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Revisiting Nasal Coda Merger in Taiwan Mandarin: A Corpus Study*

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Taiwan Mandarin allows two nasal codas, [n] and [ŋ]. Previous studies revealed that possible place merger is correlated to sociolinguistic factors. To test whether incomplete neutralization of place contrasts occur acoustically, this study examines potential mergers by questioning whether words with nasal codas are truly merged. By using fine-grained acoustic analysis on a spoken corpus, we discovered that in many cases where neutralization was assumed, sounds are actually incompletely neutralized. Words with a mid vowel preceding the nasal coda tend to be phonetically reduced in connected speech (shortened in nasal murmur duration and produced with the least variation), while words with a low vowel preceding the nasal coda depend on the following place of articulation. Results provide evidence that various vowel heights use different acoustic correlates to maintain place distinctiveness; formant transition and nasal murmur alone are not enough to account for place contrasts in nasal codas in Taiwan Mandarin.

Key words: incomplete neutralization, nasal coda merger, nasal murmur, formant transition

1. Introduction

Past research has revealed that speakers constantly report a pair of sounds as the same, yet consistently differentiate them in production (Labov, Yaeger & Steiner 1972, Yu 2007). This has been labeled the "near merger" of sounds or incomplete neutralization (cf. subphonemic differences in Warner et al. 2004). Past research of incomplete neutralization has mainly focused on final devoicing, the neutralization of voicing contrasts that are maintained in other positions, a phonological process found in a variety of languages such as Polish (Slowiaczek & Dinnsen 1985, Jassem & Richter 1989), German (Fourakis & Iverson 1984, Charles-Luce 1985, Port & O'Dell 1985, Port & Crawford 1989), and Catalan (Dinnsen & Charles-Luce 1984). Although an extensive body of research has investigated voicing contrasts, it remains unclear whether the findings would extend to other instances of neutralization, namely that of the place of articulation.

In an attempt to certify the argument, nasal consonants are a good fit for an inquiry into the relative salience of contrasts due to their notorious confusion in perception (House 1957), yet certain nasal onsets with place contrasts are still common across world languages (Maddieson 1984). The acoustic similarity between

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[n] and [ŋ] renders a weaker perceptual contrast relative to the contrast of [m]-[n] and [m]-[ŋ]. From a dispersion theory point of view, the acoustic spaces occupied by [n] and [m] are maximally distinct (Kurowski & Blumstein 1987). Preferred environments for place contrasts are contexts with the better cue to place contrasts (Steriade 1999b, 2001a, Flemming 2006, among others). Understanding cues to contrasts across contexts provides important evidence for phonological restriction on the distribution of contrasts. For example, Japanese only allows place contrasts in the prevocalic position (Jun 1995, Steriade 1999a). A more interesting question would be how the place contrasts in the post-vocalic perform. Note that place contrasts in the post-vocalic position reveal relatively obscure statuses for discrimination.

In recent studies, speakers of Taiwan Mandarin are believed to merge place contrasts by interchanging coronal nasals [n] and velar nasal [ŋ] in the post-vocalic position. There has been an increasing interest in attributing the cause for nasal coda merger in Taiwan Mandarin to sociolinguistic factors (Hsu 2006, Hung 2006, Hsu & Tse 2007, Fon et al. 2011, Su 2012, Chen 2017). While most of them seem to agree on the effect of the merger of place contrasts, opinions differ in regard to what extent the vowel varies acoustically in different nasal coda contexts. Thus, the aim of this study is to examine how the acoustic cues of formant transition, nasality, vowel ratio and nasal murmur ratio are being used to distinguish place contrasts in nasal codas. Questions to be explored in regard to neutralization of place contrasts include such issues as what the nature of cues in the position that is less perceivable is, whether place contrasts are maintained in a potentially confusable position and to what extent such complete or incomplete neutralizations actually happen in natural speech, since speech is variable not only across speakers but also within a single speaker's production. We will examine a naturally occurring corpus consisting of 7,789 words of nasal place contrasts in the post-vocalic position, and after careful examination, provide evidence of incomplete neutralization of nasal codas in Taiwan Mandarin.

The following sections will discuss relevant issues with regard to the potential nasal mergers in Taiwan Mandarin. The sections are organized as follows. First, we introduce the nasal merger case in Taiwan Mandarin. We broach the issue why the post-vocalic position is less salient for place identification in Section 2. In order to offer new evidence on the issue of decreased perceptibility of place contrasts in coda position gained by systematically screening a largely spoken databank, we explain the corpus we used in this study in Section 3. Section 4 provides the results for four acoustic correlates. Finally, Section 5 discusses implications of these results and section 6 concludes the paper.

2. Literature review

Among Chinese languages, some languages (e.g., Cantonese, Hakka, Southern Min) preserve three nasal consonants [-m, -n, -ŋ] in the coda position, others (e.g., Mandarin, Xiang, Gan) contrast two places of articulation [-n, -ŋ] in the coda position, and yet others (e.g., Jin, Wu, Eastern Min) allow only [-ŋ]. Taiwan Mandarin differs from Beijing Mandarin in pronunciation, lexicon, and even syntax. These variations are attributed to language contact with the local language, Taiwan Southern Min, and they are correlated with several sound change processes. Taiwan Mandarin has five underlying vowels, but only three of them can freely combine with the existing nasal codas [-n] and [-ŋ], as in (1). Possible rime combinations in Taiwan Mandarin are in Table 1.

(1) High vowel [i]

Coronal coda		Velar coda	
[pin]	'customers'	[piŋ]	'ice'
[in]	'reasons'	[iŋ]	'girl's name'
[tɕin]	'right now'	[tɕiŋ]	'whale'

Mid vowel [ə]

Coronal coda		Velar coda	
[pən]	'run'	[pəŋ]	'crash'
[fən]	'seperation'	[fəŋ]	'bee'
[ən]	'honor'	[həŋ]	'hum'
[sən]	'forest'	[səŋ]	'monk'
[kən]	'root'	[kəŋ]	'thick soup'

Low vowel [a]

Coronal coda		Velar coda	
[pan]	'classes'	[paŋ]	'help'
[an]	'safety'	[aŋ]	'dirt'
[san]	'three'	[saŋ]	'funeral'
[kan]	'dry'	[kaŋ]	'vats'

Table 1. Rime combinations of nasal codas in Taiwan Mandarin

	i	y	u[1]	ə	a
-n	in	yn	un	ən	an
-ŋ	iŋ[2]	*yŋ	*uŋ	əŋ[3]	aŋ

One of the debated segmental changes in Taiwan Mandarin is the neutralization of the coronal nasal coda [n] and the velar nasal coda [ŋ] (Lin 2007). The pronunciation of codas [n] and [ŋ] in Taiwan Mandarin is argued to demonstrate neutralization of place contrasts, such that /ɕin ɕiŋ/ 'rising star' is pronounced as [ɕin ɕin]. Such neutralization has been observed in previous studies mainly in the discussion of merging direction (Chen 1973, Chen & Wang 1975, Zee 1985, among others).

