The effects of prosodic boundaries on nasality in Taiwan Min

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This study explores the effects of prosodic boundaries on nasality at intonational phrase, word, and syllable boundaries. The subjects were recorded saying phrases that contained a syllable-final nasal consonant followed by a syllable-initial stop. The timing, duration, and magnitude of the nasal airflows measured were used to determine the extent of nasality across boundaries. Nasal amplitudes were found to vary in a speaker-dependent manner among boundary types. However, the patterns of nasal contours and temporal aspects of the airflow parameters consistently varied with boundary type across all the speakers. In general, the duration of nasal airflow and nasal plateau were the longest at the intonational phrase boundary, followed by word boundary and then syllable boundary. In addition to the hierarchical influence of boundary strength, there were unique phonetic markings associated with individual boundaries. In particular, two nasal rises interrupted by nasal inhalation occurred only across an intonation phrase boundary. Also, unexpectedly, a word boundary was marked by the longest postboundary vowel, whereas a syllable boundary was marked with the shortest nasal duration. The results here support the hierarchical effect of boundary on both domain-edge strengthening and cross-boundary coarticulation.

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I. INTRODUCTION

Cross-linguistically, articulatory movements vary according to focus condition and boundary strength. Though focus and prominence are signaled by hyperarticulation, the effect of boundary can be implemented by either the weakening or strengthening of articulatory movements (Edwards, Beckman, and Fletcher, 1991; de Jong, 1995; Fougeron and Keating, 1996; Tabain, 2003b). These articulatory weakening and strengthening effects show gradient variations according to the strengths of adjacent boundaries.

Like traffic signs that control deceleration and acceleration of vehicular movements, boundary strength controls the duration and magnitude of articulatory movements in pre- and postboundary position. Though some languages prefer final strengthening in the preboundary position, such as phrase-final lengthening before an English IP boundary, other languages prefer initial strengthening in the postboundary position, such as phrase-initial lexical tonal strengthening in Taiwanese (Pan, in press). Thus, it is more difficult to generalize the prosodic effect of boundary on surface articulation across languages. To fully explore the effect of boundary, diversified data need to be collected from languages with different rhythmic structures.

This study expands the scope of prosodic articulatory studies from intonation-based languages, such as English (Cho, 2002, 2004, 2005, 2006) and French (Fougeron and Keating, 1996; Fougeron, 2001; Tabain, 2003a b) to a tone-based language by investigating how nasal consonants in Taiwan Min (Taiwanese) are influenced by prosodic boundaries.

A. Taiwanese nasal consonants and vowels

Min, a Chinese dialect, spoken in Fujian and Southeast Asia among Overseas Chinese who trace their roots back to Fujian, is spoken by 70% of the population in Taiwan. Taiwan Min has around 16 oral vowels and 11 nasal vowels, depending on the dialect. Taiwanese phonotactic constraints require that nasal vowels occur after initial nasal consonants /m, n, ŋ/, such as /mĩ/ "thing," and that oral vowels occur after initial oral stops /b, g, l/, such as /bi/ "rice." These phonotactic constraints have led researchers to devise various phonological rules stating the alternation between homorganic initial nasal and voiced stops. Based on auditory impressions with little empirical phonetic data, these rules change voiced stops into a homorganic nasal when followed by a nasal vowel, or vice versa, e.g., /b, l, ɡ/ -> [m, n, ŋ]/_ [nasal vowel] or /m, n, ŋ / -> [b, l, ɡ] /_ [oral vowel] (Ting, 1985; Zhang, 1989; Cheng, 1968, 1973). It should be noted that there is no /d/ in Taiwanese and /l/ is considered to be a voiced stop due to its stoplike quality (Zhang, 1989). Preliminary EPG data concerning /l/ collected by the author showed that speakers produced /l/ with an alveolar closure and with either a lateral or central release. Therefore, /l/ was included as an alveolar stop along with /b, g/.

Pan (2004) in an earlier airflow study found that Taiwanese initial voiced stops changed into homorganic nasals when preceded by a final nasal consonant. For example /b/ becomes [m] in /saŋ bi/ [saŋ mi] "send rice." This finding challenges the accepted phonological rules that govern the distribution of nasal vs oral vowels. Since oral vowels can occur after both initial nasals, as in /saŋ bi/ [saŋ mi] "send rice," and after initial voiced stop /be bi/ [be bi] "purchase rice," this contradicts the traditional description of a phonotactic constraint in which oral vowels occur after initial voiced stops and nasal vowels occur after initial nasals. Relevant to the current study is the fact that initial stops and vowels are not always nasalized to the same extent after a nasal consonant. The current investigation explores the extent of nasalization from a nasal consonant across a boundary. If a boundary is strong, then less nasalization is expected to occur on the upcoming segment; if the boundary is weak, then more nasalization across the boundary is expected. As airflow is an effective means of capturing nasality patterns in Taiwanese, data relating to it will be used in this study.

B. Nasality and prosodic boundary

Studies on articulation and boundary encompass three major issues: (1) domain-edge strengthening; (2) variation of articulation in relation to the strength of the adjacent boundary; and (3) variation of cross-boundary coarticulation in relation to the strength of the intervening boundary.

Turning to the first issue of domain-edge strengthening, previous studies have discovered hyperarticulation to be greater in domain-initial segments or domain-final segments than in domain-medial segments (Fougeron and Keating, 1997; Krakow, 1999; Cho, 2002, 2004, 2006).

To capture domain-edge-strengthening effects on velic movement, Krakow (1989, 1993) in a velocontour study investigated the coordination pattern between velic and lip movements, by placing a syllable initial nasal /m/ in either word-initial [V#mV] or -medial [V.mV] positions, and a syllable-final nasal /m/ in either word-final [Vm#] or medial [Vm.V] positions. She measured the duration and amplitude of velic and lip raising/lowering, and found that, regardless of the position within a word, the offset of velic lowering was closely timed to the end of lip raising for initial nasals but to the onset of lip raising for final nasals. In other words, velic lowering began earlier for final /m/ than for initial /m/. The velic and lip coordination patterns are influenced by the boundary positions. In addition to coordination patterns, she also discovered that a syllable's position within a word influenced the magnitude and duration of the velic and lip movements. For instance, nasals in word-final positions were lower in velic displacements, higher in velic raising, and longer in duration for both lip lowering and raising than nasals in syllable-final (and word-medial) positions. That is to say, syllable-final nasals are more hyperarticulated in word-final than in word-medial positions.

In Taiwanese, Hsu and Jun (1996a, 1996b) in a study on voice onset time (VOT) at the edge of Taiwanese tone groups discovered that VOT was longer in segments produced in the tone-group-initial position than in the tone-group-final position. So, one can surmise that evidence exists indicating that speakers of Taiwanese use articulatory strategies to indicate the existence of a boundary. However, little is known about the effect of boundary type on nasality in Taiwanese.

Turning to the second issue on boundary strengthening and articulation variations, it has been found that jaw, lingual, and lip movements vary from the most canonical to the least canonical form as boundaries vary from strong to weak in languages such as English, French, Tamil, and Korean (Fougeron and Keating, 1997; Byrd *et al.*, 2000; Fougeron, 2001; Cho and Keating, 2001; Tabain, 2003a, 2003b; Cho, 2005, 2006). Moreover, in French, velic lowering varies in a hierarchical manner at intonational phrase, accentual phrase, word, and syllable junctures. By calculating the amount of nasal airflow as an indicator of velic lowering, differences were found in a nasal airflow study on French initial /n/ (Fougeron and Keating, 1996). In this study, one of two subjects differentiated three out of four levels of boundaries based on the extent of nasality during the production of the nasal consonant. However, the other male speaker failed to produce any difference between any of the boundaries (Fougeron and Keating, 1996). Keating *et al.* (2004) extended this study by adding more speakers, and found that three out of four speakers produced differences in the amount of nasality in relation to boundary type in a speaker-dependent manner (Keating *et al.*, 2004). Both studies discovered that the stronger the preceding prosodic boundary, the lesser the amount of nasal airflow recorded from the initial /n/. Following Fougeron and Keating's study (1996), which found nasal airflow to be an effective means to study the influence of boundary on postboundary nasality, the present study also uses nasal airflow to investigate the effect of boundary on nasality patterns in Taiwanese.

Turning to the third issue, the effect of boundary type on cross-boundary coarticulation, it has been found that anticipatory nasal coarticulation is affected by boundary type in English. MacClean (1973) used frame-by-frame tracing of velic movements recorded on lateral high-speed cinefluorographic film to observe the effects of syntactic boundaries on velic movements. McClean found that the presence of major syntactic boundaries (including marked phrase, clause, or sentence boundaries) between two vowels in a CV#VN context delayed the onset of velic movements relative to the offset of the preceding initial vowels more than less-marked syntactic boundaries (including word boundary). Since English vowels are unspecified in terms of phonemic nasal features, the velum started to decline during the articulation of the preboundary vowel in CV#VN. The commencement of velic lowering in anticipation of the upcoming nasal consonant was found to be earlier in productions by English speakers after weak boundaries and later after strong boundaries (MacClean, 1973).

Generally speaking, cross-boundary coarticulation weakens as the intervening prosodic boundary varies from weaker to stronger levels in the prosodic hierarchy. As articulatory movement becomes more canonical next to a strong boundary, it is less likely to coarticulate with neighboring segments. For example, Cho (2004) reported greater V-to-V coarticulation resistance across stronger prosodic boundaries. So far there has been no study on the effect of boundary on cross-boundary carry-over nasalization. Hence, this study uses nasal airflow to investigate how cross-boundary carry-over nasalization from a final nasal to an initial voiced stop in Taiwanese varies according to the hierarchical strength of the intervening boundaries.

