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Korean Lenis and Fortis Stops: Synthesis and Categorical Speech Perception Task

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Abstract: This paper reports on an attempt to synthesize two different Korean syllables based on the previous articulatory and acoustic studies about Korean stops: /t'a/ which consists of an alveolar fortis stop and /ta/ which consists of an alveolar lenis stop. Using these two synthesized syllables as endpoints of the continuum, five more syllables between two endpoints were created for identification and discrimination tasks. Korean native speakers did not perceive the stimuli categorically; their identification boundary was not very sharp and the discrimination peak was not very high, either. Two possible reasons were proposed for this unexpected result.

1. Introduction

The stop consonants in Korean have a three-way distinction in place of articulation. For the same place of articulation there is a three-way distinction in manner of articulation in initial position. Linguists have used the following terms to describe the manner distinction. Category 1 is characterized as voiceless, tense, long, strong, forced and/or glottalized; Category 2 is voiceless, lax, slightly aspirated, and/or weak; Category 3 is voiceless, heavily aspirated. An example of this three-way distinction is shown in (1).

(1)

	1		2		3	
	t'al	'daughter'	tal	'moon'	t^{h}al	'mask'
	p'aŋ	'bread'	paŋ	'room'	p^{h}aŋ	'bang'

(Henceforth, I will call Category 1 a fortis stop, Category 2 a lenis stop, and Category 3 an aspirated stop.)

Abramson and Lisker (1964) claimed that they could be classified into three groups simply in terms of VOT differences. However, others have noted that fortis and lenis stops have overlapping VOT values.[1] Kim (1965) found this overlap made by the same speaker on the same day. A perceptual experiment done by Han and Weitzman (1970), where subjects were asked to identify stimuli which were

[1] Abramson and Lisker (1964: 403) also observed the overlap in VOT, but attached little importance to it, saying merely that the distribution of values is "somewhat anomalous."

made by cutting off portions of the aspirated part of an aspirated stop, showed that at least 75% of the responses were for a lenis stop even when the VOT was reduced to 1 ms or less, which is within the range of VOT for fortis stops. The result of Abramson and Lisker's (1971) perception test also indicated that there must be another dimension that works with VOT in distinguishing the categories.

Since the VOT difference alone is not enough to distinguish these two stops, there must be other characteristics which differentiate them significantly from each other. The present study consists of three parts. First, I will review the existing experimental literature on the production of the distinction. Second, I will report on an attempt to synthesize these two sounds using synthesizer parameter settings based on the articulatory and acoustic findings made in the previous studies. By synthesizing the stops we should be able to see what kinds of differences contribute most to distinguish them from each other. Third, I produced a lenis-fortis continuum along the dimensions of contrast used in the synthesis of the two types and used it in categorical perception tasks. I will report on how Korean native speakers perceive that continuum.

2. Summary of existing production studies

Previous production studies can be classified into four approaches: acoustic records, fiberscopic and EGG observation of laryngeal vibration and glottal area, EMG records of muscle activity, and measurements of air pressure and air flow. Results generally agree with an interpretation of the fortis stop as having ejective characteristics and the lenis stop as having breathy voiced characteristics. For example, Kim (1965) found that right after the release of fortis stops, the acoustic intensity was greater and the fundamental frequency was higher than after corresponding lenis stops. Han and Weitzman (1970) similarly found that at the voice onset following fortis stops, the amplitude rise time is shorter and intensity is greater than that for the corresponding lenis stops. Higher fundamental frequency at the voice onset of the vowel following the fortis stops was also reported in studies such as Han and Weitzman (1967, 1970), Hardcastle (1973) and Kagaya (1974). These results are suggestive of high f0 after fortis stops and low f0 around breathy consonants in other languages as cited in Hombert (1979). Kagaya (1974) observed longer duration of formant of transition for fortis stops than for the corresponding lenis stops.

