if VOT is the single cue to characterize the phonemic contrast between /p^h/ and /p/ in Korean, the VOT physical values should be significantly different between adult /p^h/ and child /p/, as well as between adult /p^h/ and adult /p/ and between child /p^h/ and child /p/ because both groups produce the same phonemic contrast. Therefore, in the next section, I compare the physical values of VOT, SCD, and HA between two groups, as well as within each group, in order to investigate whether each of VOT, SCD, and HA can be the single cue to characterize the phonemic contrast of Korean stop consonants.

3. Experiments of Production

3.1 Data Collection and Reduction

Each group[3] consists of two males and two females. Speech samples consist of near-minimal triplets of the three-way contrast for Korean word-initial and inter-vocalic stops. They were produced in the carrier sentence, *iken* ___ *(i)ta* 'This is ___' for word-initial stops and *ku-ka*

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[3]Adult subjects are called SH, TW, MS, and SJ, and child subjects are called TH, YK, YJ and KY.

___ *seyo* 'He was ___' for inter-vocalic stops. A complete list of test sentences appears in Appendix. Like in the perception test, recordings were made using Sony (DAT) *TCD-D8* with a high-quality microphone in a sound-proof room. Subjects, sitting comfortably on the chair, were recorded with the microphone attached to the front of their clothing approximately 15-cm from the lips. All recordings were completed in a single session. Each child session lasted 15-20 minutes, and each adult session lasted 10-15 minutes. Child subjects were cued with index cards containing test sentences and pictures, and adult subjects were cued with index cards containing test sentences. Total seven tokens for each sentence were obtained from each subject. All recorded data were saved in a computer using *Sound Edit 16*. Among seven tokens for each test sentence, the first and final tokens were not taken in this experiment. Therefore, the total number of stimuli is 720 ((2) groups × (4) subjects × (18) sentences × (5) tokens) for VOT analysis, and 360 (((2) groups × 4 subjects × (9) sentences[4] × (5) tokens) for SCD and Harmonic Amplitude (HA) analyses.

3.2 Voice Onset Time and Category Mapping

Subjects' productions were analyzed using *Signalyze* version 3.12. Wide-band spectrograms were made. The analysis parameter was set as half range (0-2756 Hz), pre-emphasis, no log scale, no smoothing, and no floating FFT for the spectrograms. VOT values were measured from the beginning of stop release to the onset of voicing[5] in the following vowel in both waveforms and wide-band spectrograms. I measured VOT twice for each token, examining spectrograms and waveforms simultaneously.[6] When the difference of two measurements

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[4]I measured only inter-vocalic stop consonants for SCD. In contrast, I measured HA of the vowels following word-initial stop consonants. Thus, nine possible types were measured in nine sentences.

[5]Following Silva (1992), I measured the onset of voicing with the presence of prosodic energy in the waveform and a voicing bar in the spectrogram.

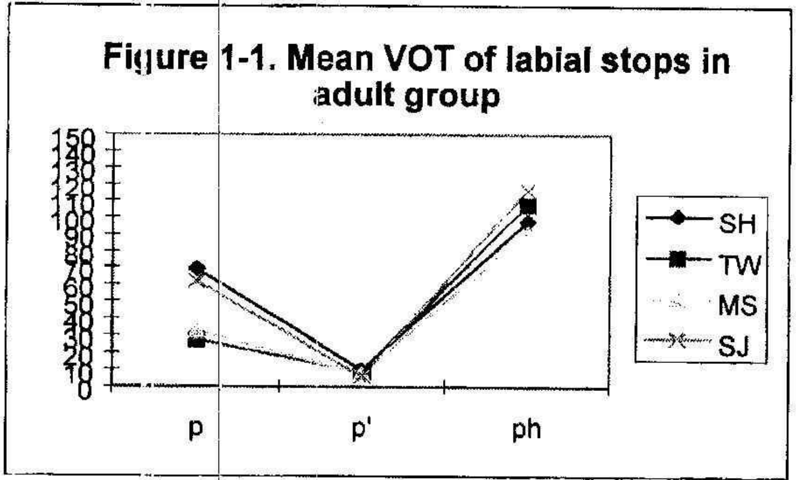
[6]There are some ways to achieve the accuracy of VOT measurement. Macken and Barton (1979, 1980) measured VOT twice: on a Tektronix Oscilloscope and on a spectrogram. When the difference between the two measurements was equal to or less than 3ms, they were averaged to give a final VOT. When the oscilloscope

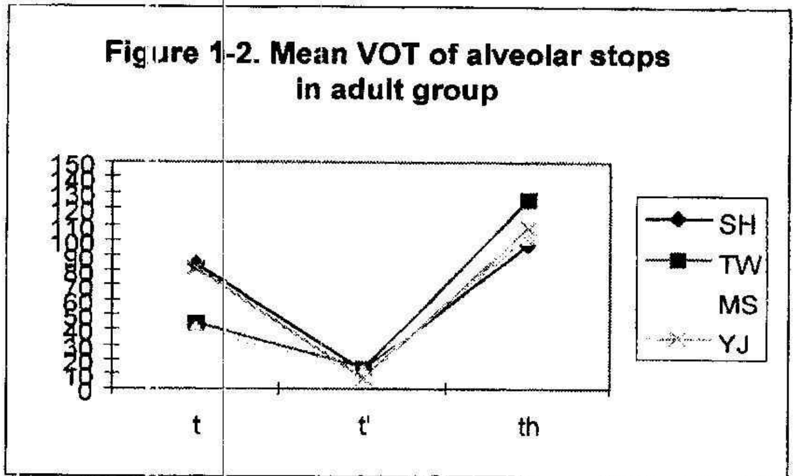
was less than 3ms, I determined the mean value of them as the VOT value for the token. And when it was more than 3ms, the problem was identified and then resolved by remeasurement.