C. Speaker-dependent articulatory patterns

Before moving on to investigate the relationship between boundary and nasality in Taiwanese, it should be noted that, as previously mentioned in the airflow study on French nasality (Fougeron and Keating, 1996; Keating *et al.*, 2004), speaker-dependent nasality patterns have already been widely observed. Furthermore, the effect of boundary type on jaw, lip, and acoustical parameters also varies from speaker to speaker (Tabain, 2003a, 2003b; Cho, 2005). For example, among the acoustical and articulatory data of five speakers producing English /#bi/ and /#ba/, it was found that all the speakers produced /a/ with the greatest jaw movement and /i/ with the least jaw movement at strong boundaries; however, the duration of lip opening during the articulation of a vowel varied among the same speakers. Only two speakers produced vowels with a longer lip opening after a strong boundary (Cho, 2005). Tabain (2003a) studied the acoustic patterns of French word-final /a#C/ sequences produced at an utterance, intonational phrase, accentual phrase, or word boundary and found that there was much variation among speakers. Speakers used different cues to indicate different prosodic strengths. For example, some speakers used vowel duration to distinguish four types of boundaries, i.e., utterance > intonational phrase > accentual phrase > word, whereas others classified the vowel duration before different boundaries into two groups, i.e., utterance = intonational phrase = accentual phrase > word. Moreover, when looking at the spectral tilt for consonants, /#f, s, ʃ/, all subjects grouped the boundaries at two levels; however, two subjects also made a distinction between word and higher level boundaries (utterance = intonational phrase = accentual phrase > word), whereas another subject made a distinction between utterance and lower level boundaries (utterance < intonational phrase = accentual phrase = word).

Keating *et al.* (2004), in an EPG study on VOT and lingual contacts during the production of Taiwanese initial /t/ and /n/ after utterance, intonational phrase, accentual phrase, word, and syllable boundaries by two speakers, discovered that although there was a general trend for lingual peak contact to vary with boundary type, speaker-dependent patterns were nonetheless still observed. It was found that one speaker failed to vary the production of /t/ at all, whereas another speaker varied the production of /t/ in relation to the prosodic boundary strength.

Nearly all previous studies on articulation and boundary have discovered speaker-dependent articulatory patterns (Fougeron and Keating, 1996; Keating *et al.*, 2004). It is, therefore, likely that there are a certain number of patterns that a speaker can choose from, as well as some other factors which influence articulatory pattern in addition to boundary. The following is a discussion on the influence of focus, declination, and speaking rate on velic movements.

D. Other factors influencing velic movements

Stress, declination, and speaking rate have been found to influence velic movements (Krakow, 1993; Bell-Berti *et al.*, 1995). For example, stress affects velic height by enhancing the position of the velum. That is, the high velic position for an oral stop is higher, whereas the low velic position for a nasal stop is lower in stressed syllables (Vaissiere, 1988). In addition to stress, declination also affects velic movements. It was discovered that velic displacement of nasals produced in words in serial position gradually decreased from the beginning to the end of a sentence. In other words, the earlier the nasal is in a sentence, the lower the position of the velum (Bell-Berti and Krakow, 1991; Krakow, Bell-Berti, and Wang, 1995).

In addition to stress and declination, speaking rate also influences velic height. Bell-Berti and Krakow (1991) in a study on velic height for /s/ and /n/ found that the faster the speaking rate is, the lesser the difference in velic height between the oral and nasal consonants. Conversely, the slower the speaking rate, the larger the difference between the velic positions for /s/ and /n/. Kuehn (1976) noticed that these effects are speaker dependent. Though both speakers in Kuehn's (1976) study reduced the distance of velic movement in fast speech, one speaker reduced the extent of velic lowering by raising the lowest velic position, whereas the other speaker reduced the distance of velic movement by lowering the highest velic position. Kent, Carney, and Severeid (1974) reported that as speaking rate increased from a conversational to a rapid rate, speakers increased the velocity of velic movements, or reduced the extent of the velic movement, or used both strategies to produce the same sentence.

In addition to a control on the effects of focus and declination, as previous studies have done, this study also adopts a control on global speaking rate in an attempt to minimize speaker-dependent variations, and to reveal the effect of boundary on nasality.

E. Objectives

After controlling the confounding factors, this study followed the line of study of the variations of velic movements within multiple prosodic domains. By using nasal airflow, a successful method used to record the effect of boundary on French initial nasals and on cross-boundary nasalization in Taiwanese, the present study explores the effects of different prosodic boundaries on (1) domain-final nasality and (2) cross-boundary nasalization.

II. METHOD

A. Speakers

Three male native Taiwanese speakers participated in the experiments. They were students at National Chiao Tung University at the time of recording. The three speakers were also fluent in Mandarin and had received more than 10 years of ESL education.

B. Materials

Three types of contexts were used in the current study. The first was a baseline context which elicited utterances not ending with a nasal and, thus, no cross-boundary nasalization. The baseline data set consisted of syllable-final vowels followed by initial voiceless stops, abbreviated as Vptk (vowel # /p/, /t/, /k/) or voiced stops, abbreviated as Vblg (vowel # /b/, /l/, /g/). The syllable-final vowels and following stops were produced across intonational phrase, word, and syllable boundaries. As previously mentioned, /l/ was included together with /b, g/ due to its stoplike quality. (2) The second context elicited comparison data with a final nasal followed by an initial voiceless stop that prohibits cross-boundary nasalization, abbreviated as Nptk (nasal # /p/, /t/, /k/) across intonational phrase, word, and syllable boundaries. (3) The third and final context elicited experimental data with a final nasal that allows for cross-boundary nasalization. The experimental data consisted of final nasals placed before voiced stops across intonational phrase, word, and syllable boundaries, abbreviated as Nblg (nasal # /b/, /l/, /g/). The comparison data in the Nptk context address the first research question involving the effect of boundary on final nasals, whereas the data in the Nblg context address the second research question concerning the strength of the intervening boundary on cross-boundary nasalization.

To minimize speaker-dependent articulatory variation, focus and declination were controlled in the corpus design. Although lexical stress does not exist in Taiwanese, words are produced with a longer duration and an expanded *f*0 range for lexical tones when under narrow focus (Pan, 2006). Therefore, the effect of focus condition is controlled by asking the subjects to produce the utterances with a broad focus.

To control declination effects, intonational phrase, word, and syllable boundaries were placed between the second and third syllables of sentences containing six syllables [$\sigma\sigma$ # $\sigma\sigma\sigma\sigma$]. The final oral vowels and three final nasals, /m, n, ŋ/ at the end of second syllable were followed by either one of the three initial voiced stops, /b, l, g/, or one of the three initial voiceless unaspirated stops, /p, t, k/, at the beginning of the third syllable, [Vmnŋ] # [blg], [Vmnŋ] # [ptk], [V] # [blg], or [V] # [ptk]. Declination effect was minimized by having target syllables far from the end of the sentence.

Sentence (1) is an example of a sentence used to elicit utterances with an intonational phrase boundary between the target syllables. In sentence (1), the first and second syllables formed a surname. A comma was placed after the second syllable in the sentence to elicit the production of the surname as a vocative. The right edge of the intonational phrase (IP) boundary was defined by an *f*0 final lowering and a long pause and a postboundary pitch reset.

Tonal grouping:

$((\sigma_{\mathrm{s}}\ \sigma_{\mathrm{j}})^{\text{tone group}})^{\mathrm{IP}}((\sigma_{\mathrm{s}}\ \sigma_{\mathrm{s}}\ \sigma_{\mathrm{s}}\ \sigma_{\mathrm{j}})^{\text{tone group}})^{\mathrm{IP}}$

Syntactic grouping:

[$_{\mathrm{np}}$ a p**a**], PRO [**l**ai k^{h}i təŋ la]

dad come go home exclamation

“Daddy, let’s go home.”

s: syllable with sandhi tone; j: syllable with juncture tone; PRO: pronoun

(1)

In Taiwanese every lexical item has two tones, namely a juncture and a sandhi tone. A juncture tone surfaces on the last syllable within a tone group, whereas a sandhi tone surfaces on syllables located at the nonfinal position of a tone group. The domains of tone group are syntactically and prosodically determined; however, no complete account on Taiwanese tone group delineation has been offered yet. In order to elicit productions with a word boundary but not with a tone-group boundary between the target syllables, sentences composed of an NP followed by an adjective phrase were used, as in (2).

Tonal grouping:

$((\sigma_{\mathrm{s}}\ \sigma_{\mathrm{s}}\ \sigma_{\mathrm{s}}\ \sigma_{\mathrm{j}})^{\text{tone group}}(\sigma_{\mathrm{s}}\ \sigma_{\mathrm{j}})^{\text{tone group}})^{\mathrm{IP}}$

Syntactic grouping:

[$_{\mathrm{np}}$[$_{\mathrm{n}}$si ki**n**] [$_{\mathrm{n}}$**l**ai a]] [$_{\mathrm{ap}}$ sĩũ dzɛ]

four kilogram pear too much

“Four kilograms of pears are too much .”

AP: adjective phrase (2)

In sentence (2), the first and second syllables, /si kin/ “four kilograms,” is a quantifier, whereas the third and fourth syllables /lai a/ “pear,” is the noun modifed by “four kilograms.” There is a word boundary between the second and third syllables, that is, between the quantifier and the noun. The tone-group boundary is located after the NP, e.g. “four kilograms of pears.”