In addition to these acoustic characteristics of Korean lenis and fortis stops, Kim (1965) observed weaker intensity of aspiration noise for the lenis stops than for the corresponding aspirated stops. He and others (e.g. Han and Weitzman 1970) also observed weaker higher formants (f3 and/or f4) which is believed to be indicative of breathy voice. Kim noted that Korean lenis stops were heard with a lot of breathiness by Westerners. This observation is supported by some spectrographic studies such as Han and Weitzman (1967). They found a mixture of voicing and noise at the onset of the vowel following the lenis stop. This can be seen in the spectrogram of my voice given in Fig. 1. Noise appears at the beginning of the vowel /a/ following the lenis stop /p/.

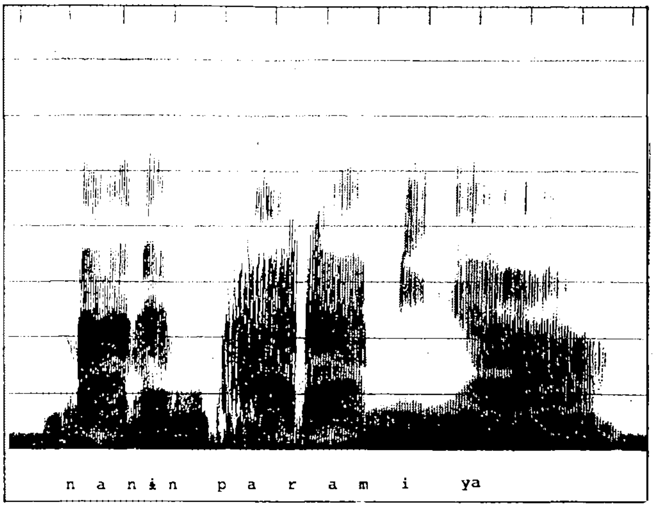

Fig. 1: A spectrogram of the Korean sentence /nanɨn paramiya/.

According to Kagaya's (1971, 1974) fiberscopic studies and Dart's (1987) summary, the peak value of glottal width during articulatory closure was largest for the aspirated stop, intermediate for the lenis stop, and smallest for the fortis stop. The timing of the narrowing gestures relative to articulatory release is also different in the various kinds of stops. For the aspirated stop, release generally occurred near the moment of maximal glottal opening. With lenis stops, the glottis began to close gradually through the occlusion, although the glottis was still open at release.[2] During the fortis occlusion, on the other hand, the vocal folds were in complete contact from 80 to 100 ms before release. Abberton's (1972) laryngographic study found that waveforms of the fortis stop showed the long closed phase and slow opening characteristics of creaky voice.

EMG studies of the intrinsic laryngeal muscles such as Hirose et al. (1974) showed a marked increase in lateral cricoarytenoid and vocalis muscle activity just

[2] In addition, a complete contact of the vocal folds is observed all through the utterance with the vocal folds vibrating for the lenis stop in the intervocalic position.

before release in the fortis stop. This means that the glottis is tightly closed before release by a tensing of these adductor muscles. Kim's (1965) EMG and palatograph study reported greater muscle activity at the lips during fortis bilabials and more contact between the tongue and the roof of the mouth in fortis alveolar stops. This indicates greater tension in the whole vocal tract which causes air to be compressed as in ejectives. On the basis of his own observation such as higher fundamental frequency, sharper formant structure and less air flow for fortis stops, Hardcastle (1973) also concluded that before the occlusion of the glottis during production of fortis stops, the muscles of the vocal folds and pharynx are stiffened by an increase in isometric tension and the glottis is tightly adducted. Vibration, however, does not occur during this occlusion because of the increased tension in the vocalis muscle.

