FORMANT TRANSITIONS AS EFFECTIVE CUES TO DIFFERENTIATE THE PLACES OF ARTICULATION OF BAN PA LA-U SGAW KAREN NASALS[1]

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Abstract

The Sgaw Karen dialect of Ban Pa La–u, Amphoe Hua Hin, Thailand, has four nasals: /m/, /n/, /ɲ/, and /ŋ/, that appear in syllable–initial position. Review of the relevant literature indicates that initial /ɲ/ has been less studied acoustically due to the lack of palatal nasals in the consonant systems of most languages. Thus, this Sgaw Karen dialect is suitable for investigating the place of articulation of nasals.

The acoustic characteristics examined include the duration, intensity, and frequencies of the formants (resonances) of the nasal murmurs as well as the frequencies of the formant transitions into the following vowels /a/ and /ɔ/. The significance of each acoustic characteristic as a place cue has been statistically tested with ANOVA and Tukey's HSD.

The results confirm the previous findings (Liberman, Delattre, Cooper and Gerstman 1954, Malécot 1956, Recasens 1983, Harding and Meyer, 2003) that transitions provide better cues for differentiating place of articulation for nasals. Furthermore, this study found that among the formant frequencies in a formant transition, the F2 transition provides the most effective cue to identifying the places of nasal articulation, i.e. /ɲ/ has the highest F2 frequency value at the nasal–vowel juncture, followed by /n/, /ŋ/, and /m/, respectively. The relational pattern between F2–F3 transitional directions can also aid in differentiating nasal articulation places; however, the pattern of transitional direction depends on vocalic context. The F2–F3 transitional patterns among the places of articulation clearly differ in the /ɔ/ context. In the case of a following /a/, the F2–F3 transitional patterns for /n/ and /ŋ/ are very similar and do not act as a place cue. Although the second nasal formant (NF2) evinces consistent relational patterns, differences among /m/, /n/, and /ɲ/ are not statistically significant, implying their similarity. Likewise, neither intensity nor duration of nasal murmurs can be used as cues to differentiate place of articulation for nasals.

1. Introduction

In the production of nasal sounds, the oral and nasal cavities are coupled by the lowering of the velum. As a result, the acoustic characteristics of nasal sounds are more complex than those of purely oral sounds. In the case of nasal

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consonants, there is an obstruction in the oral cavity, but the velum is lowered, allowing air to flow through the nasal cavity. The nasal cavity acts as the main resonator, while the oral cavity acts as a side branch, absorbing sound energy. According to Ohala (1975), since the nasal cavity is fixed in shape and size, the nasal formants caused by resonance in the nasal cavity are similar for the various places of articulation. The first nasal formant (NF1) is very low in frequency. Formants above the first nasal formant are low in energy. On the other hand, the antiformant corresponding to sound energy being absorbed in the oral cavity varies from one place to another. The shorter the oral tract is, the higher the antiformant frequency value becomes. The antiformant can, then, serve to differentiate place of articulation for the various nasal stops.

Place contrast for nasals has been acoustically and perceptually studied to find what the best cue to place of articulation is. Some studies have found that nasal murmurs consisting of nasal formants and the antiformant act as place cues. Others have argued that transitions provide better cues. However, due to the limited number of languages being examined, only three places of articulation have commonly been investigated, i.e., bilabial, alveolar, and velar. The database compiled by Maddieson and Precoda (1984) reveals that the bilabial nasals are found most frequently in world languages, followed by velar, alveolar, and palatal, in descending order of frequency. Study of palatal nasals has been rare. Fortunately, nasal sounds in the Sgaw Karen of Ban Pa La–u in Hua Hin District are articulated in four places of articulation, i.e., bilabial, alveolar, palatal, and velar, thus offering an excellent opportunity to examine the cross–linguistically rare nasal /ɲ/.

According to Matisoff (2008), the Sgaw Karen language belongs to the Karenic branch of the Tibeto–Burman language family. In Thailand, Sgaw Karen people are mostly found in the northern and western provinces. In this study, the Sgaw Karen dialect spoken at Ban Pa La–u, located in Hua Hin District, Prachuap Khiri Khan Province, has been examined. The population of Ban Pa La–u numbers one thousand one hundred and is made up of Sgaw, Pwo, and Thais. Most of the Karen people are Christian, although some are Buddhist. Their birth places vary; some were born in the village, some in Myanmar and some around the Myanmar–Thailand border. My Sgaw Karen informants speak both Thai and Sgaw. See the sound inventory of the Ban Pa La–u Sgaw Karen in Table 1 and 2.

To find nasal place cues, both nasal murmurs and formant transitions have been widely examined. Some studies have examined data from natural speech, while others have conducted experiments using synthetic speech. The results of these previous studies suggest that formant transitions provide better cues for differentiating place of articulation; however, nasal murmurs also play a place–contrastive role. The relational patterns among the nasal formants and antiformants of nasal murmurs and the formant frequencies of formant transitions reported in these various studies have been fairly consistent.

Table 1 Sgaw Karen Consonant System

Manner \ Place	bilabial	alveolar	palatal	velar	glottal
stop	ph p b	th t d	ch c	kh k	ʔ
nasal	m	n	ɲ	ŋ	
fricative		s		x ɣ	h
trill		r			
approximant	w	l	j		

Only /ʔ/ can occur in final position.

