Nasality in Taiwanese

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Key words

airflow

nasal

perception

Taiwanese

voiced stops

Abstract

This study used perceptual and articulatory data to investigate a language specific phonemic inventory, and allophonic rules for homorganic initial voiced stops versus homorganic nasal stops, and oral versus nasal vowels in Taiwanese. Four experiments were conducted: concept formation, gating, and two airflow studies. Results of a first nasal airflow study on syllable initial voiced stops and nasal stops showed that initial voiced stops were nasalized when preceded by a nasal consonant across a word boundary. Results of a concept formation experiment indicated that Taiwanese listeners grouped homorganic voiced stops and nasal stops into the same category. A gating experiment showed that subjects were insensitive to the phonetic differences between homorganic voiced stops and nasal stops. The presence or absence of nasality within the vowel nucleus was the crucial cue to the identification of oral and nasal syllables. A second nasal airflow study on vowel nuclei demonstrated that oral vowels were nasalized at their onset and offset when preceded or followed by a nasal consonant respectively. The distinction between oral and nasal vowels was maintained at the center of the vowel nuclei. By classifying homorganic initial voiced stops and nasal stops into the same category, Taiwanese speakers were able to ignore the phonetic difference between them and relied on the distinction between nasal vowel versus oral and nasalized vowel to distinguish between nasal versus oral syllables. Taiwanese speakers produced a clear distinction between oral and nasal vowels to retain the crucial role that oral versus nasal contrasts on vowel nuclei played during perception experiments. This study offers phonetic evidence to answer the controversial nasality issue in Taiwanese. Furthermore, a link was found between perception and extent of application of allophonic rules during production.

1 Nasality in Taiwanese

Languages differ in terms of phonemic inventories, allophonic rules and phonotactic constraints. Linguistic influence that speakers and listeners experience from different native phonological systems leads them to perceive the same contrast differently. The role that linguistic experience plays in shaping speech perception has been demonstrated in infant developmental study (Best, McRoberts, & Sithole, 1988;

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Eilers, Gavin, & Oller, 1979; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Werker & Lalonde, 1988; Werker & Tees, 1984) and in cross language research on adults (Best & Strange, 1992; Cutler et al., 1986; Flege & Hillenbrand, 1986; MacKain, Best, & Strange, 1981; Otake & Cutler, 1999; Tees & Werker, 1984; Underbakke, Polka, & Strange, 1988).

Relevant to phonemic inventory, Beddor, & Strange (1982) demonstrated the influence of phonemic categorization on speech perception. In their cross-language study on adult English and Hindi native speakers, a significant effect of native phonemic inventory was observed on the perception of /b/–/m/ and oral vs. nasal vowels. It was shown that both Hindi and English speakers performed equivalently on consonant contrast in /ba–ma/, since /b/ and /m/ are contrastive phonemes in both languages. However, the vowel contrast in /ba–bã/ was perceived categorically by Hindi speakers, but more continuously by English speakers. The performance difference was attributed to the fact that in Hindi oral vowels and nasal vowels belong to different phonemic categories, but in English nasal vowels are allophones of phonemic oral vowel categories. The responses from the two groups reflected the different phonemic inventories in Hindi and English.

Relevant to language specific allophonic rules, perception of phonetic contrasts further revealed the attunement of selective perception by adult monolinguals (Best & Strange, 1992). Beddor and Krakow (1999) reported a systematic difference in native Thai and English speakers' responses to nasal vowels in nasal consonant contexts. In their study, Thai listeners attributed less nasality on vowels in NṼN syllables to the coarticulatory context than did English speakers. Again the performance difference was attributed to the fact that in English contextual nasalization is a more robust allophonic rule than in Thai. Moreover, this study demonstrated the correspondence between nasalization and its perception.

In addition to observing the relationship between language specific phoneme inventories and the perception of oral and nasal contrasts, the present study incorporates the issue of phonotactic constraints and uses acoustical and articulatory data to resolve a phonologically controversial issue about the phonemic inventory and allophonic rules in Taiwanese homorganic initial voiced stops and nasal stops.

1.1
Taiwanese initial stop / nasal and oral / nasal vowel nuclei

Taiwanese, one variety of the Southern Min language, spoken by around 70% of people in Taiwan, has a mixture of various Southern Min accents brought over hundreds of years ago by immigrants from Fukien, China. Taiwanese was also influenced by Austronesian, Mandarin, Hakka, Japanese, and even some European languages during different settlements. Due to the language policy enforced at schools, though some elders are literate in Taiwanese, younger generations only use Taiwanese in its spoken form and are illiterate in Taiwanese.

There are four types of syllable structures: V, CV, CVN, and CVC in Taiwanese. According to syllable constraints, in CVN syllables, only three nasal stops are allowed in final position, /m, n, ŋ /. Furthermore, nasal vowels are not allowed in CVN syllables. In CVC syllables, only four voiceless unreleased stops are allowed in final position: /p, t, k, ʔ/. In syllable initial position, homorganic initial voiced stops and nasal stops are in complementary distribution, that is, syllable initial voiced stops are followed by oral vowels (e.g., /bi/ 'smell') while syllable initial nasal stops are followed by nasal vowels (e.g., /mĩ/ 'noodle'). There are phonotactic gaps in syllable structure that occur mainly between oral versus nasal syllables, as shown in Table 1. There are six oral monophthongs, /a, o, ɔ, e, i, u/, four nasal monophthongs, /ĩ, ẽ, ã, ɔ̃/, eight oral diphthongs, /ai, au, ia, io (iɔ), iu, ua, ue, ui/, six nasal diphthongs, /ãĩ, ãũ, ĩã, ĩũ, ũã, ũĩ/, two oral triphthongs, /iau, uai/, and two nasal triphthongs, /ũãĩ, ĩãũ/. Among the 16 Taiwanese consonants, there are two fricatives, /s, z, h/, two affricates, /ts, ts^h/, three voiceless unaspirated stops, /p, t, k/, three voiceless aspirated stops, /p^h, t^h, k^h/, three nasal stops, /m, n, ŋ /, and two voiced stops /b, g/. The lateral /l/ is considered to be a voiced stop due to its stop-like quality (Zhang, 1989). Preliminary EPG data of /l/ showed that speakers produced /l/ with an alveolar closure and with either a lateral or central release. According to Zhang (1989), Taiwanese voiced stops, /b, l, g/, are 'prenasalized' and the prenasalization is voiceless, that is, [ᵐ̥b, ⁿ̥l, ᵑ̥g]. However, results of nasal airflow studies showed that prenasalization occurs in an inconsistent pattern in citation form, while some speakers prenasalize syllable initial voiced stops more often, others never prenasalize any of the syllable initial voiced stops (Pan, 1994). In word or phrase medial position, syllable initial voiced stops were consistently not prenasalized (Pan, 1994). It was proposed that the prenasalization was not an essential characteristic of syllable initial voiced stops in Taiwanese, but a facilitating strategy used by some subjects to release the air pressure built up in the oral cavity allowing them to sustain voicing. Given these results, no consistent pattern was observed (Hsu & Jun, 1996).

Due to complementary distribution between homorganic initial voiced stops and nasal stops, the phonemic status of Taiwanese initial voiced stops and nasal stops has been a much debated phonological issue with a long history (Bao, 1990; Chung, 1996; Li, 1990; Lin, 1989; Tung, 1968, 1988, 1990; Wang, 1995, 1999b). While some studies (Tung, 1968; Zhang, 1989) claimed an allophonic relationship between homorganic initial voiced stops, [b, l, g], and initial nasal consonants, [m, n, ŋ], based on their complementary distribution, that is, initial voiced stops are followed by oral vowels while nasal consonants are followed by a nasal vowel, for example, [bi˧˩] 'rice' versus production of [mĩ˧˩] 'things', other studies supported a phonemic relationship and transcribed homorganic voiced stops and nasal stops with different symbols, for example, /m/ as a phoneme, and /b/ as a different phoneme (Cheng & Cheng, 1987; Ding, 1985; Wu, 1987). Moreover, in studies that proposed homorganic voiced stops and nasal stops as belonging to two different phonemic categories, their complementary distribution pattern was viewed as an accidental gap in phonotactic constraints. Unlike some allophones that also possessed a morphological relationship between each other, such as the alternation between final voiced and voiceless stops in plural and singular forms in German, no morphological evidence was observed between morphemes with homorganic initial voiced stops and nasal stops in Taiwanese.

So far, the debate of phonemic status between homorganic initial voiced stops and nasal stops has been approached only from traditional phonological perspectives relying on data such as field transcription and informant intuition without consulting

TABLE 1

Phonotactic gap between initial consonants and vowel nuclei in Taiwanese syllables. A slash '/' means the initial consonant is not followed by a vowel nuclei. An empty space means such segment combinations exist in Taiwanese

Initial Consonants	i	u	a	o	e	ɔ	ĩ	ã	ẽ	ɔ̃	ia	ua	io	ue
b							/	/	/	/	/			
l							/	/	/	/				
g							/	/	/	/				
m	/	/	/	/	/	/					/	/	/	/
n	/	/	/	/	/	/					/	/	/	/
ŋ	/	/	/	/	/	/					/	/	/	/
p						/								
t						/								
k														
pʰ						/								
tʰ						/								
kʰ						/								
ts				/		/								
tsʰ				/		/								
s						/								
z			/	/	/	/	/	/	/	/				
h					/									

Initial Consonants	ui	iu	ai	au	ĩã	ũã	ĩũ	ũĩ	ãĩ	ãũ	uai	iau	ũãĩ	ĩãũ
b		/			/	/	/	/	/	/			/	/
l					/	/	/	/	/	/	/		/	/
g	/			/	/	/	/	/	/	/	/		/	/
m	/	/	/	/			/				/	/		
n	/	/	/	/							/	/	/	
ŋ	/	/	/	/		/					/	/	/	
p											/			/
t											/			/
k														/
pʰ											/			/
tʰ											/			/
kʰ														/
ts														/
tsʰ											/			/
s											/			/
z	/		/	/	/	/	/		/		/	/	/	/
h														/

phonetic evidence. Following the tradition of using phonetic data to investigate nasal features (Huffman, 1993), both articulatory and perceptual data were obtained in the present study to approach these issues from a different perspective.

There were four aims of this study. First was to investigate the possibility of variation between initial voiced stops and nasal stops with respect to the preceding segment, and thus test the validity of complementary distribution previously described in phonological studies. If voiced stops are found to change into nasal stops when preceded by a nasal, then the complementary distribution as described in phonological studies is inaccurate. Second was to collect psycholinguistic evidence to resolve the controversy of the phonemic status of voiced stops and nasal stops. Third was to explore the perceptual cues that subjects used to recognize an oral versus nasal syllable. This was done by monitoring subjects' responses to homorganic voiced stop and nasal contrasts, and nasal versus oral vowel contrasts. Fourth was to support perceptual results with production data by investigating the application of a vowel nasalization rule in a C̃_N context.

To address each one of the questions above, different experimental paradigms were used. Due to the claim that Taiwanese voiced stops are prenasalized and this prenasalization is voiceless (Zhang, 1989), direct recording of nasal leakage captures the extent of nasality better than acoustic data. To investigate the alternation between homorganic initial voiced stops and nasal stops with respect to the preceding context across a word boundary, articulatory nasal airflow of initial voiced stops and nasal stops preceded by oral and nasal segments across a word boundary was studied.

