Aerodynamic Coarticulation in Sound Change or How Onset Trills Can Condition a Falling Tone

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1 Introduction

It has been noted by several scholars that dialects of Khmer, a Mon-Khmer language spoken primarily in Cambodia, Thailand, and Vietnam, have developed a tonal contour in words historically containing an apical trilled [r] in the onset (**r*). Impressionistic accounts of the change in the colloquial Phnom Penh dialect have described a low-rising pitch (Huffman 1967, Noss 1968) or a falling-rising pitch (Pisitpanporn 1999). Thach (1999) also reports the development of a falling tonal contour in Khmer spoken in Vietnam. Interestingly, in some cases, the loss of **r* and the development of the tonal contour are also associated with the development of aspiration and vowel changes. A singleton **r* onset often became a voiceless onset to the vowel, usually transcribed as [h] and an **r* that was part of an onset cluster often induced aspiration on the proceeding stop or fricative consonant. In addition, low vowels often acquire a mid or high onglide. For example, Pisitpanporn (1999) reports the change of **krah* > [kʰi̯ăh] 'thick'. More recently, an acoustic investigation of the Phnom Penh dialect for words previously containing **r* in onset clusters was reported by Wayland and Guion (to appear). Productions from standard Khmer, which retains the **r*, and the Phnom Penh dialect were compared. A falling-rising tonal contour, aspiration, and vowel changes were all documented. For example, the standard Khmer forms [pram] 'five', [triw] 'correct', and [kru] 'teacher' were produced as [pʰe̯ăm], [tʰɨ̆w], and [kʰŭ] in the Phnom Penh dialect.

The purpose of this paper is to investigate a possible phonetic motivation for some aspects of the historical development of **r* in onset clusters in Khmer. It is proposed that the aerodynamic needs of the apical trill condition a falling fundamental frequency (F0) contour at syllable onset. Specifically, it is hypothesized that the pressure build-up needed to initiate and maintain trilling increases airflow across the glottis, which has the effect of increasing the Bernoulli effect and raising the rate of vocal fold vibration. In addition, the development of aspiration is proposed to arise from trill devoicing, which may result from difficulty in maintaining the complex aerodynamic balance of simultaneous voicing and trilling.

Fundamental frequency and oral airflow data from Thai speakers producing stop and stop-[r] onsets are presented here. The results indicate that [r] clusters have a greater falling pitch contour than singleton stops and that the [r] production has greater airflow at voicing onset than words beginning with a singleton stop. These results are interpreted to provide evidence for a phonetic conditioning of the sound changes associated with [r] loss in Khmer.

1.1 Brief review of tonogenetic mechanisms

Much of the literature on tonogenesis (i.e., the origin of tones in a language) has focused on the development of high and low tones after voiceless and voiced onset clusters respectively or on the effect of lost laryngeal coda consonants, with [ʔ] conditioning a rising tone and [h] usually conditioning a falling tone (see, e.g., Haudricourt 1954, Matisoff 1973, Hombert 1978). A wide variety of languages such as Chinese, Karen, Tibeto-Burman, Austronesian, Miao-Yao, Vietnamese, and Tai languages are thought to have undergone such changes. The focus of this review will be on the effects of onset consonants, the type of tonogenesis under investigation here.

An early view of the effect of onset consonant voicing on the development of tones was aerodynamic. Basically, the proposal was that voiced stops induce a lower F0 due to the voicing during the closure. That is, as the voicing continues throughout the closure, the transglottal pressure

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reaches an equilibrium by the time of release, resulting in a relatively lower rate of airflow. On the other hand, the voiceless stops are not voiced during the closure and, thus, have a transglottal pressure drop at the time of release, resulting in a relatively higher rate of airflow. This higher rate of airflow should result in a stronger Bernoulli effect and, thus, a higher F0 at the time of release. If voicing distinctions were lost in onset position, the differential F0 onsets could be phonologized as high and low tones.

Ohala (1978) offered a critique of the aerodynamic view on several grounds. First, he noted that the differing aerodynamic effects only last for a few ms, whereas the F0 effects reported for voicing distinctions last for over 100 ms. Second, he noted that subglottal pressure builds after the release of voiced stops and decreases rapidly after the release of voiceless aspirated stops. This would serve to actually raise F0 for the voiced stops and lower F0 after the voiceless stops at vowel onset. In addition, more recently, Ohala and Sprouse (2003) reported that perturbing the transglottal pressure drop by venting pharyngeal pressure did not affect the F0 of the following vowel.