Table 2 Sgaw Karen Vowel System

Height \ Advancement	front	central	back
high	i	ɨ	u
mid	e	ə	o
low	ɛ	a	ɔ

Two diphthongs, /ai/ and /au/, are found.

There are four tones in Sgaw Karen:

Tone 1 is a mid tone with the phonetic realization [33] in non–checked syllables.

Tone 2 is a low tone with the phonetic realization [21̤] or [21] in non–checked syllables.

Tone 3 is a high tone with the phonetic realization [44] in non–checked syllables.

Tone 4 is a falling tone with the phonetic realization [452] in non–checked syllables.

1.1 Nasal murmurs

Nasal murmurs have been found to be potential cues in differentiating the places of articulation in some studies (Malécot 1956, Recasens 1983). Nasal murmurs occur during the closure phase of nasal stop production and consist of nasal formants (NF) and an antiformant (NZ). Nasal formants arise from resonance in the nasal cavity, which functions as the main resonator. Ohala (1975) has argued that nasal formants tend to be stable across different places of articulation due to the fixed size and volume of the nasal cavity. Ohala (1975), Recasens (1983), and Harding and Meyer (2003) state that the first nasal formant (NF1) occurs at about 200–300 Hz and has more energy than other nasal formants, which occur at higher frequencies. Furthermore, the disappearance of energy at certain frequencies is the result of energy absorption in the oral cavity. According to Ohala (1975), the antiformant frequency is inversely proportional to the length of the oral cavity. A longer oral cavity produces a lower antiformant frequency. Comparisons of the nasal murmurs for different places of articulation have shown that the highest to lowest frequency values for NF1 run from /ŋ/ through /ɲ/ and /n/ to /m/. As for the antiformant, /ŋ/ likewise has the highest frequency value, followed by /ɲ/, /n/, and /m/. Moreover, the antiformant lies close to a particular nasal formant at each place of articulation, i.e., NZ is close to NF2 of /m/, NF3 of /n/, NF4 of /ɲ/ and NF4 or higher of /ŋ/. Furthermore, perceptual studies such as Dukiewicz (1967), House (1957), Nakata (1959), Henderson (1978) (as cited in Recasens 1983: 1346), Malécot (1956) have found that the murmurs of /m/ and /n/ were quite effective in allowing identification of place of articulation, with /m/ receiving the highest correct score due to its having the lowest nasal formant and antiformant of all the nasal stops, and Ohala (1975) and Recasens (1983) have claimed that /ŋ/ is distinguishable from /n/ and /ɲ/ due to its higher NF1 value and the lack of an antiformant in the middle of the nasal spectrum.

1.2 Formant transitions

Formant transitions have been proven to be effective cues in distinguishing place of articulation for nasals, especially with respect to the second formant (F2). Formant transitions start from the release of the consonant and move toward the more–or–less steady state of the vowel. F2 has been the focus of place cue studies since its transitional direction and frequency value at the nasal–vowel juncture has proven to be a cue in many acoustic–perceptual studies. Studies on the contrastive role of transitions have shown that transitions following nasal initials differ by places: a rising transition follows /m/; a flat or falling transition depending on vowel type follows /n/ (Liberman et al. 1954, Recasens 1983) a falling (Liberman et al. 1954) or a slightly rising, falling, or flat transition follows /ŋ/ and a falling transition follows /ɲ/ (Recasens 1983). Additionally, some studies have found that the first formant (F1) and third formant (F3) aid in differentiating place of articulation (Recasens 1983, Narayan 2008).

Although F1 is not usually examined because all final nasals show the same falling transition, various studies (Recasens 1983) have found that the degree of fall differs among the various place of articulation. F1 transitions fall the farthest for /ɲ/ and the least for /ŋ/, with /m/ and /n/ lying in between. This means that /ŋ/ has the highest F1 value at the nasal–vowel juncture, followed by /m/–/n/ and /ɲ/, in that order.

Narayan (2008) has found that the F3 value at the nasal–vowel juncture helps to distinguish between /n/ and /ŋ/, which have similar F2s. Furthermore, Recasens (1983) has found that F3 falls between /n/ and a vowel, while it rises after /ŋ/. However, results for F3 transitions vary from study to study. Some have found that the F3 transition falls for /m/, /n/ and /ŋ/ after vowels and rises for /ɲ/ (Magdics 1969, Vagges, Ferrero, Caldognetto–Magno, and Lavagnoli 1978, Dukiewicz 1967 and Fant 1960, all cited in Recasens 1983: 1347), but Recasens (1983) has found that the F3 transition after vowels falls for /m/ and /ŋ/ but rises for /n/ and /ɲ/.

This study aims to find effective cues for differentiating place of articulation of four initial nasals: /m/, /n/, /ɲ/, and /ŋ/, in the Sgaw Karen dialect of Ban Pa La–u, with the primary focus being the palatal nasal /ɲ/, which has been less studied acoustically. The acoustic parameters that were taken into account were the intensity, duration, and formant frequency of the nasal murmurs and the formant frequency of the formant transitions of /a/ and /ɔ/. Although, a review of the relevant literature shows intensity and duration to be considered generally poor place cues, they were examined in this study to verify the previous claims. The hypotheses of this study are (1) that formant transitions, especially F2, provide better cues for distinguishing place of articulation for nasal stops and (2) that of the four nasals, /n/ and /ŋ/ share the most similar acoustic characteristics.