To investigate the phonemic status between homorganic voiced stops and nasal stops, a concept formation experimental paradigm was used (Jaeger, 1986). A concept formation experimental paradigm is a psychological method used to test categorical linguistic phenomena. During a concept formation experiment, a subject's ability to form a particular category is taken as evidence for the pre-existence of that category in the subject's perception. In this study, a concept formation experimental paradigm was used to explore the psychological status of phonemic categories for homorganic initial voiced stops and nasal stops, and the internal composition of these phonemic categories. The ease with which a category is formed and the way subjects include new stimuli into a category reveals not only the phonemic category but also the allophones in that category.

To determine the perceptual cues used by subjects to distinguish oral versus nasal syllables, subjects' sensitivity to the phonetic difference between initial voiced stops and nasal stops, and between nasal versus oral vowels was investigated using a gating experimental paradigm.

To further support the perceptual results, the extent that nasalization spread from the final nasal consonant to the vowel nuclei within a C̃__N syllable was also investigated. The extent of vowel nasalization should converge with the role that presence and absence of nasality on vowel nuclei play during perception of oral and nasal syllables.

2 Nasal airflow study of nasalization across a syllable and a word boundary

The first nasal airflow study was used to investigate whether the alternation between homorganic initial voiced stops and nasal stops actually agreed with the description of traditional phonological studies. According to previous research, homorganic voiced stops are followed by oral vowels, while homorganic nasal consonants are followed by nasalized vowels in tautosyllabic contexts. Airflow study analysis explores the alternation between homorganic initial voiced stops and nasal consonants with respect to the preceding nasal context across a syllable boundary.

2.1 Method

Subjects. Three female native Taiwanese speakers, JC, HP, and DL, participated in the experiment. They were either students or staff at the National Chiao Tung University at the time of recording. All subjects spoke Mandarin and English in addition to Taiwanese.

Corpus. An example of the corpus is shown in Table 2. There were 29 disyllabic phrases with three voiced stops, /b, l, g/, two nasal stops, /m, n/, and three voiceless unaspirated stops, /p, t, k/, in initial position of a second syllable preceded by either a final nasal consonant or oral vowel in the first syllable, N#__ and V#__. According to phonotactic constraints shown in Table 1, the three voiced stops, [b, l, g], were placed in two tautosyllabic contexts, +__VN, and +__V; the nasal stops, [m, n], were placed in one tautosyllabic context, +__V; and the three voiceless unaspirated stops were placed in tautosyllabic contexts, +__Ṽ, +__VN, +__V. By matching the three tautosyllabic contexts, +__Ṽ, +__VN, +__V, with the two contexts across word boundaries, V#__ and N#__, there were four different contexts that the three initial voiced stops were produced in (N#__VN, N#__V, V#__VN, and V#__V); one context that the two nasal stops were produced in (V#__ Ṽ); and six different contexts that the three initial voiceless stops were produced in (V+__Ṽ, N+__VN, N+__V, V+/#__VN, and V+__V). Other than one lexical item, /a˥ kɔŋ˥/ 'grandfather' with a voiceless stop in the V+/#__VN context with a syllabic boundary between first and second syllable context, all the other lexical items were designed with a word boundary between the first and second syllable. Each disyllabic phrase was repeated three times, and so 87 tokens, [(3 voiced stops × 4 contexts) + (2 nasal stops × 1 context) + (3 voiceless stops × 5 contexts)] × 3 repetitions, were produced by each subject.

Instruments. A SONY ECM-144 microphone clipped on the subject's collar was used to record acoustical signals which were then relayed to a SONY WM-D6C professional walkman. A nasal airflow mask (model P0789 manufactured by Hans Dudolph Inc.) connected to a (model PTL-1 manufactured by glottal Enterprise) airflow system (model MS-100 by Glottal Enterprise) was used to pick up nasal airflow. Both the acoustical signals from the walkman and airflow signals from the airflow system were simultaneously captured by CspeechSP software and recorded onto a PC.

TABLE 2

A portion of the corpus used in the nasal airflow study on initial voiced stops and vowel nuclei (gray background). V: oral vowel, Ṽ: nasal vowel, C: voiced stop /b, l, g/, C̥: voiceless stop /p, t, k/, C̃: nasalized voiced stop /b, l, g/, N: nasal /m, n/

<table>
<tr><td colspan="3" rowspan="2"></td><td colspan="2">Heterosyllabic Context: Across a Word/Syllable Boundary</td></tr>
<tr><td>N#</td><td>V+/#</td></tr>
<tr><td rowspan="12">Tautosyllabic Context: Within a Word/Syllable</td><td rowspan="4">Nasal Vowel</td><td rowspan="2">+NṼ</td><td></td><td>V#<u>N</u>Ṽ</td></tr>
<tr><td></td><td>/ bo ˨˦ mɔ̃ ˥ /‘no fur’</td></tr>
<tr><td rowspan="2">+C̥Ṽ</td><td></td><td>V#C̥Ṽ</td></tr>
<tr><td></td><td>/gɔ ˧ pũã ˨˦/ ‘five plates’</td></tr>
<tr><td rowspan="8">Oral Vowel</td><td rowspan="2">+CVN</td><td>N#<u>C̃</u>VN</td><td>V#<u>C</u>VN</td></tr>
<tr><td>/kin ˥˧ bɔŋ ˥ /‘quickly touch’</td><td>/bo ˨˦ bɔŋ ˥ /‘didn’t touch’</td></tr>
<tr><td rowspan="2">+CV</td><td>N#<u>C̃</u>V</td><td>V# <u>C</u>V</td></tr>
<tr><td>/kim ˥ bɔ ˧ /‘golden hat’</td><td>/tsau ˥˧ bɔ ˧ / ‘straw hat’</td></tr>
<tr><td rowspan="2">+C̥VN</td><td>N#C̥VN</td><td>V+/#C̥VN</td></tr>
<tr><td>/hiaŋ ˨˩ tɔŋ ˥ / ‘face east’</td><td>/tʃiu ˥ tɔŋ ˥ / ‘fall, winter’</td></tr>
<tr><td rowspan="2">+C̥V</td><td>N#C̥V</td><td>V#C̥V</td></tr>
<tr><td>/san ˥˧ pɔ ˨˦ /‘midwife’</td><td>/lau ˧ pɔ ˨˦ / ‘old woman’</td></tr>
</table>

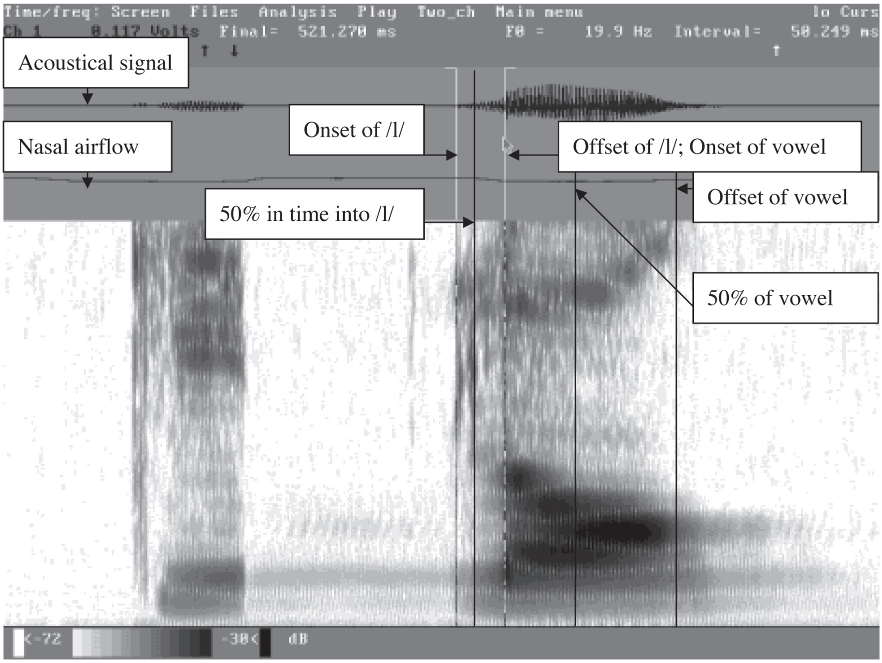
Experimental procedure. The recordings were conducted in the phonetics lab at the National Chiao Tung University. Subjects were asked to hold the nasal airflow mask in their hand and wait for the experimenter’s signal. When the experimenter signaled the start of recording, by saying “please,” subjects placed the mask over their face covering their nose and then read a disyllabic phrase from the corpus list. Subjects paused after each disyllabic phrase to allow the experimenter to save the acoustical and airflow signals. After saving the signals onto the PC, the experimenter started the recording function again and gave subjects a signal to repeat the procedure.

Data analysis. Digitized airflow and acoustic data were analyzed using CspeechSP. Spectrograms were generated from the acoustical data aligned in time with the trace of nasal airflow. Using spectrographic cues, the times at the onset and offset of initial voiced stops, nasal stops, and voiceless stops were determined. The duration of initial consonants and the amplitude of nasal airflow at onset, offset, and the 25%, 50%, and 75% time intervals of initial voiced stops, nasal stops, and voiceless stops were taken, as shown in Figure 1.

Nasal airflow of initial voiced stops (C) preceded by oral vowels across word boundary, V# __V, and V#__VN, abbreviated as V#CV(N), were pooled together, as

Figure 1

Measurement points of nasal airflow for initial stops and vowel nucleus of /kiŋ ˥˧ lɔŋ˥/ ‘quickly goes through an enclosed space’



were the amplitude of nasal airflow for initial voiced stops (C) in N#__V, and N#__VN contexts, abbreviated as N#CV(N), the amplitude of nasal airflow for initial nasals (N) across V#__Ṽcontext, and the amplitude of nasal airflow for voiceless stops (C̥) across V#__V and V#__VN contexts, abbreviated as V#C̥V(N), or across N#__V and N#__VN contexts, abbreviated as N#C̥V(N). Duration of initial voiced stops (C) in the V#__V(N) context were pooled together, as were the duration of voiced stops (C) in the N#__V(N) context, and the duration of voiceless stops (C̥) in the V#__V(N) context.

Two one-way ANOVA’s with subject as the independent factor were used to analyze the amplitude of nasal airflow for initial stops and duration of initial stops. One-way ANOVA’s with context, N#CV(N), V#CV(N), V#NṼ, V#C̥V(N), N#C̥V(N), as the independent factor were used to analyze the duration and average airflow at 25%, 50%, and 75% intervals during initial voiced stops and voiceless stops, and nasal stops.