A number of studies (Kubler 1985, Tse 1992, Yueh 1992, Hung 2006, Yang 2010) observed that the velar nasal coda [ŋ] is neutralized to a coronal nasal coda [n] in the post-vocalic position. Alveolarization is attested except in words with a low vowel. For instance, [ɕiŋ] 'star' tends to be pronounced as [ɕin] 'new'.

A similar judgment experiment, which recruited participants with varying degrees of language contact with Taiwan Southern Min, further attributed the merging phenomenon to the effects of the local language (Fon et al. 2011). The authors found that people from different dialectal backgrounds show inconsistent sound change patterns. The direction of the merger depends on conflicts of social connotation: they regard merger patterns as negative Min transfer and innovations. Still, other studies that do not agree with the unidirectionality of nasal merger provide evidence for vowel-dependent nasal coda merger (Ing 1985, Lin 2002, Hsu & Tse 2007, Lai 2009, Fon et al. 2011). For example, they claim that [-n] tends to neutralize to [-ŋ] in mid vowel contexts, while [-ŋ] inversely is prone to neutralize to [-n] in high vowel contexts.

The relationship between phonetic perceptibility and phonological patterns has often been discussed in the literature. Speakers tend to neutralize phonological

[1] One anonymous reviewer pointed out that more thoughts should be made on the pronunciations of [un] and [uŋ]. Speakers of Taiwan Mandarin pronounce the rimes differently from such in Beijing Mandarin (Duanmu 2000, Lin 2007). For example, [un] is ill-formed in Beijing Mandarin, leading to schwa insertion [wən], while no schwa insertion exists in Taiwan Mandarin. And a similar case is found with [uŋ]. In addition, Taiwan Mandarin speakers tend to replace [u] in a [uŋ] rime with [ɔ] or [o] (Lin 2007). For example, 'east' is pronounced as [toŋ]/[tɔŋ] in Taiwan Mandarin.

[2] Note that in Beijing Mandarin /iŋ/ surfaces as [iᵊŋ], with a transitional schwa (Duanmu 2000), while the transitional schwa is not attested in the same structure in Taiwan Mandarin. For example, "丁" is pronounced with a less audible transitional schwa in [tiᵊŋ] for Taiwan Mandarin speakers than for Beijing speakers. We appreciate one anonymous reviewer for pointing out the variation.

[3] Lin (2007) pointed out the possible alternation of [o]/[ɔ] in an [əŋ] rime when preceded by a labial consonant.

contrasts in the place that is less perceptible (Steriade 1997, 2001b). In other words, people are prone to avoid changes that are perceptually clear.

As for nasality, it is the integration of acoustics, perception, and articulation. Certain acoustic properties can result in perceived nasalization, such as formant frequency transitions, formant amplitude and anti-formancy, while other acoustic characteristics, such as phonation type and vowel duration, are unrelated to the velopharyngeal opening (VPO). Kurowski & Blumstein (1984) assessed the role of both the nasal murmur and formant transitions as perceptual cues for place across a number of vowel environments. Similarly, Harrington (1994) reviewed several methods of detecting nasal place of articulation and concluded that using both nasal murmurs and vowels to distinguish nasal place results in the highest score of nasal identification.

The acoustic characteristics of CV and NV are roughly equivalent within place since the locus equations[4] of CV and NV are consistent within place and across manner (Sussman & Shore 1996). The perceptual study also confirmed that formant loci at NV juncture serve as cues for nasal place identification (Repp & Svastikula 1988). The observation is consistent with the acoustic similarity between homorganic nasal and oral stops in the pre-vocalic position (Stevens 1998). The results of those studies suggest that both nasal murmurs and formant transition to vowel are robust cues, and onset position provides enough information for those cues to be realized.

Mou (2006) made a comparative experiment on the distribution of acoustic correlates of nasalization contained in the vowel transition and the murmur regions in vowel-nasal environment in English and standard Chinese. Results showed that vowel quality of [a] varied in different nasal coda context in standard Mandarin, while the identical vowel in English did not. Also, more intra-language variation occurred with respect to different vowel heights. The mid vowel /ə/ in standard Chinese shifted in F2 while the high vowel /i/ did not.

To summarize, the studies reviewed so far provide indirect evidence for the previous observations that nasal merger occurs in Taiwan Mandarin. However, it still lacks direct support for how acoustic vowel quality is affected by the different nasal coda contexts. Thus, in order to understand the issue, we need to go back to a more fundamental question: what is the nature of acoustic patterns in VN syllables in Taiwan Mandarin and how do the possible acoustic cues behave in such contexts? Chen (1997, 2000) first replicated the hypothesis in standard Mandarin, showing that both the mid vowel [ə] and the low vowel [a] produced a fluctuation in formant

[4] Locus equations, which specify a fit line from the F2 frequency of the vowel at the release of the consonant to the midpoint of the vowel, are used to characterize consonantal places.

frequencies in anticipation of the following place contrasts. Note that the acoustic results may not be directly compatible in the case of Taiwan Mandarin, but this still serves to shed light on the two dialects' similarly structured phonology systems. Moreover, nasality cues may be biased for a limited number of speakers. Individuals implement different strategies[5] to reach different degrees of VPO (Gick, Wilson & Derrick 2013, Biavati, Wiet & Rocha-Worley 2017), yielding a disparity in coarticulation. Thus, a large number of speakers is required for certifying the phenomenon in question. Taken together, the current study, using a large spoken corpus, aims to investigate the acoustic cues of formant frequencies, nasality, nasal murmur ratio and vowel ratio to understand the nature of place contrasts in Taiwan Mandarin.

3. Corpus

In an attempt to answer the research question above, we used a large naturally occurring corpus for analysis. We briefly introduce the recordings of the data in Section 3.1 and specify the procedure we used on the test materials in Section 3.2. Then, we explain the acoustic feature extraction method in Section 3.3.

3.1 Recordings

We used the naturally occurring corpus Sinica Phone-Aligned Chinese Conversational Speech Database (SPCCSD) (more information in Tseng 2013) as speech material. The database is composed of the speech of 16 participants recruited in Taipei, ages 16 to 45. Participants were invited to do the recordings at the Academia Sinica lab with SONY TCD-D10 Pro II DAT audio recorders and Audio-Technica ATM 33a microphones.