2. Methods

2.1 Participants

Seven Sgaw Karen females aged between 19 and 43 were recorded. All speakers had Sgaw parents; however, their birth places varied. Some had been born on the Thai–Myanmar border, some had been born in Prachuap Khiri Khan Province, and one had been born in Myanmar. Females were chosen to avoid variation between genders; however, the participants' ages varied because of the difficulty in finding participants and the limited working time. Given the eight–day time limit, it was hard to find ideal participants since most Sgaw Karen people had to go to work. Therefore, in order to complete the field record on time, I controlled age range as much as possible, and most participants were between 30 and 43 years old, with one speaker of 19 and another of 24. Despite the wide age range, analysis showed that age had not affected the acoustic results.

2.2 Corpus and setup

The corpus consisted of two word lists, one containing words with the vowel /a/ and the other words with /ɔ/. These were chosen because /a/ and /ɔ/ were the only two vowels that co–occurred with all 4 initial nasal stops. In both lists, the four nasals /m/, /n/, /ɲ/,[3] and /ŋ/ were in syllable–initial position. Here are

[3] /ɲ/ indicates a palatal nasal with an offglide.

the test words with their meanings: in /a/ context, *ma1* 'do' or *ma3* 'wife', *na1* 'you' or *na3* 'ghost', *me2ɲa1* 'front', *ŋa1/do2ŋa1* 'hire'; in the /ɔ/ context, *mɔ3* 'bite (classifier)', *nɔ3* 'older sister', *ɲɔ3* 'easy' and *ŋɔ3ŋaʔ2* 'dumb'[4]. In the /a/ context, *ma3* and *na3* were substituted for *ma1* and *na1* in case the recorded sound of words with a mid level tone was not of good quality.[5] Although three test words were disyllabic, the syllable under examination in all these words, except *ŋɔ3ŋaʔ2*, was stressed, which was assumed to have characteristics similar to those of monosyllabic words. Word lists were recorded in mono through a Sony ECM–719 microphone via a Creative USB Sound Blaster Play into a Lenovo notebook at a sampling rate of 16 kHz using Praat version 5.2.2.6. The Praat program was suitable for recording in this study due to the limited time and the surrounding environment. The data were collected over eight days of fieldwork, and the short time and noisy environment, where uncontrolled sounds from rain, animals, passing vehicles, etc. could not be avoided, were not ideal for recording. Therefore, sounds recorded with Praat had to be checked immediately to see if they were clear enough for further measurement and analysis. The speakers were asked to hold the microphone about 5″ from their lips, which pretesting revealed to be the optimal distance, and to pronounce each word in the list at least 5 times. The total number of recorded test words was 280 (8 words × 5 times × 7 participants).

2.3 Acoustic analysis

Two characteristic parts of the acoustic signal were examined: nasal murmurs and formant transitions of the following vowels. Segmentation was based on waveform and wide–band spectrogram. Nasal murmurs were measured from the first periodic pulse to the beginning of the subsequent vowel, which was signalled by a high–amplitude periodic pulse. Formant transitions were measured from the nasal murmur offset to the beginning of the vocalic steady state, signalled by the end of F2 distortion. See Figure 1 for an example of segmentation.

In the nasal murmur phase measurement were taken of acoustic characteristics including intensity, duration, and nasal formant frequency. Murmur intensity was measured at three positions: 0%, 50%, and 100%. These positions were chosen because the transitional directions in all nasal contexts were the same; therefore, it was not necessary to measure at additional positions. Murmur duration, corresponding to the period from the point where the nasal murmurs began with the first periodic pulse to the beginning of the vowel, was measured. Only nasal formants in the /ɔ/ word list were examined due to sound quality. The first, second, and third nasal formants (NF1, NF2, NF3) were measured at 25%, 50%, and 75% of the total nasal murmur duration to ensure that the frequency values truly belonged to the nasal formants. In the formant transition phase, the first, second, and third formants (F1, F2,

[4] Tone numbers 1–4 used here match those given earlier in this paper.

[5] This happened with only one informant. It was not clear why she uttered words containing /a/ and a mid tone with more breath. Therefore, words were recorded that had the same structure except for the tone, resulting in test tokens suitable for further acoustic analysis.