2.2
Results

Results of a one-way ANOVA (subject) showed that the duration of initial stops produced by three subjects were significantly different from each other, $F(2,226)$

$= 3.27$, $p < .05$. Therefore the duration of initial stops in the same context was not averaged across the three subjects, instead separate ANOVA's (context) were used to analyze the duration of initial voiced stops produced by each subject. Altogether, there were three ANOVA's (context). Results of the ANOVA's (context) showed that the duration of initial stops in N#CV(N), V#CV(N), V#NṼ, V#C̥V(N) and N#C̥V(N) contexts produced by JC, $F(4, 72) = 1.03$, $p = .397$, and HP, $F(4, 69) = 2.0$, $p = .1$, were not significantly different from each other. The duration of voiced stops, nasal stops, and voiceless stops were comparable to each other. However, for subject DL, the duration of voiced stops (C), nasal stops (N), and voiceless stops (C̥) were significantly different from each other, $F(4, 73) = 5.05$, $p < .01$. Results of a post hoc Tukey test ($\alpha = 0.05$) showed that, for subject DL, the duration of voiceless stops (C̥) in the V#__V(N) and N#__V(N) contexts and the nasal stop (N) in the V#__Ṽ context was significantly longer than the duration of voiced stops in N#__V(N) and V#__V(N) contexts (Fig. 2).

Results of an ANOVA (subject) showed that there was no significant difference between the average nasal airflow produced by JC, HP, and DL, $F(2, 226) = 2.75$, $p = .128$. Therefore mean nasal airflow was further averaged across the three subjects in N#CV(N), V#CV(N), V#NṼ, N#C̥V(N), and V#C̥V(N) contexts.

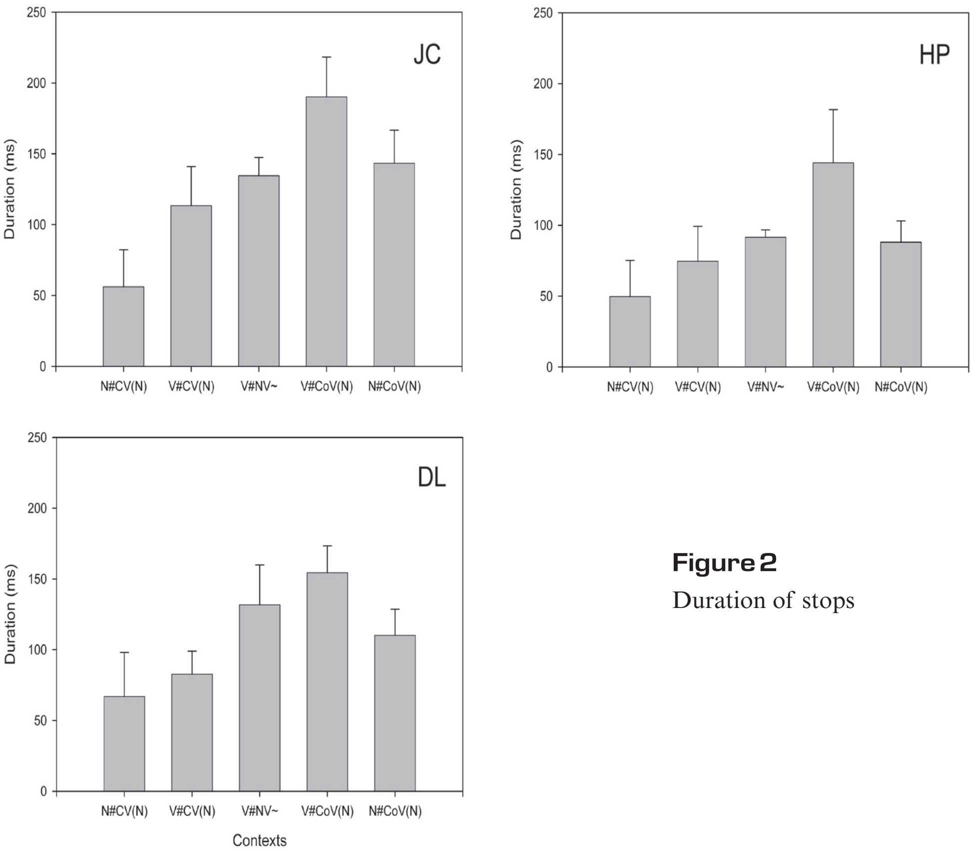


Figure 2
Duration of stops

A significant main effect of context was found on averaged nasal airflow of voiced stops (C) in V#__V(N) and N#__V(N) contexts; nasals (N) in the V#__Ṽ context; and voiceless stops (C̥) in V#__V(N), and N#__V(N) contexts, $F(4,224) = 21.63$, $p < .01$. Results of a post hoc Tukey HSD test showed that averaged nasal airflow of initial voiceless stops (C̥) in V+/#__V(N), N#__VN, and voiced stops (C) in V#__VN contexts were significantly lower than that of initial voiced stops (C) in N#__V(N) and initial nasals (N) in V#__Ṽ the context, as shown in Figure 3.

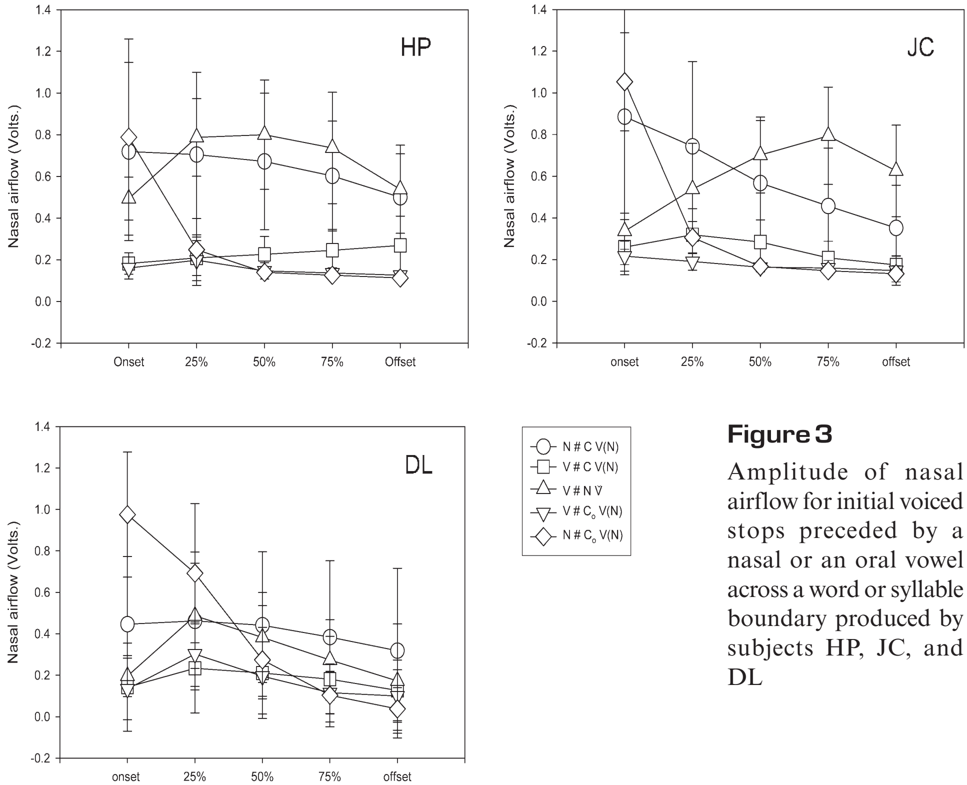


Figure 3

Amplitude of nasal airflow for initial voiced stops preceded by a nasal or an oral vowel across a word or syllable boundary produced by subjects HP, JC, and DL

2.3 *Discussion*

For all three subjects, the nasal airflow amplitude of initial voiced stops (C) preceded by a nasal consonant in N#__V (N) was not significantly different from nasal airflow of nasal stops in the N#__Ṽ context, but were significantly greater than the nasal airflow of voiced stops (C) in V#__V(N) contexts and voiceless stops (C̥) in V#__V(N) and N#__V(N) contexts. The results suggest that while initial voiced stops preceded by a nasal were nasalized to some degree, voiced stops preceded by an oral vowel remained an oral segment. The nasalized voiced stops in postnasal consonant contexts showed a different pattern of nasal airflow from that of nasal stops, and will hence be symbolized as C̃, that is, [b̃, l̃, g̃]. At the onset, the nasal airflow of nasalized voiced stops began with greater amplitude of nasal airflow than that of nasal stops due to the spread of nasalization from the preceding nasal consonant. The extent of nasalization for nasalized voiced stops steadily decreased from the stop onset to stop offset. Even so, the amplitude of nasal airflow of nasalized voiced stops was still greater than that of voiceless stops and voiced stops at the offset. For HP and JC, the extent of nasal airflow at the onset of nasal stops was lower than that of nasalized voiced stops, but the nasal airflow of nasal stops began to rise and exceeded the nasal airflow of nasalized voiced stops in the latter half of the nasal stop. For subject DL, the nasal airflow of the nasalized voiced stop remained greater than the nasal consonant through the entire segment. DL showed a stronger pattern of nasalization than JC and HP. Even her voiceless stops (C̥) in N#__VN context, were nasalized for a greater percentage of time than those produced by JC and HP.

Though traditional phonological studies describe the alternation between nasalized initial voiced stops and nasal stops only with respect to the following oral and nasal vowels in a tautosyllabic context, it was discovered in this study that Taiwanese voiced stops are nasalized when preceded by a nasal across a syllable boundary. Results of the present study have discovered alternation between the initial voiced stop and nasal depends on the preceding context and poses problems for traditional phonological studies that describe the alternation between nasalized voiced stops and nasal consonants only with respect to the following context, that is, oral versus nasal vowel, respectively. This discovery has not been documented in any previous phonological study of Taiwanese.

Traditional phonological studies ignored the influence of nasal consonants across syllable boundaries on initial voiced stops and described the alternation between initial voiced stops and nasal stops only with respect to tautosyllabic nasal or oral vowels. The discrepancy between traditional phonological studies and the present airflow study raises more questions. Why was the alternation between homorganic voiced stops and nasal stops not captured by phonological studies that were based on transcription and informant intuition? Can any psycholinguistic and perceptual evidence be found to clarify this issue?

3 Concept formation study on the phonemic categorization of [b] and [m]

Concept formation (CF) studies have been used to categorize linguistic components such as phonemic categorization as in the present study. In CF experiments, it is assumed that the easier a category is formed by a native speaker, the stronger the likelihood that the category preexists in the native speaker's phonemic inventory. Following this assumption, the categorization of initial voiced stops and nasal stops in heterosyllabic and tautosyllabic contexts was investigated to explore how homorganic voiced stops and nasal stops are categorized using native speakers' linguistic competence.

3.1 *Method*

Experimental procedure. The CF experimental paradigm consisted of three sessions: a learning session, a test session, and an interview session. During the learning session, subjects were presented with both positive and negative tokens that were followed by feedback indicating whether the token was a member of the category requested in each test. Positive tokens had common features or segmental properties of a phonemic category, while negative tokens did not contain such properties. After the presentation of a token, subjects responded by circling either "yes" or "no" on an answer sheet before the feedback was presented. The feedback consisted of a recording of a female voice saying "yes" or "no" in Taiwanese four seconds after a token was presented. Subjects were encouraged to make guesses when responding to the first several tokens and then compared their answers with the feedback allowing them to gradually abstract the common property of the category.

After subjects completed the learning session, their answers were checked to see if there were 15 continuous trials with two or less errors. According to Jaeger (1986), the chance of passing this criterion by chance is rare (p = .004, 1-tailed binomial test). Subjects who passed the criterion proceeded on to the test session.