To elicit utterances with a syllabic boundary between the target syllables, sentences such as (3) containing a word spanning from the preboundary (second) syllable to the postboundary (third) syllable were used. The word containing target final nasal /oral vowel and initial stops was either a noun, or a verb, or an adjective. In the following case, the word was an adjective.

Tonal grouping:

$((\sigma_s\ \sigma_s\ \sigma_s\ \sigma_j)^{\text{tone group}}\ (\sigma_s\ \sigma_j)^{\text{tone group}})^{\mathrm{IP}}$

Syntactic grouping: (3)

[$_{\mathrm{vp}}$ [v ts^{h}i **ŋ**] [$_{\mathrm{np}}$[$_{\mathrm{Adj}}$ **k**an tan e] [$_{\mathrm{n}}$ hɔk tsɔ**ŋ**]]

wear simple clothing

“Wear simple clothing .”

After designing the corpus, three reading lists were composed, with each reading list containing only sentences with only one type of boundary between target syllables. In other words, there was one reading list with sentences designed to elicit an intonational phrase boundary between second and third syllables, another to elicit a word boundary, and a third one to elicit a syllable boundary. The order of sentences within each list was randomized.

C. Instrumentation

Nasal airflow was recorded from a transducer mounted on a nasal airflow mask, a Hans Rudolph model P0789 adult nasal mask, which covered only the nose of the speaker. The transducer was connected to an MS100-A2 airflow system manufactured by Glottal Enterprises. Nasal airflow was lowpass filtered at 36.5 Hz and then dc recordings were made by using a DT-2801 card installed in a PC. The signals were digitized at 11 kHz using CSPEECHSP software.

Acoustic signals picked up by a TEV microphone connected to a TEAC cassette deck were sent to a PC to be digitized simultaneously with nasal airflow at 11 kHz using CSPEECHSP software.

A Seiko quartz metronome with blinking lights and ticking sounds to signal beats was used to regulate the global speaking rate. The ticking sounds were sent through a Beyerdynamic headphone to pace speaking rates for the first and second syllables of each sentence. See below for further discussion of how the global speaking rate was controlled.

D. Recording procedure

Airflow system calibration was carried out first by warming up the system for 1 h before recording and then adjusting the voltage displayed on the front panel of the system to zero "0" while no signals were being received. Then, the software was also calibrated by adjusting the volts of empty signals recorded to 0 volts as well. The flow was not actually calibrated; thus, the amplitudes reported in this study were volts rather than units of actual flow (e.g., cc/s).

After hardware and software calibrations, the recordings were made in a sound-proofed room in the phonetics laboratory of National Chiao Tung University, Taiwan. During the recordings, both the speaker and the experimenter were present in the sound-proofed room. The experimenter controlled the CSPEECHSP software, signaled the speaker to put on the nasal airflow mask, and to read one sentence from the reading list. Speakers paused after each sentence to allow the experimenter time to save the nasal airflow and acoustic data at 11 kHz.

To control for global speaking rate, which previously had been found to influence nasal patterns, speakers wore a headphone emitting the ticking sounds from the metronome at a speed of 144 beats per minute. Based on native speakers' judgments, this speed is compatible with the speaking rate during a normal conversation. None of the speakers reported that the speed deviated from what they normally used during conversation. There was also a blinking light on the metronome which was synchronized with the beats. Before the recordings were made, speakers were instructed to read the first and second syllables of the sentence at a speed with one ticking sound corresponding to the first syllable, and the second ticking sound corresponding to the second syllable. After pacing the speed at the beginning of the sentence, speakers were then free to slow down or speed up while producing the rest of the sentences to preserve the natural prosodic cadence of their utterances.

Altogether there were 162 target sentences recorded in the Nblg and Nptk contexts (3 final nasals ×6 initial consonants ×3 prosodic boundaries ×3 repetitions) and 54 baseline sentences in the Vblg and Vptk contexts (1 final vowel ×6 initial consonants ×3 prosodic boundaries ×3 repetitions). Due to typing errors on the reading lists, three repetitions of one sentence that should have had a final /m/ followed by an /l/ across a syllable boundary and three repetitions for each of the two sentences containing a final vowel followed by an /l/ across an intonational phrase boundary were discarded from the Nblg context.

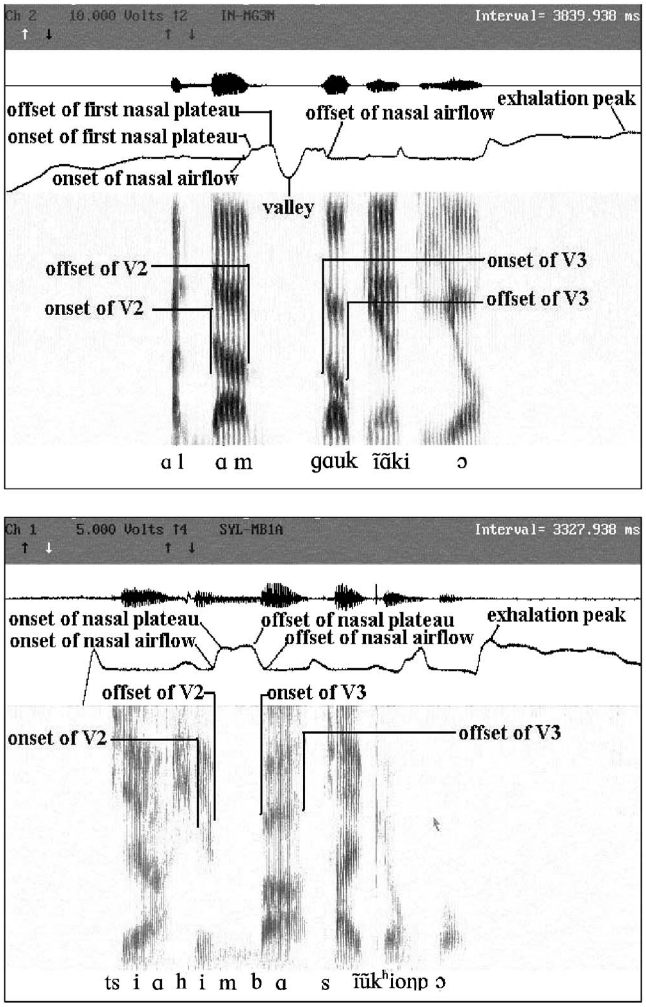

FIG. 1. Measurement points taken from nasal airflow with (a) two rises and (b) one rise between the second and third vowels.

E. Data analysis

As shown in Fig. 1, spectrograms generated by CSPEECHSP were used to locate the time at the second vowel onsets (V2On), and the offsets (V2Off) as well as the third vowel onsets (V3On), and the offsets (V3Off).

The time and amplitude of nasal airflow during production of the first nasal rise were taken to determine the timing and amplitude of nasality. These values were extracted at the following locations: (1) the onset of the initial nasal rise (On); (2) the start of the first nasal plateau (1On); (3) the end of the first nasal plateau (1Off); (4) the offset (Off) of the falling slope for the last nasal rise; and (5) the magnitude of the maximal nasal peak at the end of each utterance during normal exhalation was extracted (max) (Fig. 1). The start of a nasal plateau was the point in time when the rising slope of first nasal rise stopped and turned into a level contour, whereas the end of a nasal plateau was the point where the level nasal plateau started to change into a falling slope. If there was only a nasal peak without a plateau, then amplitudes and times of two points at the peak were taken. For nasal contours with two rises, the lowest point between the two rises (V) was also taken.

For the following discussion, refer to (4a)–(4e). After taking these measurements, further calculations were applied to these values to derive the temporal aspects of the nasal airflow, including the duration of the nasal plateau during the first nasal rise [R1PlDur (4a)], and the duration of the nasal airflow [NasDur (4b)]. In utterances with two nasal rises, the duration of the nasal airflow did not truly represent the duration of the continuous nasal airflow because it included the duration of the nasal inhalation between the two nasal rises. According to Pan (2004), in the Nblg, Vblg, and Vptk contexts, postboundary vowel nasalization occurs only during the initial 25% of vowel duration. In order to reveal the actual duration of nasalization during postboundary initial stops and vowels, the current study calculated the offset latency of nasal airflow relative to the onset of the third vowel, by subtracting the time at the offset of the nasal airflow from the time of the onset of the third vowel, as shown in [CVNasDur (4c)]. The positive values of the duration of postboundary initial consonant and vowel nasalization (CVNasDur) indicate the duration of the third vowel nasalization, whereas the negative values revealed the duration of nasalization in the initial voiced and voiceless stops. In addition to the magnitude and temporal aspect of nasal airflow, the duration of the second and third vowel /a/ was also calculated in [V3Dur (4d); V2Dur (4e)].

$$\begin{aligned}&\text{Duration of first nasal plateau (R1PlDur)}\\&\quad=\text{time at end of first nasal plateau (1Off)}\\&\qquad-\text{time at start of first nasal plateau (1On);}\end{aligned}\tag{4a}$$

$$\begin{aligned}&\text{Duration of nasal airflow (NasDur)}\\&\quad=\text{time at offset of nasal airflow (Off)}\\&\qquad-\text{time at onset of first nasal airflow rise (On);}\end{aligned}\tag{4b}$$

$$\begin{aligned}&\text{Duration of postboundary stop and vowel nasalization}\\&\qquad\text{(CVNasDur)}\\&\quad=\text{time at offset of nasal airflow (Off)}\\&\qquad-\text{time at onset of third vowel (V3On);}\end{aligned}\tag{4c}$$

$$\begin{aligned}&\text{Duration of postboundary vowel /a/(V3Dur)}\\&\quad=\text{offset of postboundary vowel (V3Off)}\\&\qquad-\text{onset of postboundary vowel (V3On);}\end{aligned}\tag{4d}$$

$$\begin{aligned}&\text{Duration of preboundary vowel /a/(V2Dur)}\\&\quad=\text{offset of preboundary vowel (V2Off)}\\&\qquad-\text{onset of pre-boundary vowel (V2On).}\end{aligned}\tag{4e}$$

The overall nasal amplitude contour, the nasal amplitudes at the start and end of the first nasal plateau, and the derived parameters were analyzed statistically. The purpose of the statistical analysis was to determine interactions using three-way repeated analysis, to isolate the interactions by dividing the data into subsets according to interactions, to reveal the effect of boundary on each data set, and to identify the ranking and distinction for levels of boundary. The α level was set at 0.05. The following is the rationale behind each statistical analysis.

