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Why are Korean tense stops acquired so early: The role of acoustic properties

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Abstract

Transcription-based studies have shown that tense stops appear before aspirated or lax stops in most Korean-acquiring children's speech. This order of mastery is predicted by the short lag Voice Onset Time (VOT) values of Korean tense stops, as this is the earliest acquired phonation type across languages. However, the tense stop also has greater motor demands than the other two phonation types, given its pressed voice quality (negative H1-H2) and its relatively high f0 value at vowel onset, word-initially. In order to explain the observed order of mastery of Korean stops, we need a more sensitive quantitative model of the role of multiple acoustic parameters in production and perception. This study explores the relationship between native speakers' transcriptions/categorizations of children's stop productions and three acoustic characteristics (VOT, H1-H2 and f0). The results showed that the primary acoustic parameter that adult listeners used to differentiate tense vs. non-tense stops was VOT. Listeners used VOT and the additional acoustic parameter of f0 to differentiate lax vs. aspirated stops. Thus, the early acquisition of tense stops is explained both by their short-lag VOT values and the fact that children need to learn to control only a single acoustic parameter to produce them.

Keywords

tense stop; Voice Onset Time; fundamental frequency (f0); transcription accuracy; Korean stop laryngeal contrast; phonological acquisition

1.0 Introduction

One of the most noteworthy achievements of modern phonetics is our understanding of how phonation categories map onto voice onset time (VOT) cross-linguistically. VOT is a continuous measure of the temporal relationship between two acoustic events that signal the

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onset of vocal fold vibration and the release of the oral constriction, but the three qualitatively different VOT relationships of "before" versus "simultaneous with" versus "well after" capture the three most commonly attested phonation categories across languages. For example, in Lisker & Abramson's (1964) seminal investigation of stop VOT distributions across eleven languages, the two stop phonation types in Dutch, Hungarian, Spanish and Tamil could be classified as "true" voicing contrasts that differentiated between lead and short lag values, whereas the two stop phonation types of Cantonese and English could be classified as aspiration contrasts between the long lag VOT range for aspirated stops and the short lag VOT range for unaspirated stops. The three stop phonation types of Eastern Armenian and Thai were a simple union of these two two-way contrasts.

Using VOT to describe stop phonation categories has also made it possible to capture several consistent trends in children's acquisition of these categories across languages and to generalize these trends as a well-motivated developmental universal. Across languages, children first produce short lag VOT values (Kewley-Port & Preston, 1974; Macken & Barton, 1980a; 1980b; Clumeck, Barton, Macken, & Huntington, 1981; Allen, 1985; Gandour, Petty, Dardarananda, Dechongkit, & Mukongoen, 1986; Pan, 1994; Davis, 1995). These early productions are perceived by adults as /p, t, k/ in languages such as Spanish and French where voiceless stops are unaspirated (Macken & Barton, 1980b; Allen, 1985) but as /b, d, g/ in English where voiceless stops are aspirated and the contrasting `voiced' stops are often not prevoiced (Kewley-Port & Preston, 1974; Macken & Barton, 1980a). In languages with a contrast between short and long lag VOT values, children learn to produce this contrast at a fairly young age, while the contrast between short lag and lead VOT values is not mastered until considerably later. This is true both when comparing across languages (e.g., the English and Cantonese long-lag stops are mastered by about 24 months, whereas the French pre-voiced stops are not mastered until about 4 or 5 years) and when comparing within languages with more than two stop series (e.g., the very youngest Thai-speaking children in the Gandour et al.'s study had long lag VOT values in their aspirated stops, but only the oldest children had voicing lead in their voiced stops).

Kewley-Port & Preston (1974) relate the earlier mastery of the short lag VOT category to the more precise motor control that is required to meet the challenging aerodynamic conditions for voicing lead and long lag VOT. The production of long lag VOT requires a precise temporal adjustment between the oral articulation and the glottal opening gesture. The temporal coordination needs to be precise enough to align the maximum glottal opening with the oral constriction release. In the same vein, voiced stops (particularly in initial position) are the last category to be acquired and this is predicted by their challenging motoric demands. The production of lead VOT requires that the glottal adduction gesture be made prior to the oral constriction release and also that supra-glottal air pressure be low enough relative to the sub-glottal pressure in order for vocal fold vibration to begin during the closure (Westbury, 1983; Keating, 1983; Westbury & Keating, 1986). When one end of the vocal cavity is closed, it is not easy to maintain a supra-glottal pressure that is lower than the sub-glottal pressure. Compared to long lag VOT and lead VOT, the production of short lag VOT is relatively easy in that it can be achieved by making an active glottal opening gesture at any time during the oral occlusion. It can even be achieved without any active glottal opening gesture, if there is also no other gesture such as pharynx widening or larynx lowering to insure the trans-glottal pressure differential required for voicing onset.

In this paper, we examine how VOT and two other acoustic properties can help to explain the mastery pattern for stop phonation types in Korean. Korean is unusual in having a three-way contrast that does not use the "default" voiceless unaspirated category, but instead contrasts tense laryngealized stops (also called `fortis' stops) with two types of more or less long lag stops (i.e., lax or `lenis' and aspirated). As Kim and Duanmu (2004) pointed out, the

Korean system resembles the three-way contrast in the Wu dialects of Chinese in that the lax stops of Korean, like the so-called `voiced' stops in the Wu dialects, are associated with a breathy voice quality and low tone when in phrase-initial position. The two systems differ, however, in that the Korean lax stops have considerably longer voiceless intervals before the onset of breathy voice, whereas the voiced stops of the Wu dialects have zero VOT or short lag VOT values comparable to the so-called `slack voice' /b, d, d̥, g/ of Javanese (see, e.g., Hayward, 1995; Thurgood, 2004). Moreover, the Korean tense stops are not like the "plain" voiceless unaspirated /p, t, k/ of the Wu dialects, but instead are more similar to the `stiff voice' /p, t, ʈ, k/ of Javanese. That is, they are associated with a tense `pressed' voice or (in some talkers) even a creaky voice quality at vowel onset rather than with the "default" modal voice quality that is observed at voice onset after the aspirated stops. In the next section, we review how the mastery pattern has been described in many transcription-based studies of Korean stops, and how it is related to the predictions based on VOT values.

1.1 Acquisition of Korean phonation categories

As noted above, a common finding in the cross-linguistic literature on stop consonant acquisition is that voiceless unaspirated stops are mastered before any other contrasting stop phonation types. This finding predicts that the earliest stop productions by Korean-speaking children should be tense stops, since this is the only Korean phonation type that has short lag VOT values today. This prediction is based on data from the VOT distributions of the three phonation categories in young adult Korean speakers, as their VOT distributions have changed over the past four decades. That is, the three phonation types in Korean have always been described as showing at least some VOT overlap. Earlier studies (Lisker & Abramson, 1964; Kim, 1965; Han & Weitzman, 1970) found some overlap between lax and tense stops in the short lag VOT range, while aspirated stops had values in the long lag VOT range that were clearly separated from the other two phonation types. However, more recent studies have shown a different pattern of VOT overlap. Korean speakers born after the 1970s produce tense stops in the short lag VOT range that are clearly separated from both lax and aspirated stops in the long lag VOT range. This newer pattern of VOT overlap in Korean stops has been described as a diachronic sound change in Silva (2006), Wright (2007) and Kang & Guion (2008).

So, given the VOT characteristics of the three phonation types in Korean today, we would predict that Korean-speaking children should first produce tense stops. This prediction accords with the results of prior transcription-based studies, which predominately date from the current millennium. Both cross-sectional and longitudinal studies of phonological development in Korean children have found that tense stops are mastered first, although all three phonation types are mastered by 4 years of age. For example, Kim & Pae (2005) studied Korean-speaking children aged 2;6 to 6;5 (years;months) and found that all three types were mastered by 75% of children in the age group from 3;1 to 3;6. However, tense stops were mastered before lax or aspirated stops, in that word initial /p'/ and /t'/ were produced correctly by 95% of children before 2;6. This accords with an earlier study by Pae (1994), who found that tense and lax stops were in the consonant inventories of children younger than 2;6 and tense stops were commonly substituted for lax stops. It also accords with a more recent study by Kim (2008), who transcribed multiple repetitions of target word-initial stops per child. Tense stops /p', t', k'/ were produced with 75% accuracy by more than 75% of children at 2;6, while the same accuracy rates for aspirated stops /p^h/, /t^h/ and /k^h/ and lax stop /t/ were not achieved until 3;0 and 4;0, respectively. Similarly, in a longitudinal case study by Jun (2007), word-initial tense stops were recorded to appear at 17 months, before aspirated (18 mo.) and lax (20 mo.).

Although predictions based on VOT of the relative order of mastery of the three types of stops accord well with this previous research, it is somewhat surprising that tense stops are mastered so early, given that the motoric demands for tense stops are greater than for those for lax stops. While tense stops are similar to voiceless unaspirated stops in other languages in that they all have short lag VOT values, tense stops are different from voiceless unaspirated stops in that they have greater motoric demands in other respects. The "tenseness" of Korean tense stops results from a laryngeal muscle tenseness (activation of the vocalis muscle) that suppresses vocal fold vibration despite an adducted glottis before the oral constriction release (Hardcastle, 1973; Kagaya, 1974; Hirose, Lee & Ushijima, 1974; Dart, 1987; Hong, Nimii & Hirose, 1991). There is also a general vocal tract tension that restrains the passive expansion of the supra-glottal cavity in order to maintain higher supra-glottal pressure relative to sub-glottal pressure. This prevents vocal fold vibration from beginning as soon as the glottis is completely adducted. We might predict that the greater motoric demands associated with tense stops would result in later mastery of this phonation type, especially since the other two phonation types of stops in Korean have more cross-linguistically typical laryngeal conditions. Lax stops are characterized by a gradual glottal closing with a moderate suppression of adduction muscle (lateral cricoarytenoid) activity during the stop closure (Kagaya, 1974; Hirose et al., 1974; Hong et al., 1991). The glottal gestures are not precisely timed, resulting in a mildly aspirated stop in initial position, and also producing the passive voicing of intervocalic lax stops in Korean. In this respect, lax stops are closer to an unmarked (or unspecified) phonation category in Korean (see Kim & Duanmu 2004 for a comprehensive discussion of the phonological status of the three phonation categories in Korean). By contrast, the aspirated stop is distinguished from the lax as well as from the tense stop categories by having a clear suppression of adduction muscle activity immediately before the release, as well as by a prolonged activation of abduction muscles which gives way to peak activation of adduction muscles soon after the release (see, e.g., Hirose, Lee, & Ushijima, 1974; Hong, Niimi & Hirose, 1991; Hong, Kim & Niimi, 2002). This results in the glottis being held open for a long enough interval to have a period of turbulent aspiration noise before the onset of modal voice (Hirose et al., 1974; Kagaya, 1974; Hong et al., 2002; Kim, Honda & Maeda, 2005). Lax stops are also more frequent in Korean than tense stops or aspirated stops, although tense stops are somewhat more frequent in infant-directed speech than in adult-directed speech (18% and 10%, respectively, Lee, Davis & MacNeilage, 2008). Given these laryngeal conditions of the three stop categories, as well as the relative frequencies of the two types, it is somewhat surprising that Korean-speaking children master the tense category so early relative to the lax stop.