Figure 1 Segmentation of nasal murmurs /n/, transition signalled with ‘t’ and /ɔ/ vowel

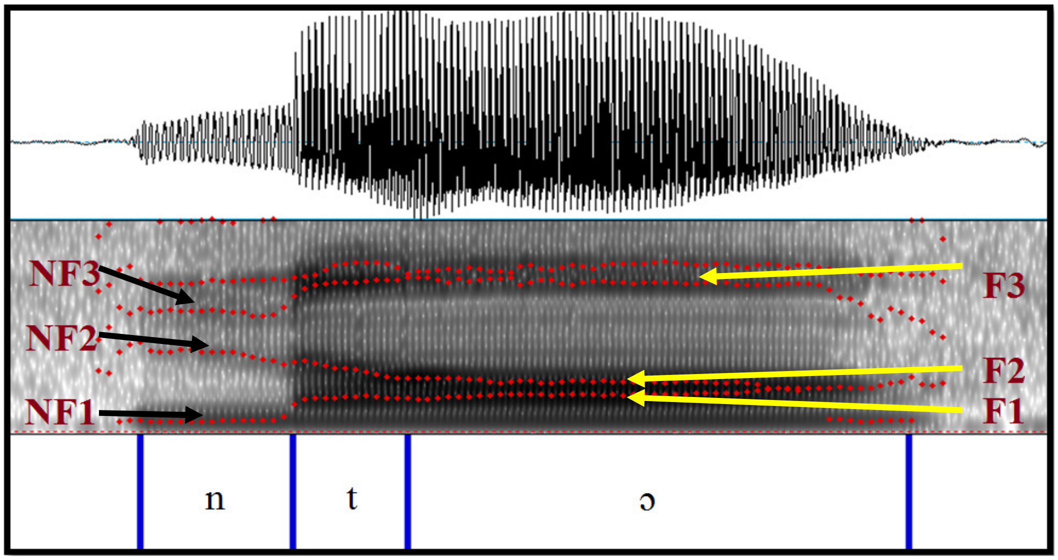


Table 3 Mean ($\overline{x}$) and Standard Deviation (SD) Values for Intensity (dB) during Murmurs

vocalic context	position	value	place of articulation			
			m	n	ɲ	ŋ
a	0%	$\overline{x}$	53.07	51.07	50.43	49.05
		SD	6.69	5.32	4.70	7.34
	50%	$\overline{x}$	58.78	56.96	53.41	54.32
		SD	6.20	5.71	5.26	6.94
	100%	$\overline{x}$	62.20	61.42	58.90	54.84
		SD	8.83	6.19	6.16	8.09
ɔ	0%	$\overline{x}$	47.69	48.10	47.13	46.53
		SD	4.88	3.81	3.16	3.64
	50%	$\overline{x}$	54.19	54.42	54.59	52.97
		SD	4.54	3.50	3.25	3.13
	100%	$\overline{x}$	59.84	59.27	58.39	57.93
		SD	7.20	4.75	4.49	4.08

F3) were each measured at five positions: 0%, 25%, 50%, 75%, and 100% of the total formant transition duration. These positions were chosen to enable transitional direction graph plotting.[6] The frequencies of the nasal murmur formants and of the formant transitions were obtained automatically using Praat's formant tracker (LPC analysis).

2.4 Statistics

The significance of each acoustic characteristic as a cue in differentiating place of articulation for nasal stops was statistically tested with ANOVA (analysis of variance) and Tukey's HSD, a multiple comparison test. ANOVA provides the means to test whether several groups differ significantly. It is suitable only for comparing more than 2 groups. The T–test was not chosen because it is suitable only for comparing 2 groups, resulting in a higher chance of committing an error. However, ANOVA only tells us whether there are statistically significant differences among groups. It cannot identify which pair is significantly different. Therefore, Tukey's HSD is required to find out which pairs differ significantly.

3. Results

3.1 Intensity

Intensity was not a cue for differentiating place of articulation since it showed no regular pattern either within a vowel or between two vowels. See the mean and SD values for intensity (dB) measured from 0%, 50% and 100% of nasal murmurs in Table 3.

The measurements were submitted to ANOVA and Tukey's HSD. ANOVA revealed no statistically significant difference among nasal places of articulation in the /ɔ/ context, but there was a statistically significant difference among nasal places at the 50% and 100% position in the /a/ context with $p < 0.01$. The results of Tukey's HSD revealed that the intensity values of /m/ were significantly greater than those of /ɲ/ with $p < 0.05$ at the 50% and 100% position. The intensity value of /m/ was significantly greater than that of /ŋ/ with $p < 0.05$ at 50%, and the intensity value of /n/ was significantly greater than that of /ɲ/ with $p < 0.01$ at 100%.

Although some statistically significant differences were found in the /a/ context, they were not consistent across every position in both vocalic contexts. Moreover, when compared with studies examining the acoustic characteristics of stops and nasals with different places of articulation (Trongdee 1987, Tarnsakun 1988), the intensity results showed no regular relational pattern of intensity in different places. Therefore, intensity could not distinguish nasal places of articulation. This result accords with intensity not usually being examined as a potential place cue. This may be due to the great variation in speakers' speech volume, which is very hard to control.

[6] Nasal formants can be studied by measuring spectra based on observation of nasal formant frequencies or relative spectral energy changes in low– and high–frequency ranges at the nasal release; however, due to time consumption in obtaining the values, spectra measurements were not attempted in this study.

3.2 Duration

The results show that duration was not a place cue. There was no regular pattern of real–time duration across four nasals in two different vocalic contexts. Durations in milliseconds (msec) of nasal murmurs for nasal stops at four different places of articulation are shown in Table 4.