During the test session, negative and positive tokens were presented along with test tokens with new properties that were not encountered before by subjects during the learning session. The category membership of the test tokens was unclear. Whether subjects extended the category to test tokens provides information regarding the pre-existence of a category. There was no feedback following each token in the test session. Subjects responded to each token by circling "yes" or "no" on the answer sheet during a three second Inter-Stimulus-Interval (ISI) between tokens.

During the interview session following the test session, subjects were asked to write down a description of the category, and a description of the criterion on which they based their decisions.

Subjects. Subject HP who participated in the nasal airflow study on voiced stops produced the tokens used in the CF experiment. Different numbers of subjects were recruited for each of the three CF experiments to come up with 10 subjects that passed the criterion in the training sessions of each CF experiment. Together, 91 students from the National Chiao Tung University participated in three CF experiments, with 30 native Taiwanese listeners participating in CF I, 11 native listeners participating in CF II, and 50 native listeners participating in CF III. It should be noted that only two out of the 50 subjects recruited for CF III passed the criterion, because the task in CF III was so unnatural that few subjects were able to perform the task. The data of two subjects that were able to perform the task in CF III was atypical data that did not represent the responses of the majority of native listeners. To continue recruiting subjects to find 10 subjects that could perform the unnatural task in CF III, we would have ended up with unrepresentative data that did not reveal the phonemic categorization of the majority of native speakers. Therefore, it was decided that the criterion level was not used in CFIII.

Corpus. A summary of the token types is shown in Table 3. In CF I, monosyllabic Taiwanese syllables were presented. They were all real words. During the learning session, subjects were presented with positive tokens with initial [b] and negative tokens with interfering initial segments, such as voiceless stops, fricatives, and affricates (Table 3). In the test session, positive and negative tokens were presented along with test tokens with initial [m]. The design was developed to train subjects to form a category with [b] and observe whether test tokens with initial [m] were included in the same category.

In CF II and CF III, the same real disyllabic Taiwanese words or phrases were used. The difference between CF II and III was the feedback that subjects received after each token in the learning session, as shown in Table 3.

During the learning session of CF II, positively reinforced tokens were real disyllable words or phrases with the first syllable ending in an oral vowel followed by either initial [b] or [m] in a second syllable (CV + /# [b] V, CV + /# [m] Ṽ), while the negatively reinforced tokens were disyllabic words or phrases containing interfering segments including stops, affricates, and fricatives at the initial position of the second syllable (Table 3). Subjects were trained to form a category with both [b] and [m] in CF II. During the test session of CF II, negatively reinforced real disyllabic words or phrases, with interfering segments, [p, t, ts, s], at the initial position of the second syllable, were presented along with positively reinforced words or phrases, that is, V + /# [b] V, V + /# [m] Ṽ, and test tokens with first syllables ending in final nasal consonants and second syllable beginning with a 'so called' "voiced stop" that was nasalized in N + /#_V position, that is, [saŋ ˥ b̃i ˥] 'send rice' (Table 3).

During the learning session of CF III, positively reinforced disyllabic phrases with initial [b] at the second syllable preceded by oral segments across a word or syllable boundary (V + /# [b]V), were presented along with negatively reinforced disyllabic phrases consisting of interfering segments, including stops, fricatives, and affricates, at the initial position of the second syllable or with [m] at the beginning of the second syllable preceded by an oral segment (V + /# [m]Ṽ). It should be noted that disyllabic phrases with V + /# [m]Ṽ structure were positively reinforced in CF II, but negatively reinforced during the learning session of CF III. In other words, the category trained in CF II was composed of both [b] from V + /# [b] V and [m] from V + /# [m]Ṽ, while the category in CF III was composed of only [b] from V + /# [b]V.

During the test session of CF III, in addition to positive tokens with initial [b] (V + /# [b]V) and negative tokens with initial [m] (V + /# [m]Ṽ), test tokens with the nasalized initial voiced stop [b̃] initiating the second syllable preceded by final nasal consonants across a word or syllable boundary, N + /#[b̃]V, were presented. By monitoring subjects' responses to these nasalized 'voiced stops', allophonic composition of the category was determined.

Data analysis. As assumed in CF experiments, that the more readily a category is formed, the more likely the category pre-exists in the native listener's mind. Ease of category formation was determined by analyzing four factors: (1) the total number of subjects recruited that resulted in 10 subjects passing training criteria in three CF experiments, (2) the number of tokens required during the learning session to form each category in each test, (3) the number of mistakes made during the learning session before subjects reached the criteria, and (4) the number of mistakes that subjects made after passing the criteria. Mistakes were positively reinforced stimuli in learning sessions that received negative responses in test sessions and vice versa. The percentage of test tokens presented together with positively reinforced stimuli was also determined.

TABLE 3

The contexts for syllable initial consonants in positive, negative, and test tokens in CF Experiments I, II, and III

Token Types

CF Experiment	Learning Session			
	Positive	n.	Negative	n.
I	[b]V	15	[p, t, k, t^h, k^h, h, s, tʃ, ts]V(N/C)	17
II	V +/# [b]V V+/# [m]Ṽ	27	V(N/C) +/# [p, t, p^h, k^h, ts^h, h, s] V(N/C)	13
III	V +/# [b]V	14	V +/# [m] Ṽ V(N/C) +/# [p, t, p^h, k^h, ts^h, h, s] V(N/C)	26

Token Types

CF experiment	Test Session							
	Positive	n.	Negative	n.	Test	n.	Control	n.
I	[b]V	11	[p, t, ts, s, h]V(N/C)	10	[m]Ṽ	8		
II	V+/# [b]V V+/#[m]Ṽ	17	V(N) +/# [p, t, ts, s]V(N/C)	7	N +/# [b̃]V	16	N+/# [m]Ṽ	11
III	V+/# [b]V	10	V +/# [m] Ṽ V(N) +/# [p, t, ts, s] V(N/C)	14	N +/# [b̃]V	16	N+/# [m]Ṽ	11

3.2
Results

Comparisons between numbers of subjects recruited to obtain 10 subjects are shown in Table 4. The fewest number of subjects, only 11, were needed in CF II to arrive at 10 subjects who achieved the criterion, followed by the second lowest number of subjects assigned to CF I, 30 subjects. In CF III, only two of the 50 subjects achieved the criterion. Fifty was the maximal number of subjects assigned to each test. Data of the two subjects who achieved the criterion in CF III were atypical cases and did not represent the perception of the remaining 48 native listeners who were unable to isolate [b] in V+/# __V, from [m] in V+/# __Ṽ contexts when presented with both [b] and [m].

As shown in Table 4, the average number of tokens required to reach the criterion was the smallest for CF II, 18.1, followed by the second smallest number, 23.5, in CF III. CF I, 24.2, required the highest number of stimuli. Among the three

TABLE 4

The results of concept formation experiments I, II, and III

(a) Results of CF experiment I (monosyllabic test).

10 / 30 subjects passed criterion	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	Avg.
Tokens required to reach criterion	32	22	22	18	32	27	16	17	28	28	24.2
Mistakes before reaching criterion	7	5	4	3	9	1	1	3	3	5	4.1
Mistakes in test session	1	1	0	3	0	3	0	0	0	0	0.8
Test items included (max=8)	8	8	8	8	8	8	8	8	7	8	7.9

(b) Results of CF experiment II (disyllabic phrase).

10 / 11 subjects passed criterion	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Avg.
Tokens required to reach criterion	24	16	18	18	25	15	16	15	19	21	18.7
Mistakes before reaching criterion	1	1	2	2	3	0	1	0	1	0	1.1
Mistakes in test session	1	0	0	1	0	0	0	0	0	0	0.2
Test items included (max=16)	15	15	15	16	16	16	16	16	15	14	15.4

(c) Results of CF experiment III (disyllabic phrase).

2 / 50 subjects passed criterion	P1	P2	Avg.
Tokens required to reach criterion	28	19	23.5
Mistakes before reaching criterion	4	4	4
Mistakes in test session	0	0	0
Test items included (max=16)	15	16	15.5

CF experiments, not only did CF II require the least number of tokens to reach criterion, but also the fewest number of subjects. Also shown in Table 4 is the number of mistakes made before reaching criterion. Not surprisingly, the fewest mistakes, only 1.1, were made in CF II.

Turning to number of test tokens included in the target category, an average of 7.9/8 test tokens with initial [m] were included in the [b] category in CF I. Similarly, an average of 15.4/16 [b̃] in the N+/#__V context were included in the [b, m] category in CF II, while 15.5/16 of [b̃] in the N+/#__V context were included in the [b] category in CF III.

3.3 Discussion

Among subjects who passed criteria in the three CF experiments, there were few mistakes made during the test session. In other words, categories /b/ in CF I and category /b, m/ in CF II were perceptually strong for 10 subjects who achieved the criterion as was the /b/ category for two subjects who achieved the criterion in CF III. However, whether these categories pre-existed in the majority of native speakers' perceptual space was related to the percentage of subjects that were able to form such categories. For the category /b/, excluding [m], in CF III, only two out of 50 subjects were able to master the task. In other words, few subjects could separate [b] from [m] when presented with both sounds. Though being less difficult, only one third of the subjects who participated in CF I reached the criterion and formed a category with /b/ when presented with only [b]. Though more than 50% of subjects in CF I and III had difficulty in forming a category with only [b], almost all subjects who participated in CF II grouped [b] and [m] together and formed the target category with ease by requiring the least number of tokens to reach the criterion, that is, 18.7 tokens. Following the assumption that the easiest task is the most natural one, it is proposed that these Taiwanese listeners have a phonemic category that contains both [b] and [m] that is more natural than a category with only one allophonic member, [b], in it.

Moreover, the naturalness of a category containing both [b] and [m] was further supported by the number of test items included with the positively reinforced stimuli. In CF I, almost 100% of the monosyllabic test items, that is, initial [m] in the __Ṽ context, were included with initial [b] in the __V context. Furthermore, in CF III, even the two subjects who were able to form a [b] category by including [b] in the V + /#___V context and excluding [m] in the V + /# ___Ṽ context categorized nasalized [b̃] in the N + /#___V context together with initial [b] in the V + /#__V context.

It was proposed that the presentation of both oral and nasal stops, [b, m], facilitates category formation. Similar results were reported for categorization of velar nasal stops and oral stops, [g, ŋ] (Wang, 1999a). However, for [l] and [n], native Taiwanese listeners were more unlikely to group them into the same category. Wang (1999a) proposed that this was due to phonetic interference from Mandarin of which [l] and [n] are two separate phonemes.