The muscle tenseness of tense stops affects not only VOT but also other acoustic dimensions such as fundamental frequency (f0) and voice quality. In addition to having a short lag VOT, the Korean tense stop is further characterized as having a higher f0 immediately after voice onset and a somewhat pressed voice quality, due to the vocal cords being pressed (Hardcastle, 1973; Kagaya, 1974; Hirose et al., 1974; Dart, 1987; Jun, 1993). Also, the glottal configurations of Korean stops affect the following vowel quality in such a way that the vocalic onset after the tense stop has a pressed quality, whereas the vocalic onset after the lax stop has a breathy quality and only the aspirated stop has an unspecified or modal voice quality. When H1-H2 (the amplitude difference between the first and second harmonics; Holmberg, Hillman & Perkell, 1988; Hanson & Chuang, 1999) is measured to capture the voice quality in the vowel just after lax, aspirated, and tense stops, the lax stop is characterized as having the greatest H1-H2 value and the tense stop as the smallest (i.e., negative) H1-H2 value. This acoustic parameter of H1-H2 can distinguish tense from lax and aspirated stops in Korean in adult speakers' productions (Cho, Jun & Ladefoged, 2002; Kim, Beddor & Horrocks, 2002; Kim, 2008). Thus, VOT is only one of several acoustic characteristics that differentiate tense stops from lax and aspirated stops in Korean.

1.2 Predictions

One hypothesis that relates the mastery pattern suggested in transcription studies to the acoustic characteristics of Korean stops is that despite the multiple acoustic parameters that differentiate the tense type from the other two types in Korean, native speakers' transcribed accuracy of children's stops mostly depends on VOT values of the tokens. This hypothesis is compatible with the literature on "covert contrast" — i.e., the well-attested ways in which adult native speakers stereotypically accommodate to children's less-skilled speech production by assimilating intermediate or imperfectly differentiated sounds to one or another phoneme category in the target language (see, e.g., Macken & Barton, 1980a; Maxwell & Weismer, 1982; Scobbie, Gibbon, Hardcastle & Fletcher, 2000, among many others). It is compatible also with the changing role of VOT in differentiating the three-way phonation-type contrast found in adult stop productions in more recent studies. Since short-lag VOT is a sufficient acoustic cue for differentiating the tense category from the other two categories in Korean today, a Korean adult transcriber might judge the accuracy of tense stops based on VOT alone, with little influence from other acoustic parameters such as f0 and H1-H2. If this kind of "categorical perception" were the norm, a young child's short lag VOT tokens should be heard as tense stops, even though the child is not producing the voice quality that characterizes these stops in adult productions.

This hypothesis can be tested by assessing the relative role of VOT and other acoustic cues in determining the transcription accuracy of tense, lax and aspirated categories in Korean. Therefore, the goal of this study was to examine the relationship between the acoustic properties of Korean children's stop productions and the categories given by a native transcriber (a common assessment of mastery order). First, we investigated which acoustic parameter in Korean stops best determined the accuracy of the different stop phonation types in children's productions when the stop tokens were judged by a native transcriber. Specifically, the stop productions by 67 Korean-speaking children (aged 24 through 72 months) and 20 adults (aged 18 through 30 years) were analyzed in terms of the acoustic parameters of f0, H1-H2 and VOT. Regression models were used to examine the relationship between the acoustic properties of each token and the transcribed phonation type (for children) or the target phonation type (for adults). Second, we examined how the acoustic parameters affected adult Korean naive listeners' identification of the phonation-type categories when they listened to children's stop productions. This perception experiment with naïve Korean adults was conducted to see whether the patterns seen in the expert transcriber's perceptual judgments extend also to a more representative sample of the general population.

While a number of studies have examined the development of the stop phonation-type contrast in Korean, their interest was focused on either transcription accuracy rates for children's productions in different age groups (Pae, 1994; Kim & Pae, 2005; Kim & Shin, 2004) or on relating the acoustic characteristics of children's stops to the target categories (Kang, 1998; Jun, 2007; Lee & Iverson 2008; Kim & Stoel-Gammon, 2009). The current study is unique in that we relate transcription and other perceptual measures to acoustic measures in order to try to explain the relative order of mastery of the different types in Korean-acquiring children.

2.0 Experiment I: production of Korean stops and trained phonetician judgments

2.1 Method

2.1.1 Materials—The target consonants were word-initial lingual stops in three vowel contexts (/i/, /a/ and /u/). The stimuli are part of a larger experiment that focuses on acquisition of lingual obstruents (Edwards & Beckman, 2008). We did not add more words to the larger list in order to look at /p/, /p'/ and /pʰ/, because labial stops are mastered as early as 2;6 (Kim & Pae, 2005). Three words were selected to elicit the target in each vowel context. For example, Korean /t/ vs. /t'/ vs. /tʰ/ in the /a/ context were elicited in [taŋ.gɨn] `carrot', [t'al.gi] `strawberry' and [tʰa.dʒo] `ostrich'[1]. The presentation order of the words was determined by a randomizing algorithm that insured that words with the same sequence of target consonant and vowel were not adjacent to one another in the list and that, at most, two words for any CV type were presented in either of two blocks. We chose target words that were familiar to young children (see Table 1 for the lists of word used to elicit the target lingual stops). Multiple tokens of the target words were recorded by an adult female native speaker of Korean using a child directed speaking style. Only tokens that at least four adult listeners repeated correctly were selected as stimuli in the experiment. In addition to the audio stimuli, culturally appropriate pictures of target words were presented along with the audio stimuli in the production experiment.

2.1.2 Subjects—There were 67 child participants, aged 2;0 to 5;11, and 20 adult participants, aged 18 to 30 years (see Table 2). Both adults and children were recruited and recorded in Seoul, Korea. All the child and adult participants passed a hearing screening.

2.1.3 Task—Target consonants were elicited using a picture-prompted word-repetition task. On each trial, a computer program presented a picture on the monitor and played the recorded audio stimulus naming the picture through an external speaker. Subjects were asked to repeat the target word after the audio presentation. Their repetitions were recorded for later transcription and acoustic analysis. We used a unidirectional tabletop microphone.

The child subjects were also given an articulation test (Urimal Test of Articulation and Phonology: U-TAP; Kim & Shin, 2004) and a receptive vocabulary test (Picture Vocabulary Test; Kim, Chang, Lim & Paek, 1995) in order to make sure their language development was age-appropriate. Recordings were made in childcare centers or in the children's homes for the youngest children.

2.2 Analysis

2.2.1 Transcribed accuracy/error analysis—If children produced more than one token, only the first production was included in the analysis. All of the productions were transcribed by the first author, a trained phonetician and a native speaker of Korean. First, the transcriber coded the consonant as correct or incorrect. Then, the transcriber provided an alphabetic transcription of those productions that were judged as incorrect. While non-plosive productions were regarded as errors, place of articulation errors were coded as correct for the purpose of the current analysis as long as the phonation-type categories were correct. For example, [t] or [tʃ] for a target /k/ was counted as correct for voicing, despite the error in the place of articulation. We excluded errors of deletion, distortion and non-plosive productions from the analysis. 10% of the data were transcribed by a second native-speaker transcriber in order to assess the inter-transcriber reliability. Phoneme-by-phoneme inter-rater reliability was 92%, 91% and 76% for tense, aspirated and lax stops, respectively. The distribution of tokens used for the analysis is presented in Table 3.

The mastery pattern of each stop phonation-type category was predicted in two apparent-time analyses, one based on the transcribed accuracy and the other on the error patterns,

[1]The target consonants were elicited either in open- or closed-syllable structures. However, this syllable structure difference did not affect the results of subsequent analysis.

using mixed effects logistic regression models (Snijder & Bosker, 1999; Raudenbush & Bryk, 2002). Equation 1 and Equation 2 show the formulae for the two models.

The first model was fit to all of the productions. It predicts the log odds that a token will be transcribed as an accurate rendition of the target phonation type (*Accuracy*), based on the child's age in months (*Age*) and the phonation type (*Phon.Type*). The intercept and the slope of the phonation types variable at the speaker level are added as random effects to the model, denoted as γ in Equation 1.

$$\log\left(\frac{Accuracy}{1-Accuracy}\right)=\beta_0+\beta_1 Phon.Type+\beta_2 Age+\gamma Speaker$$

Equation 1

The second model was fit just to the target lax and aspirated stops which were identified as having phonation type errors. It predicts the log odds of being substituted by a tense stop, based on the child's age in months (*Age*) and the target consonant phonation type (lax or aspirated: *TargetCat*). Again, the model included the intercept and the slope of the target consonant phonation type as random effects at the speaker level.

$$\log\left(\frac{Subst.Tense}{1-Subst.Tense}\right)=\beta_0+\beta_1 TargetCat+\beta_2 Age+\gamma Speaker$$

Equation 2

2.2.2 Acoustic analysis—VOT was measured by subtracting the onset of the burst (i.e., the beginning of an abrupt energy rise after the closure) from the time of the first indication of voicing, evident from the voicing bar in the spectrogram, as well as a visible initiation of the first regular cycle of periodicity in the waveform.

f0 was measured by taking the reciprocal of the interval between two neighboring pulses at 20 ms after the voicing onset. The glottal pulses were automatically detected using the pulse function in Praat (this is an auto-correlation based periodicity detector). The f0 measurement was made at 20 ms after the voicing onset, instead of immediately at the voicing onset, because it was observed that the function was more reliable (higher correlation coefficient) several glottal pulses after the exact onset of voicing.