In both vocalic contexts, /ɲ/ had the highest duration value. In the /a/ context, the /ɲ/ duration value was followed by those for /ŋ/, /m/, and /n/, in descending order. In the /ɔ/ context, on the other hand, the duration of /ɲ/ was followed by /n/, /ŋ/, and /m/, in that order. ANOVA revealed no statistically significant difference in the /ɔ/ context; however, the /a/ context produced a statistically significant difference among nasal places of articulation with $p < 0.05$. Tukey's HSD then showed that, in the /a/ context, the duration value for /ɲ/ was significantly higher than those for /m/ and /n/, with $p < 0.05$. These inconsistent results of relational patterns and statistical differences suggest that duration does not distinguish place of articulation for nasal stops. Furthermore, comparison with other works (Trongdee 1987, Tarnsakun 1988, Narayan 2008) did not show a consistent pattern. This confirms the fact that duration is not usually investigated as a potential cue to place differentiation. The variation found across vowels may have been affected by speech rate. The difference in speech rate may lengthen or shorten the duration of nasals in a non–systematic way.

3.3 Nasal formants

Due to sound quality, only nasal formants during nasal murmurs from the /ɔ/ word list were examined. However, the NF3 of nasals preceding /ɔ/ could possibly be noise formants. Of the three nasal formants, only NF2 produced a consistent relational pattern: at all three measurement positions /n/ > /ɲ/ > /m/ > /ŋ/. The mean values for NF2 at different points in the nasal murmur are shown in Table 5.

ANOVA showed some statistically significant differences among nasal places, with $p < 0.001$ for NF1 and $p < 0.01$ for NF2, but there was no statistically significant difference among nasal places for NF3. Furthermore, Tukey's HSD revealed that only the NF2 values for /n/ and /ɲ/ were significantly higher than those of /ŋ/, with $p < 0.05$ for every measurement position. At 75%, the NF2 value for /n/ was significantly higher than that of /m/, with $p < 0.01$. As for the other two nasal formants, NF1 and NF3 did not produce regular relational patterns across three different positions. However, Tukey's HSD revealed some patterns for NF1. The NF1 values for /ŋ/ were significantly greater than those for /m/ and /n/, with $p < 0.05$ for every measurement position. Moreover, at 50% and 75%, the NF1 values for /ŋ/ were significantly higher than those for /ɲ/, with $p < 0.05$. The mean values for NF1 at different points are shown in Table 6.

3.4 Formant transitions

Measurements at 0% and 25% were subjected to ANOVA and Tukey's HSD since the values

Table 4 Duration of Murmurs in Milliseconds

vocalic context	value	place of articulation			
		m	n	ɲ	ŋ
a	$\bar{x}$	121	119	175	132
	SD	67	60	108	38
ɔ	$\bar{x}$	117	124	140	121
	SD	37	48	44	35

Table 5 Mean and Standard Deviation Values for NF2 during Murmurs

vocalic context	position	value	place of articulation			
			m	n	ɲ	ŋ
ɔ	25%	$\bar{x}$	1157.85	1376.11	1338.03	1101.53
		SD	227.77	422.39	280.42	146.40
	50%	$\bar{x}$	1146.38	1324.61	1303.28	1089.84
		SD	181.57	376.50	288.17	190.72
	75%	$\bar{x}$	1108.95	1345.61	1300.70	1046.07
		SD	148.18	329.01	303.41	142.13

Table 6 Mean and Standard Deviation Values for NF1 during Murmurs

vocalic context	position	value	place of articulation			
			m	n	ɲ	ŋ
ɔ	25%	$\bar{x}$	274.61	278.98	306.37	352.46
		SD	78.66	57.86	55.26	93.25
	50%	$\bar{x}$	292.52	285.07	302.89	363.37
		SD	108.79	57.76	54.09	83.11
	75%	$\bar{x}$	317.78	293.41	297.24	386.95
		SD	121.21	59.14	53.03	90.05

at both positions were the two closest to the initial nasals and, therefore, had the better potential for displaying the different acoustic characteristics of the four nasals. Consistent relational patterns were found for F2 across nasal places. The F2 values for /ɲ/ were the highest, followed by /n/, /ŋ/, and /m/. Mean values for F2 in all four places of articulation are shown in Table 7.

ANOVA revealed that all four places differed significantly in both vocalic contexts with $p < 0.001$. However, statistical results for /ɔ/ and /a/ contexts differ according to Tukey's HSD. In the /ɔ/ context, almost every nasal pair differed significantly, with $p < 0.001$, except for the /ŋ/–/m/ pair, where /ŋ/ was significantly greater than /m/, with $p < 0.05$. The statistically significant difference among nasal places in the /ɔ/ context reflects the potential for F2 being a place cue. However, while almost every nasal pair differed significantly in the /a/ context, with $p < 0.001$, /n/ and /ŋ/ did not differ significantly, reflecting their similarity. The scatter plots in Figure 2 and Figure 3 show F2 and F3 at the 0% position in both vocalic contexts.