Phoneme boundaries were manually labeled and each boundary was doubled-checked by the author[6]. Pragmatic particles (e.g., fillers and feedback words), uncertain segments and speaker inhalation were detail-coded. All recorded materials were manually labeled by trained phoneticians based on acoustic and perceptual cues

[5] Conventionally, the trapdoor method is the most commonly used way of closing the velopharyngeal port (VPP). A second way is the circular method, which involves contracting the levator palate, velum and superior pharyngeal to squeeze the trapdoor medially; this is possible for at least 20% of people. Another possibility for some speakers (15-20% of people) is to combine VPP closure with Passavant's ridge advancement when articulating nasality (Gick, Wilson & Derrick 2013).

[6] Six transcribers were trained to pass a consistency test prior to the annotation. Each of them was responsible for one third of the recordings. For each segment, there were two sets of annotation data. The averaged timing point was reported as the final result for the boundary. After, the author manually checked all of the labeled boundaries of the target syllables.

using Praat and were marked by hand with one to four points, depending on how many segments occurred in the syllable. For example, [pan] 'move', consisting of three phonemes, was given four points: the initial point for the sound pressure signal after the consonant release, the second point for the voicing bar of the vocalic nucleus, the third point for the boundary of the VN transition and the fourth point for the decrease in amplitude and change in wave shape of the nasal consonant.

We converted the self-coding system in SPCCSD to the corresponding IPA phonemes for ease of data analysis. Non-typical segments perceived by native speaker transcribers, which are still part of the language but mainly serve as discourse fillers or discourse markers originating from Taiwan Southern Min – a major dialect spoken in Taiwan, were also coded accordingly. In total, the corpus comprises 3 hours and 24 minutes of recordings (Tseng 2013).

3.2 Data analysis

In the current study, we extracted target syllables containing nasal codas and open syllables with monophthongs. In Taiwan Mandarin, only three vowels, [i], [ə] and [a], can freely combine with a nasal coda, yielding our test targets, e.g., [pan] 'move' and [paŋ] 'help' for the low vowel [a], [kən] 'root' and [kəŋ] 'cultivate' for the mid vowel [ə], [pin] 'guest' and [piŋ] 'ice' for the high vowel [i]. Onset consonants were included and coded accordingly for data analysis.

Pragmatic particles, non-typical segments and syllables with liaison were all excluded from our analysis. We also set a threshold of 30 ms[7] for vowel duration such that syllables were deleted when vowels lasted less than 30 ms. As a result, 14,435 target tokens were kept and subsequently divided according to syllable types: vowels in open syllables (6,646 tokens) and vowels in nasal coda syllables (7,789 tokens).

All measured features were automatically extracted with the help of a customized Praat script (mainly based on Styler 2015).[8] A series of checks were implemented to detect common errors. For example, F1 is unlikely to be 1500 Hz, and an FFT spectrum will show no peak for measurement. Anomalous numbers, which may have been caused by non-modal voice quality, such as creakiness or laryngealization, were checked against specified thresholds of vowel-relative values, and then rerun. If the procedure still failed, the anomalous numbers were flagged and excluded for the sake

[7] 30 ms is an empirical number for data analysis. In spontaneous speech, syllable duration is often shorter than careful lab speech and based on the author's experience vowel duration which is less than 30 ms is too short for perceptual identification.

[8] The nasality script was mainly coded by Rebecca Scarborough, with bits of code borrowed from Bert Remijsen, Mietta Lennes, and Katherine Crosswhite, and then revised by Styler.

of accuracy. One example is creaky speech, which often results in undefined formant frequencies. According to our method, any valleys in formant frequency greater than 4 dB between the first and second harmonics were rerun and then flagged for exclusion if the anomalous values persisted.

3.3 Acoustic feature extraction

A sequence of acoustic features using a Praat script were collected. A previous study on nasality by Styler (2015) used a series of linear mixed-effect regressions to examine 29 potential perceptual features in an English and French database. The results showed significant oral-to-nasal feature differences, with formant frequencies, A1-P0 and vowel duration resulting in the highest recognition of nasal detection. Based on this finding, we selected these three features as the main acoustic cues for nasal detection.

F1, F2, and F3 values were calculated and logged for three different temporal points—the initial point (p1), the midpoint (p2) and the end point (p3)—in each vowel to observe the trajectory of formant frequency in different nasal coda contexts. Formant frequencies were measured using Praat (version 5.4.22, Boersma & Weenink 2016) and, again, anomalous formant frequency numbers and formant bandwidth were checked and flagged for non-modal voice quality using a Praat script (Styler 2015). Any acoustic differences within the vowel were interpreted as evidence for the indicators of the effect of the place of articulation on the neighboring segment.

A reduction in *A*1, the amplitude of the first formant spectral peak, has been observed to be the primary cue of nasalization (Delattre 1954, House & Stevens 1956, Fant 1960). As observed in previous theoretical studies, the velopharyngeal opening is positively correlated with the coupling of the nasal sinuses, which introduces additional prominent peaks at the lower harmonics in the spectrum of a nasal vowel: one between the first two formants with amplitude *P*1 and one at lower frequency, often below the first formant, with amplitude *P*0 (Chen 1997). The amplitude of these low frequency peaks can increase 3-6 dB for nasal coupling, and are thus considered to be evidence for quantifying nasalization (described most thoroughly in Chen 1997). *A*1-*P*0 is recognized as a standard measure of nasality distinction for non-high vowels, while *A*1-*P*1 is believed to be a good alternative for high vowels (Chen 1995, 1997, 2000, Styler 2015). As noted, when the measurement of the difference between *A*1 to *P*0 and *A*1 to *P*1 is smaller, it denotes an increase in nasalization of the vowel. In other words, a vowel with a larger degree of nasalization would have smaller numbers of *A*1-*P*0 and *A*1-*P*1 due to the lowering of *A*1 and the raising of *P*0 and *P*1.