An alternative hypothesis is that there is greater tension on the vocal folds during voiceless than voiced stop productions. Löfqvist et al. (1989) found greater activation of the cricothyriod muscle in voiceless than voiced segments. This may create greater tension on the vocal folds during voiceless consonant production, inducing a higher F0 on the vowel following a voiceless (aspirated) stop than a voiced stop.

1.2 The current study

Here we return to aerodynamics for a possible explanation of the tonogenesis documented in Khmer. However, a different conditioning environment than previous research is considered. Namely, it is proposed that the falling tone in Phnom Penh Khmer was conditioned by aerodynamic effects of [r].

First, consider some of the aerodynamic factors in apical trill production. A rather large pressure drop across the constriction is needed to initiate and maintain trilling (McGowan 1992). Thus, there is high rate of airflow across the constriction when released. In addition, voiceless trills have a higher rate of airflow and are less sensitive to pressure disturbances than voiced trills (Solé 2002). Thus, higher pressure and airflow create more aerodynamically stable trills.

The aerodynamics needs of trill production are predicted to raise F0 by conditioning greater airflow across the glottis. Specifically, the F0 during the voiced portion of [r] is predicted to be higher than the voicing onset of the vowel following the same consonant type. For example, the F0 of [r] in stop-[r] clusters (TrV) should be higher than the F0 at vowel onset in stop only onsets (TV), producing a greater falling pitch contour for the TrV than TV syllables.

The prediction that TrV syllable onsets should have a greater falling pitch contour than TV syllable onsets was tested by investigating the production of words in Thai (a Tai-Kadai language and the national language of Thailand). Thai was chosen as the language of investigation for this study for several reasons. First, the assumption that phonetic conditions giving rise to sound change can be found in any living language was held (see e.g., Ohala 1993). Second, Thai has the consonant onsets of interest here: voiceless unaspirated stop (TV), voiceless unaspirated stop-[r] (TrV), voiceless aspirated stop (T^hV), and voiceless aspirated stop-[r] (T^hrV). Third, Thai is a tonal language and thus, should have relatively stable pitch across words of the same tone type. Finally, Thai was of interest because the [r] in T^hrV syllables is partially devoiced and it seems likely that Phnom Penh Khmer went through the stages of TrV > Tr̥V > T^hV. Thus, the Thai T^hrV syllables may represent an intermediate stage in the loss of [r].

2 Method

2.1 Participants

Five native Thai speakers living in Oregon, four female and one male, participated in the study. All had grown up in Thailand speaking Thai as their native language. They had studied English at school, but were not immersed in an English-speaking environment until they were adults.

2.2 Materials

Nine (near)-minimal quadruplets of the following types were used in the study: TV, TrV, T^hV, T^hrV. Table 1 presents the words used. All were real words known to the participants. The words were presented to the participants in Thai orthography, though they are represented here in phonetic transcription. All words had a mid tone and either ended in an open syllable or had a resonant (nasal or glide) coda. Thus, the tonal contour of the words could be measured from vowel onset to syllable offset.

Table 1. List of Thai words used in the study.

T	Tr	T^h	T^hr
taː 'eye'	traː 'seal'	t^haː 'to smear'	nît <u>t^hraː</u> 'sleep'
paːn 'birthmark'	praːn 'live'	p^haːn 'tray'	p^hraːn 'hunter'
paːŋ 'period'	praːŋ 'cheek'	p^haːj 'to paddle'	p^hraːŋ 'to camouflage'
paːm 'palm (tree)'	praːm 'to forbid'	p^haːn 'tray'	p^hraːm 'Brahman'
kaːw 'glue'	kraːw 'sound of leaves falling'	k^haːw 'fishy smell'	k^hraːw 'time'
kaːm 'sexual desire'	kraːm 'jaw, chin'	k^haːm 'to threaten'	k^hraːm 'indigo'
kɔːŋ 'to/a heap'	krɔːŋ 'to filter'	k^hɔːn 'to perch'	k^hrɔːŋ 'to rule'
kuː 'I'	kruː 'to run up together in crowds'	k^huː 'moat'	k^hruː 'teacher'
kam 'hold in one's palm'	kram 'to tolerate'	k^ham 'word, mouthful'	k^hram 'sewer water'