We used H1-H2 as our spectral tilt measurement to capture the breathiness at the vowel onset. It was measured by subtracting the amplitude (in dB) of the second harmonic from the amplitude of the first harmonic in the fast Fourier transform spectrum generated based on a 25 ms analysis Hamming window beginning at the voicing onset. The frequency location of the first harmonic was automatically detected by Praat, referring to the fundamental frequency as an initial value, and then the researcher checked the precise frequency locations for the first and the second harmonic in a token-by-token manner in order not to be confused between DC noise and H1 or between H2 and A1 (amplitude of the first formant). There were instances where there was no clear second harmonic due to weak periodicity at the voicing onset. For these tokens, the frequency at twice the first harmonic was taken to be the frequency of the second harmonic, and the amplitude at that frequency location was taken as H2.

A mixed effects logistic regression model was used to evaluate the effects of each acoustic parameter in predicting the consonant categories as expressed in Equation 3. To accommodate the three-way contrast of Korean stop phonation, we used two equivalent sets of mixed effects logistic regression models. One set of mixed effects logistic regression models predicted the tense vs. the non-tense types (i.e., the lax and the aspirated types) as the dependent variable, and the other set of models predicted the lax vs. the aspirated types as the dependent variable. In each set of models, the log odds of the probability of being transcribed as one particular phonation type (e.g., tense versus non-tense: *Phon.Type*) were predicted by three acoustic parameters (*VOT*, *f0* and *H1H2*) that characterize each token and by the variance of these acoustic parameters that exist in the individual speaker level as the random effects. We assumed that the adults accurately produced the target stops without phonation-type errors, and therefore, we treat the target phonation types of adult productions as equivalent to the transcribed categories of the child productions.

$$\log\left(\frac{Phon.Type}{1-Phon.Type}\right)=\beta_0+\beta_1 VOT+\beta_2 f0+\beta_3 H1H2+\gamma Speaker$$

Equation 3

The coefficients (i.e., β_1, β_2, β_3) of each parameter indicate the size of the effect in determining the tenseness of the item in the tense versus non-tense model, if the coefficient is a significantly effective variable in the model. The greater the absolute value of the coefficient is, the more influential is the variable. To remove the magnitude differences among measurement units (millisecond, decibel and hertz), the three acoustic parameters were standardized using z-score transformation. The model considers that there are random effects of intercept and slope coefficients at the individual speaker level, denoted as `γ' in Equation 3.

The effects of the three acoustic parameters were estimated in three separate models of different speaker groups (children, adult females and adult males). This was done to control for sex and age differences (e.g., adult males have lower f0 and generally less breathy voice quality than females and children due to the morphological changes in the larynx at puberty).

2.3 Results

2.3.1 Transcription accuracy/error analysis—The left panel in Figure 1 presents the pattern of transcribed accuracy in Korean. Recall that we analyzed only the children's productions that were transcribed as plosives (i.e., excluding deletions, distortions and substitutions of sounds other than plosives). In this figure, the percentage of each individual child's target stops that met these criteria that were judged to have the target phonation type is plotted as a function of the child's age in months. When the inverse logit function curves (generated based on the output of the mixed effects logistic regression model) are overlaid on top of the scatter plot, the overall trend is clear. While all three phonation type categories are produced accurately at a relatively early age, tense stops are produced more accurately than the other two types at younger ages. The regression curves from the analysis predict that tense stops will be produced with 77% accuracy at 24 months, while lax and aspirated stops will be produced with 69% and 70% accuracy, respectively, at the same age.

According to the output of the model, as summarized in Table 4, the effect of lax type of consonant (`lax') was significantly different from the effect of tense stops (the reference category). The effect of aspirated type of consonant (`aspirated') in predicting the production accuracy was significantly different from that of tense stops, although the significance was only marginal at $p < 0.1$. The significant main effect of age suggests that the transcribed accuracy of each type of consonant increases as age increases.

The analysis of transcription accuracy found that the Korean tense stops were only slightly more accurate than lax and aspirated stops. The accuracy differences across the three phonation categories were relatively smaller than those found in earlier transcription studies of Korean stops. For example, in Kim (2008), only 50% of children aged 2;6–3;0 produced at least 75% of/t/ target tokens accurately, whereas all children of the same age group produced 75% of /t'/targets correctly. The relatively small accuracy difference between tense stops and lax or aspirated stops can be attributed to the judgment criteria of the accuracy where only phonation-type errors were counted as incorrect in the transcription.

The substitution patterns in the Korean children's error productions in the current data also support the idea that the tense stop appears before the aspirated stop, because tense stops were commonly substituted for target aspirated stops in the younger children's productions. The right panel of Figure 1 shows the percentage of errors on a child-by-child basis where a tense stop was substituted for a lax or aspirated stop (i.e., the number of tense substitutions divided by the number of total errors) as a function of the child's age in months. The curves show that there was a greater likelihood for a tense type to be substituted for a target aspirated stop at younger ages and the use of the tense stop as the substitution category decreased over time. Children were more likely to substitute an aspirated stop for the lax target in errored productions, as indicated by the curves laid below 50% of tense substitutions at y-axis. However, there was a trend toward fewer such substitutions at younger ages (i.e., more tense substitutions for the youngest children).

2.3.2 Acoustic characteristics: adult productions—Figure 2 shows the values of VOT, f0 and H1-H2 separated by gender (female vs. male) for productions of adult speakers. The VOT histograms in the leftmost panels show that the tense stops occupied the short lag VOT range in the adults' stop productions. While the VOT range for the tense stops overlapped minimally with the ranges for the lax or aspirated stops, lax stops shared a wide range of VOT values with aspirated stops. This almost complete overlap in VOT values between lax and aspirated stops with no overlap between lax and tense stops seen in studies from the 1960s is consistent with the results of Silva (2006),Wright (2007) and Kang & Guion (2008), where the longer lax stop VOTs were identified as indicating a sound change in progress. Our adult speakers were all younger than 30 years, so they all fall in the category of younger Korean speakers born since the 1970s who tend to have longer VOT values in the lax stops.

It was along the f0 dimension that lax stops were differentiated from aspirated stops by having lower values. As shown in the histograms in the middle panels in Figure 2, f0 values at vowel onset after lax stops were lower than those after aspirated stops.

The right-hand panels of Figure 2 show histograms for H1-H2, the breathiness measure. Although H1-H2 values for all three types produced by Korean female speakers were greater than those produced by male speakers, tense stops have smaller H1-H2 values than lax and aspirated stops for the productions of both female and male speakers.

2.3.3 Acoustic characteristics: child productions—Figure 3 shows the distributions of VOT, H1-H2 and f0 of Korean-speaking children's stop productions. In the youngest age group (2;0–2:11), shown in the top leftmost panels, the VOT values of tense stops were concentrated at a short lag range with relatively sharp peaks skewed toward zero VOT (mean VOT: 28 ms for boys and 24 ms for girls). By contrast, the lax and aspirated stops had relatively more variability in VOT values, covering both the short and the long lag ranges. In the older children's productions (3;0–5;11), the lax and aspirated stops had distributional peaks at longer VOT values that were clearly separated from the peaks for tense stops (mean VOT: 19 ms < 71ms < 79 ms for 5-year old boys' tense, lax and aspirated stops, 13 ms < 62ms < 71ms for those of 5-year old girls). At all ages, the medians for the lax stops were not greatly different from those for the aspirated stops, which is similar to the pattern in Korean adult speakers' VOT distributions. Among the three different phonation types, the VOT values of the tense stops were most adult-like in the 2-year-olds' productions in that they were realized as short lag VOT values despite wider variability. However, unlike adults' tense stops, there were a small number of tense stops that were made with lead VOT values in Korean-speaking children's productions. The duration of the prevoicing lead in children's tense stops was relatively short compared to the lead VOT for voiced stops of other languages studied in Lisker & Abramson (1964), which ranged from −170 ms to −45 ms in Spanish, for instance. We speculate that the prevoicing we observed in tense stops produced by Korean children speakers may be caused by a laryngeal setting in which the glottis is closed during oral closure but lacks sufficient laryngeal muscle tension to suppress vocal fold vibration (see Kim & Stoel-Gammon (2009) for another interpretation of the same result).

The distributions of f0 values for tense, lax and aspirated stops (middle panels) show that, while there was some overlap among the three types of stops along the f0 range, the lax stops were mostly distributed at a lower f0 range and the tense and aspirated stops were distributed at a higher f0 range where they almost completely overlapped with each other (mean f0: 261 Hz < 293 Hz < 297 Hz for 5-year old boys' lax, tense and aspirated stops, 281 Hz < 333 Hz < 361 Hz for those of 5-year old girls). This was true even for 2-year-olds' stop productions (mean f0: 296 Hz < 349 Hz < 361 Hz for 2-year old boys' lax, tense and aspirated stops, 296 Hz < 344 Hz = 344 Hz for those of 2-year old girls). While this pattern was constant across age groups, 5-year old boys had overall lower f0 ranges for the three phonation categories than 5-year old girls. This is similar to the finding in Lee & Iverson (2008) where there was a sex-differentiated use of f0 in 10-year-old Korean children, who are older than our child speakers, but are still before puberty.

In the 2-year-olds' H1-H2 distributions (top right panel), there was no distinction among the three types of stops. Values for all three types almost completely overlapped with each other. In the older children's productions, the H1-H2 values showed some separation between the tense stops and the other two types. The H1-H2 values of tense stops were generally lower than those of lax and aspirated stops (mean H1-H2: 2.3 dB < 6.9 dB, 6.6 dB for 5-year old boys' tense, lax and aspirated stops, 1.8 dB < 7.5 dB, 8.13 dB for those of 5-year old girls). In addition, although the median H1-H2 values of all three types of stops were positive, tense stops had the most tokens with negative H1-H2.