The patterns of mean VOT values of word-initial stops are presented by line graphs for each place of articulation in Figures 1 and 2 below.

(3) Mean VOTs of word-initial stop consonants

a. Adult Group





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and spectrogram measurements differed by more than 3ms, the problem was identified and then resolved by further instrumental analysis. In Davis' (1991) VOT analysis, on the other hand, a subset of the data (roughly one-fifth of the total number) were measured twice. Because the difference of two measurements was less than 3ms, the first values of all data were selected as the VOT values.

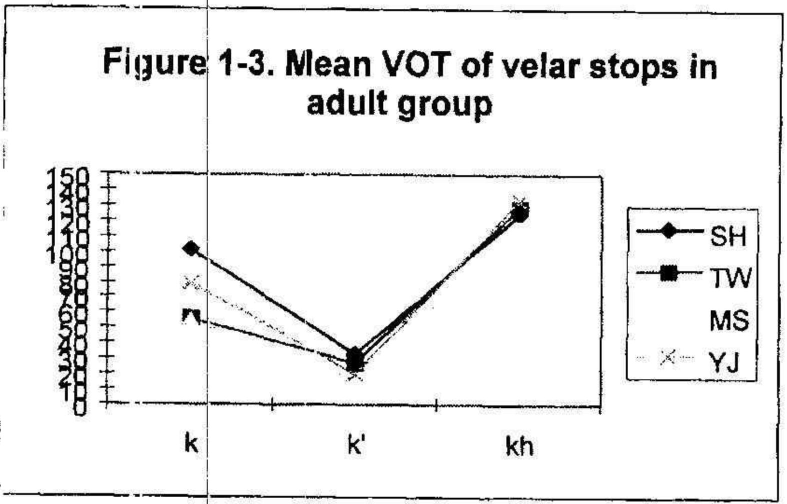


Figure 1-3. Mean VOT of velar stops in adult group

b. Child Group

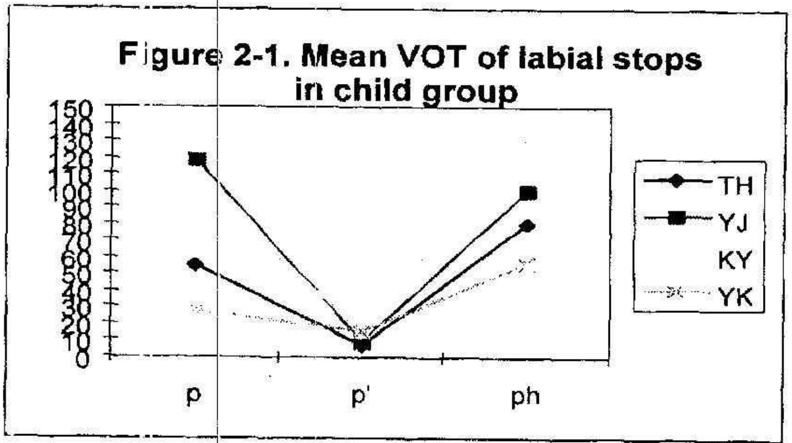


Figure 2-1. Mean VOT of labial stops in child group

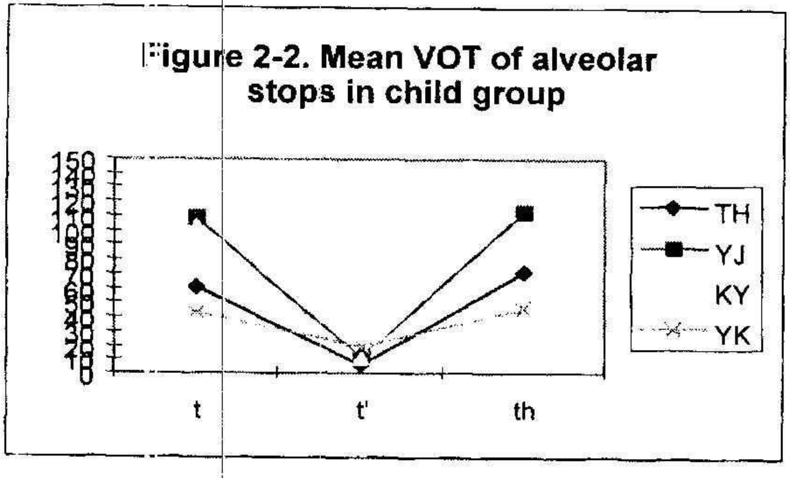
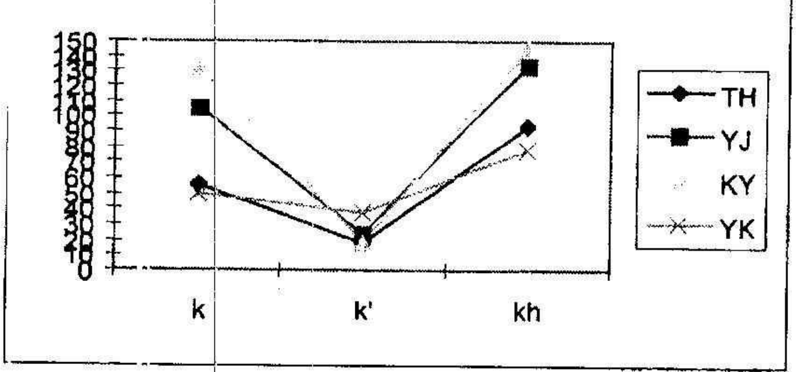


Figure 2-2. Mean VOT of alveolar stops in child group

Figure 2-3. Mean VOT of velar stops in child group



The following table summarizes the minimum and maximum VOT values of labial stops.