Results of the three CF experiments converged to the same conclusion, that is, it is more natural for subjects to group [b] and [m] into the same phonemic category and ignore phonetic differences between them. Even the two subjects in CF III who were able to distinguish [b] in the V + /#__V context from [m] in the V + /#__Ṽ context, categorized initial [b̃] in the N + /#__V context with [b] in the V + /#__V context. It is proposed that the two subjects in CF III relied on perceptual cues other than the nasality difference between [b] and [m] when differentiating [b] in V + /#__V sequences from [m] in V + /#__Ṽ sequences. For example, the presence of nasality on the vowel following [m] in the V + /#__Ṽ context ([kɔ˧ mĩ˧] 'bitter noodles'), and absence of vowel nasality following [b] in the V + /#__V context ([kɔ˧ bi˧] 'bitter taste') could be used as a cue for the two subjects to distinguish disyllabic phrases during the learning session. Consequently, as the vowel distinction that the two subjects were relying on was lost, they were unable to discriminate [b] in the V + /#__V, for example, [kɔ˧

bi˧] 'bitter taste', from [b̃] in the N + / #__V context, for example, [təŋ˧ bin˧] 'long face'. In other words the context could be another cue used to differentiate [b] in the V + / #__V from [m] in V + / #__Ṽ. According to phonotactic constraints, [b] occurs before an oral vowel, while [m] occurs only before a nasal vowel. If the two subjects who passed the critierion in CF III were unable to differentiate [b] from [m] they could still rely on the distinction between an oral versus nasal vowel to predict the occurrence of [b] and [m]. Had the two subjects in CF III relied on the oral versus nasal vowel to differentiate [b] in V + __V from [m] in the V + / #__Ṽ context, then they would not be able to differentiate [b] in V + / #__V from [b̃] in N + / #__V, since [b] and [b̃] were both followed by oral vowels in these tokens. In fact, the two subjects that passed the criterion in CF III grouped [b] and [b̃] into the same category even though the nasal airflow of [b̃] was not significantly different from that of [m].

A gating experiment was used to tap native listeners' sensitivity to initial stops, that is, [b] in the V + / # __V context, [b̃] in the N + / #__V context, and [m] in the N + / #__Ṽ context. The role that the vowel nuclei played in perception of an oral (initial voiced stop followed by an oral vowel) versus a nasal syllable (initial nasal followed by a nasal vowel) was also investigated.

4 Gating experiment on [b] and [m] in hetero and tautosyllabic oral versus nasal contexts

Though originally designed for analyzing word-recognition processes, gating experimental paradigms (Cotton & Grosjean, 1984; Elliot et al., 1987; Fox, 1992; Salasoo & Pisoni, 1985) have been used in studies on phonetic cues used during speech perception (Lahiri & Marslen-Wilson, 1992; Ohala & Ohala, 1995). In a gating experiment, words divided into consecutive incremented fragments, for example, 50 ms, are presented in progressively longer units, beginning from word onset to the nuclei and finally the syllable offset. For example, the first fragment presented contains the first 50 ms of the word, the second fragment contains the first 100 ms of the word, so on and so forth, until the entire word is presented. After presentation of each fragment, a subject responds to the stimuli by circling an answer from the multiple choices listed on an answer sheet and then rates their confidence to each answer. By analyzing the duration for the portion of a syllable or a word needed for the subject to recognize the whole syllable/word along with the confidence ratings provided with each response, and by examining the answer that subjects circled after hearing each portion of a syllable presented, one can determine perceptual cues used by subjects in lexical processing.

A gating experiment was used to determine whether native Taiwanese listeners were relying on the phonetic difference between homorganic initial voiced stops and initial nasal stops, or oral versus nasal vowels to distinguish between oral syllables (initial voiced stop followed by oral vowel) and nasal syllables (initial nasal followed by nasal vowel). By presenting only a portion of a syllable in successive gated stimuli, the perceptual responses that subjects had at different portions of the syllable were monitored. In this way it could be determined whether it was the difference between the initial voiced stop and the nasal, or the contrast between oral versus nasal vowels that was used by subjects to differentiate between oral versus nasal syllables.

4.1
Method

Subjects. A female native Taiwanese speaker, HCH, from central Taiwan produced the disyllabic phrases used in the gating experiment. She was a linguistic professor at National Chiao Tung University at the time of recording, and was unaware of the purpose of the experiment.

Ten native Taiwanese speakers participated in the gating experiment. Subjects were students at the National Chiao Tung University at the time of the study and were able to speak Mandarin and English. All subjects received education in Mandarin and were illiterate in Taiwanese. They had all been exposed to phonetic alphabets while learning English.

Corpus. Twenty-four disyllabic Taiwanese phrases were used in the gating experiment. As shown in Table 5, homorganic initial voiced stops, /b, l, g/, and nasal stops, /m, n, ŋ /, were placed at the initial position of the second syllable. To investigate the influence of context across a syllable boundary on native listener sensitivity to homorganic initial voiced stops and nasal stops, four types of contexts across word or syllable boundaries: that is, final oral vowel, final nasal vowel, voiceless unreleased final stop, and final nasal consonant; were placed at the end of the first syllable preceding a homorganic initial voiced stop and nasal across the word or syllable boundary. According to phonotactic constraints, voiced stops occur only in a + __V context followed by an oral vowel, while nasal stops only occur before a + __Ṽ context followed by a nasal vowel in a nasal syllable. By matching the two tautosyllabic contexts, + __V and + __Ṽ, with four contexts across word or syllable boundaries, V + / # __, Ṽ+ / # __, C + / # __, and N + / # __, there were altogether eight different contexts. As shown in Table 5, the initial voiced stop of the second syllable was placed in four contexts, that is, V + / # __V, C + / # __V contexts, the initial nasalized voiced stops were placed in Ṽ+ / # __V, and N + / # __V contexts, while the initial nasal was placed in V + / # __Ṽ, Ṽ+ / # __Ṽ, C + / # __Ṽ, and N + / # __Ṽcontexts. It should be noted that the so called “voiced stops” preceded by final nasal consonants in the neighboring syllable, N + / # __V, were phonetically nasalized, as determined by results of the prior nasal airflow studies on initial voiced stops.

One disyllabic phrase was designed for each one of the six voiced stops and nasal stops, that is, [b, l, g, m, n, ŋ], in four different contexts across the word or syllabic boundary. There were all together 24 disyllabic word or phrases, (3 voiced stops × 4 contexts) + (3 nasal stops × 4 contexts). The order in which the 24 disyllabic words or phrases were presented was randomized.

When a disyllabic phrase was presented, eight multiple-choice responses were listed on the answer sheet. These eight multiple choices were actual items that subjects would encounter in the gating experiment. Table 5 shows an example of the eight multiple choices listed on the answer sheet for disyllabic-phrases with a homorganic bilabial voiced stop and bilabial nasal. For example, when the initial segment of the second syllable of the disyllabic phrase presented was either [b], [m] or [b̃], four disyllabic phrases from the corpus with [b] in initial second syllable position of V + / # __V, and C + / # __V contexts, along with two disyllabic phrases with [b̃] in Ṽ+ / # __V, and

N + / #__V contexts, and four disyllabic phrases with initial [m] in the second syllable in the same contexts were listed on the answer sheet. The 24 disyllabic phrases in the corpus were divided into three sets of multiple-choice responses, one for the homorganic bilabial voiced stop and nasal, one for the homorganic lateral and alveolar nasal, and one for the homorganic velar voiced stop and nasal. In other words, as long as one of the eight disyllabic phrases with a homorganic voiced stop and nasal at the initial position of the second syllable was presented, the entire set of eight disyllabic phrases with the homorganic voiced stop and nasal at the second syllable in the corpus list was written on the answer sheet as multiple-choices.

TABLE 5

Example of multiple-choice items provided to subjects when presented with each of the eight phrases in the gating experiment. The same eight multiple choices were provided for each of the eight phrases presented

		Tautosyllabic Context	
		[b, l, g] V	[m, n, ŋ]Ṽ
Heterosyllabic Context	V+/# ___	[iu˧ bi˧] 'oily taste'	[iu˧mĩ˧] 'oily noodle'
	Ṽ+/#___	[kũã˧bi˧] 'sweaty smell'	[kũã˧mĩ˧] 'hold noodle'
	N+/#___	[p^haŋ˧b̃i˧] 'fragrance'	[p^haŋ˧mĩ˧] 'noodles that smell good'
	C+/#___	[tɔk˩bi˧] 'taste of poison'	[tɔk˩mĩ˧] 'poisonous noodle'

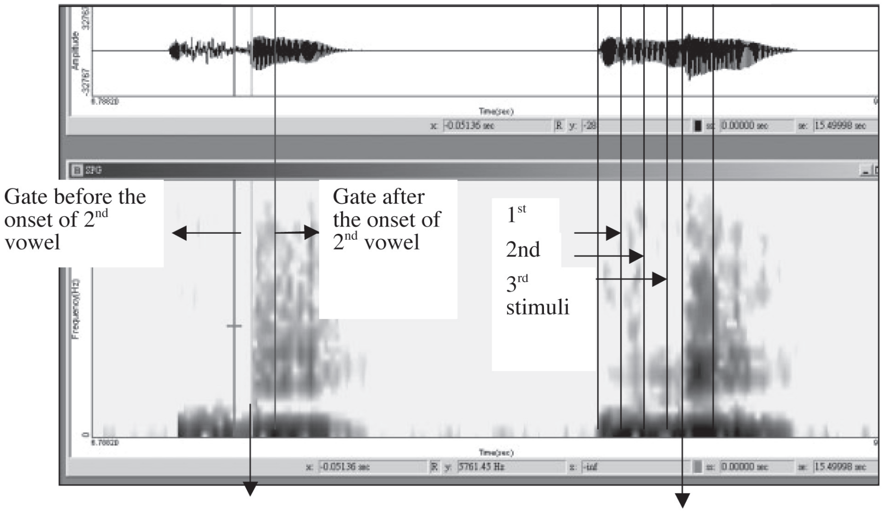
Since subjects were illiterate in Taiwanese, but were able to read Chinese characters and phonetic symbols, the choices were literal translations of Taiwanese phrases written in Chinese characters with one character for each syllable. Under each character was an IPA phonetic symbol indicating the Taiwanese pronunciation that each character stood for. Subjects had no difficulty interpreting the IPA symbols based on their previous exposure to the phonetic alphabet while learning English.

Stimuli creation. The 24 disyllabic Taiwanese phrases read by the female informant were digitized at 11.025 kHZ using CspeechSP software and then converted into .wav format. Spectrograms were generated for each one of the disyllabic phrases in order to locate the time of the vowel onset in the second syllable. Each gate was 40 ms in duration. For the purpose of the experiment, that is observing subjects' choices of lexical items before and after the onset of the second vowel, portions of the disyllabic phrase before the onset of the second vowel were calculated, 40 ms apart, backward in time up to the beginning of the disyllabic phrase. The portion of each disyllabic phrase after the onset of the second vowel was gated forward in time with a gate duration of 40 ms up to the end of the disyllabic phrase. In this way, the fragments of the disyllabic phrase before and after the onset of the second vowel were ensured to be included in different gates, see Figure 4. There are from 10 to 12 gates after the onset of the second vowel for different disyllabic words or phrases. Thus the change in choices that subjects made before and after the onset of the second vowel could be observed clearly. After the offset time for each gate was determined, stimuli containing only a portion of each disyllabic phrase were created containing fragments starting from the onset of the phrase up to the offset time of the next gate. Successive stimuli were created from the onset of the phrase progressing in 40 ms units up to the end of the disyllabic phrase.

To avoid abrupt energy drop-offs at the offset of each stimulus that would cue subjects to perceive a final stop at each gate's end, each stimulus was ramped to decrease its amplitude at its end.

Figure 4

Segmentaion criteria for stimuli used in the gating experiment



Onset of vowel /i/ in 2nd syllable /siu˧˩li˥˧/ 'miss you'

Onset of vowel /ĩ/ in 2nd syllable of /siu˧˩nĩ˥˧/ 'want to dye'

The stimuli were recorded onto a tape. A 400 Hz tone was inserted three seconds before the presentation of the first stimuli of a disyllabic phrase to indicate a change in phrase type. The first stimulus was followed by successive stimuli with an ISI (Inter-Stimuli-Interval) of three seconds.