2.3.4 Acoustic characteristics: mixed effects logistic regression models—As expressed in Equation 3, the mixed effects logistic regression models were constructed to examine how these acoustic characteristics are integrated into the transcriber's judgment of phonation types. Recall that we have two sets of models. In one set, we contrasted tense stops to the other two types (i.e., lax and aspirated stops) and in the other set, we contrasted lax stops to aspirated stops.

Tense vs. Non-tense: The output of the mixed effects logistic regression models is summarized in Table 6 for children, adult males and adult females, and the associated figures are shown in Figure 4. The sex separation was not made in the children's model, because both main effect and interaction were not significant with respect to children's sex in the model.

As shown in Table 6, there were significant main effects of coefficients associated with VOT, f0 and H1-H2 in the model of the children's productions. The absolute value of the coefficient associated with VOT was greatest among the three acoustic parameters, suggesting that the discrimination of tense from non-tense was more sensitive to VOT than to f0 or H1-H2. The negative signs of the coefficients in Table 6 simply indicate that the prediction of tense stops is negatively correlated with the acoustic values of VOT and H1-

H2. That is, higher values of VOT and H1-H2 resulted in a higher probability of the transcriber identifying the tokens as one of the non-tense types.

Unlike the model of the children's production, the two models of the adult male and female speakers showed that not all three acoustic parameters were significant in differentiating the tense category from the non-tense categories. It was only VOT that had a significant effect in the adult female productions, as shown in Table 6(c), while it was VOT and H1-H2 that had significant effects in the adult male productions, as shown in Table 6(b). Despite these differences, it was consistent that the models estimated a greater coefficient of VOT than those of f0 and H1-H2 across all three speaker groups. Because the values of the three acoustic parameters were standardized, the larger VOT coefficient relative to the H1-H2 coefficient serves as evidence that VOT plays the dominant role in the differentiation of tense from non-tense stops.

The absolute values of the coefficients determine the steepness of the slopes of the curves in Figure 4. The steepest slopes of VOT in the models for all three groups (in the leftmost panels of Figure 4) show how effective VOT was in differentiating between tense and non-tense stops for all three participant groups.

Lax vs. Aspirated stops: The output of the logistic regression model is presented at Table 7 for the children, adult males and adult females and the associated figures are shown in Figure 5. As in the tense vs. non-tense model, the children's model was not separated by sex because no significant effect was found.

As shown in Table 7(a), the coefficients of the fixed effects in the model of the children's productions suggest that there were significant main effects of VOT and f0, but no significant effects of H1-H2, in differentiating the lax stops from the aspirated ones produced by children. The results were consistent in the two adult production models, showing that the effects of VOT and f0 were significant, but the effects of H1-H2 were not significant, as presented in Table 7(b) and Table 7(c). In all three models of lax vs. aspirated, the absolute values of coefficients of f0 were higher than coefficients of VOT. This suggests that the f0 parameter was more influential than the VOT parameter in differentiating the lax stops from the aspirated stops across the three speaker groups. It is noted that, among the three groups, the absolute values of the VOT coefficients were closest to those of the f0 coefficients in the child model. The absolute values of the coefficients of f0 were only slightly higher than the coefficients of VOT.

The absolute values of coefficients determine the steepness of the slopes in Figure 5. The bottom two panels, for the adult male and female speakers' productions, have curves with steeper slopes for the f0 parameter than the VOT parameter. In the child speaker model (top panels), however, the slope of the VOT parameter was almost as steep as that of the f0 parameter. The identification of lax stops was negatively correlated with the two parameters of f0 and VOT, as indicated by the signs of the coefficients. The increase of f0 and VOT values resulted in higher probability of the transcriber identifying the tokens as the aspirated type.

2.4 Discussion

In this cross-sectional study of word-initial stops, we found that tense stops were mastered earlier than lax or aspirated stops by Korean-speaking children. Tense stops also had higher transcription accuracy than either lax or aspirated stops, and the youngest children substituted tense stops for the other two phonation types. These results are consistent with the findings of prior transcription studies (Pae, 1994; Kim & Shin 2004; Kim & Pae, 2005; Kim, 2008).

Our analysis of the acoustic characteristics of stops produced by adult Korean speakers found that VOT fully differentiated tense stops from non-tense stops in the word-initial position, but it did not distinguish lax from aspirated stops. The distinction between lax and aspirated stops was instead made by a combination of VOT and f0. The lax stops had a lower f0 than the aspirated stops. This pattern reflects a recent diachronic change in the role of VOT in the distinction among the three types of stops in initial position, as suggested by Silva (2006), Wright (2007) and Kang & Guion (2008).

The pattern of the acoustic parameters in children's stop productions resembled the adult pattern in that VOT differentiated tense stops from non-tense stops and lax stops had a lower f0 than aspirated stops. We also observed the same developmental pattern that has been observed cross-linguistically in languages such as Cantonese (Clumeck et al., 1981), English (Macken & Barton, 1980a; Kewley-Port & Preston, 1974) and Thai (Gandour et al., 1986). As in each of these other languages, Korean-acquiring children's earliest stop productions had short lag VOT values, regardless of the target phonation type. The native transcriber usually perceived these short-lag stops as tense. Thus, the tense phonation category was mastered earliest and the usual substitution pattern was to substitute tense for non-tense stops. Children's target lax and aspirated stops were perceived as tense if they had short lag VOT values and as lax or aspirated if they had long lag VOT values. Non-tense stops were largely differentiated by f0, with lax stops having a lower f0 than tense stops. The mixed effects logistic regression model found that transcribed tense categories were differentiated from non-tense ones more effectively by VOT than by f0 or H1-H2. The mixed effects logistic regression models for differentiating lax and aspirated stops found that the variations of transcribed lax vs. aspirated stops were explained by both the f0 and VOT parameters. A sex-related effect was not found in the children's model, despite different f0 ranges between older boys' and girls' productions. This suggests that the difference in production did not affect adult listener's parsing of boys' versus girls' productions, at least not for the younger children whom we studied.

VOT was almost as effective as f0 in differentiating lax from aspirated stops in the children's productions. This result suggests that lax and aspirated stops were judged as correct only when both acoustic properties of VOT and f0 met the transcriber's perceptual norms. Having lower f0 values for children's intended lax stops, which were observed even in 2-year-olds' productions in experiment I, must not have been a sufficient criterion for indentifying lax stops unless they were also differentiated from aspirated stops in terms of VOT values. The later mastery of lax and aspirated stops that we and other researchers have observed could be due to children having to master two acoustic parameters to mark this contrast.

A shortcoming of the first experiment is that children's productions were categorized into the three phonation-type categories by a single native speaker who was a trained phonetician and who could listen to each stimulus item multiple times and also examine the waveform and spectrogram. Such judgments may differ from those of the naïve listener, who is untrained and who hears a sound only one time. In this next experiment, we examine the role of the same three acoustic cues in differentiating the three phonation-type categories for stop consonants in a perception experiment with naïve Korean-speaking adults.

3.0 Experiment II: perception of naïve listeners

3.1 Method

3.1.1 Materials—A subset of adults' and children's tokens of /t/- /t^h/- and /t'/-initial words used in the production study was included as stimuli for the perception experiment with 20 Korean-speaking adult listeners. Only the consonant and vowel portion was excised from the selected words to avoid any lexical bias. The following vowel contexts were /a/, /i/ and /u/.

The stimuli included tokens produced by children and adults. Table 8 shows the distributions of talker's age and vowel context of the stimuli.

In order to balance the number of tokens which were likely to be perceived as /t/ or /t^h/ or /t'/ in Korean, the single native-speaker transcriber's judgments of the token were referred to as a rough estimation of plausible perceptual outcomes. The 400 stimuli (350 from children's production, 25 from adult males' production and 25 from adult females' production) were chosen primarily based on the stop VOT values, aiming to sample the VOT distribution so as to reflect the whole range of the natural data obtained from the production experiment. Figure 6 shows the distributions of VOT, f0 and H1-H2 in all of the stimuli used in the experiment. The quantiles for the tokens in the child speakers' stimulus set were compared with those of the children's production data for each acoustic parameter, as shown in the bottom panels in Figure 6. The distributions of f0 and H1-H2 also turned out to reflect the range of the natural data after sampling the stimuli based on the VOT variation. An additional 10 practice items were chosen, with VOT covering the same range, to be presented at the beginning of the experiment as practice trials. The listeners listened to the 400 test items and 10 practice items during the experiment session. They heard each item only once.

3.1.2 Subjects and task—Twenty college students at the Sogang University in Seoul participated in this experiment. They were all Seoul Korean speakers with no reported history of speech, language or hearing disorders.

Stimuli items were presented in random order over headphones. After each stimulus item was played, the Hangul orthographic symbols for /t/, /t'/ and /t^h/ appeared on the computer monitor. Subjects were asked to select one stop category as their choice by clicking the letter on the screen using a mouse. Immediately after the categorical response, listeners were asked to rate the goodness of the item by clicking on a double-ended arrow that appeared on the computer monitor. The two end points of the arrow were labeled as 'very good exemplar' and 'very poor exemplar' in Hangul. An optional break was given after every 100 stimuli. Listeners were paid for their participation.

3.1.3 Analysis—To analyze the results of the initial three-alternative forced-choice identification task, we performed three sets of mixed effects logistic regression models, one set for the adult male stimuli, one for the adult female stimuli, and one for the child stimuli. The dependent variable was always the adult listener's perception of the stimulus as belonging to one of the three target phonation types. As in experiment I, the acoustic parameters of VOT, f0 and H1-H2 were included as fixed effects. The subject (listener) factor was included as a random effect, with both random intercepts and slopes in the model for the child stimuli and with only random intercepts in the models for the adult stimuli. (We did not include random slopes in the adult models because the estimated log-likelihood of these models was not significantly different from those of the models with only random intercepts.) The formula for these models is given in Equation 4.

$$\log\left(\frac{Phon.Type_{perc.}}{1-Phon.Type_{perc}}\right)=\beta_0+\beta_1 VOT+\beta_2 f0+\beta_3 H1H2+\gamma Listener$$

As in experiment I, for each set of models, we ran two separate mixed effects models, one to predict tense vs. non-tense stops (i.e., lax and aspirated stops) and one to predict lax vs. aspirated stops. The three acoustic parameters were standardized using z-score transformations in order to remove the magnitude differences among measurement units (millisecond, decibel and hertz). The z-score normalization was done across all the child and adult talker stimuli.