Due to the widely reported speaker-dependent variations in previous literature, even though speaker and context were not of interest in the present study, their effects must be determined before data can be pooled across different factors for further statistical analyses. Thus, a three-way repeated MANOVA (speaker × context × boundary) was used to analyze the effect of speaker (speaker 1, 2, and 3) and contexts (Vblg, Vptk, Nblg, and Nptk) and boundaries (intonational phrase, word, and syllable) on six dependent variables, including nasal amplitudes at the offset of the second vowel, the onset of nasal airflow, the start of the first nasal plateau, the end of first nasal plateau, the offset of nasal airflow, and the onset of the third vowel. For utterances that showed a flat contour of nasal airflow, the average nasal amplitude at the offset of the second vowel and the onset of the third vowel were used to replace the values at the onset of the first nasal rise, the start of the nasal plateau during the first nasal rise, the end of the first nasal plateau, and the offset of nasal airflow. It should be noted that the repeated measurements were actually the six data points from each of the three repetitions of the nine sentences in the Nblg or Nptk contexts, and the three sentences in the Vblg or Vptk contexts.

After determining the interactions with the three-way MANOVAs, the data were further divided according to contexts, Nblg, Nptk, Vblg, and Vptk, if there was a two-way interaction between context and boundary, but no three-way interactions between speaker, context, and boundary. For parameters with significant three-way interactions between speaker, context, and boundary, the data were further divided into 12 different subsets according to the three speakers and four contexts, speaker 1 Nblg, speaker 1 Nptk, speaker 1 Vblg, speaker 1 Vptk, speaker 2 Nblg, speaker 2 Nptk, speaker 2 Vblg, speaker 2 Vptk, speaker 3 Nblg, speaker 3 Nptk, speaker 3 Vblg, and speaker 3 Vptk. After dividing the data into subsets according to interactions, one-way MANOVAs (boundary) on each of the six previously discussed subdata sets were used to explore the effect of boundary on overall nasal contours.

In addition to the overall nasal contour, the nasal amplitudes at specific points, including the start and end of the first nasal plateau (1On, 1Off), were divided into subsets according to the interactions on nasal contours, and then analyzed with one-way repeated ANOVAs (boundary) and *posthoc* Duncan tests to access the possibility of boundary distinction at particular time points.

The four parameters derived from further calculations, i.e. (4a) to (4d), were each analyzed with a three-way repeated ANOVA (speaker × context × boundary) to determine the nature of the interactions. Data for each of the four parameters showing interactions between context and boundary, but no three-way interactions between speaker, context, and boundary, were further divided into four data sets ac-

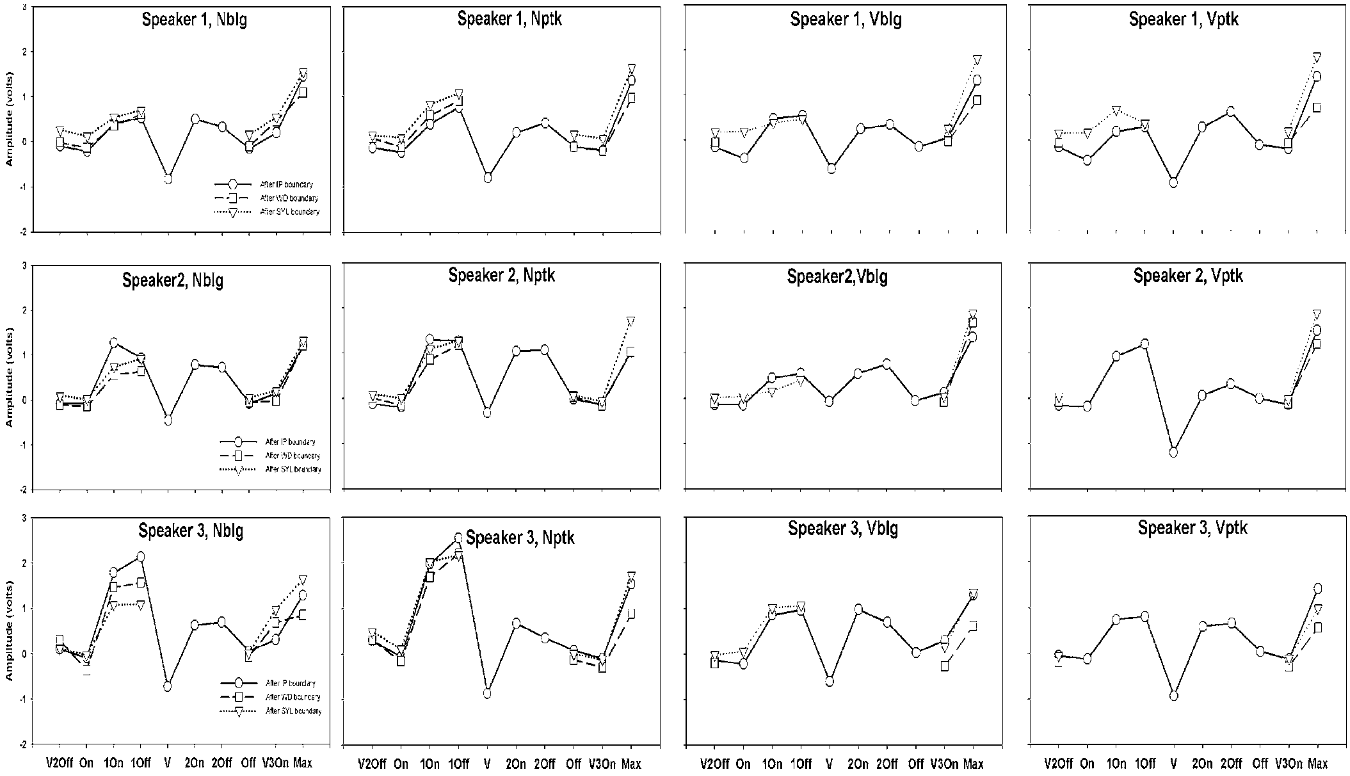

FIG. 2. Amplitudes of nasal airflow taken at ten time points through the production of target segments by three speakers at three boundaries types (intonational phrase, word, and syllable) in four segmental contexts (Nblg: final nasal followed by initial voiced stop, Nptk: final nasal followed by initial voiceless stop, Vblg: final oral vowel followed by initial voiced stop, Nptk: final nasal followed by initial voiceless stop). The points include: offset of second vowel (V2Off), onset of nasal airflow (On), start of the first nasal plateau (1On), end of the first nasal plateau (1Off), nasal inhalation (V), start of the second nasal plateau (2On), end of the second nasal plateau (2Off), offset of nasal airflow (Off), onset of the third vowel (V3On), and maximal nasal exhalation at the end of utterance (Max).

cording to contexts. The data of a parameter showing three-way interactions between speaker, context, and boundary were further divided into 12 data sets according to three speakers and four contexts. Each of these data sets was analyzed with a one-way repeated ANOVA (boundary) to access the effect of boundary. It should be noted that the repeated measurements were theoretically the 216 repetitions (3 speakers ×3 boundaries ×3 final nasals ×3 stops ×3 repetitions) in the Nblg and Nptk contexts, and the 81 repetitions (3 speakers ×3 boundaries ×1 final vowel ×3 stops ×3 repetitions) in the Vblg and Vptk contexts. However, since the first nasal rise did not appear in some repetitions in the Nblg and Nptk contexts or in most of the repetitions in the Vblg and Vptk contexts, the actual number of observations varied among the parameters. After analyzing the main effect of boundary, *posthoc* Duncan tests were performed to reveal the ranking and differences in the levels of boundary for each derived parameter.

III. RESULTS

A. Global speaking rate

This study controlled the global speaking rate by pacing the speakers' production of the first and second syllables at a speed of 144 beats per minute. To access the effectiveness of this speed-controlling method, the duration of the second vowel /a/ was compared between three speakers. The means and standard deviations of /a/ produced by speaker 1 were longer than those by speakers 2 and 3 (speaker 1: mean =159 ms, S.D. =47 ms; speaker 2: mean=148 ms, S.D. =42 ms; speaker 3: mean=146 ms, S.D. =50 ms). The results of 2-tailed *t*-tests showed that /a/ was significantly longer in productions by speaker 1 than by speaker 2 ($p<0.01$) or by speaker 3 ($p<0.01$). However, the duration of /a/ produced by speakers 2 and 3 were not significantly different from each other ($p=0.67$). Not all speakers responded to the metronome method in a similar pattern; speaker 1 exhibited a slower rate and produced longer vowels than were exhibited by speakers 2 or 3. Perceptually, speaker 1 indeed sounded slower and softer than speakers 2 and 3.