As for F1, consistent relational patterns were found at 0% for both vowels and at 25% in the /a/ context. The F1 values for /m/ were higher than those for /n/, /ŋ/, and /ɲ/, in descending order. At 25% in the /ɔ/ context, /n/ values were higher than those for /m/, /ŋ/, and /ɲ/, once again in descending order. However, this did not necessarily lead to significant differences since /m/ and /n/ did not differ significantly. ANOVA revealed a statistically significant difference among nasal places in both vocalic contexts, with $p < 0.01$. Furthermore, Tukey's HSD revealed that the F1 values for /m/ and /n/ were significantly higher than those for /ɲ/ at both positions in both vocalic contexts, with $p < 0.05$. Moreover, the F1 values for /ŋ/ were significantly higher than those for /ɲ/ in the /a/ context, with $p < 0.01$. At 25% in the /ɔ/ context, the F1 values for /n/ were significantly higher than those for /ŋ/, with $p < 0.001$. However, the fact that the F1 values for /m/, /n/, and /ŋ/ did not differ significantly, except for one significant difference between /n/ and /ŋ/ at 25% in the /ɔ/ context, shows that F1 cannot be a cue for distinguishing places of articulation.

Furthermore, the F3 values did not show regular relational patterns across nasal places in either vowel context. ANOVA indicated a statistically significant difference among nasal places in the /a/ context and at 0% in the /ɔ/ context, with $p < 0.001$. Also, Tukey's HSD revealed that the F3 values of /ɲ/ were higher than those for /ŋ/, /n/, and /m/ at 0% in the /a/ context, where /ɲ/ was significantly higher than the others, with $p < 0.001$, and /ŋ/ and /n/ were significantly higher than /m/, with $p < 0.001$. At 25%, the /ɲ/ values were higher than those for /n/, /ŋ/, and /m/; every sound was significantly higher than /m/, with $p < 0.01$, and /ɲ/ was significantly higher than /ŋ/, with $p < 0.05$. The relational patterns at both positions in the /ɔ/ context did not show the same pattern within vowels or between two vowels. Tukey's HSD revealed that at 0%, the /ɲ/ value was significantly higher than those for /m/, /ŋ/, and /n/, with $p < 0.001$, and that /m/

was significantly higher than /n/, with $p < 0.05$. At 25%, the /m/ value was higher than those for /ŋ/, /n/, and /ɲ/, but the differences were not statistically significant. The inconsistent relational patterns in both positions, with /m/ having a high F3 value, differing from the patterns in the /a/ context, resulted from high F3 values for /m/ obtained from two informants. If those values were discounted, the relational patterns at each position would be similar to those found in the /a/ context. Additionally, Figures 2 and 3 show that the F3 values at 0% of the formant transitions in both vocalic contexts are very close. The irregular patterns of the F3 frequency do not make F3 a good place cue.

Apart from formant frequency comparisons, F2 and F3 transitional directions were compared across different nasals in both vocalic contexts. The results show that the relation between F2 and F3 transitional directions in the /ɔ/ context helped in distinguishing place of articulation better than in the /a/ context, where F2 and F3 had the same falling transitional directions for /n/ and /ŋ/. Graphs showing F2 and F3 transitional directions for each vowel can be found in Table 8.

Table 8 shows outstanding patterns for /m/ and /ɲ/, namely, F2 and F3 transitions rise for /m/ and fall significantly for /ɲ/. The F2 and F3 transitional directions for /n/ and /ŋ/ are very similar in the /a/ context; however, in the /ɔ/ context, F2 falls in formant transition after /n/, while it rises only a little after /ŋ/, making it look rather flat. F3 rises after /n/, while it rises only a little after /ŋ/, once again making it look rather flat. From these results, it can be concluded that F2 and F3 transitional directions depend on vocalic context.

4. Discussion

The results appear to confirm previous studies' claims that formant transitions are better cues (Malécot 1956, Delattre, Liberman, and Cooper 1955). Comparisons with other studies reveal that F2 and F3 formant transitional directions after different nasal places were found to have a regular pattern in most studies (Liberman et al. 1954, Delattre et al. 1955, Recasens 1983). On the other hand, formant patterns within the nasal murmur were inconsistent both within this study at different positions and between this study and others (Recasens 1983, Trongdee 1987). In addition, even though the relational patterns for NF2 were regular in all three measurement positions and the NF2s for /n/ and /ɲ/ were significantly higher than those for /ŋ/, the lack of statistically significant difference among /m/, /n/, and /ɲ/ reflects the similarity of NF2 for these nasals. Therefore, NF2 is not considered a good cue to differentiate the places of articulation. This might be explained by the anatomical characteristics of the nasal cavity. According to Ohala (1975), the nasal formants correspond to resonance in the nasal cavity, which is fixed in size and volume; hence, the frequencies resonating in the nasal cavity tend to be very close regardless of place of articulation. Therefore, nasal murmurs probably do not provide place cues. Apart from the results themselves, another difficulty in the attempt to use nasal formants as place cues is that it is complicated to measure nasal formants in natural speech. The nasal formant frequencies appearing on

Table 7 Mean and Standard Deviation Values for F2 (Hz) during Formant Transitions

vocalic context	position	value	place of articulation			
			m	n	ɲ	ŋ
a	0%	$\bar{x}$	1533.37	1987.82	2620.41	1986.56
		SD	285.93	169.46	90.55	292.30
	25%	$\bar{x}$	1590.03	1977.05	2514.19	1975.71
		SD	254.77	180.35	85.27	215.93
ɔ	0%	$\bar{x}$	1006.97	1608.91	2697.74	1134.62
		SD	152.14	165.58	111.03	176.50
	25%	$\bar{x}$	1032.57	1532.44	2464.24	1150.81
		SD	146.12	165.51	150.66	159.86