(4) Minimum and maximum VOTs of labial stops (ms)
(minimum/maximum)

	p	p^h	p'
adult group	27.12/69.15	90.84/115.79	5.85/10.63
child group	28.42/117.83	55.8/134.08	7.06/15.75

In (3) and (4), first, we can see that there is no overlapping of VOT values between tense stops and the other stops in each group. What this means is that word-initial tense stops can be distinguished from the other word-initial stops by VOT in Korean. Second, while there is no overlapping of VOT values between lax stops and aspirated stops in adult group, child group exhibits the overlapping of VOT values between lax stops and aspirated stops. There is no statistically significant difference between /p/ and /p^h/ in child group ($p=0.076$). These children's data, therefore, show that the phonemic contrast between lax stops and aspirated stops in the word-initial position cannot be characterized by the VOT difference in child group. Finally, the VOT values of lax stops in child group overlap with those of aspirated stops in adult group. There is no statistically significant difference between /p/ in child group and /p^h/ in adult group ($p=0.054$).

This overlapping phenomenon shows that VOT cannot be a cue to distinguish word-initial lax stops in child group from word-initial aspirated stops in adult group. This phenomenon further shows that VOT cannot be the single cue to distinguish word-initial lax stops from word-initial aspirated stops in Korean. Since both groups produce the phonemic contrast between word-initial lax stops and word-initial aspirated stops in the same manner, as shown in Section 2, if VOT is the single cue to differentiate them, there should be no overlapping of VOT values even between lax stops in child group and aspirated stops in adult group.

Now, let us consider inter-vocalic stop consonants in terms of VOT. Lisker and Abramson (1964) and Silva (1991) report that inter-vocalic lax stops exhibit approximately 50% less VOT values than word-initial lax stops (see Table 2.2 in Silva 1992: 50). Also, Silva (1992) observes that the vowel lag values of inter-vocalic lax stops overlap with those of word-initial and inter-vocalic tense stops, and that the vowel lag values of inter-vocalic aspirated stops overlap with those of word-initial lax stops (see Figure 5.8 in Silva 1992: 154). Since the duration of vowel lag is measured from the beginning of stop release to the F2 onset of the following vowel, Silva's observation implies that, in the duration of VOT, there is also overlapping among inter-vocalic lax stops, word-initial tense stops and inter-vocalic tense stops, and between inter-vocalic aspirated stops and word-initial lax stops. The VOT values of inter-vocalic stop consonants[7)] in this paper also exhibit similar results.

As illustrated in Figures 3 and 4, the inter-vocalic lax and aspirated labial stops /p/ and /p^h/ have reduced VOT values in each group.[8)] The reduced VOT values of inter-vocalic lax stops overlap with those

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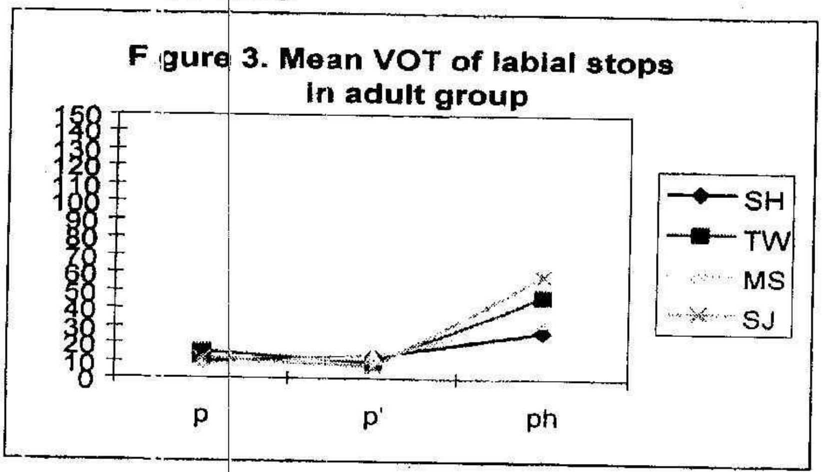
[7]These data include only inter-vocalic stops in which there were not "unbroken voicing" affected by the preceding vowel during the stop closure and release. Specifically, more than 80% of children's inter-vocalic lax stops did not exhibit unbroken voicing phenomenon.

[8]The other inter-vocalic lax and aspirated stops exhibit the same result. Here, I focus on the inter-vocalic lax and aspirated labial stops /p/ and /p^h/. It can be assumed, however, that the findings will hold for alveolar and velar stops as well because the general patterns of VOT values are almost the same in each place of articulation.

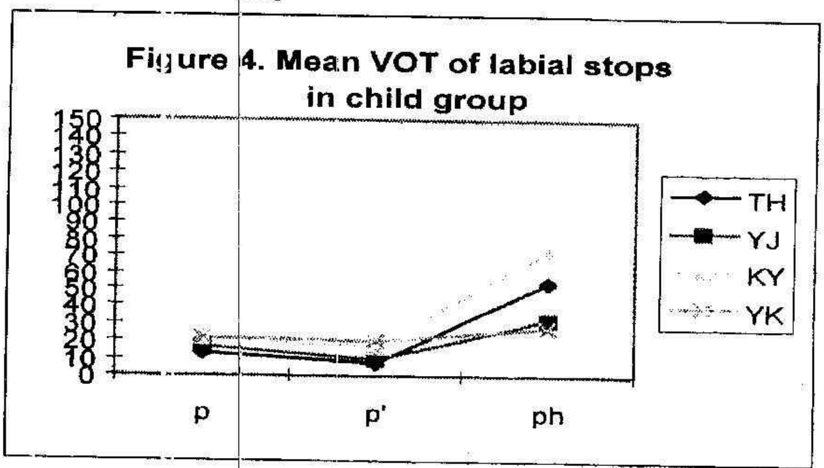
of inter-vocalic tense stops in both groups. This, therefore, shows that, in addition to the reduction of VOT value, another acoustic cue is required to phonetically represent inter-vocalic lax stops in Korean. The comparison of Figures 1, 2 and Figures 3, 4 also shows that the VOT values of inter-vocalic aspirated stops are similar to those of word-initial lax stops. In this case, also, VOT cannot be a crucial cue to distinguish lax stops from aspirated stops.