B. Nasal contour patterns and boundary types

As illustrated in Fig. 2, excluding the data from speakers 2 and 3 in the Nblg and Nptk contexts, the amplitudes of nasal airflow during the utterances were lower than the maximal nasal exhalation peak at the end of utterances (max). Therefore, speakers only used a portion of the nasal amplitude range that was available to them in most productions.

The average nasal contours across the intonational phrase boundary exhibited a first nasal rise followed by a nasal valley (inhalation) and then a second nasal rise. Across the word boundary in the Nblg and Nptk contexts, the only pattern of nasal contours observed was one nasal rise, but in the Vblg and Vptk contexts, only flat nasal contours could be

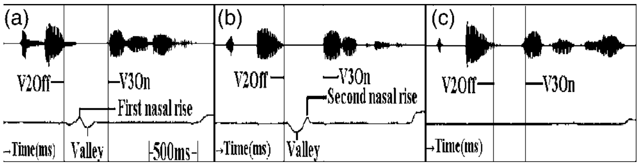

FIG. 3. Examples for nasal contours with (a) a nasal rise followed by a valley (RV); (b) a valley followed by a nasal rise (VR); and (c) no nasal rise or valley (flat). Nasal airflow is aligned with the speech signal.

observed. Nasal contours across a syllable boundary exhibited either one nasal rise or a flat nasal contour in all four contexts.

Detailed observation of the nasal contours revealed five patterns: (1) a first nasal rise followed by nasal inhalation, seen as a nasal valley with a negative nasal amplitude, and then a second nasal rise (RVR), as shown in Fig. 1(a); (2) a nasal rise (R), as shown in Fig. 1(b); (3) a nasal rise followed by a nasal inhalation (RV), as shown in Fig. 3(a); (4) a nasal inhalation followed by a nasal rise (VR), as shown in Fig. 3(b); and (5) no nasal rise or inhalation (flat), as shown in Fig. 3(c). The distribution of the five nasal patterns across speakers and boundary types is shown in Table I.

As shown in Table I, nasal inhalation could only be observed across an intonational phrase boundary when there was a pause between intonational phrase boundaries; moreover, second nasal rises were observed only across intonational phrase boundaries. Although nasal inhalation and a second nasal rise occurred only across intonational phrase boundaries, not all IPs were marked in this manner. Generally speaking, nasal inhalation occurred more often in the Nblg and Nptk contexts than in the Vblg and Vptk contexts. The frequency of nasal inhalation across intonational phrase boundaries varied from speaker to speaker. The presence of a nasal rise and nasal inhalation across an intonational phrase boundary in the Vblg and Vptk contexts where no nasal segments were present suggested that the intonational phrase boundary was a strong factor in inducing velic movements.

TABLE I. Nasal patterns categorized according to boundaries and contexts. "I," intonational phrase boundary; "W," word boundary; "S," syllable boundary; RVR, first nasal rise followed by a nasal valley (inhalation), and then a second nasal rise; RV, first nasal rise followed by a nasal valley (inhalation); VR, a nasal valley (inhalation) followed by a nasal rise; R, one nasal rise; Flat, no nasal rise or valley.

Speaker 1	Nblg			Nptk			Vblg			Vptk		
	I	**W**	**S**	**I**	**W**	**S**	**I**	**W**	**S**	**I**	**W**	**S**
RVR	17			7								
RV	1			1								
VR		1					3			3		
R	7	26	23	19	27	24	5		2	6		2
Flat			1					9	7		9	7
Speaker 2	Nblg			Nptk			Vblg			Vptk		
	I	**W**	**S**	**I**	**W**	**S**	**I**	**W**	**S**	**I**	**W**	**S**
RVR	4			3			2					
RV												
VR										1		
R	21	27	24	24	27	24	7		1	7		
Flat								9	8		9	9
Speaker 3	Nblg			Nptk			Vblg			Vptk		
	I	**W**	**S**	**I**	**W**	**S**	**I**	**W**	**S**	**I**	**W**	**S**
RVR	10			8			3			4		
RV	1			4			2			2		
VR												
R	14	25	24	15	24	24	4		2	3		
Flat		2			3			9	6		9	9

Across a word boundary in the Nblg and Nptk contexts, the pattern of nasal contours was predominantly a single nasal rise (Fig. 2). The exceptions were one utterance produced by speaker 1 with VR pattern and five utterances produced by speaker 3 with flat nasal contours. In the Vblg and Vptk contexts, the nasal contours were flat across all speakers (Table I).

Across the syllable boundary in the Nblg and Nptk contexts, the nasal patterns were one nasal rise for all, except for one production by speaker 1 in the Nblg context. In the Vblg and Vptk contexts, a flat nasal contour was the most commonly observed pattern.

In short, the existence of a strong prosodic boundary stopped nasalization from extending into the neighboring segment and so speakers produced two separate nasal contours. In contrast, when there was a weaker syllable or word boundary, nasalization extended over the boundary and so speakers were likely to produce only one nasal rise.

C. Nasal amplitude and boundary type

Nasal amplitudes taken at six points during nasal contours, including the offset of the second vowel, the onset of the nasal rise, the start of the first nasal plateau, the end of the first nasal plateau, the offset of the nasal airflow, and the onset of the third vowels, were analyzed with a three-way MANOVA (speaker × context × boundary). The results of a three-way MANOVA revealed a significant three-way interaction between speaker, context, and boundary $[F(72,3096.1)=3.53,\ p<0.0001]$. In other words, the effect of boundary on nasal amplitudes produced by the three speakers varied according to context. Thus, it was not possible to pool the data either across speakers or contexts. As a result, the data were further divided into 12 data sets according to the three speakers and four contexts.

To further determine the effect of boundary on overall nasal contours, 12 one-way repeated MANOVAs (boundary) were used to analyze the nasal contours in the Nblg, Nptk, Vblg, and Vptk contexts that were produced by all the speakers. The results of the 12 one-way repeated MANOVAs (boundary) are shown in Table II. The significant effects of boundary can be observed in the nasal contours produced by the three speakers in the four contexts. In other words, the nasal contours were influenced by the boundary types, regardless of the contexts and speakers.

In addition to the nasal contours, the nasal amplitude at specific points, including the start and the end of the first nasal plateau (1On, 1Off), were also analyzed. As the results of previous three-way repeated MANOVAs have shown three-way interactions between speakers, contexts, and boundaries, the nasal amplitudes at the start of the first nasal plateaus were divided into 12 sets according to the three

TABLE II. Results of one-way repeated MANOVAs (boundary) on nasal contours produced by three speakers in four contexts. “**” $p<0.01$.

		Nblg	Nptk	Vblg	Vptk
Speaker	1	$F(12,132)=19.35^{**}$	$F(12,140)=48.81^{**}$	$F(12,32)=8.12^{**}$	$F(12,32)=24.62^{**}$
	2	$F(12,136)=15.94^{**}$	$F(12,140)=16.03^{**}$	$F(12,38)=22.45^{**}$	$F(12,36)=11.53^{**}$
	3	$F(12,132)=16.06^{**}$	$F(12,134)=13.18^{**}$	$F(12,36)=18.93^{**}$	$F(12,38)=20.13^{**}$

speakers and four contexts, as were the nasal amplitudes at the end of the first nasal plateau. Each of the data sets was then analyzed with a one-way repeated ANOVA (boundary). The results of the one-way ANOVAs (boundary) revealed a significant effect of boundary in almost all data sets, excluding the production of speakers 2 and 3 in the Nptk context (Table III). Furthermore, the *posthoc* Duncan tests revealed no consistent cross-speaker ranking of boundary type in the Nblg and Nptk contexts (Table III). In other words, in the Nblg and Nptk contexts, the nasal amplitudes at the start and the end of the first nasal plateaus were not used to mark boundary types. However, in the Vblg and Vptk contexts there was a consistent ranking of boundary types, intonational phrase > syllable > word, on nasal amplitudes at the

TABLE III. One-way ANOVA (boundary) and *posthoc* Duncan tests on amplitudes of nasal airflow at onset (1On) and offset (1Off) of the first nasal plateau. The intonational phrase boundary is represented by “I,” the word boundary by “W,” the syllable boundary by “S.” “=” the levels of boundary were not significantly different from each other. “>” the levels of boundary were significantly different from each other. “*” $p<0.05$; “**” $p<0.01$.