Procedure. The gating experiment in the present study began with a practice session resembling the real test. Two disyllabic phrases were presented during the practice session. After the training session, subjects moved on to the experiment.

After hearing each stimulus, subjects responded by circling one of eight multiple-choice responses listed on the answer sheet, and then they also marked their confidence level of each choice on a line that was evenly divided into five sections from "purely guess" listed under the left-most tick, followed by "uncertain," "somewhat certain," "certain," and "100% certain" listed under the right-most tick. Subjects could mark anywhere on the line.

Data analysis. For each disyllabic phrase, the recognition point was determined. This point was defined as the stimulus at which a subject did not change his/her answer in subsequent stimuli.

ANOVAs with contexts across word or syllable boundary (V+/# __, Ṽ+/#__, C+/#__, N+/#__) as the experimental variables were used to analyze the recognition points of 24 disyllabic phrases.

4.2
Results

Recognition points for 24 disyllabic phrases by 10 subjects are shown in Figure 5. For most disyllabic phrases, recognition points were after the onset of the second vowel. A significant effect of context across word or syllable boundary, that is, V+/#__, Ṽ+/#__, C+/#__, N+/#__, was found on the recognition points, $F(3, 326) = 4.99$, $p < .05$. A post hoc Duncan test revealed that the mean recognition point for disyllabic phrases with final voiceless stops at the first syllable edge (C+/#__) was earlier than those with final oral vowels (V+/#__), final nasal vowels (Ṽ+/#__) and final nasal stops (N+/#__).

Responses of 10 subjects to successive stimuli of disyllabic phrases six gates before (–1 ~ –6 gates) and six gates after (1 ~ 6 gates) the onset of second vowel were pooled across voiced stops, that is, /b, l, g/, and across nasal stops, that is, /m, n, ŋ/ (Fig. 6). By looking at the choices that subjects made, and observing patterns in their erroneous choices, called a "garden path," we can deduce that at six gates before the onset of the second vowel, subjects circled only two choices, one for the disyllabic phrase presented, and the other, a near-minimal pair of the phrase presented. For example, [iu˧ bi˧] and [iu˧ mĩ˧] were the only two choices that subjects circled when presented with either [iu˧ bi˧] or [iu˧ mĩ˧]. Both choices had the same first syllable, but the initial segment of the second syllable was a homorganic voiced stop and nasal followed by an oral vowel and nasal vowel respectively. As the portion of disyllabic phrases presented gradually increased and approached the onset of the second vowel, subjects' choices gradually converged toward the correct answer with fewer responses to a near-minimal pair and a greater number of responses to the disyllabic phrase presented (see Fig. 6).

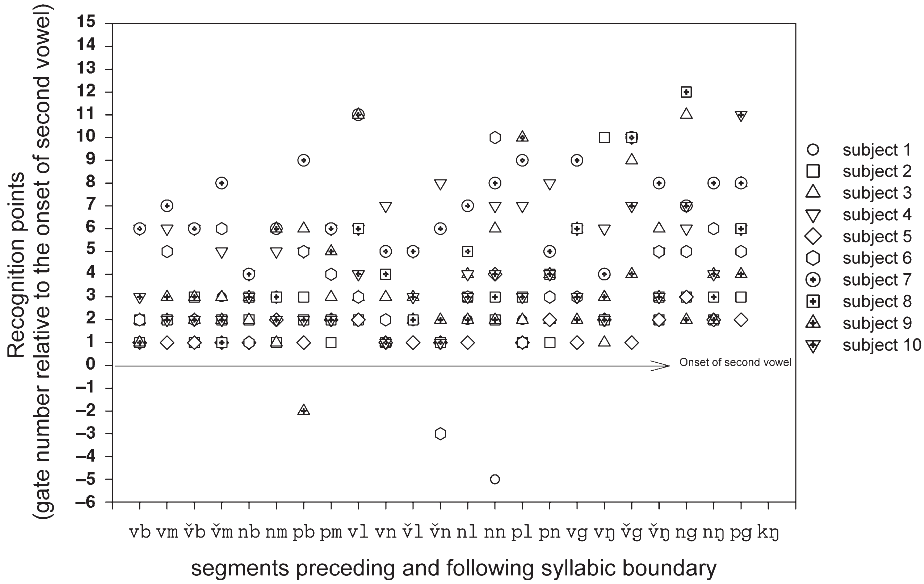
4.3
Discussion

Results of recognition point location along with the garden path information showed that disyllabic phrases were recognized after the onset of the second vowel, though only three out of the 240 disyllabic phrases (24 disyllabic phrases × 10 subjects) presented were recognized before the onset of second vowel.

The recognition points were earlier when the first syllable ended in C than when it ended in N, V, or Ṽ. Since the voice quality of first syllables with final voiceless unreleased stops had a glottalized voiced quality (Iwata et al., 1979), it is proposed that the glottalized voice quality of first syllable may have affected the contrast

Figure 5

Ten subjects' recognition points for each disyllabic phrase. The recognition points were determined with respect to the onset of the second vowel. Positive numbers along the Y-axis represent the gate number after the onset of the second vowel, while negative numbers represent the gate number before the onset of the second vowel. Some symbols are overlayed on top of each other



between absence of nasality for initial voiced stops and presence of nasality for nasal stops, and may have enhanced the contrast between initial voiced and nasal stops enabling listeners to recognize the second syllable during the presentation of initial consonants. However, further studies are necessary to investigate how glottalized voice quality coarticulates with the following syllable and how such coarticulation affects perception.

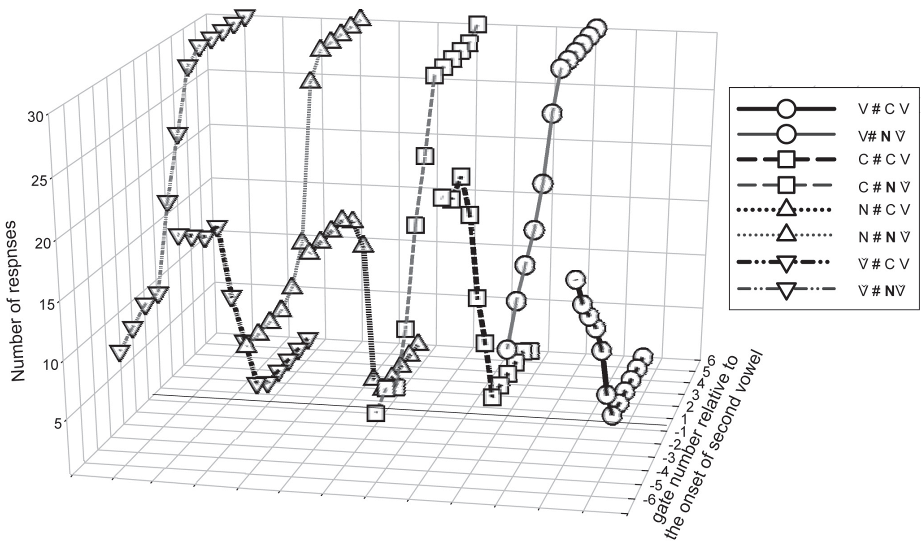
According to the garden path results, subjects' responses to a disyllabic phrase were distributed between the correct choice of the phrase presented and its minimal-pair with an identical first syllable and a second syllable with a homorganic initial voiced stop. In other words, subjects had no difficulty recognizing the first syllable of the disyllabic phrase, however, they were not able to determine the difference between the initial voiced stop and nasal in the second syllable. It was not until the vowel following the initial voiced stop and nasal in the second syllable was presented that subjects recognized the complete disyllabic phrase.

According to the results of CF I-III, native Taiwanese listeners grouped Taiwanese homorganic initial voiced stops and nasal stops into the same category. Results of the gating experiment further revealed that native listeners had difficulty in distinguishing homorganic initial voiced stops from nasal stops. As shown in the garden path results, subjects were unsure about their responses when presented with only the initial voiced stop and nasal. Not being able to distinguish homorganic initial voiced

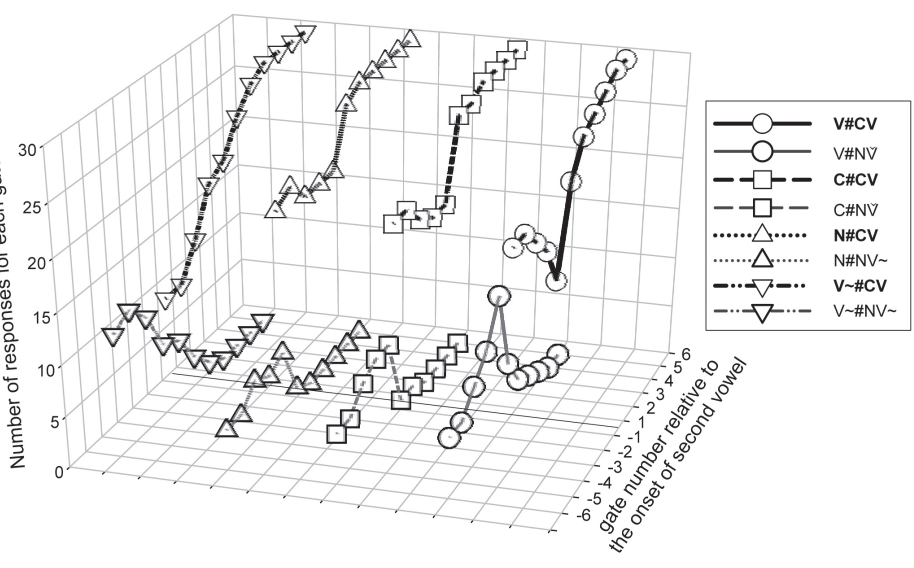
Figure 6

Garden paths for responses in the gating experiment. Responses were pooled across disyllabic phrases with either the voiced stops, /b, l, g/, or with nasal stops, /m, n, ŋ/ in four heterosyllabic contexts. Responses at six gates before (gate –6 ~ –1) and six gates after (gates 1 ~6) the onset of the second vowel are shown. Lines of the same pattern represent responses to the same disyllabic phrase

(a) Responses to disyllabic phrases with initial nasals at the second syllable



(b) Responses to disyllabic phrases with initial voiced stops at the second syllable



stops and nasal stops, native listeners relied on the presence or absence of nasality in the vowel nucleus in tautosyllabic contexts to distinguish between oral versus nasal syllables in Taiwanese.

Results of the gating experiment explain why traditional phonological analysis relying on informant intuition has ignored the occurrence of initial nasal stops with respect to the preceding context and portrayed the distribution between homorganic voiced stops and nasal stops only with respect to the following oral versus nasal vowel in a tautosyllabic context. Since native speakers were insensitive to the phonetic difference between homorganic initial voiced stops and nasal stops and perceived a syllable with an oral vowel nucleus as oral, native speakers presumably transcribed the initial segment of an oral syllable with a voiced stop. Thus, disyllabic phrases such as /saŋ ˧ bi ˥˧/ 'send rice' was never transcribed as [saŋ ˥˧ mi ˥˧] in these traditional phonological studies. Native Taiwanese listeners were insensitive to the phonetic difference between initial voiced stops and nasal stops. Instead of relying on the phonetic difference between homorganic initial voiced stops and nasal stops to distinguish the disyllabic phrases, native Taiwanese listeners used the presence or absence of nasality in the vowel nuclei to differentiate between oral versus nasal syllables and failed to recognize the fact that the so-called "initial voiced stop" was phonetically nasal in the N#__ V context.

