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Processes and Consequences of Co-articulation in Mandarin $V_1N.(C_2)V_2$ Context: Phonology and Phonetics

Mingqiong Luo

Shanghai International Studies University

joanlmq@shisu.edu.cn

Abstract

It is well known that in Mandarin Chinese (MC) nasal rhymes, non-high vowels /a/ and /e/ undergo Vowel Nasalization and Backness Feature Specification processes to harmonize with the nasal coda in both manner and place of articulation. Specifically, the vowel is specified with the [+front] feature when followed by the /n/ coda and the [+back] feature when followed by /ŋ/. On the other hand, phonetic experiments in recent researches have shown that in MC disyllabic words, the nasal coda tends to undergo place assimilation in the $V_1N.C_2V_2$ context and complete deletion in the $V_1N.V_2$ context.

These processes raises two questions: firstly, will V_1 in $V_1N.C_2V_2$ contexts also change in its backness feature to harmonize with the assimilated nasal coda? Secondly, will the duration of V_1N reduce significantly after nasal coda deletion in the $V_1N.(G)V$ context?

A production experiment and a perception experiment were designed to answer these two questions. Results show that the vowel backness feature of V_1 is not re-specified despite the appropriate environment, and the duration of V_1N is not reduced after nasal deletion. The phonological consequences of these findings will be discussed.

Index Terms: Mandarin, nasal rhymes, backness feature specification, nasal place assimilation

1. Introduction

Mandarin Chinese (MC) is known to have two contrastive nasal phonemes in the syllable-final position, i.e. the coronal nasal [n] and the velar nasal [ŋ]. It is also widely accepted that MC has no phonemic nasal vowels, but vowels are perceivably nasalized before tautosyllabic nasal codas, although the degree of nasalization varies depending on the vowel quality [1][2]. This process can be schematized in rule-based phonology as the Vowel Nasalization Rule in (1):

(1) $V \rightarrow \tilde{V}$ / VN#

Moreover, the backness feature of the nuclear vowel is closely related with the place feature of the following nasal coda. The low vowel /A/ (with the backness feature unspecified), for example, is realized as a front vowel [a] when preceding the coronal nasal /n/, whereas the allophone that precedes the velar nasal /ŋ/ is the back vowel [ɑ] [1][2][3]. These processes can be schematized as the Vowel Backness Specification Rule (henceforth **the VBS Rule**) in (2):

(2) a. $V_{[-\text{high}]} \rightarrow V_{[-\text{back}]}$ / __ n#
b. $V_{[-\text{high}]} \rightarrow V_{[+\text{back}]}$ / _ ŋ#

In addition, recent studies focusing on N.C co-articulation in MC di-syllabic words have revealed that nasal place assimilation does occur, especially when the nasal coda is a coronal /n/ [4][5][6][7][8]. Specifically, when coda /n/ is immediately followed by the bilabial onsets /p, p^h/, it is phonetically realized as [m]; when it is followed by /t, t^h/, it is phonetically realized as [n]; and when it is followed by /k, k^h/, it is phonetically realized as [ŋ]. This process can be schematized as the Nasal Place Assimilation Rule below:

(3) $n \rightarrow N_{[\alpha\text{place}]}$ / $n.C_{[\alpha\text{place}]}$

Things are more complicated for the velar nasal coda /ŋ/. [7] found that in the $V_1N_1.C_2V_2$ context, the place of constriction for C_2 begins roughly at the midpoint of /ŋ/. In another word, /ŋ/ undergoes partial assimilation and is phonetically realized as a complex nasal. This process can be formalized as the Partial Place Assimilation Rule in (4) below:

(4) $ŋ \rightarrow \widehat{ŋN}_{[-\text{velar}]}$ / __.$C_{[-\text{velar}]}V$

However, it is also accepted that even for velars, complete place assimilation is possible, especially in fast-rate connected speech [5][6][7]. The major reasons are: firstly, the nasal place feature is much better cued in the preceding nuclear vowel than in the nasal murmur *per se*; secondly, in connected speech, information about single segments can be derived from that at other linguistic levels such as the morphological and syntactic levels. Both factors render the nasal place cues in the murmur region dispensable. This process can be schematized as the Complete Place Assimilation Rule below:

(5) $ŋ \rightarrow N_{[\alpha\text{place}]}$ / __. $C_{[\alpha\text{place}]}V$

Finally, phonetic studies have found that when the nasal coda is followed by a glide-initial or vowel-initial syllable, i.e. in the $V_1N.(G)V_2$ environment, the nasal coda often undergoes complete deletion, which is true for both /n/ and /ŋ/ in connected speech [4][5][6]. This process can be formalized as the Nasal Deletion Rule below:

(6) N → Ø / __.(G)V

This process can be readily accounted for in articulatory terms: since there is no place of constriction in the oral cavity for the glides or the vowels as there is for the consonants, the place of constriction in the oral cavity for the nasal coda is likely to be deleted due to anticipatory co-articulation, especially in fast-rate speech.