Moreover, Chen (1997) proposed the adjustment technique to correct the effect of formants on the amplitude of the extra peaks since the location of $P1$ is highly dependent on the formant frequency. For certain vowels, in which F1 and F2 move closer together or toward the nasal peak, the effect of nasal consonants would result in an increase of $P1$, decreasing $A1$-$P1$. The parameters of $A1$-$P1$ and $A1$-$P0$ can be adjusted for vowel type by correcting for the effects of the formant on the amplitude of the extra peaks (Chen 1997). If the frequency of the extra peak is F_{P0}, the frequency of the first formant is $F1$, and the bandwidth of the first formant is $B1$, the effect of the first-formant component at F_{P0} is where F2 is the frequency of the second formant and B2 its bandwidth. T2 is much smaller than T1 since the second formant is further away from the nasal peak in frequency than is the first formant. Therefore, in this study, both $A1$-$P1$ and $A1$-$P0$, and adjusted $A1$-$P1$ and $A1$-$P0$ were reported via the formula proposed in Chen (1997:2363-2364):

$$T1(F_{P0}) = \frac{(0.5B1)^2 + F1^2}{[((0.5B1)^2 + (F1 - F_{P0})^2) \cdot ((0.5B1)^2 + (F1 + F_{P0})^2)]^{1/2}}$$

$$T2(F_{P0}) = \frac{(0.5B2)^2 + F2^2}{[((0.5B2)^2 + (F2 - F_{P0})^2) \cdot ((0.5B2)^2 + (F2 + F_{P0})^2)]^{1/2}}$$

Lastly, vowel duration and nasal murmur duration are both considered relevant for nasality perception (Stevens, Fant & Hawkins 1987, Beddor & Krakow 1999). Delvaux et al. (2008) showed that vowel duration varies in the time course of nasality in French, and Stevens, Fant & Hawkins (1987) argued that the time course of vowel and nasal duration within the syllable are dependent on nasality perception. Therefore, both vowel and nasal duration were included as possible acoustic features for distinguishing vowels preceding nasal codas.

As for normalization of duration, the naturally occurring corpus used in this study is a balanced database. Given that different place of articulation and manner of articulation of onset consonants may exhibit different VOT respectively, it is still lacking as a form of direct evidence that vowel duration compensates when the VOT of the onset consonant decreases. Rochet & Fei (1991) examined the effects of consonantal place of articulation and vowel quality on VOT duration in Mandarin and the results showed that the nature of the vowel had a significant effect on the VOT values of the preceding consonants, while the place of articulation of the consonant was not significant. Moreover, it is argued that different syllable types in Mandarin have different syllable duration (Wu & Kenstowicz 2015). For example, CGVN is

proved to be significantly longer than other syllable types, which indicates the insufficient motivation for vowel duration compensation.

In order to normalize duration for inter-speaker variation and variation across syllable types, vowel duration and nasal murmur were converted to a vowel duration ratio and nasal murmur ratio. Each individual period was self-normalized by the corresponding syllable duration. Raw vowel duration and nasal murmur duration were subsequently converted into a vowel ratio and nasal murmur ratio.

Table 2. Summary of sources of the possible acoustic correlates to place identification of nasal codas

Features of nasality	Description	Studies
Formant frequency	Formant frequency trajectory of vowel, including F1, F2 and F3	Delvaux, Metens & Soquet (2002)
*A*1-*P*0; *A*1-*P*1	Amplitude distance between F1 and *P*0/F1 and *P*1	Chen (1995, 1997); Styler (2015)
Adjusted *A*1-*P*0; adjusted *A*1-*P*0	*A*1-*P*0 and *A*1-*P*1 using Chen correction function	Chen (1997)
Vowel duration	Duration of vowel interval	Delvaux et al. (2008); Stevens, Fant & Hawkins (1987); Styler (2015)

4. Acoustic results

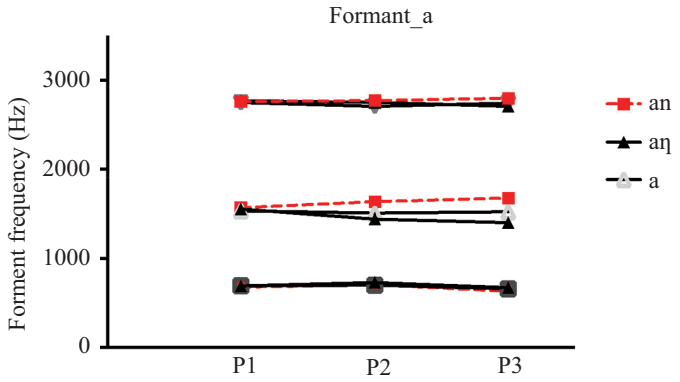
In this section, we report the comparative results of the acoustic measurements, including formant frequency in Section 4.1, nasality in Section 4.2 and duration in Section 4.3.

4.1 Formant frequency

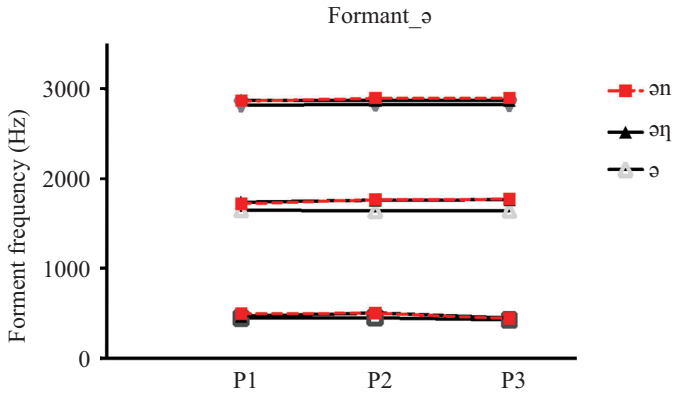
The acoustic results of 16 speakers' production of the three vowels [i], [ə] and [a] in isolation, followed by a coronal nasal coda [n] or a velar nasal coda [ŋ] were examined for formant frequency, A1-P0, A1-P1, vowel duration and nasal murmur.

Figure 1 displays the formant frequencies for three temporal points in the vowels. The data points for initial point (p1), midpoint (p2) and end point (p3) have been averaged across all tokens for visualization. A dashed line with square points represents the values of F1, F2, and F3 for a vowel followed by the coronal nasal coda [n], such as [pan] 'move' or [kan] 'dry', shown in Figure 1a. A solid line with triangle points, on the other hand, represents the formant frequency values of a vowel

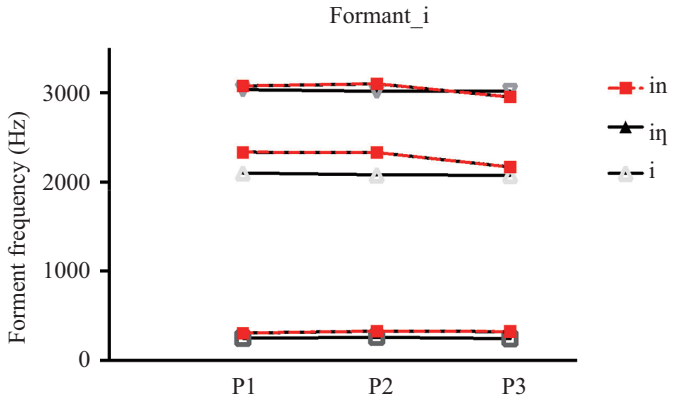
followed by the velar nasal coda [ŋ], as in [kaŋ] 'vat' and [paŋ] 'help' in Figure 1a. And a solid line with a hollowed triangle is the formant frequency value in isolation. Graphs for the mid vowel [ə] (Figure 1b) and the high vowel [i] (Figure 1c) follow the same conventions. Table 3 shows the averaged frequencies for vowels in isolation and in two nasal contexts at three temporal points: initial point (p1), midpoint (p2) and end point (p3).