(5) Mean VOT of inter-vocalic labial stops

a. Adult Group



b. Child Group



We have so far examined VOT values of Korean stop consonants. The VOT analysis shows that there are significant variation and overlapping of VOT values in Korean, depending on contexts and speakers. Therefore, though VOT can be the most reliable cue to characterize voiced/voiceless contrast or unaspirated/aspirated contrast in other languages, it cannot be the single cue for the phonemic contrast of Korean stop consonants. In addition to VOT, other acoustic cues must be considered in characterizing Korean stop consonants.

3.3 Stop Closure Duration (SCD) and Underlying Representations of Korean Stop Consonants

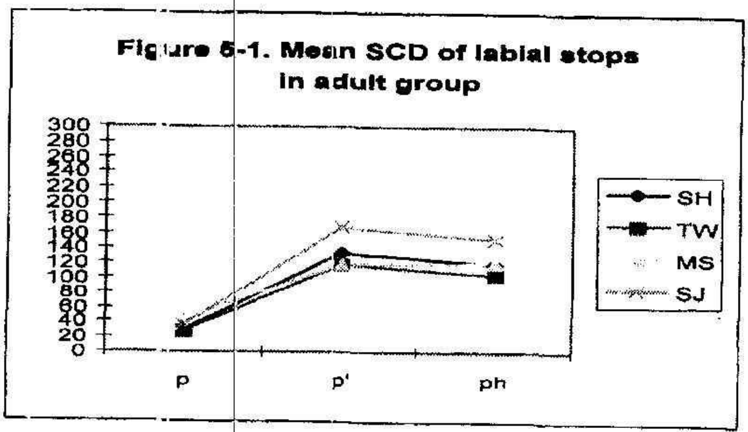
J. -I. Han (1996), who examined the data from only adult subjects, argues that SCD is the single most crucial cue to determine the underlying phonological representations of Korean lax and tense stops. She proposes that the underlying timing units of Korean stop consonants are cued with SCD values, just as the timing units of vowels are determined by vowel duration values. In J.-I. Han's framework, for instance, /p/ and /p^h / have one timing unit, but /p'/ has two timing units because /p'/ has the longest SCD value. Therefore, according to J.-I. Han's claim, /p'/ is a geminate of /p/. However, the SCD analysis in this paper shows that SCD cannot be a cue to determine the underlying phonological representations of Korean stop consonants.

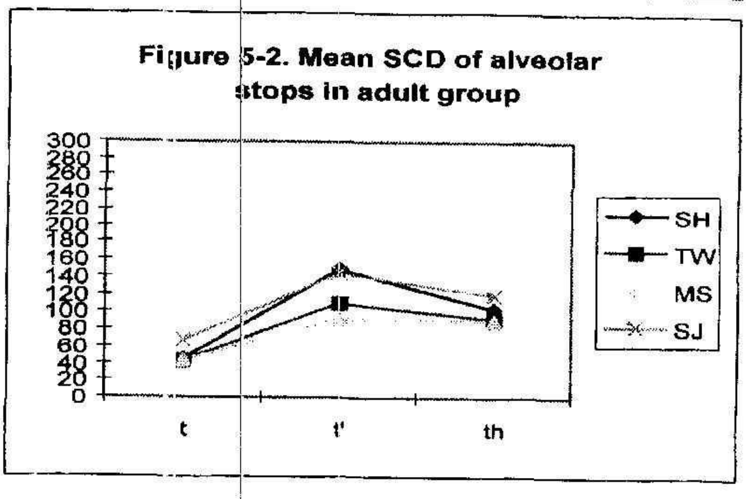
In this paper, SCD values were also measured from waveforms and wide-band spectrograms set as half range (0~2756Hz), pre-emphasis, no log scale, no smoothing, and no floating FFT. I measured the duration from the beginning of stop closure to the beginning of stop release. The beginning of stop closure is cued with the reduction of complex and periodic waves in the waveforms and the attenuation of second formant of the preceding vowel in the spectrograms. In this experiment, only the SCD values of inter-vocalic stops were measured for the following two reasons. According to J.-I Han (1996), though the SCDs of tense and lax stops in the word-initial position are significantly different, the difference is not from the timing distinction, but from the feature [Constricted Glottis] of tense stops. Since the goal of the SCD analysis in this paper is to investigate whether SCD physical values reflect timing units I did not treat SCD values of tense and lax stops in the word-initial position. The second reason is that the SCD values of word-initial stops in the phrase-initial position are significantly different from those in the phrase-internal position (see Silva 1992:132 for discussion). This means that SCD values of word-initial stops are changeable, depending on prosodic position. Since the impact of prosodic position on SCD is not the concern of this paper, I did not treat changeable SCD values of word-initial stop consonants.

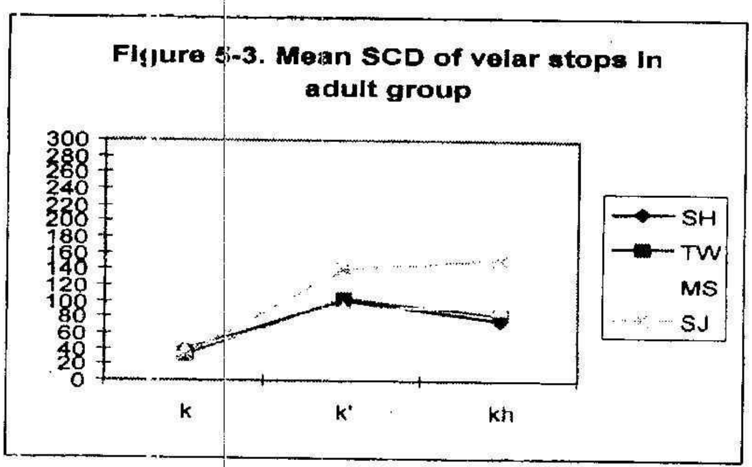
The patterns of mean SCD values are presented by line graphs for each place of articulation in Figures 5 and 6 below.