Kim found that either the duration of increased intraoral pressure was shorter or there was less amplitude of pressure -- or both -- in lenis stops. Hardcastle (1973) observed that air flow rate after release was greatest for the aspirated stop, intermediate for the lenis stop, and least for the fortis stop. Dart (1987) also observed higher oral air pressure before release and lower oral airflow after release for the fortis stop than the lenis stop, although speakers differ in their production strategies: some seem to put more emphasis on air pressure difference and others put more emphasis on oral air flow difference. Dart explored possible reasons for this difference using Keating's (1984) computer implemented aerodynamic model, given the differences in closure duration difference and glottal area function as estimated from Kagaya (1974). In addition to these two differences, the results of the modeling experiment led her to infer that fortis stops are produced with greater vocal tract wall tension than in lenis stops. Furthermore, this simulation experiment suggested the factors that could be involved in the speaker-specific production strategies observed. Speaker who depend more on the oral flow difference may show larynx lowering or other supraglottal cavity expansion just before release of the fortis stop, while speakers who depend more on the air pressure difference may show a more rapid increase in respiratory muscle force during the closure and a smaller VOT difference between the stops.

To summarize the findings thus far, we can assume that the articulation of fortis stops differs from that of lenis stops in the following ways: first, greater tension in the laryngeal muscles (especially vocalis and LCA, which are adductor muscles) is involved in the production of fortis stops, causing a very small opening followed by a complete tight contact. Lower oral airflow right after release of the fortis stops could be a consequence of a complete contact of vocal folds at the points of release, while higher oral airflow right after the release of the lenis stops could be a result of a slight opening of the glottis at the point of release which might be one of the reasons for the observed breathiness at the onset of vocal fold vibration following lenis stops. Furthermore, the greater tension in the glottis adduction explains not only why creaky voice at the onset of voicing following fortis stops is observed but also why the fortis stop is not voiced intervocalically while the lenis stop is voiced.

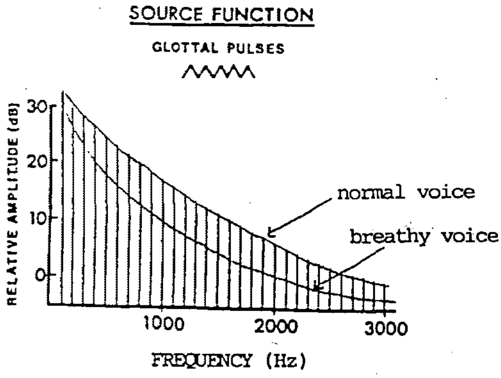

Fig. 2: The spectrum of the glottal source for a breathy voice and a normal voice (adapted from Borden and Harris 1984).

Second, as Hardcastle (1973) pointed out, fortis stops may involve an increase in isometric tension in the vocalis muscle to stiffen the vocal folds, which I believe causes them to be thinner, and thus to vibrate at a faster rate when they are closer together for voicing. Third, the tensing during the fortis stop is perhaps not confined to the glottis but is present in the rest of the vocal tract, offering an acoustically less damped formant structure. Fourth, as Kagaya (1974) suggested, the waveform of the volume velocity at the glottis for lenis stops could be characterized as a steeply falling slope from the fact that for all three types of stops, f3 and f4 are almost steady and each formant frequency is almost the same at the voice onset; but these formants of the vowel segment following the lenis stops were weaker. In other words, the amplitude of the higher harmonics for a breathy voice in the glottis would be lower relative to that for normal voice as can be seen in Fig. 2. This hypothetical steeply falling slope of the glottis waveform for Korean lenis stops acccompanied by breathiness is compatible with Fant's (1983) study about voice source by inverse filtering.

In short, the fortis vs. lenis contrast in Korean can be characterized not only by the presence vs. absence of tension in the vocal folds and the whole vocal tract but also by steepness vs. gradualness of the slope of the glottis waveform.

3. Synthesis

This study used the KLPC synthesizer program which is a version of the Klatt software synthesizer (Klatt 1980) rewritten to run on an IBM compatible PC by K. Johnson and Y. Qi. A list of the constant and variable parameter time functions that control the synthesizer is shown in the appendix.

I started with the English syllable /ta/. The whole length of the syllable is 700 ms. The value of the parameters, 'av', 'oq', and 'f0' were varied to reflect the findings of the previous studies such as differences with respect to degree of prominence in formant structure, the duration of open phase of the glottal pulse for the vowel following the stops, and fundamental frequency right after the release of the stops, respectively.