(a) Averaged formant frequencies of vowel [a] across contexts



(b) Averaged formant frequencies of vowel [ə] across contexts



(c) Averaged formant frequencies of vowel [i] across contexts

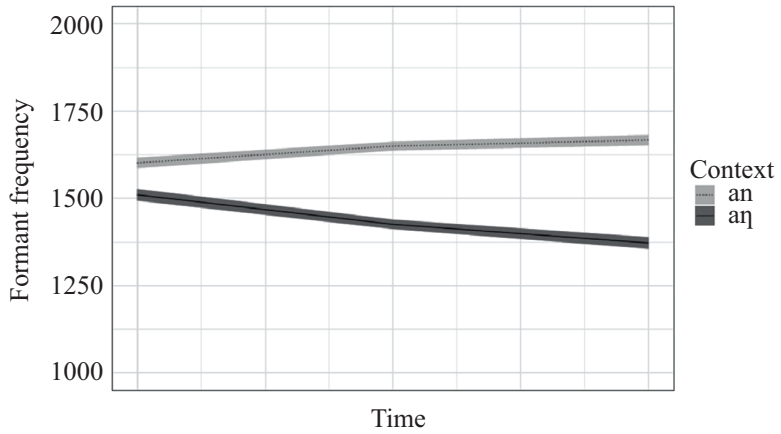
Figure 1. Formant trajectories of [a], [ə] and [i] vowels in three contexts: in isolation, with [n] coda, and with [ŋ] coda

Table 3. Averaged formant frequencies across vowel heights in isolation and in nasal coda contexts

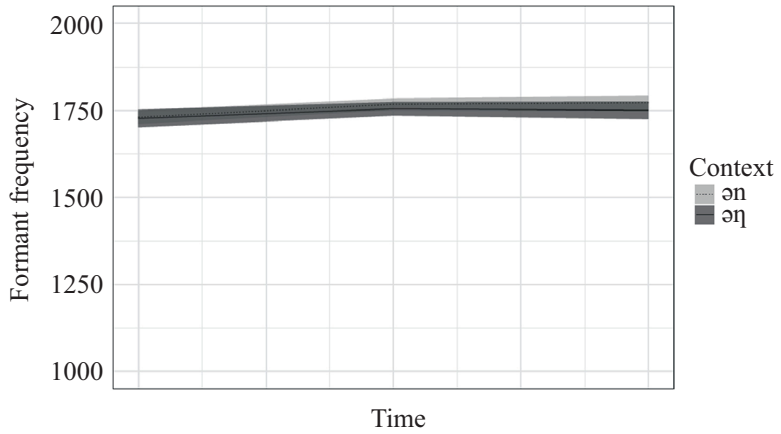
	*P*1				*P*2				*P*3		
	F1	F2	F3		F1	F2	F3		F1	F2	F3
[a]	692.45	1535.3	2748.36		702.68	1509.19	2708.63		664.31	1524.35	2743.02
[an]	672.75	1576.98	2756.75		707.77	1636.68	2755.92		631.83	1678.85	2799
[aŋ]	692.42	1555.51	2751.99		731.25	1447.03	2720.96		673.71	1403.62	2707.23
[ə]	450.79	1652.77	2814.04		452.38	1642.77	2825.93		430.73	1646.58	2822.34
[ən]	499.62	1721.79	2867.41		498.99	1769.16	2890.4		446.84	1773.51	2894.63
[əŋ]	471.21	1740.65	2874.61		497.41	1750.4	2872.28		450.57	1767.7	2871.12
[i]	246.32	2102.73	3034.06		262.38	2081.02	3016.84		245.74	2073.84	3017.83
[in]	266.13	2218.69	3056.74		282.64	2203.19	3092.14		271.76	2040.25	2952.69
[iŋ]	267.54	2226.52	3078.65		278.32	2203.74	3087.73		264.96	1923.7	3011.79

In order to get a better understanding of formant transition patterns, we implement smoothing spline ANOVA (Gu 2002, Davidson 2006) to see if formant transition in two phonological contexts is neutralized or remains distinct. If points from two curves along the time dimension do not overlap, the critical pair in question is statistically proven to be distinct. In Figure 2b, two curves of [ə], those of [ən] and [əŋ], overlap from the initial point to the end point. This overlap indicates that they are statistically indistinguishable in F2. In contrast, the low vowel [a] in the phonological contexts of [-ŋ] and [-n] remains distinct during the time span, since the two curves do not overlap. Interestingly, the curves of the high vowel [i] overlap at first, but then diverge at the end point of the vowel, signifying that the place of articulation of the nasal coda shows local anticipatory assimilation.

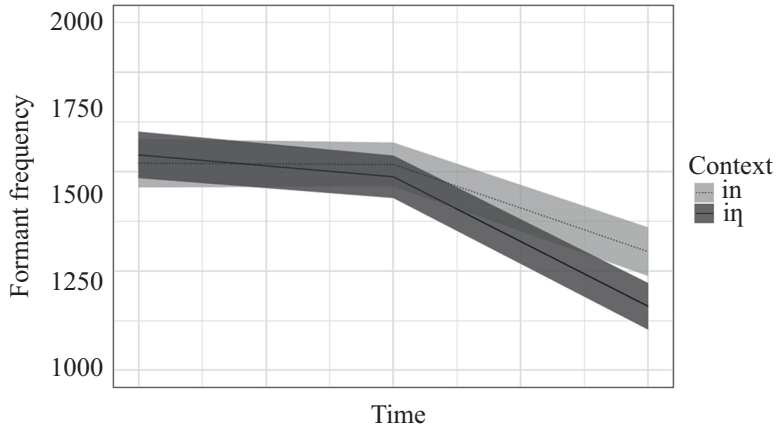
In short, the formant frequencies for the low vowel show that values for F2 increase with the coronal nasal coda but remain low with the velar nasal coda. On the other hand, the mid vowel F2 values neutralize and are indistinguishable in the two nasal coda contexts, while the high vowel values exhibit local anticipatory assimilation at the boundary of the vowel and the nasal coda.