To confirm the salient role that presence or absence of nasality on vowel nuclei play in the perception of oral versus nasal syllables, production data that would support the perceptual results was collected. It was demonstrated in Thai (Beddor & Krakow, 1999) that native Thai listeners' perception of nasality on vowel nuclei was influenced by how the allophonic nasalization rule was implemented in production. Similarly, if the presence or absence of nasality on vowel nuclei played a salient role in perception of oral versus nasal syllables in Taiwanese, then it was necessary to maintain a robust acoustic contrast between oral versus nasal vowel nuclei.

To further reveal the salient role that vowel nuclei play in recognition of oral versus nasal syllables, a nasal airflow study on oral vowels in a tautosyllabic + C̃__N context was used to demonstrate how the distinction between oral versus nasal vowels was maintained even in a + C̃__N context to preserve the contrast between oral versus nasal syllables.

5 Nasal airflow for vowel nuclei

Following the perceptual study (Beddor & Krakow, 1999) on Thai and English where nasalized vowels linked a perceptual pattern with the implementation of an allophonic rule during production, this study investigates the extent of allophonic nasalization patterns on oral vowels in order to explore whether production results agree with the perceptual pattern. According to the results of the gating experiment, the presence and absence of nasality is a crucial cue to the perception of oral versus nasal syllables in Taiwanese; if the perceptual results were to agree with the production data, then Taiwanese oral vowels should not be nasalized to the extent of losing contrast with nasal vowels in a nasal context. By keeping a contrast between oral vowels, partially nasalized vowels and nasal vowels, the perceptual contrast between oral and nasal syllables is maintained.

To investigate the nasality of vowel nuclei in different contexts across a syllable boundary, the nasal airflow data recorded in the prior nasal airflow study on initial voiced stops was analyzed to measure the amplitude of nasal airflow of vowels in various tautosyllabic contexts in the second syllable.

5.1 *Method*

Subjects. The same three female subjects, JC, HP, and DL, who participated in the airflow study of initial voiced stops and nasal stops also produced nasal airflow data for vowel nuclei.

Corpus. The corpus was the same 18 disyllabic Taiwanese phrases listed in the gray cells of Table 2. An oral vowel, /ɔ/ was placed in four tautosyllabic contexts, that is, + C__, + C__N, + C̥__, + C̥__VN in the second syllable; the nasal vowel /ɔ̃/ was placed in tautosyllabic + N__context, following an initial nasal; and a nasal vowel /ũã/ was placed in a tautosyllabic + C̥__ context. Initial voiced stops and nasal stops in the second syllable were preceded by a final nasal consonant or oral vowels in the first syllable, that is, V#__ and N#__. To match heterosyllabic with tautosyllabic contexts, oral vowels were placed in eight different contexts, that is, N#C̃__, V#C__, N#C̃__N, V#C__N, N#C̥__, V#C̥__, N#C̥__N, and V#C̥__N; whereas nasal vowels were placed in two different contexts, that is, V#N__, and V#C̥__. There were altogether 31 disyllabic phrases produced, with three repetitions for each disyllabic phrase. Vowels of 18 disyllabic phrases were analyzed. The vowels of these 18 disyllabic phrases analyzed were a nasal vowel /ũã/ in V#C__ context, and an oral vowel /ɔ/ in N#C̃__N, V#C__N, N#C̃__, V#C__, and V#C̥__ contexts. Oral vowel, V, in + C̥__ syllables and nasal vowel, Ṽ, in + C__ syllables were used as baseline data to show the extent of nasality of oral versus nasal vowels following a voiceless stop. The extent of nasality for oral vowels in + C̥__ and nasal vowels in + C̥__ contexts were compared with the extent of oral vowel nasalization in N + C̃V(N) and V + CV(N) contexts. Altogether, 54 tokens were analyzed, [(1 nasal vowel × 1 context × 3 initial voiceless unaspirated stops) + (1 oral vowel × 4 contexts × 3 initial voiced stops) + (1 oral vowel × 1 context × 3 initial voiceless unaspirated stops)] × 3 repetitions.

Data analysis. Acoustic and airflow signals were aligned in time and analyzed with CspeechSP. Spectrograms were generated from the acoustic signals. The time at the onset and offset of vowel nuclei in the second syllable was determined and the amplitudes of nasal airflow at onset and offset of the vowel and at 25%, 50%, and 75% time intervals within the vowel were taken, as shown in Figure 1.

Nasal airflow of oral vowels preceded by a nasalized voiced stop in N# C̃__(N) and nasal airflow of oral vowels preceded by a voiced stop in V#C__(N) context were compared with baseline data taken from nasal airflow of nasal vowels in V # C̥__ context, and oral vowel in V#C̥__contexts.

A one-way ANOVA (subject) was used to analyze the mean nasal ariflow of vowels averaged across the 25%, 50%, and 75% time intervals of each token produced by JC, HP, and DL. For each subject, a one-way ANOVA (context) was used to analyze the mean nasal airflow of nasal vowels averaged across the 25%, 50%, and 75% time intervals in V#C̥__ and oral vowels in N#C̃__N, N#C̃__, V#C__N, V#C__, and V#C̥__ contexts.

5.2
Results

The nasal airflows produced by the three subjects, JC, HP, and DL were significantly different from each other, $F(2, 151) = 89.25, p < .01$. Results of a post hoc test ($\alpha = 0.05$) showed that the nasal airflow of DL was significantly different from that of JC and HP ($p < .01$). Nasal airflow during production of the vowel was not averaged across the three speakers. Instead, for each speaker a one-way ANOVA (context) was used to analyze the mean nasal airflow across the 25%, 50%, and 75% time intervals.

Significant differences were found on mean nasal airflow of nasal vowels in V#C̥__, oral vowels in N#C̃__N, N#C̃__, V#C__N, V#C__, and V#C̥__contexts produced by JC, $F(5, 44) = 18.35, p < .01$, HP, $F(5, 44) = 20.77, p < .01$, and DL, $F(5, 48) = 14.26, p < .01$.

For subject JC, results of a post hoc Tukey HSD test ($\alpha = 0.05$) showed that the average nasal airflow of nasal vowels, Ṽ, in the V#C̥__ context was significantly higher than the nasal airflow of oral vowels, V, in N#C̃__N, N#C̃__, V#C__N, and V#C__ contexts, which in turn were siginificantly higher than oral vowels produced in V#C̥__contexts ($p < .05$).

For subject HP and DL, results of a post hoc Tukey HSD test ($\alpha = 0.05$) showed that the average nasal airflow of oral vowels, V, in N#C̃__N, N#C̃__, V#C__N, V#C__, and V#C̥__contexts were different from nasal vowels, Ṽ, in the V#C̥__ context ($p < .05$).

5.3
Discussion

As shown in Figure 7, nasalization can be observed at the onset of oral vowels, V, in the N#C̃__N context produced by JC, in N#C̃__N, N #C̃__, and V# C__N contexts produced by HP and in N#C̃__N, and N#C̃__ contexts produced by DL. At the offset, the oral vowel, V, was nasalized in N#C̃__N, and V#C__N contexts produced by JC and HP. DL showed a different pattern of vowel nasalization at the offset of the oral vowel. DL nasalized the offset of oral vowels in N#C̃__, V#C__ and V#C̥__contexts. Even though the pattern of nasalization at the onset and offset were different among the three subjects, none of the three subjects nasalized oral vowels at 25%, 50%, and 75% time intervals. A clear distinction between oral and nasal vowels was maintained at 25%, 50%, and 75% time intervals.

Taiwanese oral vowels in nasal contexts were not nasalized at the center of the vowel nuclei but were nasalized at the onset and offset. The maintenance of a clear distinction between oral and nasal vowel nuclei even in the N#C̃__N context agreed with the perceptual results of the gating experiment which found that the presence or absence of nasality in vowel nuclei was the salient cue used to distinguish oral from nasal syllables.

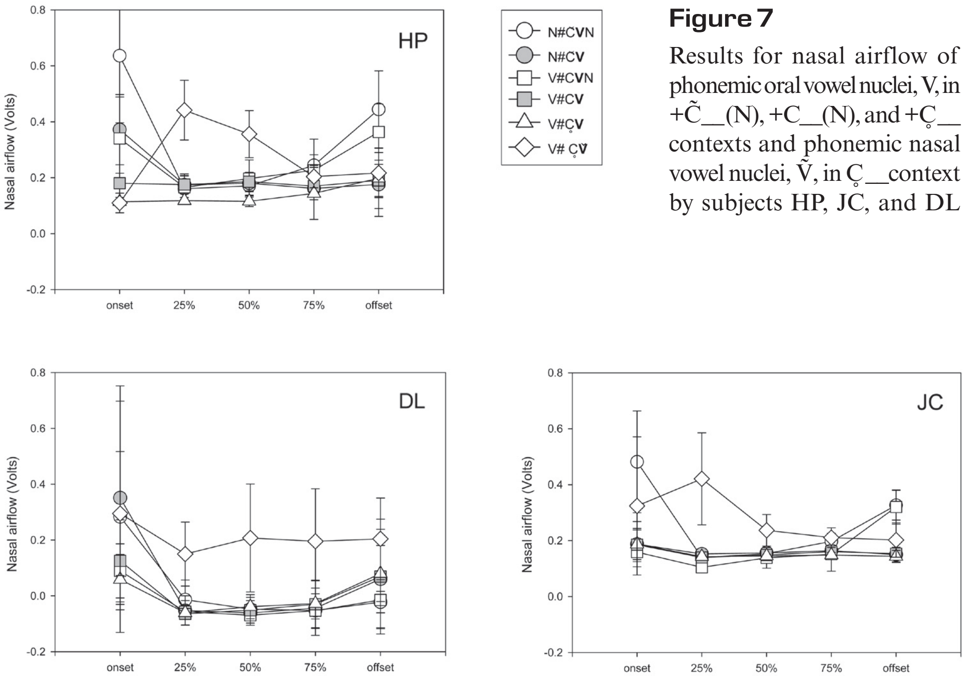


Figure 7
Results for nasal airflow of phonemic oral vowel nuclei, V, in +C̃__(N), +C__(N), and +C̥__ contexts and phonemic nasal vowel nuclei, Ṽ, in C̥__context by subjects HP, JC, and DL

A link between production and perception was established between the absence of nasalization on oral vowel nuclei in the + C̃__N context and the crucial role that the presence versus absence of nasality played in distinguishing nasal versus oral syllables. By relying on the nasal and oral contrast in vowel nuclei to distinguish between oral and nasal syllables, native Taiwanese speakers traded the ease of articulation for ease of perception. They did this by not nasalizing the center part of the oral vowels in the N# C̃__N context thereby maintaining a clear distinction between oral versus nasal vowels.