(6) Mean SCDs of Korean stop consonants

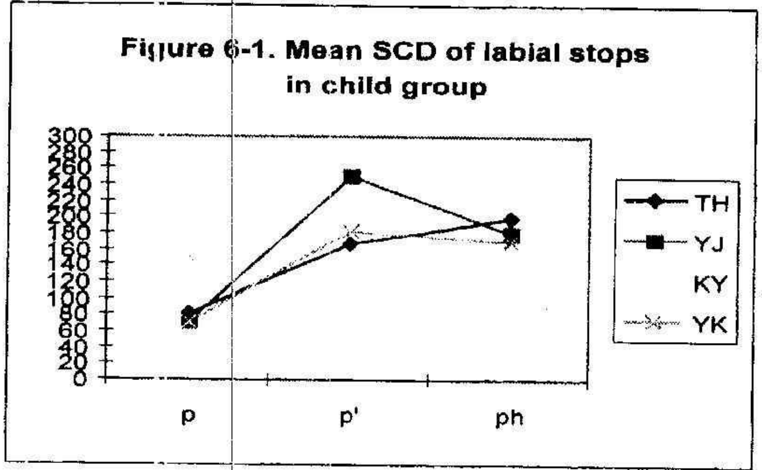
a. Adult Group







b. Child Group



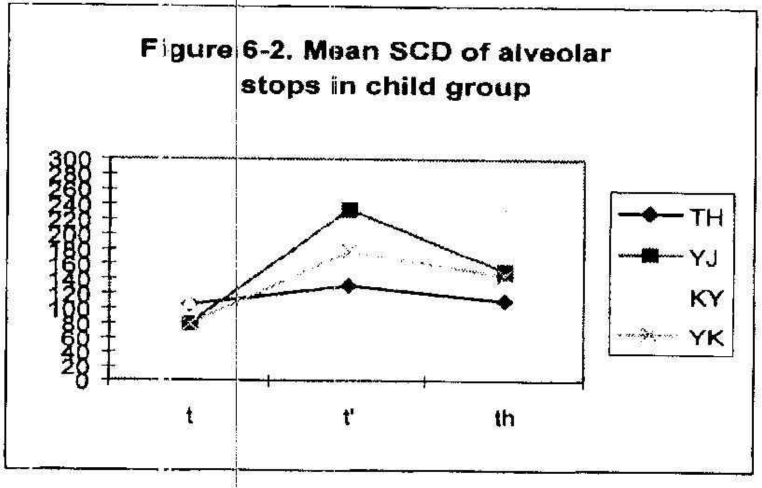
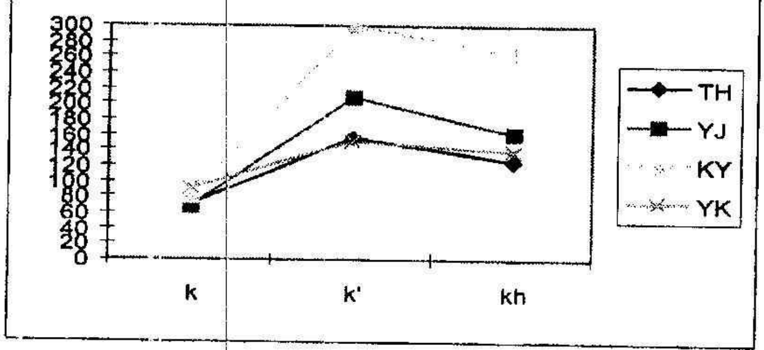


Figure 6-3. Mean SCD of velar stops in child group



These data show that SCD patterns have little difference among labial, alveolar and velar stops in both groups. One general pattern observed in Figures (5) and (6) is that SCD is correlated with phonation types. In other words, there is big difference in SCD values between lax stops and aspirated/tense stops. We can also observe another important tendency from Figures (5) and (6): mean SCD values of child group are much longer than those of adult group in the same phonation type in each place of articulation. Here, the closer examination of SCD values across phonation types is limited to a single place of articulation labial. It can be assumed, however, that the findings will hold for alveolar and velar stops as well because the general patterns of SCD values are almost the same in each place of articulation.

Now, let us examine the 'between-subject variation' in each group. This examination is designed to investigate whether each group is really homogeneous and how much wide range of SCD values each group has for each phonation type. Here, I take the SCD values of all labial stops (/p/, /p'/, and /p^h/) as a dependent variable at a time. Of course, however, each phonation type is separately categorized to avoid compounding effect; /p/: 0, /p'/: 1, and /p^h/: 2. First, the general factorial ANOVA test shows that there is no statistically significant difference among adult subjects ($F(3, 56) = 1.456$, p=0.236). Second, it shows that there is statistically significant difference among child subjects ($F(3, 56) = 4.219$, p=0.009). However, the closer examination of the multiple comparison test provides us with the information that the difference is caused by the subject KY (KY-TH: p=0.024, KY-YK: p=0.012). According to Turkey HSD, except for the subject KY, the homogeneous subset is composed of TH, YJ, and YK, as shown in (7). In other words, from the results of (7), we can see that there is no statistically significant difference among TH, YJ, and YK in terms of SCD values of labial stops ($F(2, 42) = 0.557$, $p=0.577$). The multiple comparison test in (7) also supports this result. Therefore, a homogeneous child group consists of TH, YJ, and YK in terms of SCD values.