(a) Result of smoothing spline ANOVA of F2 in low vowel [a] in different nasal coda contexts



(b) Result of smoothing spline ANOVA of F2 in mid vowel [ə] in different nasal coda contexts



(c) Result of smoothing spline ANOVA of F2 in high vowel [i] in different nasal coda contexts

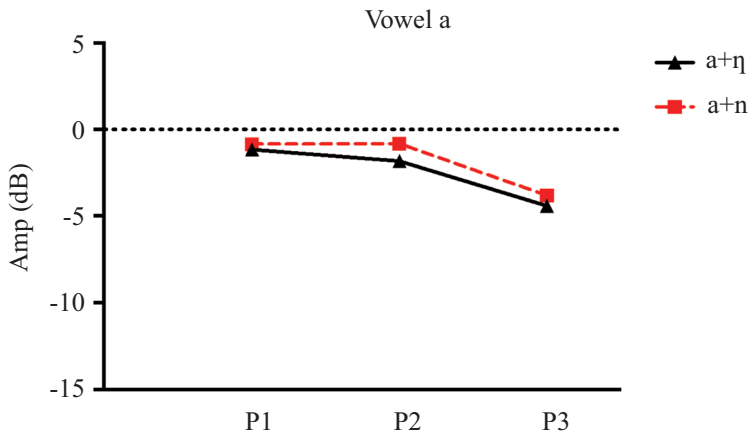
Figure 2. Results of Smoothing Spline ANOVA of vowels in the contexts of two nasal codas

4.2 Nasality

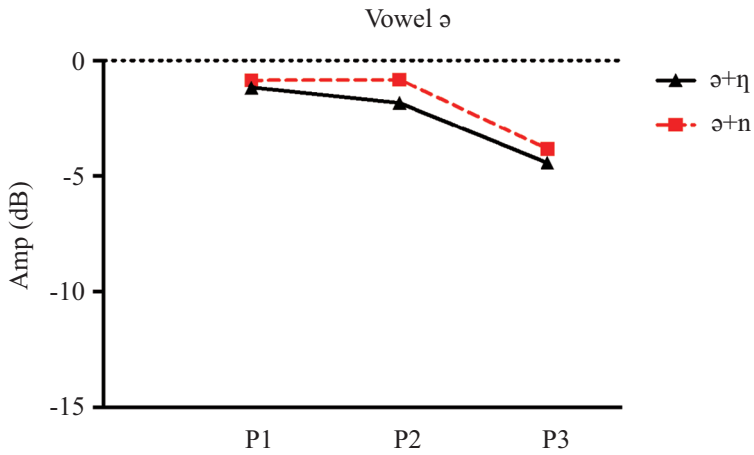
*A*1-*P*0, the amplitude difference of the highest harmonic of F1 minus the amplitude of the nasal peak, is the main cue for nasality detection (Chen 1997, 2000). The value of *A*1-*P*0 is inversely related to nasalization, which means the lower the number, the higher the nasality of the vowel. We also adopted Chen calculation formula to minimize the effects of vowel type and measurement differences.

The measurements of *A*1-*P*0 and *A*1-*P*1 made at three temporal points in the vowel were expected to show changes in the same direction with anticipatory coarticulation of nasality, i.e., lower numbers for the vowel having more nasality than for the vowel having less nasality. For example, for the low vowel [a], *A*1-*P*0 measured in the vowel followed by a coronal nasal coda $(A1\text{-}P0)_n$ is significantly different than that with the velar nasal coda $(A1\text{-}P0)_ŋ$. It is lower in the Vŋ context ($p < 0.01$), suggesting more nasality in this context. In other words, the low vowel [a] has the stronger degree of nasality in –ŋ context. The mid vowel [ə] and the high vowel [i], on the other hand, neutralize across place, as shown in Table 4.

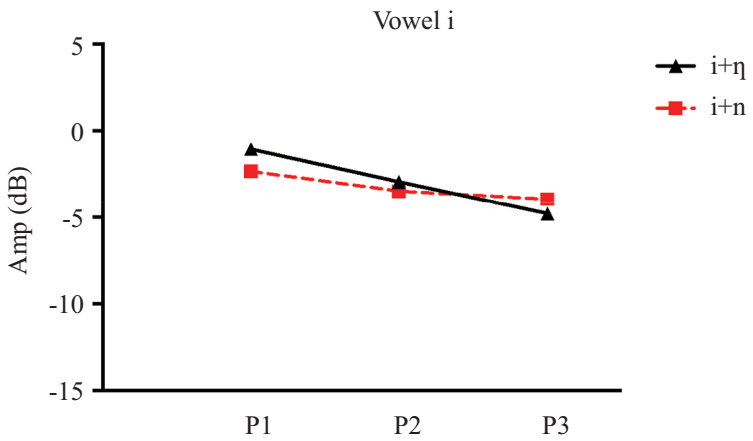
Figure 3 shows the values of *A*1-*P*0n, which are obtained by plotting *A*1-*P*0n over time at three evenly-spaced time points over the entire vowel, in three contexts: without nasal coda, with [-n] coda and with [-ŋ] coda. The haloed circle represents values obtained from an open syllable, i.e., without nasal codas. The negative values reflect a corresponding degree of velopharyngeal opening. In general, vowels in the velar coda context are found to have more negative values, which indicate a greater degree of nasalization.



(a) Averaged adjusted A1-P0 values of vowel [a] in -n/-ŋ context for speaker 16



(b) Averaged adjusted A1-P0 compensated values of vowel [ə] in -n/-ŋ context for speaker 16

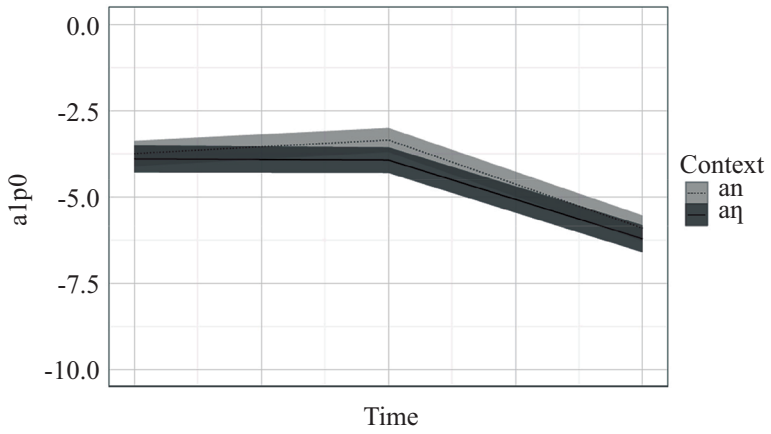


(c) Averaged adjusted A1-P1 compensated values of vowel [i] in -n/-ŋ context for speaker 16