			1On		1Off	
Context	Speaker	Boundary	Mean	ANOVA *posthoc* Duncan	Mean	ANOVA *posthoc* Duncan
Nblg	1	**I**	0.412	$(2,71)=4.12^{*}$	0.532	$(2,71)=3.15^{*}$
		W	0.359	S > I = W	0.616	S = W, W = I
		S	0.544		0.708	S > I
	2	**I**	1.277	$(2,73)=31.57^{**}$	0.939	$(2,73)=5.51^{**}$
		W	0.564	I > S = W	0.640	I > S = W
		S	0.737		0.919	
	3	**I**	1.790	$(2,71)=5.95^{**}$	2.142	$(2,71)=8.21^{**}$
		W	1.467	I = W, W = S	1.571	I > W = S
		S	1.081	I > S	1.094	
Nptk	1	**I**	0.393	$(2,75)=25.94^{**}$	0.771	$(2,75)=8.04^{**}$
		W	0.578	S > W > I	0.903	S > W = I
		S	0.830		1.083	
	2	**I**	1.303	$(2,75)=7.72^{**}$	1.271	$(2,75)=0.74$,
		W	0.852	I = S > W	1.178	$p=0.48$
		S	1.088		1.273	
	3	**I**	1.976	$(2,72)=1.44$	2.548	$(2,72)=2.03$
		W	1.695	$p=0.24$	2.201	$p=0.14$
		S	2.023		2.171	
Vblg	1	**I**	0.478	$(2,21)=11.02^{**}$	0.541	$(2,21)=11.20^{**}$
		W	−0.039	I = S > W	−0.039	I = S > W
		S	0.380		0.465	
	2	**I**	0.444	$(2,24)=28.47^{**}$	0.550	$(2,24)=28.11^{**}$
		W	−0.090	I > S = W	−0.090	I > S = W
		S	0.043		0.044	
	3	**I**	0.855	$(2,23)=13.37^{**}$	0.967	$(2,23)=18.79^{**}$
		W	−0.238	I > S > W	−0.238	I > S > W
		S	0.229		0.251	
Vptk	1	**I**	1.517	$(2,21)=121.88^{**}$	0.294	$(2,21)=12.48^{**}$
		W	−0.063	I > S > W	-0.063	I = S > W
		S	0.260		0.193	
	2	**I**	0.795	$(2,23)=21.35^{**}$	1.033	$(2,23)=31.46^{**}$
		W	−0.096	I > S = W	−0.096	I > S = W
		S	0.009		0.004	
	3	**I**	0.740	$(2,24)=19.93^{**}$	0.803	$(2,24)=34.67^{**}$
		W	−0.256	I > S = W	−0.256	I > S = W
		S	−0.082		−0.082	

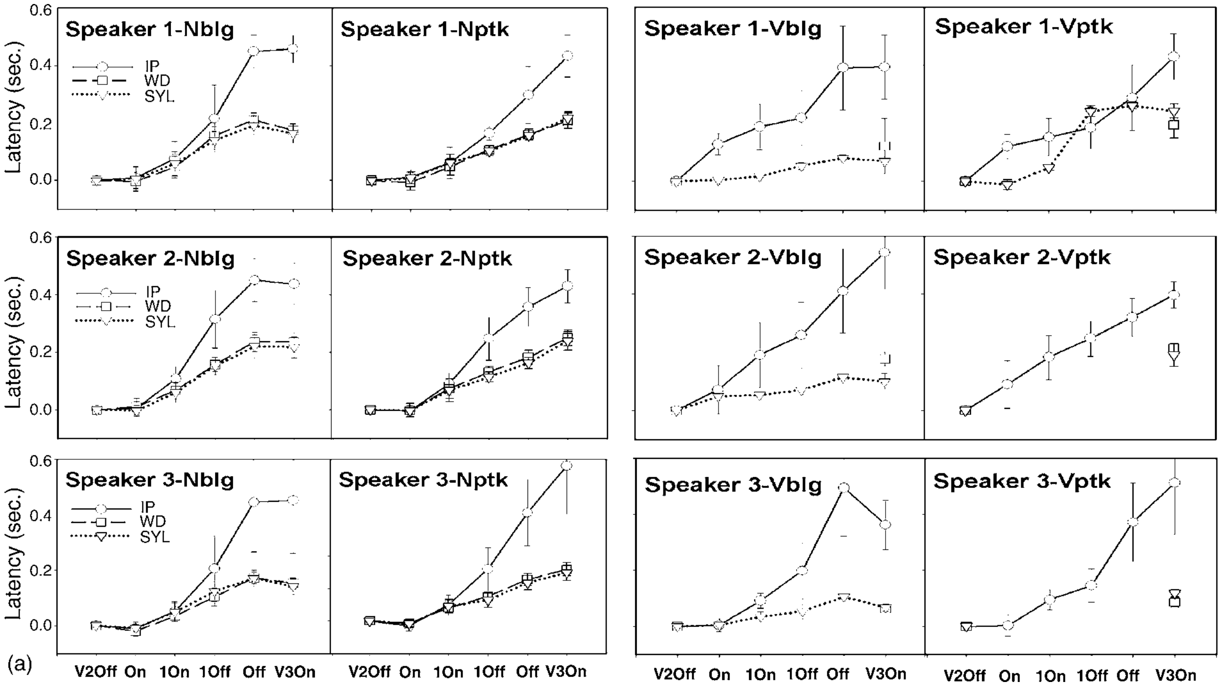

FIG. 4. Six latency measures (in seconds) of nasality taken during the production target sounds. Measures include: the end of the second vowel (V2Off), the onset of the nasal airlfow (On), start of the first nasal plateau (1On), end of the first nasal plateau (1Off), the offset of nasal airflow (Off), and the onset of the third vowel (V3On) relative to offset of the second vowel (V2Off).

start and the end of the first nasal plateau. By comparing the distribution of nasal contour patterns in Table I and the mean nasal amplitudes in Table III, it was found that this consistent ranking in the Vblg and Vptk contexts was due to the constant surface of the first nasal rise around an intonational phrase boundary which contributed to the high mean nasal amplitudes, the occasional surface of the first nasal rise at syllable boundary which led to the second highest mean nasal amplitude, and the lack of a first nasal rise at a word boundary which led to negative nasal amplitudes. In other words, speakers rarely produce a nasal rise in the Vblg and Vptk contexts. Even if they produced nasal rises, as in the Nptk and Nblg contexts, the nasal amplitudes at the start and the end of the first nasal plateau did not consistently vary with hierarchical boundary influences.

D. Temporal domain of nasal airflow and boundary type

Turning to the temporal domain of nasal airflow, as shown in Fig. 4, after the start of the first nasal plateau, as the nasal rises and valleys began to emerge, the duration of nasal airflow increased at a faster rate at the intonational phrase boundary than at other boundaries. Moreover, the duration of the nasal airflow was found to be longer at an intonational phrase boundary than at word and syllable boundaries. The temporal domain of a nasal airflow remained relatively the same at word and syllable boundaries.

As shown in Fig. 4, the duration of the first nasal plateau [R1PlDur, (4a)], between the start (1On) and end (1Off) of the first nasal rise, was shorter at word or syllable boundaries than at intonational phrase boundary. In response to the significant two-way interaction between context and boundary on the duration of the first nasal plateau revealed by a three-way repeated ANOVAs (speaker × context × boundary) (Table IV), the data were further divided into four sets according to contexts to isolate the interactions. After dividing the data, the effect of boundary on each subdata set was further analyzed through one-way ANOVAs (boundary). As shown in Table V, the results of four one-way repeated

TABLE IV. Significant interactions according to results of five three-way repeated ANOVAs (subject × context × boundary) on duration of first nasal plateau (R1PlDur), duration of nasal airflow (NasDur), duration of postboundary stop and vowel nasalization (CVNasDur), and duration of the third vowel (V3Dur). $\alpha=0.05$.

Parameters	N	Interactions	*F* value	*p* value
R1PlDur	504	Context × boundary	$F(4,476)=3.59$	$p<0.01$
		subject × context × boundary	$F(6,476)=0.38$	$p=0.89$
NasDur	514	Context × boundary	$F(4,486)=11.03$	$p<0.01$
		subject × context × boundary	$F(6,486)=1.32$	$p=0.25$
CVNasDur	515	Context × boundary	$F(4,487)=2.99$	$p<0.05$
		subject × context × boundary	$F(6,487)=1.28$	$p=0.26$
V3Dur	570	Context × boundary	$F(6,534)=5.95$	$p<0.01$
		subject × context × boundary	$F(12,534)=1.21$	$p=0.28$

TABLE V. Results of one-way repeated ANOVA (boundary) and *posthoc* Duncan tests on the duration of the first nasal plateau (R1PlDur), the nasal airflow (NasDur), the postboundary stop and vowel nasalization (CVNasDur), and the postboundary vowel (V3Dur). "I" intonational phrase boundary, "W" word boundary, "S" syllable boundary. "=" the levels of boundary were not significantly different from each other. ">" the levels of boundary were significantly different from each other "**" $p<0.001$, "*" $p<0.05$.

		R1PlDur		NasDur	
Context	Boundary	Means	ANOVA *posthoc* Duncan	Means	ANOVA *posthoc* Duncan
Nblg	**I**	0.167	$(2,221)=29.89^{**}$	0.447	$(2,222)=247.13^{**}$
	W	0.089	I>W=S	0.211	I>W=S
	S	0.084		0.196	
Nptk	**I**	0.124	$(2,228)=70.56^{**}$	0.333	$(2,228)=201.84^{**}$
	W	0.052	I>W>S	0.163	I>W=S
	S	0.035		0.147	
Vblg	**I**	0.075	$(1,26)=1.6$	0.368	$(1,29)=13.57^{**}$
	W		$p=0.217$		I>S
	S	0.026		0.084	
Vptk	**I**	0.055	$(1,19)=13.36^{**}$	0.262	$(1,25)=0.01$
	W		S>I		$p=0.917$
	S	0.195		0.272	
		CVNasDur		V3Dur	
Context	Boundary	Means	ANOVA *posthoc* Duncan	Means	ANOVA *posthoc* Duncan
Nblg	**I**	−0.001	$(2,221)=9.26^{**}$	0.144	$(2,208)=43.10^{**}$
	W	0.018	S=W>I	0.202	W>S>I
	S	0.019		0.163	
Nptk	**I**	−0.118	$(2,228)=52.03^{**}$	0.171	$(2,231)=46.68^{**}$
	W	−0.049	W=S>I	0.218	W>I>S
	S	−0.056		0.155	
Vblg	**I**	−0.084	$(1,30)=0.48$	0.160	$(2,41)=8.19^{**}$
	W		$p=0.494$	0.243	W>S=I
	S	0.021		0.175	
Vptk	**I**	−0.119	$(1,26)=7.42^{*}$	0.164	$(2,78)=20.37^{**}$
	W		S>I	0.244	W>S>I
	S	0.018		0.206	

ANOVAs (boundary) revealed a significant effect of boundary type on the duration of the first nasal plateau (R1PlDur) in the Nblg and Nptk contexts. A *posthoc* Duncan test showed the ranking for the mean duration of the first nasal plateau in the Nblg and Nptk contexts: intonational phrase > word > syllable. However, the durations of the first nasal plateau at word and syllable boundaries in the Nblg contexts were grouped together.