2.3 Procedure

Participants were recorded reading each word in a randomized order three times each in the carrier phrase [rau p^hûːt k^ham wâː _______ ʔìːk] 'We say the word _______ again'. The recordings were made on DAT tape using a head-mounted microphone (Shure SM10A). Only the first repetition of the words was used in the analysis. Oral airflow data was then collected from the participants for the same words using hardware and software from Scicon. This time, only one repetition in the carrier phrase was recorded.

2.4 Analysis

The recordings were digitally transferred to a PC using the Computerized Speech Lab 4400 from Kay Elemetrics. The F0 measurements were made using the PRAAT pitch tracker (autocorrelation method). In the case that the algorithm failed to resolve the F0, the measurements of individual glottal pulses were made. Four F0 measurements were made: F0 at onset of voiced portion of [r], F0 at vowel onset (onset was defined as the first distinct, full glottal pulse of the vowel), F0 at rime midpoint, and F0 at rime offset, before the last glottal pulse unaffected by the following glottal stop of the frame sentence. The first measurement was not made for the TV and T^hV words as they do not have an [r]. The F0 at rime midpoint was subtracted from F0 at voicing onset, either F0 at onset of voiced portion of [r] for the TrV and Tr^hV words or voicing at vowel onset for the TV and T^hV words, to get a measure of falling pitch contour.

The airflow measurements were made using PCquirer software from Scicon. Peak airflow was measured from smoothed waveforms for the aspiration in the case of ThV words, for [r] in the case of TrV words, for the voiced portion of [r] in the case of ThrV words, and for the burst in the case of TV words. In addition, airflow at vowel onset was measured for all words.

3 Results

3.1 Fundamental Frequency

Figure 1 presents the results, averaged across the five Thai speakers, from the F0 measurements. Note that the trill has a higher F0 than the vowel onset following the same stop type. In other words, the [r] in the TrV words has a higher F0 than the vowel onset of the TV words and, likewise, the [r] in the T^hrV words has a higher F0 than the vowel onset in the T^hV words.

The significance ($\alpha = .05$) of these differences was investigated using a mixed design Analysis of Variance (ANOVA) with the factors of Onset Type (TV, TrV, T^hV, T^hrV, repeated measures) and Speaker (5), and the dependent variable of F0 slope (onset of F0 minus F0 at vowel midpoint). The place of measurement for F0 onset depended on whether or not an [r] was present as described in the Analysis section but always represented the beginning of voicing for the syllable type. The main effects of Onset Type [$F(3,111) = 46.97$, $p < .001$] and Speaker [$F(4,37) = 10.98$, $p < .001$] were both significant. However, the interaction between the two factors was not [$F(12,111) = 0.71$, $p = .74$].