(7) ANOVA Test on SCD values - TH, YJ, and YK in child group

Tests of Between-Subjects Effects

Dependent Variable: CVALUES

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Noncent. Parameter	Observed Power[a]
Corrected Model	5493.307[b]	2	2746.653	.557	.577	1.113	.136
Intercept	1040471	1	1040471	210.822	.000	210.822	1.000
SUB2	5493.307	2	2746.653	.557	.577	1.113	.136
Error	207282.6	42	4935.299				
Total	1253246	45					
Corrected Total	212775.9	44					

a. Computed using alpha = .05

b. R Squared = .026 (Adjusted R Squared = -.021)

Multiple Comparisons

Dependent Variable: CVALUES
Tukey HSD

(I) subject-child group	(J) subject-child group	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
TH	YJ	-19.1500	25.652	.737	-81.4723	43.1723
	YK	6.9867	25.652	.960	-55.3356	69.3089
YJ	TH	19.1500	25.652	.737	-43.1723	81.4723
	YK	26.1367	25.652	.569	-36.1856	88.4589
YK	TH	-6.9867	25.652	.960	-69.3089	55.3356
	YJ	-26.1367	25.652	.569	-88.4589	36.1856

Based on observed means. The error term is Error.

Now, let us consider the impact of phonation types on SCD values. If J.-I. Han's argument is correct, there should be no statistically significant difference in SCD values between /p/ and /p^h/, whereas there should be statistically significant difference in SCD values between /p^h/ and /p'/.

SCD values were statistically compared between /p/ and /p'/, between /p/ and /p^h/, and between /p^h/ and /p'/ in each group. The result of comparison of /p/ and /p'/ shows that statistically significant difference is found in mean SCD values between /p/ and /p'/ in each group ($F(1, 38) = 251.740$, p=0.000 in adult group, $F(1, 28) = 54.836$, p=0.000 in child group). This result corresponds to J.-I. Han's result. However, the result of comparison of /p/ and /p^h/ shows that there is also statistically significant difference in mean SCD values between /p/ and /p^h/ in each group ($F(1, 38) = 294.592$, p=0.000 in adult group, $F(1, 28) = 140.161$, p=0.000 in child group). This result means that, if the underlying timing unit is represented by SCD, the number of timing unit of /p/ must be different from that of /p^h/. This result contradicts with J.-I Han's claim that both /p/ and /p^h/ have one timing unit. The statistical analysis further shows that there is no statistically significant difference in mean SCD values between /p^h/ and /p'/ in each group ($F(1,38) = 2.044$, p=0.161 in adult group, $F(1,28) = 0.891$, p=0.353 in child group). This result, therefore, shows that, unlike in J.-I. Han (1996), the homogeneous subset of Korean labial stops is not a set {/p/, /p^h/}, but a set {/p^h/, /p'/} in terms of SCD values. It also shows that it is incorrect to argue that /p/ and /p^h/ have one timing unit whereas /p'/ has two timing units. Therefore, we can see that SCD cannot be an acoustic property to determine underlying timing units of Korean stop consonants nor a single reliable cue to distinguish different phonation types of Korean stop consonants. This fact is also supported by the comparison of SCD values between adult group and child group. Figure 7 in (8) graphically illustrates the difference in mean SCD values between adult group and child group.

(8) Comparison of Mean SCDs of labial stops by age

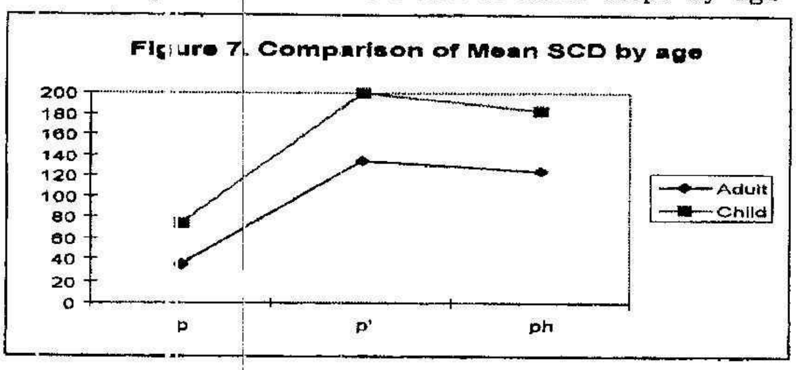


Figure 7 shows that the mean SCD of child group is much longer than that of adult group in each phonation, and that the mean SCD of /pʰ/ in child group is longer than that of /p'/ in adult group. In the perception test in Section 2, we have seen that child subjects have acquired the phonemic contrast of Korean stop consonants in production. If SCD would be the single cue to distinguish the different phonation types of Korean stops, and if the longest SCD value would represent two timing units of a tense stop, the SCD of /p'/ in adult group should be longer than that of /pʰ/ in child group. However, as illustrated in Figure 7, this is not the case. Figure 7 also shows that, though Korean children have acquired the phonemic contrast of stop consonants in their production, they do not produce Korean stop consonants in terms of SCD in the adult-like manner. What this means is that the incomplete acquisition of the SCD properties of stop consonants does not affect the phonemic contrast of Korean stop consonants.

3.4 Laryngeal Properties of Korean Stop Consonants

Unlike the spectrogram setting used in the analyses of VOT and SCD, the analysis parameter in this experiment was set as half range (0-2756 Hz) and pre-emphasis, log scale, smoothing, floating point FFT, and large track for spectrums. According to Klatt and Klatt (1990), breathy phonation is cued with the relative strength of the first harmonic known to increase as the open quotient increases ([Spread Glottis]), whereas laryngealized phonation is cued with the relative weakness of the first harmonic caused by the relatively narrow glottal pulse and the relatively short duration of the open portion of a fundamental period ([Constricted Glottis]). In order to acoustically investigate the laryngeal properties of Korean stop consonants, therefore, I measured the first harmonic amplitude (AH1) and the second harmonic amplitude (AH2) of the beginning part of the vowel following a stop consonant. In order to compare the beginning part of a vowel with the middle part of the vowel in terms of the difference in amplitudes between the first harmonic and the second harmonic, I also measured AH1 and AH2 of the middle part of the vowel following a stop consonant.