In the Vblg and Vptk contexts, due to the lack of a first nasal rise at the word boundary and a smaller number of tokens with a first nasal rise at the syllable boundary (Table I), there were no consistent rankings of boundary types on the duration of nasal plateau in the Vblg and Vptk contexts. In other words, only in the Nblg and Nptk contexts was the duration of the first nasal rise significantly longer at the IP than at the word and syllable boundaries.

As shown in Fig. 4, the duration of nasal airflow [NasDur (4b)], between the onset of nasal airflow (On) and the offset of nasal airflow (Off), was longer at an intonational phrase than at word and syllable boundaries. Results of three-way repeated ANOVAs (speaker × context × boundary) revealed significant two-way interactions between context and boundary affecting the duration of nasal airflow (NasDur) (Table IV). In response to this observation, the data were further divided into four sets according to contexts.

Results of the four one-way repeated ANOVAs (boundary) and the *posthoc* Duncan tests revealed significant effects of boundary on nasal airflow duration (NasDur) in the Nblg, Nptk, and Vblg contexts. There were consistent cross-boundary rankings on the mean duration of nasal airflow (NasDur), intonational phrase > word ⩾ syllable (Table V). However, the *posthoc* Duncan tests tended to group nasal duration at the word and syllable boundaries together in the Nblg and Nptk contexts. In other words, the duration of nasal airflow was longer at an intonational phrase boundary than at word and syllable boundaries.

In sum, the intonational phrase boundary was marked by the longest duration of the first nasal plateau and nasal airflow. Although the duration of the first nasal plateau and nasal airflow at a word boundary was the second longest, they were not significantly longer than the duration of the first nasal plateau and nasal airflow at a syllable boundary.

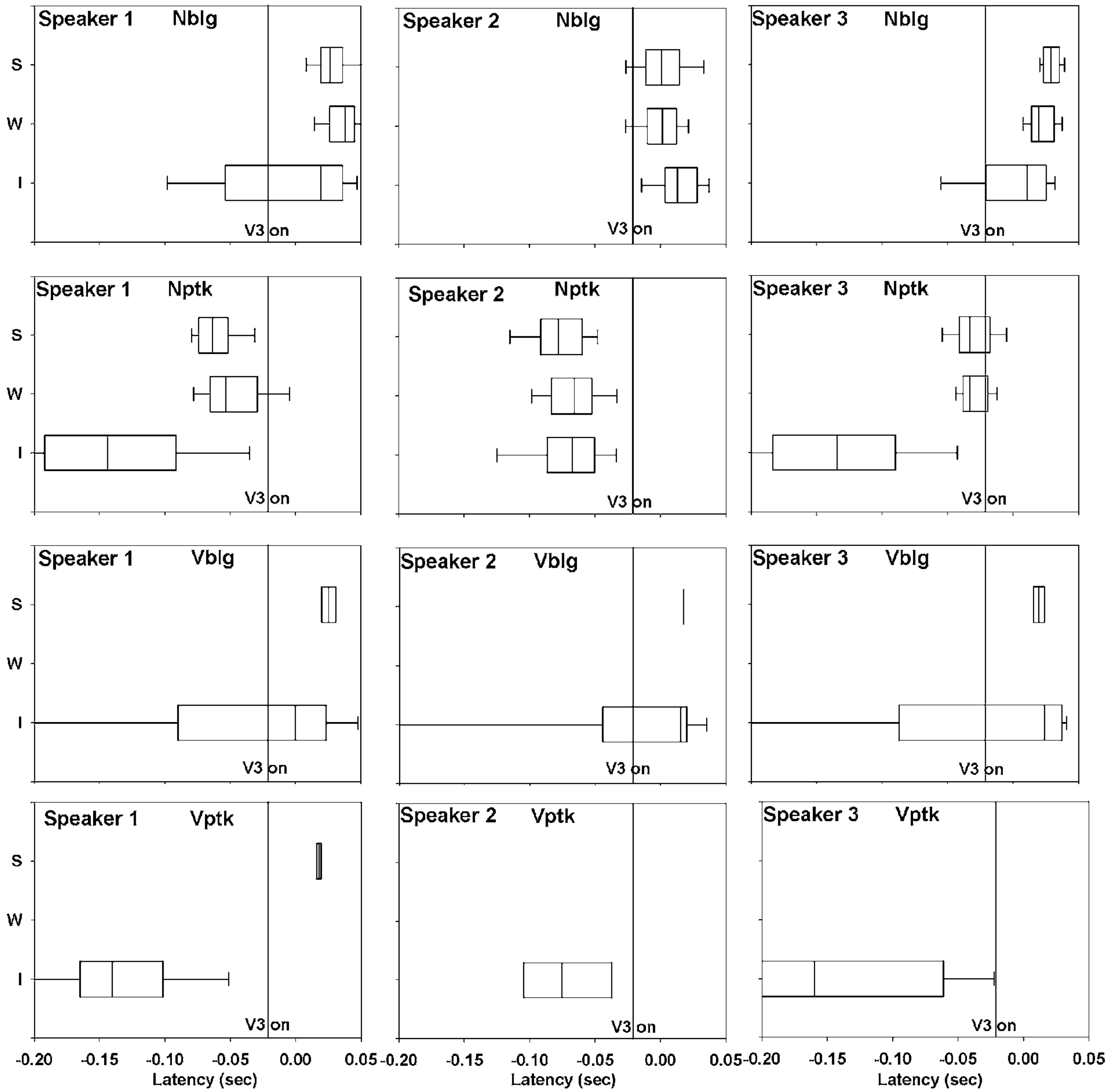

FIG. 5. Box plots for latency between the offset of nasal airflow (Off) and the onset of the third vowel (V3On) produced by three speakers, in four contexts (Nblg: the final nasal followed by the initial voiced stop, Nptk: the final nasal followed by the initial voiceless stop, Vblg: the final vowel followed by the initial voiced stop, and Vptk: the final vowel followed by the initial voiceless stop) across three boundaries (IP: intonation phrase, WD: word, and SYL: syllable boundaries). The means are indicated by the lines in the middle of the boxes, standard deviations are indicated by the frame of boxes, and the 10% and 90% data ranges are indicated by the whiskers.

E. Postboundary initial stop and vowel nasalization

Turning to the duration of the postboundary stop and vowel nasalization (CVNasDur), which was determined by the offset of nasal airflow relative to the onset of the postboundary vowel, it can be seen in Fig. 5 that there was a trend for nasal airflow to cease before the onset of the postboundary vowel in the Nptk and Vptk contexts, but after the onset of the postboundary vowel in the Nblg and Vblg contexts. In addition, boundary type also played a role in the extent of nasalization. Cross-boundary nasalization in these former two contexts was blocked earlier relative to the onset of the third vowel when there was an intonational phrase boundary. In other words, nasalization carried over from one word to the next in the Nblg and Vblg contexts as long as there was no intervening intonational phrase boundary. There were no data at word and syllable boundaries in the Vblg and Vptk contexts, as shown in Fig. 5. This was because the nasal contour remained flat in these conditions, as shown in Table I; therefore no nasalization was observed.

Due to a significant two-way interaction between context and boundary on duration of nasalization for initial stops and the vowel in the postboundary position (Table IV), the data were further divided into four sets according to contexts. The results of the one-way repeated ANOVAs (boundary) show a significant effect of boundary in the Nblg, Nptk, and Vptk contexts. The only consistent ranking observed was that the nasalization was shortest when an intonational phrase boundary separated words (Table V).

To sum up, as shown in Fig. 5, in the Vptk context there was no nasalization. In the Vblg context, the nasality terminated after the IP boundary. In the Nptk context, the nasality was terminated before or during postboundary initial voiceless stops. In the Nblg context, the nasalization process spread from the final nasal across the boundary into the postboundary initial voiced stop and vowel. Moreover, the nasal airflow was terminated earlier across an IP boundary than across other boundaries.

F. Vowel length

The results of a three-way repeated ANOVAs (speaker × context × boundary) found that there was a significant two-way interaction between context and boundary on the length of the postboundary vowel /a/ [V3Dur (4d)] (Table IV). Therefore, the durations of the third vowel /a/ were divided according to context: Nblg, Nptk, Vblg, and Vptk. The results of the four one-way repeated ANOVAs (boundary) and the Duncan tests revealed that the duration of the postboundary vowel was consistently the longest after a word boundary in all contexts (Table V). In other words, the longest postboundary vowel duration was observed after word boundary.