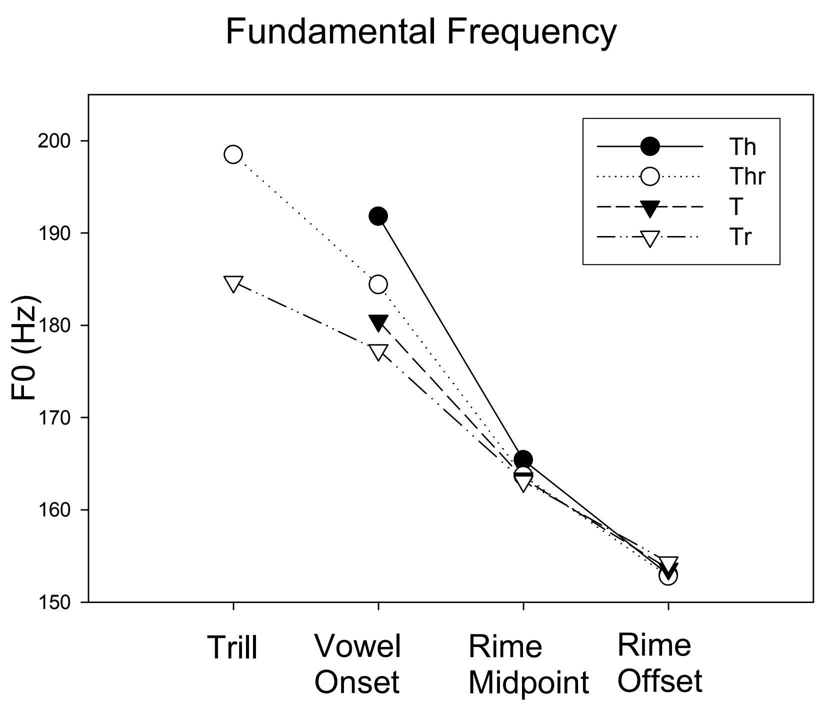

Figure 1. Mean fundamental frequencies of five native Thai speakers pronouncing real Thai words with mid tones for four onset types: voiceless aspirated stop, voiceless aspirated stop-[r], voiceless unaspirated stop, and voiceless unaspirated stop-[r].

These results can be interpreted to mean that there are differences in F0 slope across the four onset types and that the five speakers do not differ in the relative relation of the F0 slopes across the types, although they may differ in overall F0. In other words, some speakers have higher or lower voices than other speakers, but the effect of Onset Type is consistent across the five speakers.

The main effect of Onset Type was further explored in two separate ANOVAs comparing the F0 slope of onset types with and without [r], but beginning with the same stop type. The F0 slope of TrV was compared to that of TV and the F0 slope of T^hrV was compared to that of T^hV. The slope of TrV (mean 22 Hz) was found to be significantly greater than the slope of TV (mean 17 Hz) [$F(1,42) = 16.03$, $p < .001$]. Likewise, the slope of T^hrV (mean 35 Hz) was found to be significantly greater than the slope of T^hV (mean 26 Hz) [$F(1,42) = 19.55$, $p < .001$]. These results indicate that F0 is higher at voicing onset in onset clusters containing [r] than in simple stop onsets.

3.2 Oral Airflow

Example audio waveforms and airflow data are given in Figures 2 and 3. Note that the trills have a relatively high rate of airflow. For example, the trill tends to have a higher rate of airflow than the following vowel onset. In addition, the voiceless portion of trills shows a higher rate of airflow than the voiced portion.

In order to determine if the higher F0 during trill production may be related to rate of airflow, the airflow during the voiced portion of trill production was compared to the airflow at voicing onset for onset types not containing trills. The airflows for TrV vs. Tv and T^hrV vs. T^hV were compared. Two separate mixed design ANOVAs were conducted. The first examined the effect of factors Onset Type (TrV vs. TV, repeated) and Speaker (5). The main effects of Onset Type [$F(1,37) = 71.64$, $p < .001$] and Speaker [$F(4,37) = 5.64$, $p = .001$] were significant. The airflow during the trill was higher in the TrV words (mean 321 ml/sec) than the airflow at the vowel onset for the TV words (mean 47 ml/sec). The interaction between the two factors was also significant [$F(4,37) = 4.73$, $p = .004$]. The interaction was investigated by examining the effect of onset type for each speaker. All speakers had greater airflow for TrV than TV onsets, so the difference was one of magnitude. In other words, some speakers show a stronger effect, but all showed differences in the expected direction.

The second ANOVA examined the effect of factors Onset Type (T^hrV vs. T^hV, repeated) and Speaker (5). The main effects of Onset Type [$F(1,38) = 84.95$, $p < .001$] and Speaker [$F(4,38) = 10.10$, $p < .001$] were significant and the interaction was not significant [$F(4,38) = 2.46$, $p = .06$]. The airflow during the voiced portion of the trill was higher in the T^hrV words (mean 512 ml/sec) than the airflow at the vowel onset for the T^hV words (mean 129 ml/sec).

The results from the two ANOVAs are presented graphically in Figure 4. Note that the airflow at vowel onset is less than the airflow for trill production. Also note that the airflow for the voiced portion of the trill in T^hrV words is greater than the airflow for the trill in TrV words.

5 Discussion

The results of this study show that, for Thai speakers, stop-[r] onset clusters have a greater F0 difference from voicing onset to the middle of the rime than do the onsets of the *same* stop type without the [r]. In addition, the airflow during trill production is greater than the airflow at vowel onset for syllables beginning with a single stop. The higher F0 found for trills may be caused by the higher rate of airflow during trill production as compared to vowel onset. Thus, the greater falling F0 contour for stop-[r] onsets as opposed to singleton stop onsets may be an automatic consequence of trill production.