The goodness ratings of each stimulus were also examined as a function of the acoustic parameters in three regression models. Specifically, an ordinary least-squares regression analysis was performed to predict the listeners' ratings based on each of the three acoustic parameters. The dependent variable was listeners' judgments, encoded as the average of the pixel locations where the listeners clicked along the arrow presented on the monitor. VOT, f0, or H1–H2 was the independent variable.

3.2 Results

3.2.1 Categorical judgements

Tense vs. Non-tense stops: Table 9 and Figure 7 show the output of the mixed effects logistic regression models and the associated figures. According to the fixed effect coefficients in the model of the listener responses to child talker stimuli, all three acoustic parameters of VOT, f0 and H1–H2 were significant predictors in differentiating tense from non-tense stops. The primary predictive role of VOT was evidenced by the greatest absolute value of the VOT coefficients among the three parameters, suggesting that the listeners' judgments of tense stops were determined primarily by VOT. While the VOT and H1–H2 parameters were negatively correlated with the perceptual judgment of tense, the f0 parameter was positively correlated with tense perception. The primary role of VOT is illustrated in Figure 7 by the fact that the VOT parameter curve has the steepest slope.

In the models of the two other stimulus talker groups (adult males and adult females), VOT was the primary acoustic parameter in differentiating the judgements of tense stops from those of non-tense stops. In the adult female talker model, H1–H2 was also a significant predictor, and in the adult male talker model, f0 was also a significant predictor. However, as shown in Table 9(b) and Table 9(c), VOT was the strongest predictor in both of these models. The absolute regression coefficients of VOT were the greatest in these models, as illustrated by the steepest slopes of the VOT parameter curves in the bottom two panels of Figure 7.

Lax vs. Aspirated stops: The output of the mixed effects logistic regression models in each stimulus talker group is summarized in Table 10 and Figure 8. In the child stimulus talker model, as shown in Table 10(a), VOT and f0 were significant predictors in differentiating lax from aspirated stops. The absolute coefficient value of VOT was greater than that of f0, suggesting that the listeners relied more on VOT than f0 to differentiate lax and aspirated stops. According to the signs of the coefficients, increases in VOT and f0 resulted in more judgments of aspirated stops.

The output of the adult male talker model found that VOT, f0 and H1–H2 were significant predictors in differentiating lax stops from aspirated stops, as summarized in Table 10(b). Similar to the child stimulus talker model, VOT had a greater absolute coefficient value than f0 and H1–H2. However, different results were observed for the adult female talker model (Table 10(c)). The absolute coefficient value of f0 was greater than that of VOT in the adult female talker model, while the effect of the VOT parameter failed to reach significance. This suggests that listeners were not sensitive to changes in VOT, but were mainly sensitive to the change in f0 when they identified lax vs. aspirated stops produced by adult female speakers. It is noteworthy that this greater effect of f0 was achieved despite having chosen the stimuli to emphasize variation in VOT.

While the interactions of acoustic parameters between the adult- and child-stimulus types are interesting, the most important finding relative to the questions addressed in this paper is that, even for the contrast between lax and aspirated stops, VOT is the primary acoustic parameter that the naïve adult listeners used to differentiate these two phonation types when they listened to the children's productions. This is illustrated in Figure 8, which shows that the slopes of the VOT parameter curves are steeper than those of the curves for f0 in the child stimulus talker condition (top panels). The slope of the f0 curve is steepest in the adult female stimulus talker condition (bottom panels).

3.2.2 Within-category goodness judgments—Figure 9 shows box plots of the goodness ratings for each of the three talker groups and for each of the three phonation categories. The medians of the goodness ratings across the plots were located slightly closer to the `good' side, a distribution which can be explained by the fact that the stimuli needed to be good enough exemplars to be categorized as that particular sound.

The goodness ratings for each stimulus were averaged across the listeners in order to describe the relationship between the acoustic parameters and the ratings. For the children's productions, VOT was a significant predictor of the variability of the goodness ratings for tense (R^2= .19) and aspirated stops (R^2= .33), but not for lax stops (R^2 < .01). As shown in Figure 10, tense stops (leftmost top panel) tended to be judged as better exemplars as VOT values decreased. In contrast, aspirated stops (rightmost top panel) tended to be judged as better exemplars as VOT values increased. Lax stops are shown in the middle panel, and the lack of a significant relationship between VOT values and goodness ratings can be observed. H1–H2 also accounted for a small, but significant amount of variability in the goodness ratings for tense stops (R^2= .14), but was not a significant predictor for lax and aspirated stops. f0 was not a significant predictor of the goodness ratings for any of the three stop categories, in that the coefficients of the determinants were extremely small (R^2 <.03)

For the adults' productions, VOT was a significant predictor of the variability of the goodness ratings for tense (R^2= .56 for males, R^2= .64 for females) and aspirated stops (R^2= .4 for males and R^2= .15). Similar to the perception of the children's productions, the category goodness ratings were not related to VOT values in the lax stops (R^2= −.07 for males, R^2= .06 for females). H1–H2 was a marginally significant predictor of the goodness ratings for males' tense stops (R^2= .15). Unlike in the perception of the children's productions, f0 was a significant predictor of the goodness ratings for the adults' aspirated stops (R^2= .4 for males and R^2= .22 for females).

3.3 Discussion

The perception experiment examined naïve, native-speaking Korean adults' categorization of the three phonation categories of Korean stop consonants. We were interested in whether the single, trained phonetician in experiment I and the 20 naïve listeners in experiment II would show similar relationships between perception of the three phonation categories and the acoustic dimensions of VOT, f0 and H1–H2 in productions of stop consonants by children and adults. We found similar results for the trained phonetician and the naïve listeners, in spite of the fact that the trained phonetician judged many more stimuli than the naïve listeners (4469 as compared to 400) and the task demands were different for the two experiments.

The naive listeners, like the trained transcriber, relied primarily on VOT to differentiate tense from non-tense stops. This was true regardless of whether the stimuli were produced by children, adult females, or adult males. The other two acoustic parameters, f0 and H1–H2, were also significant predictors, but they had smaller effect sizes. The naive listeners, like the trained phonetician, relied both on VOT and f0 to differentiate children's productions of lax and aspirated stops. This bolsters our explanation of the later acquisition of aspirated and lax stops relative to tense stops, in that children need to learn to control two acoustic parameters to differentiate between these two phonation categories. Researchers such as Kent (1992) have suggested that categories associated with greater motor demands will be mastered later than categories that are less difficult to produce.

The naive listeners also relied primarily on VOT to evaluate within-category goodness of the three phonation types. The direction of this relationship was parallel to the categorical judgment results, in that goodness ratings increased as VOT values decreased for tense stops and as VOT values increased for aspirated stops. While VOT was a significant parameter for between- and within-category judgments for tense and aspirated stops, it was not a significant predictor of listeners' goodness ratings for the lax stop category. The goodness ratings for lax stops were not predicted by f0, although it was the acoustic parameter that best differentiated the lax category from the tense and the aspirated categories in the adult productions. This difference between the categorical judgments and the goodness ratings for the lax stops is in keeping with the fact that Korean stops are still contrastive in terms of phonation types (not fully in terms of tonal types). Although a lower f0 value could trigger the identity as a lax stop, f0 was not enough to make it a good lax stop, which also should have a longer VOT value than a tense stop but not a longer VOT value than an aspirated stop.

4.0 Conclusion

This paper investigated whether Korean children's early mastery of tense stops in transcription-based studies can be explained by the role of acoustic properties in adult listeners' categorization of children's productions. Across languages, it is typical that a more common "default" or "unmarked" consonant type should be mastered before a less common type when a language has a contrast between a more and less common type (Jakobson, 1968). This generalization leads to different predictions, depending on how we interpret what it means to be a "default" or "unmarked" type.

If we interpret the "default" type as being the more frequent and less demanding articulation, this generalization might be taken to predict that "plain" (or lax) stops of Korean should be mastered earlier than tense stops. The lax stops are by far the most frequent type and the tense stops are considerably less frequent, particularly in word-initial position (cf. Lee et al, 2008). Moreover, the production of tense stops in Korean requires the precise articulatory specifications of posturing the larynx and other articulatory systems for positive vocal cord tension and vocal track tension, while the production of lax stops does not require these highly precise articulatory specifications (Hardcastle, 1973; Kagaya, 1974; Hirose et al., 1974; Dart, 1987; Hong et al., 1991). If we make a prediction of mastery order based solely on the typologically `marked' status of the phonation category, the early mastery of Korean tense stops in the transcription studies poses a puzzle.

An alternative interpretation focuses on the distribution of VOT values in word-initial position. In other languages that contrast long-lag (aspirated) stops with short-lag (unaspirated or "voiced") stops, the short-lag type is mastered earlier. This is true even for English, where short-lag /b, d, g/ are far less common than long-lag /p, t, k/. However, although the Korean tense stops have short lag VOT values, we cannot assume that we can explain this puzzle simply in terms of the VOT distributions of the three phonation types. VOT alone does not adequately characterize the three-way laryngeal contrast in Korean stops, particularly if we look at productions across the full range of adult speakers who might act as the primary caretakers of young children. Previous studies of VOT distributions show considerable overlap between lax and aspirated stops in younger adults and between tense and lax stops in older adults (Silva, 2006; Wright, 2007; Kang & Guion, 2008). Therefore, two other important acoustic characteristics (i.e., pressed vs. breathy voice quality and high or low fundamental frequency) need to be considered in distinguishing among the three phonation types (see, e.g., Cho et al., 2002; Kim et al., 2002).

In order to understand the early mastery of tense stops, we explored the role of adults' perception of children's productions. We hypothesized that VOT would play the primary role in adults' differentiation of tense vs. non-tense stops produced by children and that adult judgments would be less affected by the other acoustic parameters, H1–H2 and f0. This hypothesis was based in part on the changing characteristics of the Korean stop phonation categories with respect to VOT and f0. In recent years, VOT has come to differentiate tense from non-tense stops, and f0 has come to differentiate lax from aspirated stops.