Figure 2 F2 and F3 at 0% of formant transitions in the /a/ context

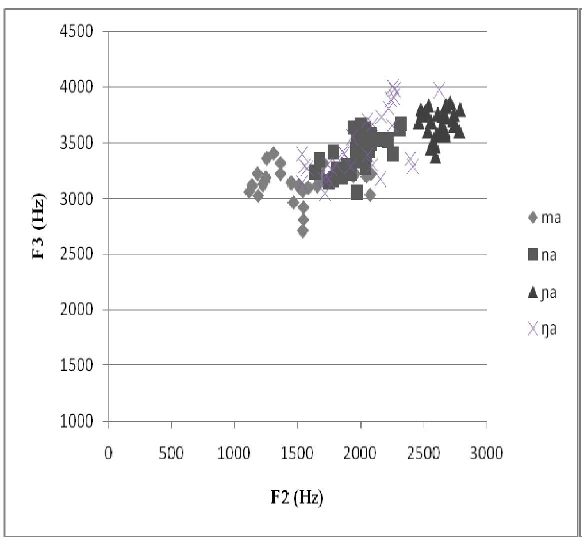
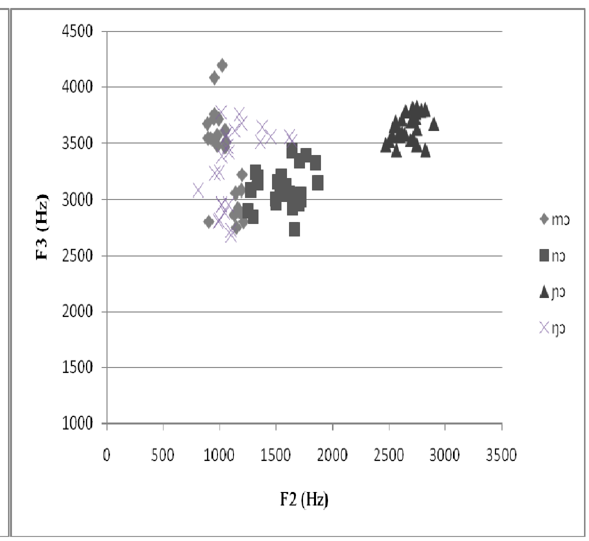
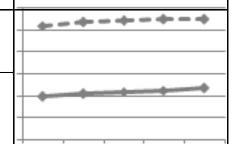
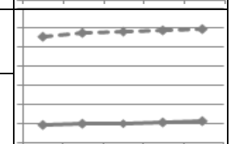
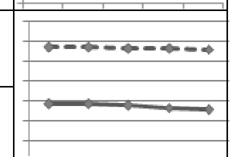
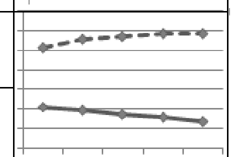
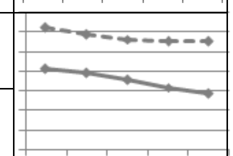
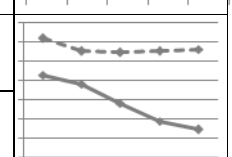
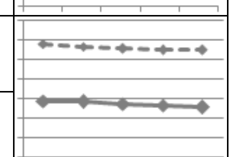
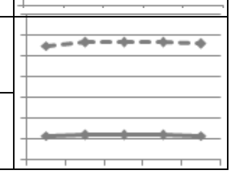


Figure 3 F2 and F3 at 0% of formant transitions in the /ɔ/ context



In Figure 2, the F2s of /n/ and /ŋ/ overlap greatly. In Figure 3, there was a clearer grouping of F2s for each place of articulation; however, although /ŋ/ somewhat overlapped with /m/, the statistic result indicated their difference.

Table 8 Mean Values of F2 and F3 during Formant Transitions and F2 and F3 Transitional Directions Following Four Initial Nasals in the /a/ and /ɔ/ Contexts

place of articulation	vocalic context	formant frequency (Hz)	position of formant transition					Graph
			0%	25%	50%	75%	100%	
m	a	F3	3136.61	3223.08	3256.90	3280.74	3282.79	
		F2	1533.37	1590.03	1638.7	1673.85	1720.81	
	ɔ	F3	3319.62	3402.49	3456.24	3475.71	3507.56	
		F2	1006.97	1032.57	1052.77	1076.73	1108.10	
n	a	F3	3407.83	3400.96	3378.32	3374.83	3352.67	
		F2	1987.82	1977.05	1936.4	1892.36	1841.99	
	ɔ	F3	3121.43	3326.46	3399.61	3468.77	3474.17	
		F2	1608.90	1532.44	1419.62	1332.78	1226.54	
ɲ	a	F3	3669.07	3498.27	3367.47	3317.05	3312.09	
		F2	2620.41	2514.19	2326.26	2133.68	1978.39	
	ɔ	F3	3651.34	3312.07	3279.88	3321.12	3365.44	
		F2	2697.74	2464.24	1963.57	1495.95	1289.14	
ŋ	a	F3	3465.31	3386.07	3336.20	3308.43	3291.56	
		F2	1986.07	1975.36	1919.81	1879.68	1831.17	
	ɔ	F3	3385.39	3388.64	3380.63	3345.89	3385.39	
		F2	1150.80	1161.45	1161.33	1136.37	1150.80	

the spectrum were neither clear nor consistent throughout the nasal murmur phase, and it was hard to separate noise frequencies from those of nasal formants.