To reflect the more prominent and sharper formant structure at the onset of the vowel following fortis stops and results of the perception test in Han and Weitzman (1970), the parameter 'av' was used. The variable 'av', "amplitude of voicing", is the amplitude in dB of the voicing source waveform. For the fortis stop, the value of 'av' was set at 0 at release (195 ms) and raised to 60 within 5 ms, i.e., a very sharp rise. In contrast, 'av' was allowed to rise gradually for the lenis stops (from 0 at 195 ms to 60 at 260 ms) as seen in Fig. 3a.

To reflect the difference in the duration of the open phase of the glottal pulse for the vowel following the fortis and lenis stops, i.e., creaky voice vs. breathy voice, at the onset of the vowels, the parameter 'oq' was employed. 'oq', "percent of voicing period with glottis open", is a nominal indicator of the length of the glottal pulse relative to the period when using the default impulse train glottal source. Generally, three phases are evident in the cycle of vibration in normal voice: a rapid closing, a slower opening and an open phase. Breathy voice is characterized by a long duration of the open phase and a slow closing phase; creaky voice by a long closed phase and slow opening as can be seen in Fig. 4. For the creakiness in the fortis stop, the value of 'oq' was set at 10 from 0 ms to 195 ms, i.e., during closure for the fortis stop, and it goes to 50 during the first 50 ms of the following vowel. This means that the closure phase of one glottal pulse is much longer relative to an open phase. For the breathiness in the lenis stop, the value of 'oq' was set at 70 during the stop closure and it goes down to 50 during the first 50 ms of the following vowel as in Fig. 3b.

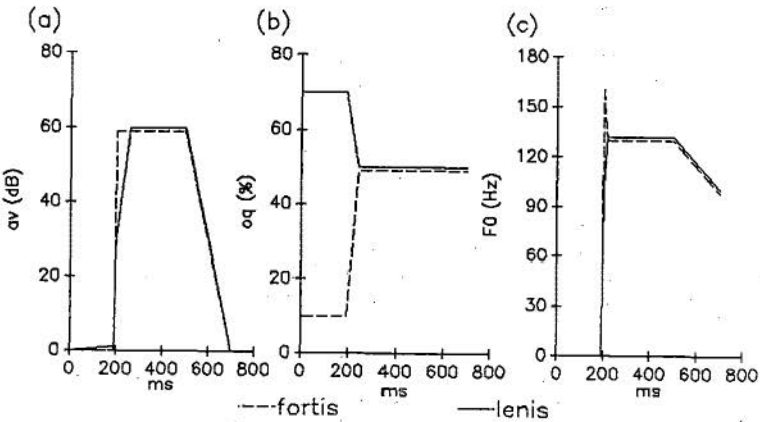

Fig. 3: The values of the parameters for Korean fortis and lenis stop syllables.

To reflect the higher fundamental frequency right after the release of the fortis stop and the lower one for the lenis stop, the parameter 'f0', "fundamental frequency", was varied as seen in Fig. 3c.

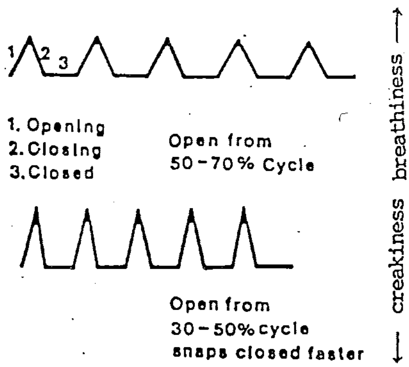

Fig. 4: Movement of the vocal folds during voicing for breathiness and creakiness (adapted from Borden and Harris 1984).