6 General Discussion

From the results of the nasal airflow study on homorganic initial voiced stops and nasal stops, concept formation, gating, and nasal airflow studies on vowel nuclei, the following were proposed: First, Taiwanese initial voiced stops are nasalized when preceded by a nasal consonant across a word boundary. Second, [b] and [m] and [b̃] are perceived as belonging to the same category. Third, the presence and absence of nasality on vowel nuclei is used by subjects to distinguish oral syllables from nasal syllables. Fourth, a clear oral versus nasal vowel distinction is maintained at the center of vowel nuclei, even in C̃__N context, to distinguish nasal from oral vowels.

The fact that traditional phonological studies failed to transcribe the nasalization of initial voiced stops, C̃, in a N#_V context revealed that Taiwanese native listeners were not sensitive to the phonetic difference between homorganic voiced stops, nasalized voiced stops, and nasal stops which were allophones of the same phonemic category. By ignoring the difference between homorganic initial voiced stops, nasalized voiced stops, and nasal stops, native listeners relied on the presence or absence of nasality on vowel nuclei to distinguish the second syllables in phrases such as [saŋ˧ ĩi˧] 'Give you as present' from [saŋ˧ nĩ˧] 'Who dyes'. By relying on the presence or absence of nasality on vowel nuclei to recognize syllables with a homorganic initial voiced stop and nasal, a clear distinction between nasal versus oral vowels is maintained. It was concluded that the center of oral vowels in N#C̃__N context is not nasalized even when surrounded by nasal segments to retain a clear perceptual contrast at the expanse of ease of articulation.

This study demonstrated the influence of phonemic categorization on speech perception, and how language specific perception of allophones influenced the production of allophonic rules. By providing phonetic evidence to capture abstract phonological competence, such as phonemic categorization and the extent of application of allophonic rules in Taiwanese, the controversial issue on phonemic categorization of homorganic initial voiced stops and nasal stops in Taiwanese was resolved.

For future study, perception and production data can be used to explore and compare the status of nasality in languages that (1) have a phonemic distinction between nasal and oral vowels, but lose the distinction between nasal and oral vowels in a nasal context, such as Bengali, and Hindi (Lahiri & Marslen-Wilson, 1992; Ohala & Ohala, 1995), (2) have a phonemic distinction between oral and nasal vowels, but do not lose the contrast in a nasal context, such as in French (Cohn, 1990; Huffman, 1993), (3) do not have phonemically specified nasal vowels, but heavily nasalized oral vowels in a nasal context, such as English, or (4) do not have nasal vowels and do not allow heavy nasalization, such as Thai (Beddor & Krakow, 1999) and Japanese (Ushijima & Hirose, 1974). By providing phonetic data showing phonemic categorization and production of allophonic rules in languages with different patterns of realization for a nasal feature, we can gain more insight into how native listeners' perception is shaped by phonemic categorization and the extent of application of allophonic rules. Furthermore, the link between perception and production of allophonic rules can be established.

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References

BAO, Z. (1990). Fanquie languages and reduplication. *Linguistic Inquiry*, **21**, 317–350.

BEDDOR, P. S., & STRANGE, W. (1982). Cross-language study of perception of the oral-nasal distinction. *Journal of the Acoustical Society of America*, **71**, 1551–1561.

BEDDOR, P. S. (1993). The perception of nasal vowels. In M. K. Huffman & R. A. Krakow (Eds.), *Phonetics and phonology series, v. 5: Nasals, naslization, and the velum* (pp. 171–196). San Diego: Academic Press.

BEDDOR, P. S., & KRAKOW, R. A. (1999). Perception of coarticulatory nasalization by speakers of English and Thai: Evidence for partial compensation. *Journal of Acoustical Society of America*, **106**(5), 2868–2887.

BEDDOR, P. S., & ONSUWAN, C. (2003). Perception of prenasalized stops. *Proceedings of 15th International Congress of Phonetic Sciences*, 407–410.

BEST, C. T., McROBERTS, G. W., & SITHOLE, N. M. (1988). Examination of perceptual reorganization for non-native speech contrasts: Zulu click discrimination by English speaking adults and infants. *Journal of Experimental Psychology: Human Perception and Performance*, **14**, 345–60.

BEST, C. T., & STRANGE, W. (1992). Effects of language-specific phonological and phonetic factors on cross-language perception of approximants. *Journal of Phonetics*, **20**, 305–30.

CHENG, R. L., & CHENG, S. S. (1987). *Phonological structure and romanization of Taiwanese Hokkian* (pp. 41–46; 57–59). Taipei: Student Book.

CUTLER, A., MEHLER, J., NORRIS, D., & SEGUI, J. (1986). The syllable's differing role in the segmentation of French and English. *Journal of Memory and Language,* **25**, 385–400.

CHUNG, R.-F. (1996). *The segmental phonology of southern Min in Taiwan* (pp. 167–216). Taipei: The Crane Publishing.

COTTON, S., & GROSJEAN, F. (1984). The gating paradigm: A comparison of successive and individual presentation formats. *Perception & Psychophysics*, **35**, 41–48.

EILER, R. E., GAVIN, W. J., & WILSON, W. R. (1979). Linguistic experience and phonemic perception in infancy: A crosslinguistic study. *Child Development*, **50**, 14–18.

ELLIOT, L. L., HAMMER, M. A., & EVAN, K. E. (1987). Perception of gated, highly familiar spoken monosyllabic nouns by children, teenagers and older adults. *Perception & Psychophysics*, **42**, 150–157.

FLEGE, J. E., & HILLENBRAND, J. (1986). Differential use of temporal cues to the /s/–/z/ contrast by native and non-native speakers of English. *Journal of the Acoustical Society of America*, **79**, 508–517.

FOX, R. A. (1992). Perception of vowel quality in a phonologically neutralized context. In Y. Tohkura, E. Vatikiotis-Bateson, & Y. Sagisaka (Eds.), *Speech perception, production, and linguistic structure*. Tokyo: IOS press.

GOTTFRIED, T. L. (1984). Effects of consonant context on the perception of French vowels. *Journal of Phonetics*, **12**, 91–114.

HSU, C.-S., & JUN, S.-A. (1996). Prosodic strengthening in Taiwanese: Syntagmatic or paradigmatic? *UCLA Working Paper in Phonetics*, **92**, 69–89.

HUFFMAN, M. K. (1993). Phonetic patterns of nasalization and implication for feature specification. *Phonetics and phonology, Volume 5: Nasals, nasalization, and the velum* (pp. 303–327). Orlando: Academic Press.

IWATA, R., SAWASHIMA, M., HIROSE, H., & NIIMI, S. (1979). Laryngeal adjustments of Fukienese stops. *Annual Bulletin of Research Institute of Logopedics and Phoniatrics*, **13**, 61–81.

JAEGER, J. J. (1986). Concept formation as a tool for linguistic research. In J. Ohala., & J. Jaeger (Eds.), *Experimental phonology* (pp. 211–238). Oralando: Academic Press.

KUHL, P. K., WILLIAMS, K. A., LACERDA, F., STEVENS, K. N., & LINDBLOM, B. (1992). Linguistic experience alters phonetic perception in infants by 6 months of age. *Science*, **255**, 606–608.

LAHIRI, A., & MARSLEN-WILSON, W. (1992). Lexical processing and phonological representation. In G. J. Docherty & D. R. Ladd (Eds.), *Papers in laboratory phonology II: Gesture, segment, prosody* (pp. 229–254). Cambridge, U.K.: Cambridge University Press.

LI, J.-K. (1990). The nasality problem in Minnan. In H. C. Gong & D.-A. Ho (Eds.), *Proceedings of the first international symposium on Chinese languages and linguistics, I* (pp. 210–221). Taipei: Academic Sinica.

LIN, Y.-H. (1989). *An autosegmental treatment of Chinese segments.* Ph.D. dissertation, Unversity of Texas, Austin.

MacKAIN, K. S., BEST, C. T., & STRANGE, W. (1981). Categorical perception of English /r/ and /l/ by Japanese bilinguals. *Applied Psycholinguistics*, **2**, 369–390.

OTAKE, T., & CUTLER, A. (1999). Perception of suprasegmental structure in a non-native dialect. *Journal of Phonetics*, **27**(3), 229–254.
OHALA, J. J., & OHALA, M. (1995). Speech perception and lexical representation: The role of vowel nasalization in Hindi and English. In B. Connell & A. Arvaniti (Eds.), *Papers in laboratory phonology IV: Phonology and phonetic evidence.* Cambridge, U.K.: Cambridge University Press.
PAN, H.-H. (1994). *Voicing contrast of Taiwanese (Amoy) initial voiced stops: Data from adult and children.* OSU Ph.D. Dissertation.
SALASOO, A., & PISONI, D. (1985). Interaction of knowledge sources in spoken word identification. *Journal of Verbal Learning and Verbal Behavior*, **24**, 210–231.
TING, P. H. (1985). *Taiwan yuyan yuanliou* (Sources of languages in Taiwan). Taipei: Student.
TEES, R. C., & WERKER, J. F. (1984). Perceptual flexibility: Maintenance or recovery of ability to discriminate non-native speech sounds. *Canadian Journal of Psychology*, **38**, 579–590.
TUNG, J. C.-H. (1968). *The phonological system of Gaoxiong, a Min dialect of Chinese. POLA 5* (Serial no.2). University of California, Berkeley.
TUNG, J. C.-H. (1988). Nasality and orthography. In H. C. Gong & D.-A. Ho (Eds.), *The structure of Taiwanese: A modern synthesis* (pp. 398–405). Taipei: The Crane Publishing.
TUNG, J. C.-H. (1990). Three ways of treating nasality in South Min. In H. C. Gong & D.-A. Ho. (Eds.), *Proceedings of the first international symposium on Chinese languages and linguistics, II* (pp. 398–405). Taipei: Academic Sinica.
USHIJIMA, T., & HIROSE, H. (1974). Electromyographic study of the velume during speech, *Journal of Phonetics*, **2**, 315–326.
UNDERBAKKE, M., POLKA, L., GOTTFRIED, T. L., & STRANGE, W. (1988). Trading relations in the perception of /r/–/l/ by Japanese learners of English. *Journal of the Acoustical Society of America*, **84**, 90–100.
WANG, H. S. (1995). *Experimental studies in Taiwanese phonology* (pp. 66–85). Taipei: The Crane Publishing.
WANG, H. S. (1999a). A concept formation experiment for Taiwan Min voiced stop consonants. *Symposium Series of the Institute of Linguistics (Preparatory Office)*, Academia Sinica, Number 2 (pp. 233–249). Taipei: Academia Sinica.
WANG, H. S. (1999b). A concept formation experiment for Taiwan Min voiced stop consonants. In *Chinese languages & linguistics V: Interactions in language.* Y.-M. Yin, I-L. Yang, H.-C. Chan (Eds.), Symposium series of the Institute of Linguistics (Preparatory Office), Academia Sinica, Number 2. Taipei: Academia Sinica.
WERKER, J. F., & LALONDE, C. E. (1988). Cross-language speech perception: Initial capabilities and developmental change. *Developmental Psychology*, **24**, 672–683.
WERKER, J. F., & TEES, R. C. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development*, **7**, 49–63.
WU, S.-L. (1987). *The collective basic Minnan Taiwanese Dictionary.* Taipei: Wen Shi Zhe (The Liberal Arts Press).
ZHANG, Z.-X. (1989). *Taiwan Minnan Fangyan Jilyue* (Notes on Southern Min dialects). Taipei: Wen Shi Zhe (The Liberal Arts Press).