The greater F0 drop after trilled [r] has a likely explanation in the aerodynamics of trill production. The translingual pressure drop needed for the apical trill production necessitates a high rate of glottal airflow. The greater airflow conditions faster vibration of the vocal folds during the voiced portion of the trill as compared to the voicing period of vowel onsets. These effects may provide an explanation for an automatic falling F0 after trilled onsets.

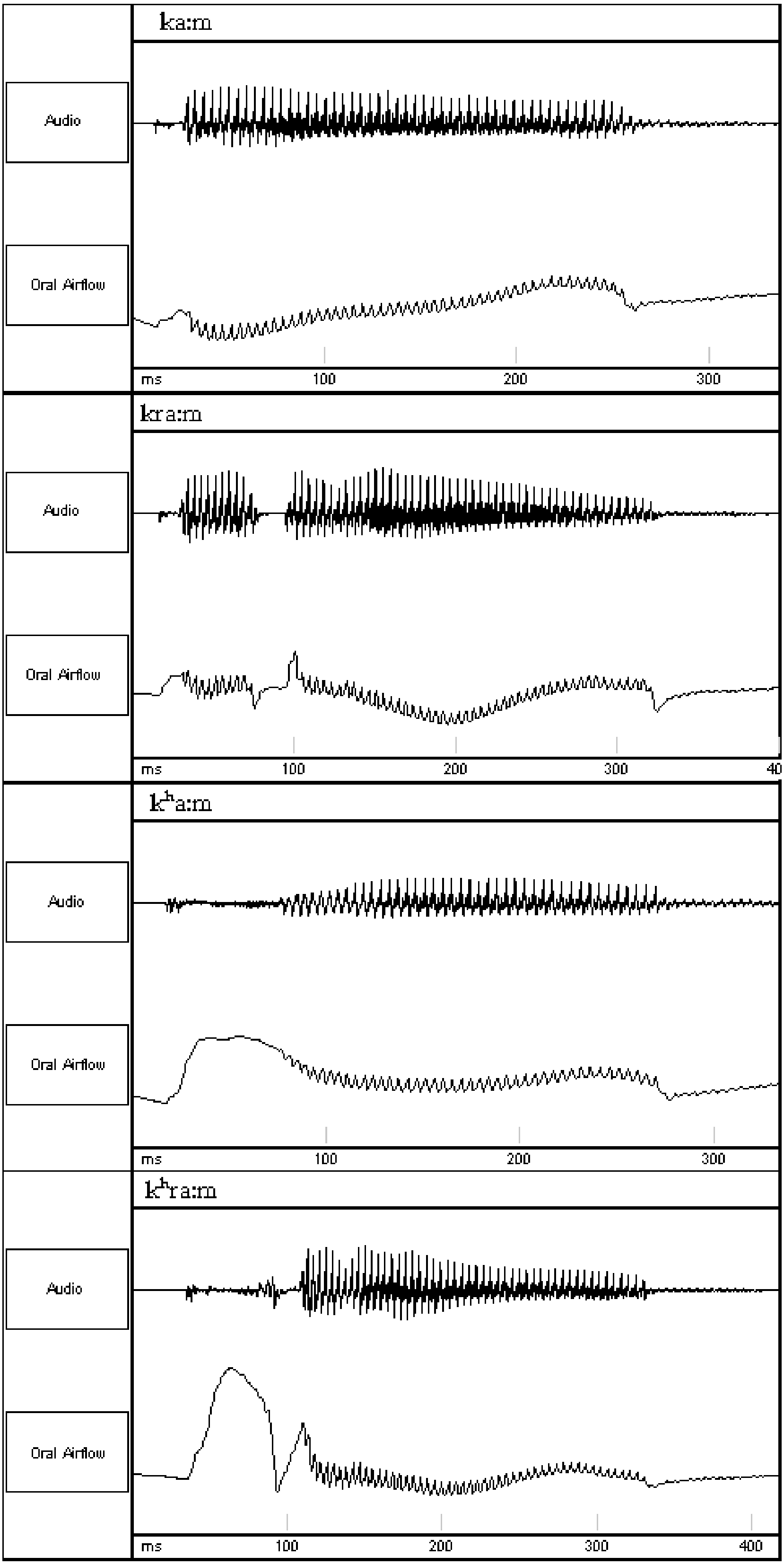

Figure 2. Audio waveform and oral airflow examples from a single speaker for [ka:m], [kra:m], [kʰa:m], and [kʰra:m].