With the parameters used so far, I was able to synthesize an acceptable fortis stop. However, more parameters had to be changed for the lenis stop. The parameter 'tl' was used to reflect Kagaya's (1974) observation mentioned in section 2 that the higher formants, f3 and f4, are weaker at the onset of the vowel following the lenis stop, which was assumed to be due to the slope of the glottal waveform. The variable 'tl', "spectral tilt of voicing", is the additional downward tilt of the spectrum of the voicing source, in dB, as realized by a soft one-pole low-pass filter. This parameter is an attempt to simulate the spectral effect of a "rounding of the corner" at the time of closure in the glottal volume velocity waveform of breathiness, which is due either to an incomplete closure, or an asynchronous closure such that the anterior portion of the vocal folds meet at the midline before the posterior portions come together (Klatt 1980). The value of 'tl' was set at 0, the default value, for the fortis stop during the closure of the fortis stop but at 12 for the lenis stop. After the lenis closure, it went down to 0 during the first 50 ms of the following vowel as in Fig. 5a.

When changing the parameter 'tl', still I did not produce a good lenis stop. I tried turning on the 'ah' parameter to reflect some degree of intensity of the aspiration of the breathy release of the lenis stop. The variable 'ah' "amplitude of aspiration" is the amplitude in dB that is combined with periodic voicing, if present ('av'>0), to constitute the glottal sound source that is sent to the cascade vocal tract. I varied the value of 'ah' as in Fig. 5b.

In synthesizing these syllables, I only concentrated on getting those two sounds, not on determining what is the most important or primary cue. One thing that was observed by accident was that the fortis stop could not be synthesized with low f0 value with other parameters remaining unchanged. It would be interesting to see if there is a hierarchy among parameters used in this study in terms of the participation, or if they work equally in cueing those two types of stops.

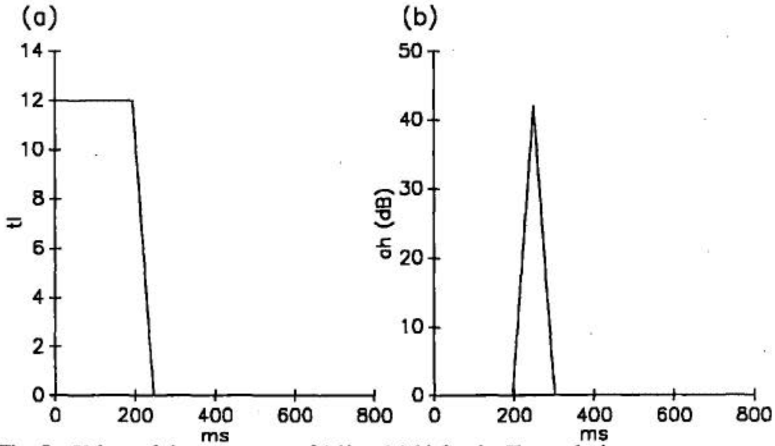

Fig. 5: Values of the parameters of 't1' and 'ah' for the Korean lenis stop.

4. Experiment (Speech perception tasks)

To test the synthesized fortis and lenis stops, I did a preliminary perception study.

4.1 Methods

4.1.1 Materials

A Korean lenis-fortis continuum was employed as the experimental stimuli. I used the two syllables which I had synthesized earlier as endpoints of the continuum. The basic pattern for each stimulus item consisted of 4 steady-state formants for the vowel [a] to which were added the appropriate release burst and formant transitions to produce alveolar fortis and lenis stops. The continuum consisted of 7 stimulus syllables which were varied in equal steps with respect to the same parameters used earlier, 'av', 'oq', 'f0', 'tl', and 'ah'.

4.1.2. Subjects

Four Korean native speakers served as subjects for this experiment. They were graduate students with ages ranging from 24 to 30. Of these subjects, 3 were female and 1 was male, and all had normal hearing as reported subjectively. Dialect variance between subjects was not considered because I thought that it would not affect perception of Korean stops at all.

4.1.3 PROCEDURE

Seven syllables were randomized by K. Johnson's (1985) ERS program (Experiment Running System) for identification tasks and a 2 step AX discrimination task. For the identification task, each token was represented 20 times and for the discrimination task, each pair of tokens were represented 10 times, with 15 practice items for each task.

Subjects were tested individually in the recording room at the OSU Linguistics Lab. They were instructed to press one button out of two to respond to the stimuli depending on whether they heard fortis or lenis. The ERS program tabulated responses of each subject.