The findings of this paper supported our hypothesis. That is, the early mastery of tense stops seems clearly to be related to the findings that (1) not only do young, Korean-speaking children tend to produce short lag VOTs in their earliest stop consonant productions (as is common cross-linguistically) but also that (2) adult Koreans (both naive listeners and a trained phonetician) tend to identify these productions with short lag VOT values as the tense type. Furthermore, the later acquisition of lax and aspirated stops may be related to the fact that children must learn both to produce long lag VOT values and to control f0. In short, we cannot just look at transcriptions or just at the acoustic patterns in young children's productions. Rather, we need to examine the interactions between adult perceptions and the acoustics of children's productions in order to explain mastery patterns across languages.

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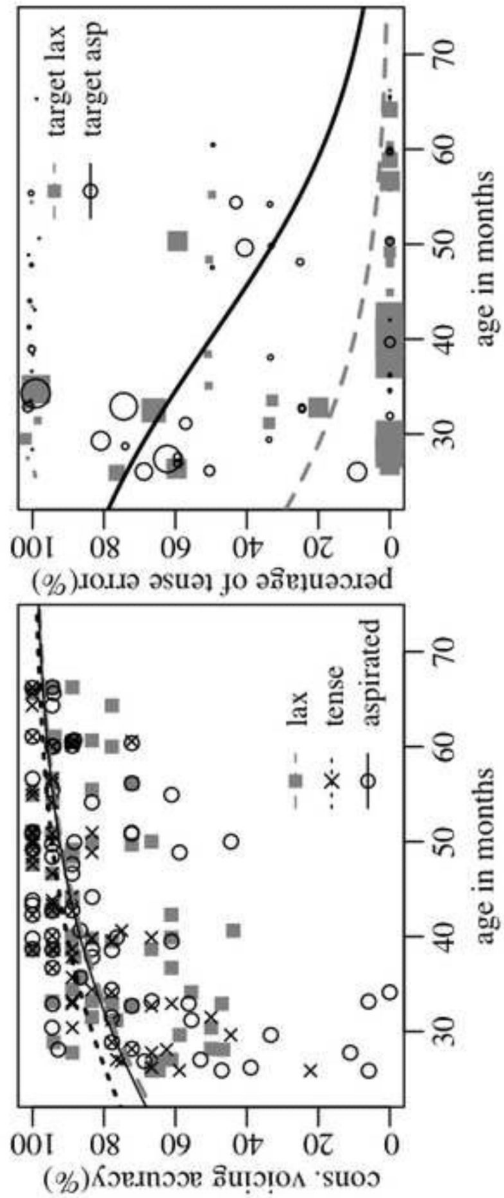

FIGURE 1.

Transcribed accuracy of phonation-type categories for children's word-initial stops in Korean (left figure) and a scatter plot of percentages of substituted tense categories for errored productions of non-tense categories (i.e., [tense] for /lax/ and /aspirated/) as a function of the child's age in months (right figure). In the right figure, the size of the plotting character indicates the number of relevant errors that the child made in the production. The curves are the inverse logit curves predicted by the mixed effect logistic regression models (Table 4 and Table 5).

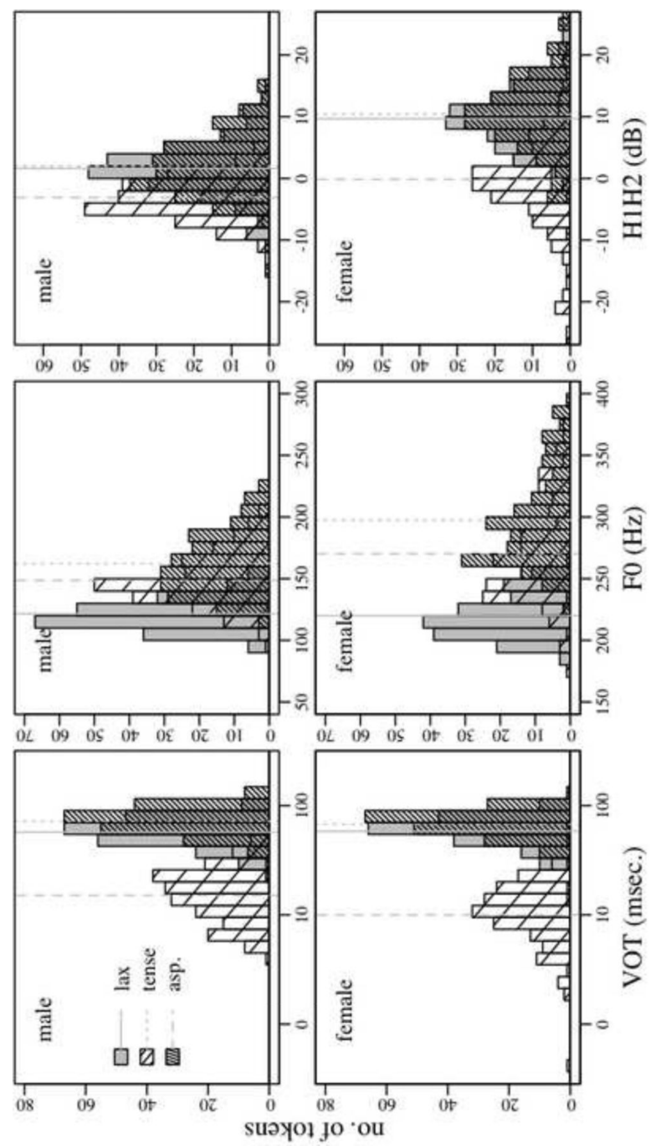

FIGURE 2.

Histograms of VOT, f0 and H1–H2 for lax, tense and aspirated stops produced by Korean adult male and female speakers. Vertical lines indicate median values. Note that there is a difference in scale of the x-axis for the f0 figures.

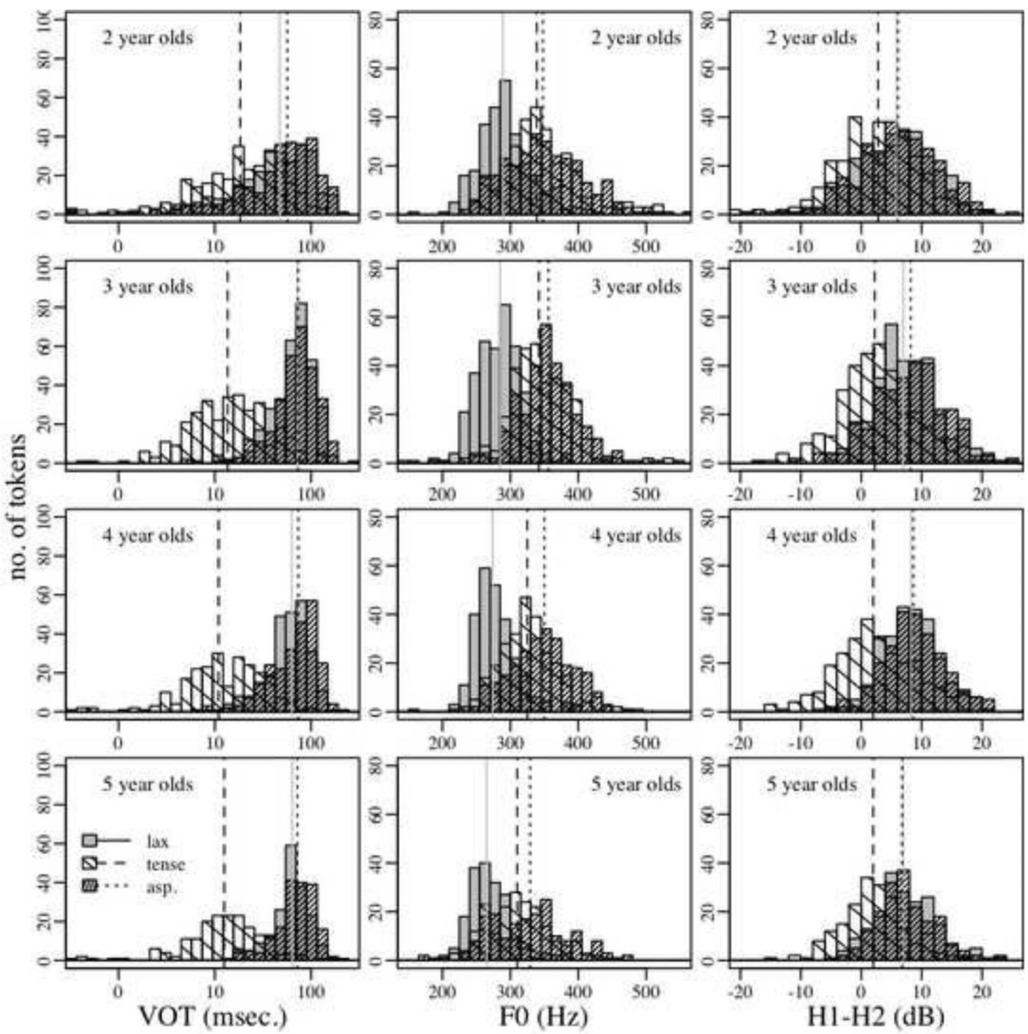

FIGURE 3.
Histograms of VOT, f0 and H1–H2 in stops produced by Korean-speaking children by age group. Vertical lines indicate median values.

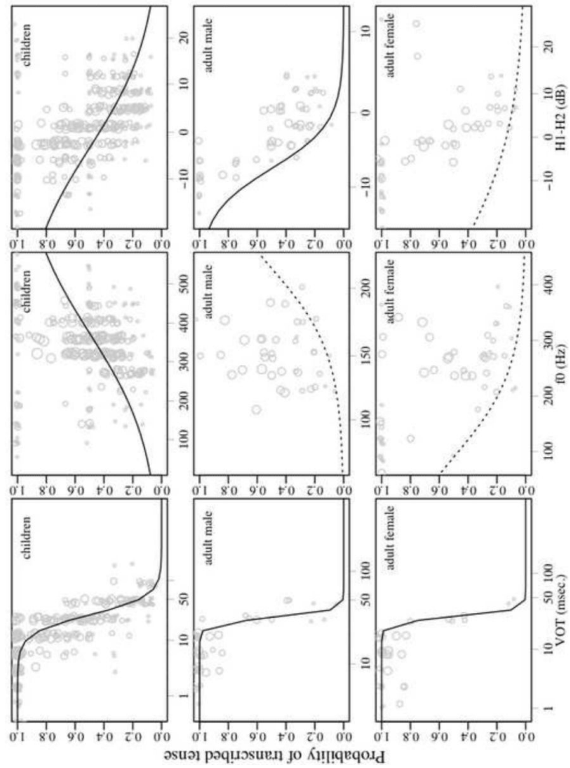

FIGURE 4.