Following Klatt and Klatt (1990), I assume that there is an impact of the laryngeal property of a stop consonant on the beginning part of the following vowel, but that the impact is not extended to the middle part of the vowel. Under this assumption, we can make three hypotheses in (9).

(9) When AH1 is an amplitude value of the first harmonic, and when AH2 is an amplitude value of the second harmonic,

a. If a stop has the feature [Spread Glottis], AH2 minus AH1 (AH2 - AH1) in the middle part of the following vowel will be higher than AH2 minus AH1 (AH2 - AH1) in the beginning part of the vowel because the feature [Spread Glottis] of the stop consonant makes AH1 in the beginning part of the vowel higher than AH1 in the middle part of the vowel.

(AH2-AH1 of the middle part of the vowel » AH2-AH1 of the beginning part of the vowel)

b. If a stop has the feature [Constricted Glottis], AH2 - AH1 in the middle part of the following vowel will be lower than AH2 - AH1 in the beginning part of the vowel because the feature [Constricted Glottis] of the stop consonant makes AH1 in the beginning part of the vowel lower than AH1 in the middle part of the vowel.

(AH2-AH1 of the middle part of the vowel « AH2-AH1 of the beginning part of the vowel)

c. If a stop does not have [Spread Glottis] nor [Constricted Glottis], AH2 - AH1 in the middle part of the following vowel will be almost the same as AH2 - AH1 in the beginning part of the vowel because there is no feature affecting the beginning of the following vowel.

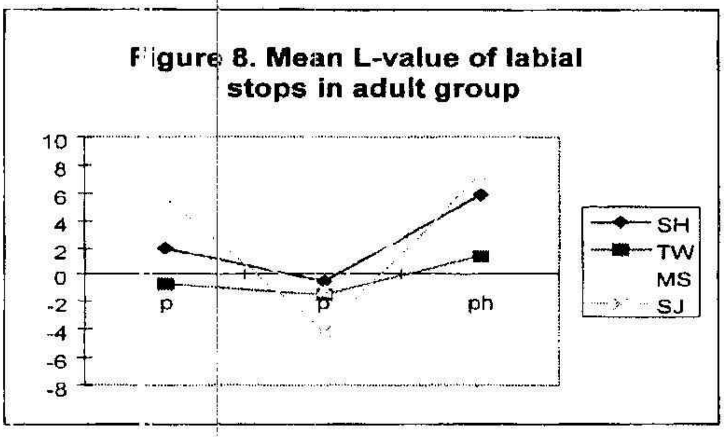
(AH2-AH1 of the middle part of the vowel = AH2-AH1 of the beginning part of the vowel)

Therefore, the measurement procedure of harmonic amplitudes is summarized as follows:

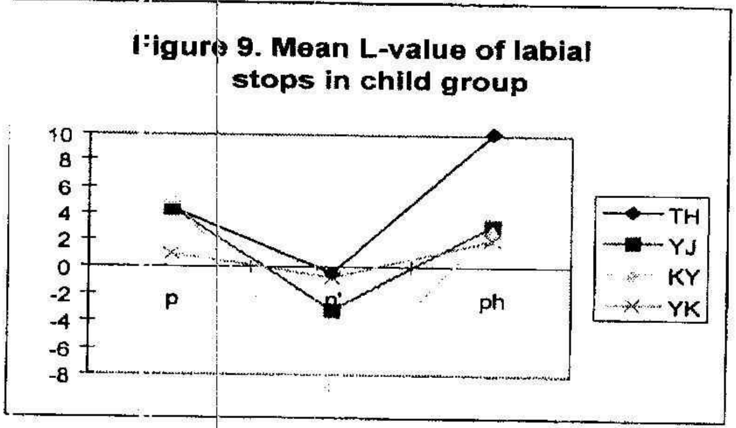
(10) When AH_b1 is the first harmonic amplitude of the beginning part of the vowel following a stop consonant;
AH_b2 is the second harmonic amplitude of the beginning part of the vowel following a stop consonant;
AH_m1 is the first harmonic amplitude of the middle part of the vowel following a stop consonant, and;
AH_m2 is the second harmonic amplitude of the middle part of the vowel following a stop consonant,
a. the measurement of AH_b1 and AH_b2
b. the measurement of AH_m1 and AH_m2
c. $\alpha = (AH_m2 - AH_m1) - (AH_b2 - AH_b1)$

Now, we can investigate the laryngeal properties of stop consonants by measuring the α value in (10c). In other words, if a vowel follows a [Constricted Glottis] stop, the α value will be negative, whereas the α value will be positive if a vowel follows a [Spread Glottis] stop. We can also predict that, if a vowel follows the modal stop consonant which do not have [Spread Glottis] nor [Constricted Glottis], the α value will be about zero. For the convenience of the calculation, I scaled up 10 dB in each value so that most numbers are positive. I will call the value calculated by Formula (12c) Laryngeal Feature Value α (L-value α). I present line graphs of mean L-values of word-initial labial stops in Figures 8 and 9 in (11).