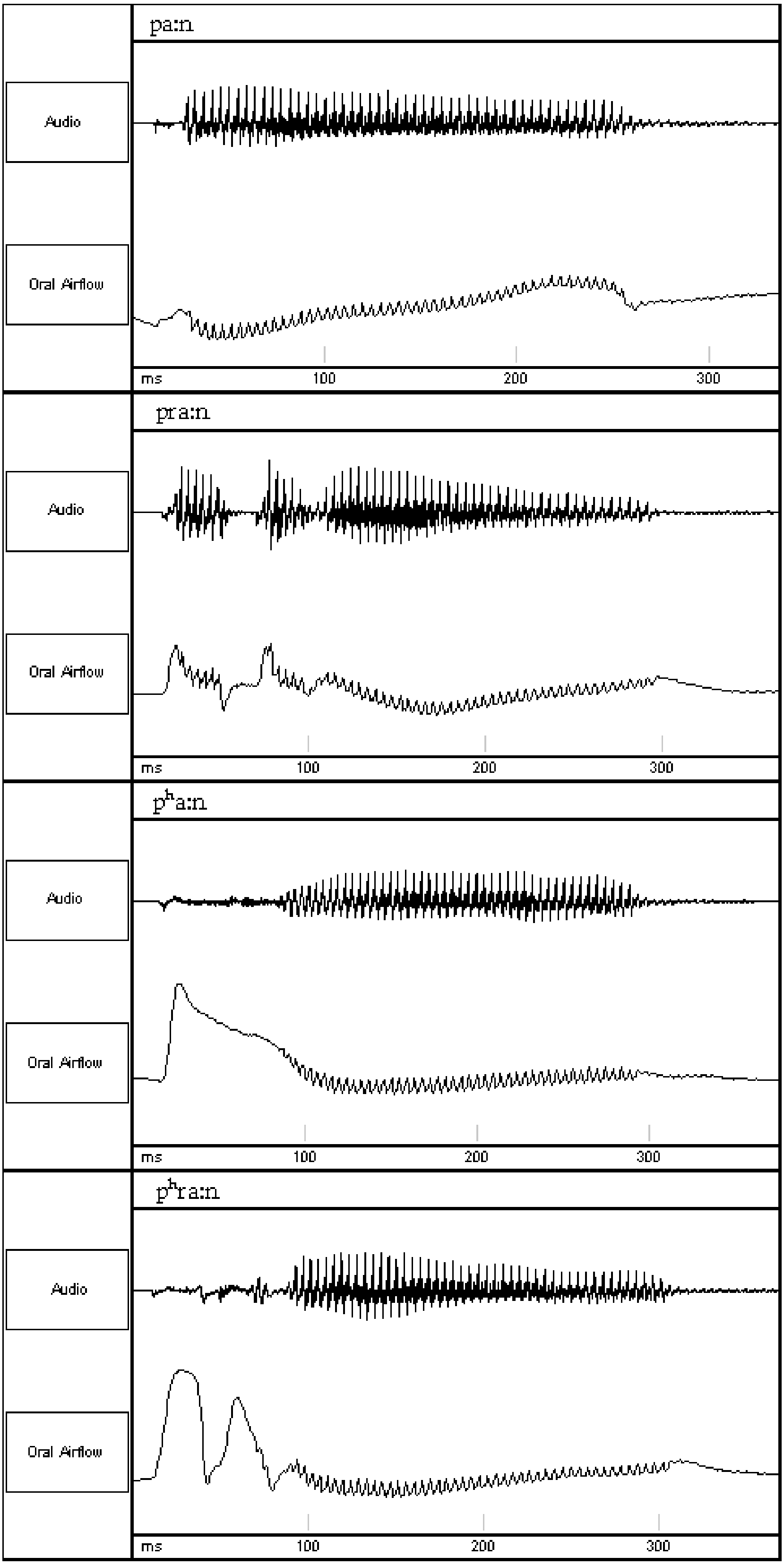

Figure 3. Audio waveform and oral airflow examples from a single speaker for [pa:n], [pra:n], [pʰa:n], and [pʰra:n].