Scatter plots of the probability of tense stops with respect to VOT, f0 and H1–H2 parameters estimated by the mixed effects models of logistic regression. The plots are separated by the three speaker groups (i.e., child, adult male and adult female). Each data point of the plots represents a proportion of individual speaker's tense type tokens to the stop productions, whose acoustic values fall in a particular bin along the specified acoustic dimension. The curves are the inverse logit curves drawn based on the output of the mixed effects logistic regressions shown in Table 6. Solid curves show significant predictors and dashed curves show non-significant predictors.

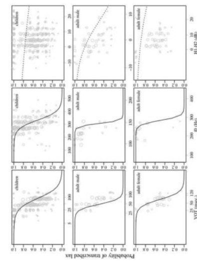

FIGURE 5.
Scatter plots of the probability of lax stops with respect to VOT, f0 and H1–H2 parameters estimated by the mixed effects models of logistic regression. The plots were separated by the three speaker groups (i.e., child, adult male and adult female) in each column. The curves are the inverse logit curves drawn based on the output of the mixed effects logistic regressions shown in Table 7. Solid curves show significant predictors and dashed curves show non-significant predictors.

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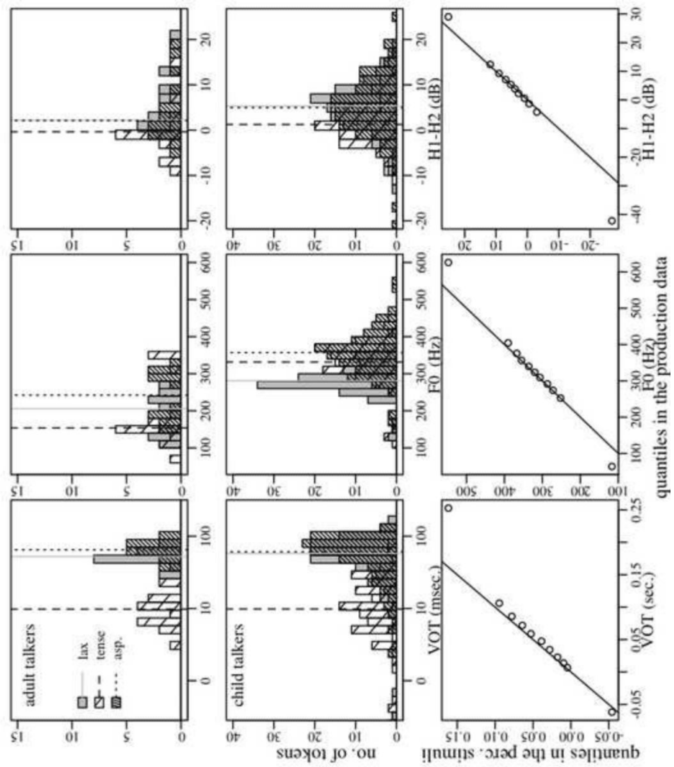

FIGURE 6.

The histograms of VOT, f0 and H1–H2 of the 400 stimuli used in the perception experiment. 50 of the total stimuli were taken from the adult speakers' word productions (top panels) and 350 of them came from the child speakers' word productions (middle panels). The bottom panels show the quantiles of the stimuli distributions for the subset of tokens used in the perception experiment plotted against all of the children's production data included in experiment I.

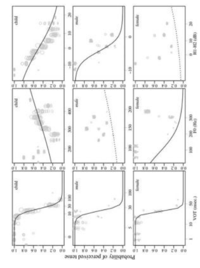

FIGURE 7.
Scatter plots of the probability of being perceived as a tense stop as a function of its acoustic value of VOT, f0 and H1–H2. The probability is estimated by calculating the number of tense responses divided by the total number of stimuli provided at each bin along each acoustic continuum. The curves are the inverse logit curves drawn based on the output of the mixed effects logistic regressions shown in Table 9. Solid curves show significant predictors and dashed curves show non-significant predictors.

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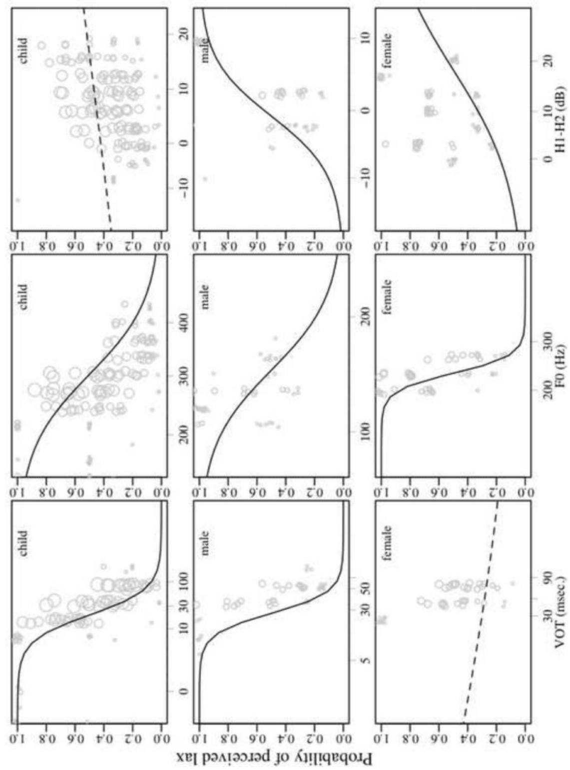

FIGURE 8.

Scatter plots of the probability of perceived lax stops with respect to VOT, f0 and H1–H2 parameters estimated in Korean adults' perception to adults' and children's productions. Each data point in the scatter plots represents a proportion of individual listener's perceived lax stops over the responses whose acoustic values fall in each bin along the acoustic dimensions. The curves are the inverse logit curves drawn based on the output of the mixed effects logistic regressions shown in Table 10. Solid curves show significant predictors and dashed curves show non-significant predictors.

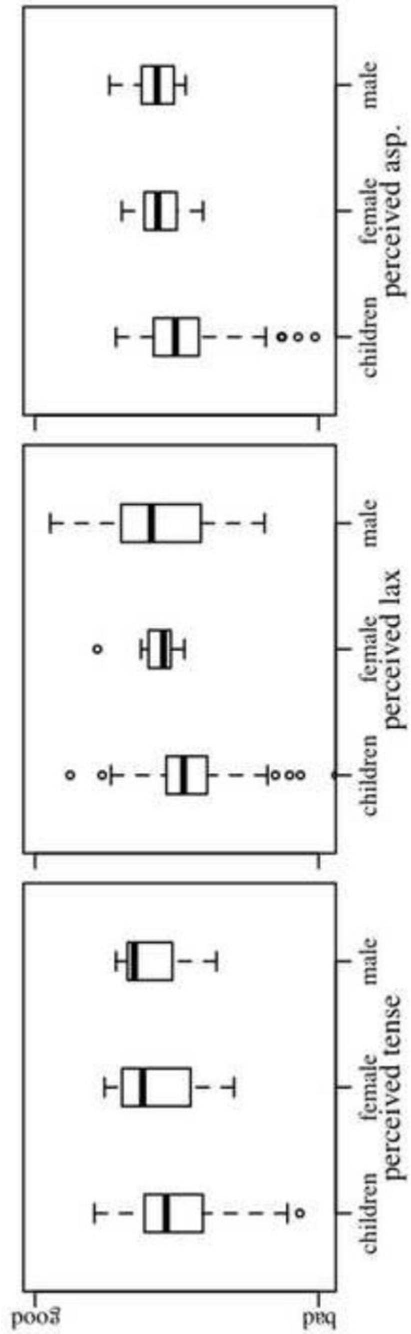

FIGURE 9.
Box plots of the goodness ratings of stimuli identified as tense, lax and aspirated types, separated by the talker groups (children, adult females and adult males).

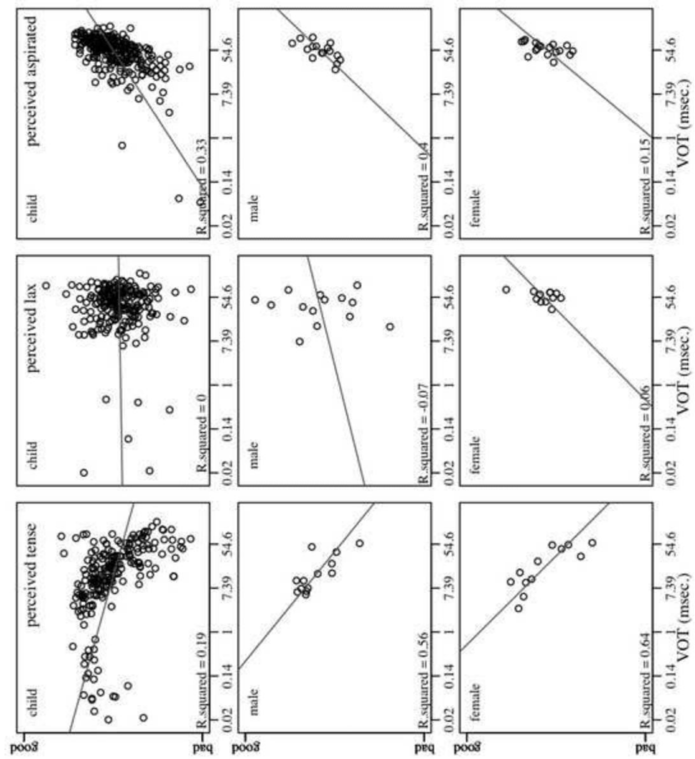

FIGURE 10.

Scatter plots of category goodness ratings for stimuli identified as tense, lax and aspirated types as a function of VOT. The plots are separated by the stimulus talker groups (children, adult males and adult females).

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Table 1

A list of Korean words that were elicited in the word repetition task to Korean-speaking children and adults.