4.2 Results

When we look at the average results given in Fig. 6, it seems that Korean native speakers do not perceive the fortis-lenis continuum categorically. The identification boundary between token 4 and token 5 is not very sharp and the discrimination peak between token 4 and token 6 is not high, either.

The individual subject's responses given in Fig. 7 agree with this average result. No subject identified the lenis and fortis in a strongly categorical manner, and especially subjects KB and KC identify even the endpoint stimulus with about 15 or 20% responses for the other category. Furthermore, the peak in the

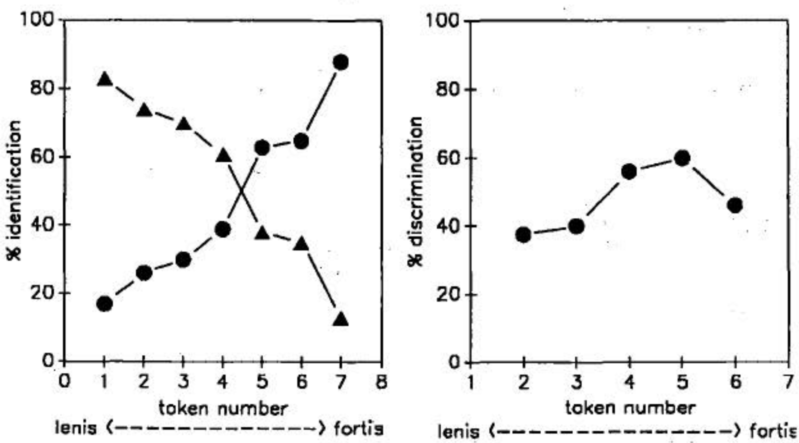

Fig. 6: Average response functions for the Korean native speakers on the identification and discrimination tasks.

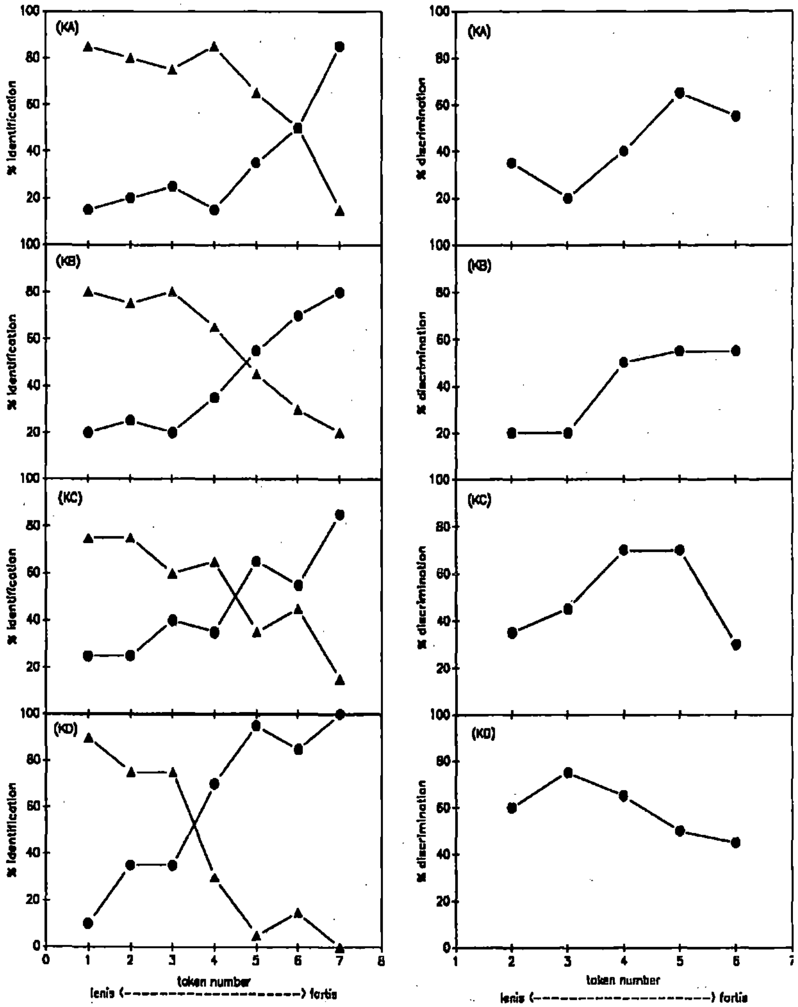

Fig. 7: Individual response functions on identification and discrimination tasks.