F2 being an effective cue is consistent with other works (Delattre et al. 1955, Recasens 1983, Harding and Meyer 2003). Acoustic–perceptual studies have found the presence of certain F2 transitional directions at each place of articulation to be essential for correct place identification. The transitional direction rises after /m/, falls after /n/ and /ɲ/, and either falls or lies rather flat after /ŋ/, depending on which vowel follows. The F2 transitional directions of labial, alveolar, and velar nasal consonants arrived at in my research agree with previous studies on transitional directions of corresponding stops (Delattre et al. 1955, Pickett 1980). The frequency values for F2 at the nasal–vowel juncture in the /a/ context in the present study were similar to the results achieved by Recasens (1983), in which /ɲ/ had the highest value, /m/ had the lowest value, and the values for /n/ and /ŋ/ fell in between. The difference is that, in Recasen's study, /n/ and /ŋ/ were differentiated because the F3 of /ŋ/ rose before vowels. In contrast, I found the F3 of /ŋ/ to fall in a manner similar to /n/. However, the F2 values for /n/ and /ŋ/ in the /ɔ/ context differed significantly. Both the F2 values and transitional directions, then, aid in contrasting places of articulation. F3 showed more than one pattern. This can be seen in the case of the F3 transitional directions of /ŋ/ which differed in the /a/ and /ɔ/ contexts. Moreover, the F3 values of /n/ and /ŋ/ which helped distinguish both nasal places in Narayan (2008) did not differ significantly in the present study. Therefore, it could not help differentiate alveolar and velar places of articulation.

F1 is not an effective cue because the patterns are not consistent across studies. A comparison of F1 relational patterns between the present study and the literature review in Recasens's study (1983) shows different patterns. In Recasens's paper, /ŋ/ had the highest F1 value, followed by /m/ or /n/ and /ɲ/. In the present study, in contrast, /m/ had the highest F1 value, followed by /n/, /ŋ/, and /ɲ/ in descending order. These inconsistent patterns may reflect language–specific traits or the ineffectiveness of F1 as a place cue. However, the lowest F1 value of /ɲ/ can be explained by the oral constriction/F1 rule which says that "the frequency of F1 is lowered by any constriction in the front half of the oral part of the vocal tract, and the greater the constriction, the more the F1 is lowered." (Pickett 1980). In producing a palatal nasal /ɲ/, the tongue moves towards the hard palate, forming a constriction at the palate; hence, the F1 value decreases. Furthermore, the rising of the F1 during formant transitions after nasals likewise accords with the oral constriction/F1 rule, which also applies to constriction at the lips or teeth. In producing nasal consonants, oral constrictions occur in the front half of the mouth or at the lips, whereas there is no constriction in the oral cavity when producing vowels. Therefore, F1 is lower in nasals than in vowels, and the transitional direction is upward.

The transitional directions of F2 can be explained by the relationship between F2 and vocal–tract length. A sound produced in a longer vocal tract has a lower formant frequency. In producing /n/, /ɲ/, and /ŋ/, there is an obstruction within the oral cavity, causing the resonating chamber to be shorter; thus, the F2 rises. On the other hand, during vowel production, there is no obstruction, so the vocal tract is longer. Therefore, the F2 of a vowel is lower than that of nasal consonants. Consequently, when a vowel follows a nasal stop, F2 falls during the transition phase. This is true in the /a/ context but not in the/ɔ/ context. In the /ɔ/ context, the F2 rises only a little after /ŋ/, making it look rather flat. This might be because in producing both /ɔ/ and /ŋ/, the tongue moves toward the velum, even touching it for /ŋ/, so their places of articulation are rather similar. This may result in only minor changes of the vocal tract, so the F2 values for /ɔ/ and /ŋ/ are close, producing a flat transition. In the case of /m/, the resonating chambers of /m/ and vowels seem to have close to the same vocal–tract length, so the length of the vocal tract may not be the reason why the F2 of /m/ is lower than that of the following vowel. This may, instead, be explained by the lip closure which results in a lowering of formant frequencies (Ladefoged 1993). Hence, the F2 of /m/ is lower than that of the following vowel. Consequently, the formant rises from low to high, during the nasal–to–vowel transition phase

To obtain more concrete results, future research should study both formant transitions in more vocalic contexts and stops at corresponding places of articulation. This would help confirm the general characteristics of each place of articulation found in nasal place cue studies. Additionally, formant transitions are noticeably easier to analyze due to the clarity of formant frequencies during formant transitions. In contrast, nasal murmurs are much less clear due to sound quality and the characteristics of the nasal murmurs themselves. Nasal formants are hard to determine since the formant frequencies shown on the spectrogram are not continuous and they can be altered by noise formants. Moreover, the location of antiformants cannot be specified due to sound quality. This situation can probably be overcome by using extra–high–quality recording equipment; however, recording during fieldwork makes it hard to avoid surrounding noise.

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