IPA	gloss	IPA	gloss
tal.p^{h}ɛŋ.i	snail	ka.baŋ	bag
tan.tʃ^{h}u	button	kam.dʒa	potato
taŋ.gɨn	carrot	kaŋ.adʒi	puppy
ta.ram.dʒwi	squirrel	ka.wi	scissor
tiŋ.gul.diŋ.gul	rolling about	ki.tʃ^{h}a	train
tiŋ.doŋ.dɛŋ	bell-ringing sound	ki.rin	giraffe
tuŋ.gɨl.gɛ	round	ku.du	shoe
tul	two	kuk.dʒa	scoop
tu.bu	tofu	kuk.su	noodle
t'al.laŋ.i	noise maker	k'ak.t'u.gi	radish kimchi
t'aŋ.k^{h}oŋ	nut	k'a.ma.gwi	black bird
t'al.gi	strawberry	k'aŋ.t^{h}oŋ	can
t'a.rɨ.rɨŋ	tinkling	k'a.man.sɛk	black color
t'iŋ.doŋ	door-bell sound	k'i.wʌ.jo	sticking in
t'i.t'i.p'aŋ.p'aŋ	car-honking	k'iŋ.k'iŋ	groaning sound
t'uŋ.bo	plump person	k'ul.k'ʌk	gulping sound
t'uk. t'uk	dripping sound	k'ul.bʌl	honey bee
t'u.kʌŋ	lid	k'ul. k'ul	oink-oink
t^{h}a.i.ʌ	tire	k^{h}a.dɨ	card
t^{h}a.ol	towel	k^{h}al	knife
t^{h}a.dʒo	ostrich	k^{h}a.me.ra	camera
t^{h}ak.dʒa	table	k^{h}a.rɛ	curry
t^{h}i.bi	television	k^{h}i.wi	kiwi
t^{h}i.sjʌ.tʃ^{h}ɨ	T-shirt	k^{h}i.da.ri	tall man
t^{h}u.dʌl.t^{h}u.dʌl	grumbling	k^{h}u. k^{h}i	cookie
t^{h}uk.t^{h}uk	beating around	k^{h}ul. k^{h}ul	snoring
t^{h}uŋ.t^{h}uŋ	stamping	k^{h}u.sjʌn	cushion

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Table 2

The age and sex distributions of child and adult participants.

	2; 0 – 2; 11	**3; 0 – 3; 11**	**4; 0 – 4; 11**	**5; 0 – 5; 11**	**adults**
female	12	11	7	5	10
male	9	9	8	6	10

Table 3

Number of tokens (categorized by age and sex) used for the acoustic analysis and the transcription analysis (in parenthesis).

	[t']		[t]		[t^h]		
	fem.	**male**	**fem.**	**male**	**fem.**	**male**	**total**
2; 0 – 2; 11	181(200)	119(151)	165(195)	110(136)	166(191)	121(148)	862(1021)
3; 0 – 3; 11	173(183)	148(156)	175(190)	144(152)	161(183)	135(155)	936(1019)
4; 0 – 4; 11	125(125)	140(142)	117(121)	137(143)	109(119)	131(140)	759(790)
5; 0 – 5; 11	86(90)	101(103)	83(87)	101(107)	85 (89)	97 (104)	553 (580)
adults	170	174	180	179	180	176	1059
total	735(768)	682(726)	720(773)	671(717)	701(762)	660(723)	4469(4169)

Table 4

The output of mixed effects logistic regression model that predicts the production accuracy of phonation types spoken by Korean-speaking children: Equation 1 and Figure 1 (left panel). The tense stop was the reference category of the model.

Fixed effects:

	Estimate	Std.Error	z-value	Pr (> |z|)
(Intercept)	2.48	0.14	17.48	< 0.001***
age	0.06	0.01	7.24	< 0.001***
aspirated	−0.35	0.21	−1.69	0.09·
lax	−0.41	0.19	−2.16	< 0.05*

Significance codes:

*** 0.001

** 0.01

* 0.05

0.1

Table 5

The output of mixed effects logistic regression model that predicts the substituted category of tense stops for the intended targets of aspirated or lax stops: Equation 2 and Figure 1 (right panel). The age was centered at the grand mean of children's age in months, which is 38.5 months.

Fixed effects:

	Estimate	**Std.Error**	**z-value**	**Pr (> |z|)**
age	|−0.07	0.02	−3.14	< 0.01**
aspirated	0.12	0.29	0.40	0.68
lax	−2.08	0.51	−4.06	< 0.001***

Significance codes:

*** 0.001

** 0.01

* 0.05

0.1

Table 6

The output of the mixed effects logistic regression model that predicted the transcribed tense category in contrast with the non-tense types (i.e., the lax and aspirated categories) in the productions of children, adult males and females.

(a) Children's model Fixed effects:

	Estimate	Std.Error	z-value	Pr(>|z|)
(Intercept)	−0.53	0.11	−4.71	< 0.001***
VOT	−3.75	0.26	−14.43	< 0.001***
f0	0.60	0.09	6.56	< 0.001***
H1–H2	−0.60	0.09	−6.57	< 0.001***

(b) Adult males' model Fixed effects:

	Estimate	Std.Error	z-value	Pr(> |z|)
(Intercept)	−2.17	0.90	−2.40	< 0.05*
VOT	−10.77	1.84	−5.83	< 0.001***
f0	0.80	0.45	1.75	0.08·
H1–H2	−1.37	0.58	−2.35	< 0.05*

(c) Adult females' model Fixed effects:

	Estimate	Std.Error	z-value	Pr(> |z|)
(Intercept)	−2.16	0.63	−3.39	< 0.001***
VOT	−10.85	2.17	−4.99	< 0.001***
f0	−0.79	0.81	−0.97	0.32
H1–H2	−0.50	0.55	−0.91	0.36

Significance codes:

*** 0.001

** 0.01

* 0.05

0.1

Table 7

The output of the mixed effects logistic regression model that predicted the transcribed lax type in contrast with the aspirated type in stop productions of children, adult males and adult females.

(a) Children's model Fixed effects:

	Estimate	Std.Error	z-value	Pr(> |z|)
(Intercept)	1.17	0.20	5.80	< 0.001***
VOT	−2.51	0.25	−10.03	< 0.001***
f0	−2.64	0.24	−10.94	< 0.001***
H1–H2	−0.12	0.09	−1.31	0.19

(b) Adult males' model Fixed effects:

	Estimate	Std.Error	z-value	Pr(> |z|)
(Intercept)	1.13	1.75	0.64	0.51
VOT	−4.43	1.42	−3.10	<0.01**
f0	−8.12	1.38	−5.88	< 0.001***
H1–H2	−0.60	0.46	−1.30	0.19

(c) Adult female's model Fixed effects:

	Estimate	Std.Error	z-value	Pr(> |z|)
(Intercept)	2.18	0.74	2.93	< 0.001***
VOT	−3.19	0.99	−3.21	< 0.001***
f0	−5.44	0.83	−6.51	< 0.001***
H1–H2	−0.30	0.44	−0.69	0.48

Significance codes:

*** 0.001

** 0.01

* 0.05

0.01

Table 8

The age and vowel distributions of 400 stimuli.

	t			t'			t^h			
	/a/	**/i/**	**/u/**	**/a/**	**/i/**	**/u/**	**/a/**	**/i/**	**/u/**	**total**
2; 0 – 2; 11	22	1	6	13	2	7	20	3	12	85
3; 0 – 3; 11	19	4	10	17	6	10	20	3	7	96
4; 0 – 4; 11	9	12	8	16	6	14	20	4	8	97
5; 0 – 5; 11	13	5	10	8	6	6	17	4	2	71
adults	7	5	5	8	3	6	6	4	6	50
total	70	27	5	8	3	6	6	4	6	400

Table 9

The output of the mixed effects logistic regression model that predicts the perceived tense stops in contrast to the non-tense stops (tense vs. non-tense stops) produced by children, adult males and adult females.

(a) Child talker model Fixed effects:

	Estimate	Std.Error	z-value	Pr(> |z|)
(Intercept)	−0.25	0.08	−2.94	< 0.01**
VOT	−4.29	0.20	−21.14	< 0.001***
f0	0.30	0.03	7.65	< 0.001***
H1–H2	−0.55	0.05	−10.72	< 0.001***

(b) Adult male talker model Fixed effects:

	Estimate	Std.Error	z-value	Pr(> |z|)
(Intercept)	−1.21	0.32	−3.75	< 0.001***
VOT	−4.92	0.61	−8.01	< 0.001***
f0	0.23	0.29	0.79	0.42
H1–H2	−1.76	0.63	−2.80	< 0.01**

(c) Adult female talker model Fixed effects:

	Estimate	Std.Error	z-value	Pr(> |z|)
(Intercept)	−2.03	0.44	−4.58	< 0.001***
VOT	−6.90	1.09	−6.30	< 0.001***
f0	−0.87	0.33	−2.63	< 0.01***
H1–H2	0.28	0.42	0.68	0.49

Significance codes:

*** 0.001

** 0.01

* 0.005

0.1

Table 10

Output of the mixed effects logistic regression model that predicted perceived lax stops in contrast with aspirated stops (lax vs. aspirated stops) produced by children, adult males and adult females.

(a) Child talker model Fixed effects:

	Estimate	Std.Error	z-value	Pr(> |z|)
(Intercept)	−0.22	0.32	−0.69	0.48
VOT	−2.69	0.25	−10.63	< 0.001***
f0	−0.92	0.05	−16.23	< 0.001***
H1–H2	0.12	0.07	1.66	0.09·

(b) Adult male talker model Fixed effects:

	Estimate	Std.Error	z-value	Pr(> |z|)
(Intercept)	−0.11	0.41	−0.28	0.77
VOT	−3.31	0.52	−6.36	< 0.001***
f0	−0.93	0.19	−4.66	< 0.001***
H1–H2	1.20	0.25	4.67	< 0.001***

(c) Adult female talker model Fixed effects:

	Estimate	Std.Error	z-value	Pr(> |z|)
(Intercept)	−0.86	0.51	−1.66	0.09·
VOT	−0.17	0.57	−0.30	0.75
f0	−3.96	0.49	−8.08	< 0.001***
H1–H2	0.59	0.18	3.26	< 0.01**

Significance codes:

*** 0.001

** 0.01

* 0.05

0.1