Let's take the derivation of the disyllabic words /$fAn^{55}.k^hAi^{55}$/ ('open'), /$ʂAn^{55}.Au^{51}$/ ('col'), /$p^hAŋ^{35}.tA^{51}$/ ('enormous') and /$fAŋ^{35}.Ai^{51}$/ ('interfere') as the examples to illustrate the application of the rules in (1-6):

(7)	i. /fAn.k^hAi/	Underlying form
	fãn.k^hai	Vowel nasalization & backness specification
	fãŋ.k^hai	Nasal place assimilation
	[fãŋ.k^hai]	Surface form
	ii. /ʂAn.Au/	Underlying form
	ʂãn.ɑu	Vowel nasalization & backness specification
	ʂã.ɑu	Nasal deletion
	[ʂã.ɑu]	Surface form

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iii. /pʰAŋ.tA/	Underlying form
pʰɑ̃ŋ.tA	Vowel nasalization & backness specification
a. pʰɑ̃ŋ͡n.tA	Partial place assimilation
b. pʰɑ̃n.tA	Complete place assimilation
[pʰɑ̃ŋ͡n.tA]	Surface form (a)
[pʰɑ̃n.tA]	Surface form (b)
iv. /fAŋ.Ai/	Underlying form
fɑ̃ŋ.ai	Vowel nasalization & backness specification
fɑ̃.ai	Nasal deletion
[fɑ̃.ai]	Surface form

The rules and processes listed in (7) are well documented for MC. However, notice that the surface forms of the nasal rhymes of the initial syllables in (7i) and (7iiib) provide the appropriate environments for the VBS Rule to re-apply. Specifically, the surface form [ãŋ] in (8i) could change into [ɑ̃ŋ] by the VBS Rule, and that of [ɑ̃n] in (8iiib) could change into [ãn] for the same reason. The question is: does the VBS Rule re-apply (Question 1)?

Moreover, Figures 3&4 show that MC nasal codas in the $V_1N.V_2$ context are indeed deleted in phonetic realization. Since it is recognized that the nasal coda is moraic in MC syllables, we must also ask whether the deletion of the nasal coda results in a reduction of syllable weight in the V1N.V2 context (Question 2).

The rest of the paper is arranged as follows: Section 2 reports two phonetic experiments that are used to address Questions 1 and 2 mentioned above; Section 3 discusses the phonological consequences implied by the experiment results; and Section 4 is the conclusion.

2. Two Phonetic Experiments

Two phonetic experiments were implemented in this section: firstly, a production experiment that is used to examine the acoustic changes happening to V_1 in the $V_1N.C_2V_2$ context and the durational changes of the nasal rhymes in the $V_1N.V_2$ context; secondly, a perception experiment used to examine the perceptual consequence of the acoustic changes in V_1.

It is noteworthy that we focus on the non-high vowels /a, e/ because only these two vowels in MC are subject to the VBS Rule, whereas the other three high vowels, i.e. /i, u, y/, are not.

2.1 Experiment 1: Production

A corpus of 96 disyllabic words was constructed for the $V_1N.C_2V_2$ sequence and 16 ones for the $V_1N.V_2$ sequence. Specifically, V_1 is either /a/ or /e/, and the nasal coda was either /n/ or /ŋ/. Thus, we have four underlying nasal rhymes, i.e. /an, aŋ, en, eŋ/. Each rhyme can pattern with four tones, so altogether we have 16 different combinations of V_1N plus tone.

The onsets of the initial syllable were restricted to the same consonant for all the 16 V_1N rhymes, which was not aspirated so as to avoid affecting the duration of the following vowel.

The onset of the second syllable C_2 comes from six major consonantal groups categorized according to the place of articulation, namely, the bilabial /p, pʰ, m/, the alveolar /t, tʰ, n, l/, the velar /k, kʰ, x/, the dental affricates /ts, tsʰ, s/, the retroflexes /tʂ, tʂʰ, ʂ, r/ and the palatals /tɕ, tɕʰ, ɕ/. The obstruent, either aspirated or unaspirated, was chosen from each group. In addition, the second syllable neither had a nasal rhyme nor carried a zero tone.

Ten female students[1] in college were invited to record for this experiment. All the subjects spoke a northern Mandarin dialect as their first native language. Each of them was asked to read the disyllabic words five times in normal speed, with a three-minute interval between every two readings.