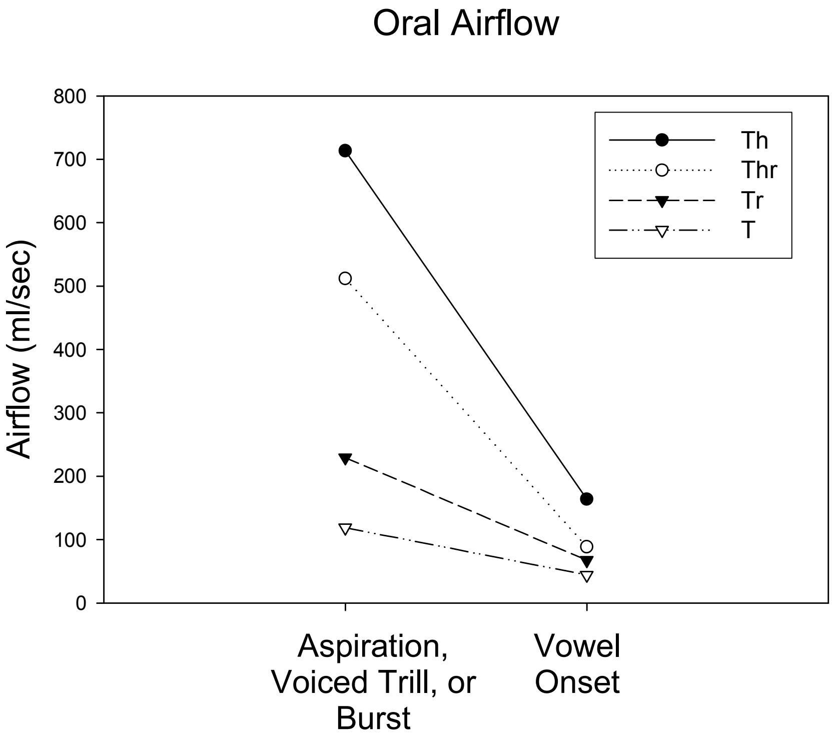

Figure 4. Mean oral airflow of five native Thai speakers pronouncing real Thai words with mid tones for four onset types: voiceless aspirated stop, voiceless aspirated stop-[r], voiceless unaspirated stop, and voiceless unaspirated stop-[r].

The results obtained from the Thai speakers provide a possible origin for the sound changes observed in dialects of Khmer in which onset [r] was lost, conditioning a falling-rising tone and aspiration. It is assumed that the greater falling F0 in [r] onsets found in Thai is an automatic consequence of trill production and, thus, should be found in all languages, including earlier stages of Khmer in which onset [r] was still present.

Thus, at a stage before the sound change had occurred, the F0 drop in trill clusters may have been an automatic consequence of the production. As the trill began to weaken and devoice, the F0 drop may have been even greater, as suggested by the higher F0 during the trills after the aspirated stops in which the trills were partially devoiced than the trills after the unaspirated stops which were voiced throughout. As the trill was ultimately totally devoiced and reinterpreted as aspiration, the F0 drop may have remained part of the lexical representation of the word.

The proposed account suggests that the F0 drop forms part of the lexical representation even though it is an automatic consequence of the trill production. Thus, when the trill is lost or devoiced, the F0 drop remains. Such a proposal is supported by results from behavioral research which suggest that phonetically detailed episodes of word usage (i.e., actual productions and perceptions) constitute the basic representations in the mental lexicon (Palmeri, Goldinger & Pisoni 1993; Goldinger 1998).

Finally, the lenition of [r] may also find an aerodynamic explanation. The high oropharyngeal pressure needed for trilling may make it difficult to coordinate the transglottal pressure drop needed for voicing (Solé 2002). If the transglottal pressure drop is not maintained, the trill could be devoiced. In addition, small oropharyngeal pressure variations during trill production can lead to fricativization (Solé 2002). Because consonant clusters with trills are difficult to produce (note the rarity of such clusters) due to the narrowly defined lingual and aerodynamic constraints, [r] in a cluster may be especially prone to fricativization and devoicing.

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