discrimination task is not so high, and especially subjects KA and KB have discrimination peaks just around 50 or 60. It is interesting to note that Korean subjects did not have identification boundaries at the same point along the continuum: subject KA has it around token 6; and subjects KB and KC, between token 4 and token 5; subject KD, between token 3 and token 4.

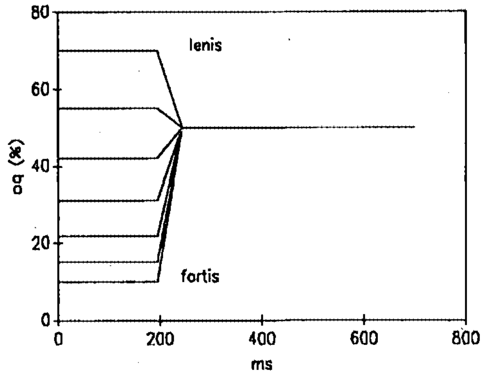

Fig. 8: Value of the parameter 'oq' in unequal steps.

It is also interesting that subjects KA, KB, and KC's discrimination peaks are expanded on the last two or three pairs, i.e., on pairs 3-5, 4-6, and 5-7. This observation could be interpreted as follows. The same articulatory or acoustic distance could be perceived as different distances depending on where in the continuum they are. For the lenis stop part along the continuum, the perception distance may be much closer than for the fortis stop part. In other words, in order for perception distance to be the same between each token, some parameters could be varied in unequal steps. For example, the parameter 'oq' should be varied in a larger step size around the lenis part and in a smaller step size around the fortis stop part along the continuum as in Fig. 8.

4.3 Discussion

We could think of some possible reasons for these unexpected results. One possible reason is that the parameters employed here in producing the lenis-fortis continuum do not work equally. Some parameters should be varied in smaller step sizes than other parameters or some in larger step size than others. To test this possibility we need to synthesize stimuli with each parameter changing separately and see what Korean speakers perceive.

Another possible reason is that most subjects were influenced by their native dialects. Three out of four subjects who participated in this experiment are native speakers of the Chonnam dialect where the pitch of the vowel is determined by the type of the preceding consonant in accentual phrase initial position: when the fortis or aspirated stop precedes a vowel, it is realized with a low or rising tone depending on its length (Jun 1990, this volume). Note that stimuli employed in this study were long (700 ms) and fundamental frequency was high (132 Hz) considering the fact that formant values were appropriate for a male speaker. So, the native speakers of this dialect, KA, KB, and KC, might identify the lenis and fortis stops sometimes by the quality of the following vowels. It might be very difficult for them to discriminate tokens all of which are long and high. This possibility is supported partially by the result of KD who is a native speaker of the Seoul dialect where this kind of consonant-dependent vowel pitch does not exist. The result of this subject is closer to the expected patterns of categorical speech perception than the others. The identification function is sharper and is less ambiguous for the endpoint stimuli. Furthermore, the discrimination peak of this subject is the highest.

The second possibility that speakers were influenced by their native dialects could be supported by the results from one subject which I have not mentioned in this study. She is also a native speaker of the Chonnam dialect. She perceived almost all the stimuli as syllables which contain a fortis stop. After serving as a subject of this experiment, she said that she did not hear any lenis stops but she was forced to push the button for the lenis stop sometimes because of the influence of instruction given for this experiment. It is very likely that she was concentrating on the vowel quality, not on the consonant quality, when she was asked to identify the type of consonants. To test this possibility, we need to get more subjects while controlling for dialect and put the syllables in non-initial position.