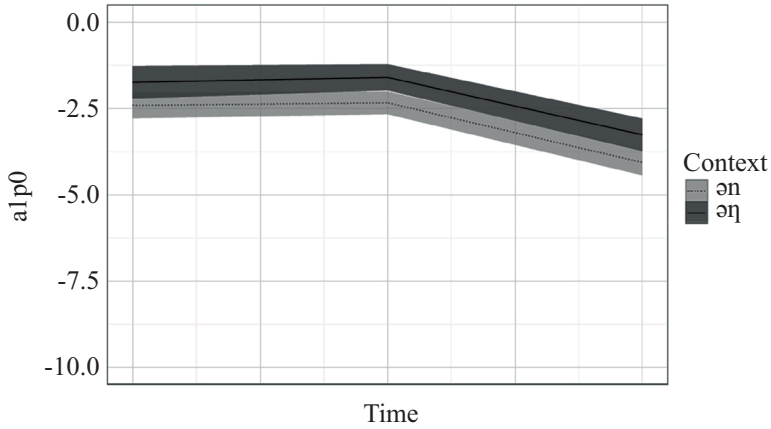
Figure 3. Averaged adjusted A1-P0/A1-P1 values of vowels in the contexts of two nasal codas

Again, SSANOVA is implemented to help distinguish if nasality differs in the two nasal coda contexts. The curves for [iŋ] and [in] of the SSANOVA results in Figure 4c overlap in the beginning but are significantly distinct from the midpoint to the end point. Similarly, two curves for the mid vowel [ə] slightly overlap in the beginning, but remain distinct from the midpoint. By contrast, it is evident in Figure 4a that the nasality curve of [an] overlaps with that of [aŋ] for (almost) the entire duration.

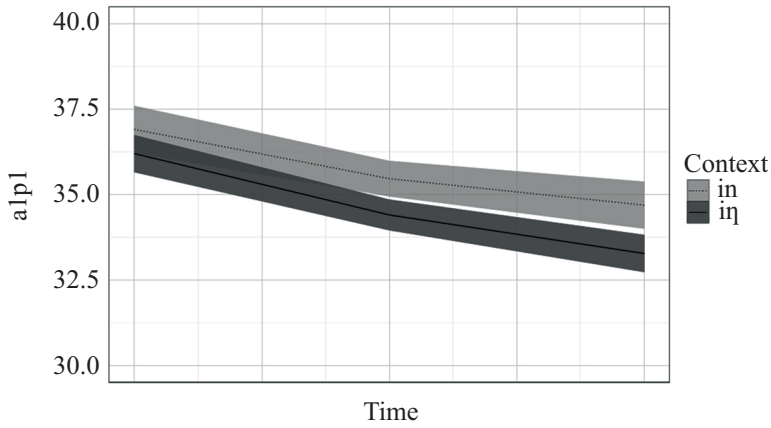
In sum, our analysis shows that nasality in syllables with [-n] coda and [-ŋ] coda is not completely neutralized for non-low vowels, whereas it is neutralized for the low vowel.



(a) SSANOVA result of adjusted A1-P0 values of vowel [a] in -n/-ŋ context for speaker 16



(b) SSANOVA result of adjusted A1-P0 values of vowel [ə] in -n/-ŋ context for speaker 16



(c) SSANOVA result of adjusted A1-P1 values of vowel [i] in -n/-ŋ context for speaker 16

Figure 4. Results of Smoothing Spline ANOVA of adjected A1-P0/A1-P1 values in the contexts of two nasal codas

4.3 Duration

The effect of word length on nasal place identification is another focus of this study. There are two measurements of duration: vowel duration and nasal murmur duration. Nasal murmur is argued to be an important acoustic cue for the place of articulation (Malécot 1956, Recasens 1983, Kurowski & Blumstein 1987, Qi & Fox 1992).

Syntactically, the syllables before pauses are found to lengthen in syllable duration by about 60-200 ms, i.e., prepausal lengthening (Oller 1973, Klatt 1975).[9] Normalized nasal murmur ratios are shown in Table 4. The nasal murmur ratio equals the duration of the nasal murmur divided by the duration of the syllable and indicates the nasal murmur proportion of the syllable. When the syllable is lengthened in the prepausal position, the ratio for nasal murmur will remain stable.

A two-way ANOVA analysis shows that vowel height and place contrast in the coda both have a significant impact on the nasal murmur ratio ($p < 0.0001$). The significant effect of place contrast shows that the nasal murmur ratio of [ŋ] is generally longer than that of [n]: the averaged nasal murmur ratio of [ŋ] is 0.37; the averaged nasal murmur ratio of [n] is 0.34. Most importantly, place contrast in the nasal coda and vowel height show a significant interaction effect. A contrast analysis comparing vowel height shows that [ŋ] is significantly longer than [n] in the [aN] context, and, similarly [ŋ] is proved to be longer in the [iN] context. However, the difference of duration between [ŋ] and [n] is insignificant in the [əN] context, as shown in Table 4.

Table 4. Mean nasal murmur ratios

aN		əN		iN	
[n]	[ŋ]	[n]	[ŋ]	[n]	[ŋ]
N=2558	N=2841	N=2802	N=934	N=515	N=877
30.55%	36.33%	38.59%	38.79%	33.24%	38.93%
****				****	

As for vowel ratio, significant main effect is obtained for vowel height [$F(2, 7789) = 292.285$, $p < 0.0001$]. The main effect of place contrast in the nasal coda fails to reach significance [$F(1, 7789) = 0.142$, $p = 0.706$]. However, vowel height and place contrast in the nasal coda have a significant interaction effect

[9] Comments from the anonymous reviewer were extremely helpful in shaping the discussion in this section.

[F (2, 7789) =170.918, $p < 0.0001$], signifying the possibility of distinguishing place contrast in the nasal coda in different vowel height contexts. The mean vowel ratio by place contrast in the nasal coda is plotted in Figure 5. A red circle indicates the vowel ratio preceded by the coronal nasal coda [n], and a black square represents the vowel ratio preceded by the velar nasal coda [ŋ]. The low vowel [a] and the high vowel [i] are longer when followed by [n]. However, the result is inverted for the mid vowel [ə].