IV. DISCUSSION

A. Nasality and boundary type

This study addresses two research questions, namely (1) the effect of boundary on nasality, and (2) the effect of boundary on cross-boundary nasalization. The effect of boundary on nasality was revealed through patterns of nasal contours, the duration of the first nasal plateau, the duration of nasal airflow, and the measurement of nasal temporal latency and nasal amplitudes at the onset of nasal airflow, the start and the end of the first nasal plateau, and the offset of nasal airflow. The effect of boundary on nasalization was revealed by the duration of nasalization on initial stop and following vowel combinations in postboundary syllables.

It was found that boundary influences the pattern of nasal contour. For example, nasal patterns with a first nasal rise followed by a nasal inhalation and a second nasal rise can only be observed at an intonational phrase boundary, whereas nasal contours with one nasal rise were observed at word and syllable boundaries in the Nblg and Nptk contexts. Flat nasal contours were found at word and syllable boundaries in the Vblg and Vptk contexts.

In order to capture the differences in patterns of nasal contour, various measures, including (1) magnitude differences and (2) temporal aspects of nasal airflow, were investigated. Although there were significant effects of boundary on overall nasal contours, neither the nasal amplitudes at the start (1On) or the nasal amplitudes at the end (1Off) of the first nasal rise varied consistently according to boundary type in the Nblg and Nptk contexts. Regardless of the lack of a consistent pattern in the magnitude of nasal airflow, the duration of the first nasal plateau (NasPlDur) and nasal duration (NasDur) varied consistently according to boundary type in the Nblg and Nptk contexts: intonational phrase > word ⩾ syllable. It was observed that the stronger the prosodic boundary, the longer was the nasal duration and the duration of the first nasal plateau in both the Nptk and Nblg contexts. It should be noted that the durations of the first nasal plateau and nasal airflow at word and syllable boundary tend to be grouped together in the current study. It is actually a common finding in articulatory prosody studies that word and syllable boundaries are not distinguished. Future studies are necessary to further explore this issue.

With reference to the first research question identified earlier regarding the influence of prosodic boundary on nasality, it can be said that although there were no consistent patterns in the magnitude of nasalization at the onset and offset of the first nasal plateau, due to the different amplitude ranges used by different speakers, each speaker realized boundary strength differences in the same direction (Fig. 2). In addition, there was an effect of boundary strength on the overall nasal trace for individual speakers (Table II). Moreover, there were consistent patterns in the temporal domain that varied in relation to boundary type. These included the duration of nasal airflow and duration of the first nasal plateau.

Taiwanese is not the only language where prosodic influences on articulation are more prominent on temporal patterns than on spatial magnitude patterns. For example, Byrd *et al.* (2000) in a study of the jaw, lip, and lingual movements of [n#m] and [m#n] across the word and phrasal boundaries in Tamil, discovered little effect of phrasal position on the spatial domain, but did find a significant effect of phrasal position on timing and duration. In the current study boundaries influence the pattern of nasal contour and nasal temporal, but not nasal magnitude, parameters in Taiwanese.

The lack of consistent variations in nasal magnitudes at the onset and offset of the nasal plateau across speakers may be random variability, due to the fact that once the velopharyngeal port is open, it is difficult to control airflow magnitude in a sufficiently variable manner, especially if respiratory effort remains fairly constant. Thus, nasal magnitudes do not vary according to boundary type. Alternatively, it is suggested that there may be several patterns of boundary effects on nasal magnitudes that speakers can choose from; thus, no consistent rankings of boundary type can be observed. To fully reveal the patterns of nasal magnitudes that speakers can use, in further prosodic articulatory studies, more subjects are needed in order to find out how many patterns of variations actually exist.

Although the results of this study indicate that nasal magnitude does not vary according to boundary type in the Nblg and Nptk contexts, the variation in the duration of nasal airflow in relation to hierarchical boundary strength suggests that speakers may use temporal cues to signal boundary types. In fact, a study which did not use speech signals as stimuli found that for two tones played with the same frequency but with differing lengths, the thresholds for longer signals were lower in dB than for short signals (Watson and Gengel, 1969; Yost, 2000). In other words, the longer signals required less intensity to be perceived, whereas the shorter signals required higher intensity. Thus, the duration of a sound can influence its perceptibility. Furthermore, Ha *et al.* (2004) found that the mildly hypernasal speech of children with a cleft palate showed longer temporal characteristics of a nasal onset interval, nasal offset interval, and total nasalization duration, than did children of the same age without cleft palates. In other words, the longer nasal temporal characteristics may contribute to the perception of hypernasality. This evidence suggests that nasal duration affects the degree of perceived nasality. Further perceptual studies are necessary to explore the relationship between nasal duration and nasality as perceived at different boundary types.

B. Cross-boundary nasalization and boundary type

With reference to the second research question regarding the effect of boundary on cross-boundary nasalization, this study has found that cross-boundary nasalization terminates earlier when it occurs across an intonational phrase boundary. This pattern supports Cho's hypothesis (2004) which states that the stronger the prosodic boundary, the more resistance there is to cross-boundary coarticulation. Furthermore, as articulatory gestures become more canonical, as when around a stronger boundary, the gesture is less likely to coarticulate with the neighboring segments. Both the hierarchical influence of boundary on domain-edge strengthening and the effect of intervening boundary on cross-boundary coarticulation find support in this paper.

When considering context, it was found that nasal airflow ceases before the end of words closed with a voiceless stop (Nptk context), but continues after a word boundary in words closed with a voiced stop (Nblg context). In other words, nasalization can cross over voiced consonants. It is proposed that there are speech aerodynamic reasons behind the different nasalization patterns observed in Nptk and Nblg contexts. First, from the point of building up intraoral air pressure, complete vocal-tract closure involving the oral cavity and the velopharyngeal port is necessary for voiceless stops to develop and maintain the required intraoral air pressure between the oral cavity and the atmosphere. Second, in reference to the maintenance of voicing, the opening of the velopharyngeal port during the production of voiced stops helps to release the supralaryngeal pressure, which must be lower than the sublaryngeal pressure, in order for pulmonic air to flow through the glottis and to cause the vocal folds to vibrate (Ohala and Riodan 1979). Thus, for aerodynamic reasons, the closure of the velopharyngeal port leads to the cessation of nasality during voiceless stops, and the opening of the velopharyngeal port leads to nasalization during voiced stops.

C. Idiosyncratic and gradient hierarchical boundary markers

In addition to the prosodic and hierarchical influence of boundaries on patterns of nasal contours and nasal temporal parameters [i.e., duration of the first nasal plateau (R1PlDur) and duration of the nasal airflow (NasDur)], there are acoustic markers uniquely associated with each boundary type that facilitate boundary identification. For example, an intonational phrase boundary can be marked by nasal inhalation and a second nasal rise, the longest duration of a first nasal plateau and duration of nasal airflow, or the shortest duration of postboundary stops and vowel nasalization (CVNasDur), whereas a syllable boundary is marked by the shortest duration of nasal temporal parameters, such as duration of the first nasal plateau and duration of nasal airflow. As for a word boundary, it is marked by the longest duration of the postboundary vowel (V3Dur). In fact, this same effect was also discovered in Pan's (in press) study on the initial lexical tone after a word boundary. As there are two types of word boundaries in Taiwanese, it is proposed that the longest postboundary vowel duration marks a word boundary that does not coincide with a tone group boundary, whereas the surface of juncture tone in a preboundary vowel marks a word boundary that coincides with a tone group boundary. Future studies are necessary to further explore this issue.

Not all articulatory or acoustical cues contribute equally to perception. Wightman *et al.* (1992) in a perceptual study of the boundary effect on final lengthening found that the lengthening of the rhyme of the syllables preceding boundaries can be used perceptually to distinguish at least four types of boundaries. They asked subjects to assign seven levels of break indices to a read speech corpus. The results showed that different boundaries were distinguished by different sets of durational cues including the coda consonants, the vowel nucleus, all segments between the final stressed vowel and the final vowel, and the final stressed vowel of preboundary syllables. Moreover, the perception of certain boundaries relied more on the duration of coda consonants and vowel nuclei, whereas the perception of other boundary types relied more on the duration of the final stressed vowels. In the present study, different types of boundaries have been distinguished hierarchically not only by nasal temporal cues, but also by unique phonetic markers, such as patterns of the nasal contour and the duration of the postboundary vowel.

From a perceptual point of view, further perceptual experiments which analyze the perceptual salience of patterns of nasal contour, hierarchical nasal temporal cues, and idiosyncratic boundary markers can shed light on cues that listeners use to distinguish boundary types. As the influence of language-specific phonemic categorization has been demonstrated to influence the perception of nasality and cross-boundary nasalization (Beddor and Strange, 1982; Beddor and Krakow, 1999), it is necessary to conduct cross-linguistic perceptual studies to enhance our understanding of domain-edge nasality strengthening and cross-boundary nasalization.

V. CONCLUSIONS

The present study reveals how boundary type influences the pattern of nasal contours and the temporal aspects of both acoustic and nasal airflow data in Taiwanese. In addition to the hierarchical ranking of boundary type on nasal temporal parameters, each boundary type is associated with specific phonetic markings that facilitate the identification of boundary. Finally, with a view to future work in this area, it would be interesting to expand the scope of prosodic articulatory studies on nasality into the area of speech pathology and to explore the effect of boundary on nasality and nasalization produced by subjects who exhibit hypernasal speech.

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