(11) Mean L-values of labial stop consonants
a. Adult Group



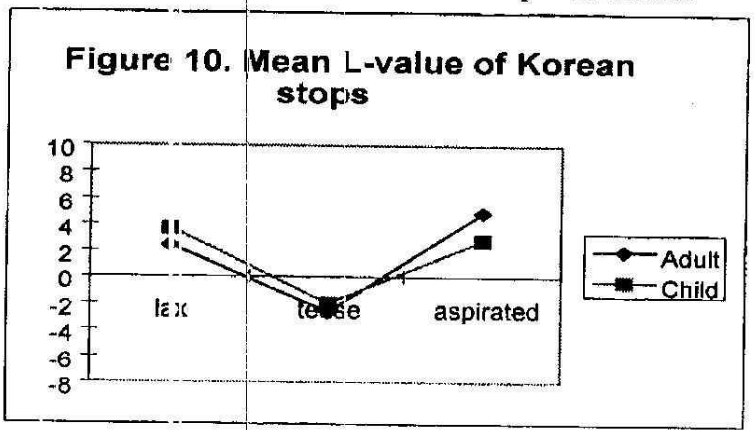
b. Child Group



As graphically represented in Figures 8 and 9, the tense stop /p'/ has the lowest L-value, and the L-value of the aspirated stop /p^h/ seems to be higher than that of the lax stop /p/. In every subject, the mean L-value of /p'/ is below zero, whereas that of /p^h/ is above zero. Moreover, except for TW, all subjects have the L-values of the lax stop /p/ above zero.

Now, let us consider the L-values in terms of phonation types. Assuming that the difference in place of articulation does not significantly affect the L-value, I combined the L-values in terms of each phonation type. Figure 10 below demonstrates the patterns of L-values in terms of phonation types.

(12) Mean L-values of Korean stop consonants



Tense stops in (12) have negative L-values, whereas lax and aspirated stops have positive L-values in both groups. Aspirated stops have the higher value than lax stops in adult group, whereas lax stops have the higher value than aspirated stops in child group. ANOVA statistics shows that the difference in mean L-values between lax stops and aspirated stops is significant in adult group (p=0.000). On the other hand, it shows that the difference in mean L-values is not significant between lax stops and aspirated stops in child group (p=0.085).

These results, therefore, show that Korean tense stops have negative L-values which are significantly different from those of lax stops and aspirated stops in each group. In other words, the negative L-values of tense stops indicate that the feature [Constricted Glottis] makes the lowering of H1 in the beginning part of the following vowel. Therefore, we can see that Korean tense stops have the feature [Constricted Glottis], and that the negative L-value representing [Constricted Glottis] is a crucial cue to distinguish Korean tense stops from the other Korean stops. Interestingly, ANOVA statistics shows that there is no statistically significant difference in mean L-values of tense stops between adult group and child group (p=0.283). What this means is that child subjects produce tense stops represented by the feature [Constricted Glottis] in the adult-like manner.

Now consider the L-values of lax stops and aspirated stops. We hypothesized that, if Korean lax stops do not have [Spread Glottis] nor [Constricted Glottis], the L-values would be about zero. However, our experimental results show that Korean lax stops have positive L-values. Therefore, we can see that the open quotient of glottal pulse increases in Korean lax stops. However, the fact that there is statistically significant difference in mean L-values between lax stops and aspirated stops in adult group shows that the open quotient is relatively less in Korean lax stops than in Korean aspirated stops. Also, the fact that there is no statistically significant difference in mean L-values between lax stops and aspirated stops in child group shows that Korean children under 7;0 have not acquired the complete control over the aspiration of lax and aspirated stops.

4. Conclusion

We have so far examined phonetic and acoustic properties of Korean stop consonants exhibiting three-way phonemic contrast. The acoustic and statistical analyses have shown that the phonemic contrast of Korean stop consonants cannot be cued with any single acoustic property. In the VOT analysis in 3.2, we have seen that while VOT can be a cue to distinguish tense stops from the other stops in the word-initial position, there are significant variation and overlapping of VOT values, depending on contexts and speakers. The SCD analysis in 3.3 has shown that while SCD can be a cue to distinguish lax stops from tense and aspirated stops, it cannot be a cue to distinguish aspirated stops from tense stops, as summarized in (13).

(13) Distinction of stop consonants in terms of SCD in Korean: both groups

	Lax	Aspirated	Tense
SCD	short	long	long

On the other hand, the experiment of laryngeal properties in 3.4 has shown that tense stops have the feature [Constricted Glottis]. Therefore, the phonemic contrast between tense stops and the other two types of stops can be cued with the negative L-value acoustically representing [Constricted Glottis], as shown in (14).

(14) Distinction of stop consonants in terms of L-value in Korean

a. Adult Group

	Tense	Lax	Aspirated
L-value	negative	positive	positive, higher than lax

b. Child Group

	Tense	Lax	Aspirated
L-value	negative	positive	positive

However, lax stops cannot be phonemically differentiated from aspirated stops in terms of L-value in child group. Therefore, we can see that Korean stop consonants cannot be phonemically differentiated by just a single acoustic cue, but that they can be differentiated by the combination of multiple acoustic cues, specifically by the combination of the L-values to distinguish tense stops from the other stops, and the SCD values to distinguish lax stops from the other stops.

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Appendix: A Complete Listing of Test Sentences

Ref	Korean/Translation	
00	i-ken	pal-ita
	'This is a foot.'	
01	i-ken	p^hal-ita
	'This is an arm.'	
02	i-ken	p'allay-ta
	'This is laundry.'	
03	ku-ka	capa-seyo
	'He caught (something)'.	
04	ku-ka	ap^{h}a-seyo
	'He was sick.'	
05	ku-ka	nap'a-seyo
	'He was bad.'	
06	i-ken	tal-ita
	'This is the moon.'	
07	i-ken	t^hal-ita
	'This is a mask.'	
08	i-ken	t'al-ita
	'This is a daughter.'	
09	ku-ka	kate-lakuyo
	'He went away.'	
10	ku-ka	nat^{h}ana-seyo
	'He came out.'	
11	ku-ka	twit'el-ece-seyo
	'He was behind.'	
12	i-ken	kalsek-ita
	'This is brown.'	
13	i-ken	k^hal-ita
	'This is a knife.'	
14	i-ken	k'achi-ta

'This is a Korean magpie.'

15 kɨ-ka takawa-seyo
'He was coming (toward us).'

16 kɨ-ka cik^hye-seyo
'He was guiding (somebody).'

17 kɨ-ka kak'awa-seyo
'He was nearby (something).'

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