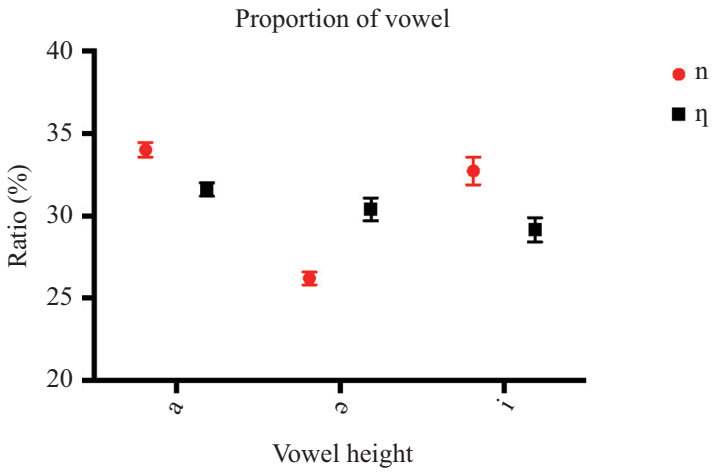


Figure 5. The proportion of vowel duration (vowel ratio)

5. General discussion

Our results illustrate patterns of incomplete neutralization of the ongoing nasal coda mergers in Taiwan Mandarin and suggest that different acoustic cues are used by different vowel heights to maintain contrast in place of articulation, as shown in Table 5. In this section, we discuss the findings from the previous production experiment.

Table 5. Summary of acoustic cues to distinguish nasal codas across vowel heights

	Formant frequency	Nasality	Nasal murmur ratio	Vowel ratio
[a]	✓	×	✓	✓
[ə]	×	✓	×	✓
[i]	✓	✓	✓	✓

First, different acoustic correlates are responsible for the preservation of place contrasts across vowel heights. For instance, place contrasts for [a] can be detected by formant frequencies, the nasal murmur ratio and the vowel ratio, while place contrasts for [ə] can only be detected by nasality and the vowel ratio. Previous studies have focused on the roles of formant transition and nasal murmur for distinguishing place across vowels (Kurowski & Blumstein 1984). However, our results show that formant transition and nasal murmur alone are not enough to account for place contrasts in nasal codas in Taiwan Mandarin, especially for the mid vowel [ə]. For example, the formant transitions for [ən] and [əŋ] exhibit similar trajectories (see Figure 2b). Furthermore, the nasal murmur ratio of [n] and [ŋ] is indistinguishable in the mid vowel context. Therefore, the possible acoustic cues for distinguishing two near mergers in mid vowel contexts in Taiwan Mandarin are nasality and the vowel ratio (i.e., [ə] is significantly longer when it is followed by coda [ŋ]).

Second, the formant frequency patterns of results in the low vowels agreed with previous acoustic experiments (Lin & Yan 1991, Mou 2006, Hsu & Tse 2007, Lai 2009). For example, the end point of F1 for [a] with nasal coda [n] is significantly lower than with nasal coda [ŋ], indicating a higher tongue position toward the end of the vowel with an intended [n] as the syllable coda (as in Figure 1). The trend found in frequency differences exists from the initial point of the vowel, suggesting that anticipatory coarticulation of tongue height involves the entire vowel duration. On the other hand, averaged F2 values showed a corresponding trend, for which the F2 value decreases for the nasal coda [ŋ], suggesting a more retracted tongue position. It is obvious that the low vowel [a] is distinct in different nasal coda contexts. The production of the vowel [a] is highly dependent on the subsequent consonant. The current acoustic results lend support to Rhyme Harmony (Duanmu 2000). This is in fact the case: the low vowel [a] is expected to be more anterior in [an] and, accordingly, is expected to be pulled backward in [aŋ].

Third, formant frequency data for mid vowels in Taiwan Mandarin reveal a lesser degree of contextual variation in syllables having nasal codas. The nature of mid vowel schwa [ə] is different from its realization in English, Dutch (Booij 1995) or Southern Italian dialects (Maiden 1995), where the vowel quality is reduced or neutralized. It is frequently observed that the quality of schwa in languages such as English and Dutch varies substantially across contexts. The answer to the phenomenon in question as to why the mid vowel in Taiwan Mandarin exhibits a lesser degree of contextual variation in syllables having nasal codas is still not clear. Phonologically speaking, Lin (2007) claims that the phoneme [ə] undergoes fronting [e], rounding [o] and backing [ɤ] accordingly, and it surfaces as [ə] in syllables with nasal codas (cf. Cheng 1973). Simply put, there is a four-way contrast for mid vowels,

namely, [e-ə-ɤ-o], in the surface representation. It seems that the number of phonetic vowels may constrain the degree of contextual variation. However, more follow-up research, such as if the other three phonetic vowels [e], [o] and [ɤ] also show less contextual variation, is needed.

6. Conclusion

This study aims to understand the nature of the quality of vowel in different contexts with place contrasts. We looked at the acoustic attributes for three vowels, [a], [ə] and [i], with nasal codas in a spoken corpus. We found that Taiwan Mandarin is undergoing segmental sound changes, and that the featural reduction in place contrasts is highly dependent on vowel height. Mid vowels with nasal codas show more cue reduction but less contextual variation, while low vowels with nasal codas strictly depend on the following segment's place of articulation. The results of this study illustrate that although the proposed nasal merger is believed to occur, the potential nasal coda mergers still maintain place distinctiveness in the post-vocalic position, and additionally, that formant transition, nasality, the nasal murmur ratio and the vowel ratio are all responsible for distinguishing contrastive place of articulation in Taiwan Mandarin.

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台灣華語鼻音韻尾合流的語料庫研究分析

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台灣華語鼻韻尾合流的文獻中，許多文獻聚焦在討論不同發音位置的鼻韻尾合流和語者的語言背景等社會語言學的關連性。但本研究將焦點拉回最基本的討論：台灣華語的鼻韻尾[-n]與[-ŋ]在聲學特徵上是否仍保持著位置上的對比抑或是已呈現合流，以及哪些聲學特徵可以如實呈現鼻音韻尾發音位置的對比。本研究使用大量的語料庫語音資料進行聲學分析，研究結果顯示，鼻音韻尾呈現不完全合流，而且單獨使用頻率走向或鼻音噪音解釋在台灣華語中鼻音發音位置的對比是不足的。其中不同位置的元音各自使用不同的聲學特徵去維持發音位置的對立，例如：若單看頻率走向或是鼻音噪音位置，央元音後的鼻音韻尾發音位置的聲學特徵趨向中合弱化，但卻可區辨低元音後的鼻音韻尾的發音位置。

關鍵詞：不完全中合現象、鼻音韻尾合流、鼻音共鳴區、頻率走勢