5. Conclusion

The first part of this paper describes an attempt to synthesize the Korean alveolar fortis and lenis stops and to figure out what kinds of articulatory and acoustic properties must be involved based on previous studies about those two types of Korean stops. To produce an acceptable fortis stop, the parameter 'av' (amplitude of voicing), 'oq' (percent of voicing of period with glottis open), and 'f0' (fundamental frequency) were employed which reflect respectively differences in prominence of formant structure, duration of opening phase of glottis and the fundamental frequency at the onset of the vowel following fortis and lenis stops as observed in earlier studies. To get an acceptable lenis stop, two more parameters, 'tl' (spectral tilt of voicing) and 'ah' (amplitude of aspiration) were used to reflect the observed weaker higher formants (f3 and/or f4) and some amount of intensity of the aspiration noise with voicing at the onset of the vowel following lenis stops.

The second part of this paper concentrated on the categorical perception experiments: the identification task and discrimination task using seven synthesized tokens along the lenis-fortis continuum. The result could be summarized as follows: Korean native speakers did not perceive the stimuli categorically. Their identification boundary was not very sharp and the discrimination peak was not very high, either.

To interpret the unexpected results of this study, two possible reasons were proposed: one is that all the parameters employed here may not work equally in cueing Korean lenis and fortis stops. Another is that most subjects in this experiment were influenced by their native dialects where the pitch of the phrase-initial vowel is determined by the type of the preceding consonant. In later work, I will test these two possibilities.

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Appendix: Constant and variable parameter time functions that control the synthesizer.

SYM	V/C	MIN	VAL	MAX
sr (sampling rate)	c	5000	10000	20000
du (duration)	c	30	700	5000
ui (update interval)	c	1	5	20
f0 (fundamental frequency)	v	0	1000	5000
f1 (first formant)	v	180	500	1300
f2 (second formant)	v	550	1500	3000
f3 (third formant)	v	1200	2500	4800
f4 (fourth formant)	v	2400	3250	4990
f5 (fifth formant)	v	3000	3700	4990
f6 (sixth formant)	v	3000	4990	4990
fz (frequency nasal zero)	v	180	280	800
fp (frequency nasal pole)	v	180	280	500
ah (amplitude of aspiration)	v	0	0	80
at (amplitude of turbulence)	v	0	0	80
af (amplitude of frication)	v	0	0	80
a1	v	0	0	80
a2	v	0	0	80
a3 (amplitudes parallel	v	0	0	80
a4 formants)	v	0	0	80
a5	v	0	0	80
a6	v	0	0	80
an (amplitude parallel nasal formant)	v	0	0	80
ap (amplitude voicing parallel)	v	0	0	80
g0 (overall gain control)	v	0	60	80
db	v	0	0	400
nf (number of formants in cascade vocal tract)	c	1	5	8
ss (source switch)	c	1	2	2
rs (random seed)	c	1	1	99
av (amplitude of voicing)	v	0	60	80
b1 (first bandwidth)	v	30	60	1000
b2 (second bandwidth)	v	40	90	1000
b3 (third bandwidth)	v	60	150	1000
b4 (fourth bandwidth)	v	100	200	1000
b5 (fifth bandwidth)	v	100	200	1500
b6 (sixth bandwidth)	v	100	500	4000
bz (bandwidth nasal zero)	v	40	90	1000
bp (bandwidth nasal pole)	v	40	90	1000
oq (percent of voicing period with glottis open)	v	10	50	80
tl (spectral tilt of voicing)	v	0	0	34

SYM	V/C	MIN	VAL	MAX
sk (skew to alternative periods)	v	0	0	100
p1	v	30	80	1000
p2	v	40	200	1000
p3 (bandwidths parallel	v	60	350	1000
p4 formants)	v	100	500	1000
p5	v	100	600	1500
p6	v	100	800	4000
ab (bypass path amplitude)	v	0	0	80
os (output waveform selector)	c	0	0	20
df	v	0	0	100