The recordings were made with a DR-05 Tascam linear PCM recorder in an audio-visual classroom with sound attenuation facilities on campus. The recordings were analyzed with Praat 15.0 [14] on the computer.

The first three formants of V_1 (henceforth **VF1, VF2 and VF3**) were used as the phonetic correlates for the quality of V_1, the second formant in the vowel-nasal transition area (henceforth **VNTRF2**) the phonetic correlate for the place of articulation of the nasal coda [9][10][11][12], and the duration of V_1N the phonetic correlate for syllabic weight [13].

The segmentation of the nuclear vowel was made mainly by visual inspection of the waveform and the formant tracking in the spectrogram, supplemented by audio verification. The midpart of the vowel, which includes the duration between the point at around 15ms from the vocalic onset and that at around 25ms from the vowel-nasal boundary, was measured for the first three formants. Vowel-nasal transition refers to the part of the vowel within 15 ms from the vowel-nasal boundary.

The annotation was done manually in textgrid with Praat and the measurement of the formants and duration was done using FormantPro [15]. The sampling rate was set at 44100, the formant frequency 5500Hz and the formant number 5.

Raw data on VF1, VF2, VF3, VNTRF2 and the rhyme duration were collected by averaging across all the subjects participating in Experiment I. The raw data were normalized into Z-score before the statistics were done with the lme4 package in R [16]. The formula was set with C_2 as the independent variable and with VF1, VF2, VF3, VNTRF2 and rhyme duration as the dependent variables, respectively. The /n.T/ sequence was set as the baseline of comparison in VF1, VF2, VF3 and VNTRF2 for the nasal rhymes closed with the /n/ coda, the /n.C_2/ sequence the baseline of comparison between nasal rhymes closed with coda /n/ and those with coda /ŋ/, and the /n.V_2/ and /ŋ.V_2/ sequences the baseline of comparison in rhyme duration for the nasal rhymes closed with /n/ and of those closed with /ŋ/, respectively.

2.1.1 Results for vowel /a/

The results of the comparison of vowel /a/ in different contexts are presented in Table 1 below, taking Tone 1 as the example. The results of comparison between [ɑ]**ŋ**.C_2V_2 and [ɑ]**ŋ**.KV_2 contexts and those in the VF1 and VF3 correlates are not included because few significant differences were found.

Table 1: *T values for comparisons of vowel /a/ with T1.*

	VF2		VNTRF2		RDUR	
	n.C2 ~n.T	**ŋ.C2~ n.C2**	**n.C2~ n.T**	**ŋ.C2~ n.C2**	**n.C2~ n.V2**	**ŋ.C2~ ŋ.V2**
p	-2.801	-16.32	-3.105	-8.871	-1.983	0.683
t	---	-17.76	---	-22.03	0.391	-0.038
k	-2.909	-18.519	-4.987	-11.925	-1.955	-3.581
ts	-0.9	-16.182	0.811	-17.89	-3.63	-4.886
tʂ	0.692	-19.31	3.595	-15.3	-2.199	-4.105
tɕ	0.978	-19.064	4.724	-21.62	-0.803	-0.933
Ø	0.914	-17.613	---	---	---	---

[1] Previous research has confirmed that gender differences have a marked impact on the phonetic realization of nasal and nasalized segments [10].

(Note: T values highlighted with the grey shade indicate statistically significant differences. The (~) sign indicates the comparison between a pair of rhymes with the rhyme before the (~) sign being the target and that after, the baseline. The minus sign (-) indicates that the value of the target is lower than that of the baseline. This note is applicable to vowel /e/.)

First, in the [a**n**.C_2V_2] context, VF1 and VF3 are not significantly different for all C2s, but VF2 is significantly lower when C_2 is /p/ ($p<0.01$) and /k/ ($p<0.005$) as compared with the baseline where C2 is /t/, but not when it is followed by other onsets, including the zero onset. This result suggests that vowel backness of /a/ may be affected in the /V_1n.PV_2/ and /V_1n.KV_2/ sequences.

In the [ɑ**ŋ**.C_2V_2] sequence, however, none of the first three vowel formants varies significantly with different C2s. This result implies that the vowel quality of [ɑ] is unaffected in either V_1ŋ.C_2V_2 or V_1ŋ.V_2 contexts.

Secondly, in the /a**n**.C_2V_2/ context, VNTRF2 is significantly different for all C_2s except /ts/ as compared with the baseline. In the [ɑ**ŋ**.C2V2] context, however, VNTRF2 does not vary significantly with different C2s. These results support previous research findings that the nasal coda /n/ undergoes complete place assimilation in the V1N.C2V2 context (Rule (4)), whereas coda /ŋ/ is only partially assimilated (Rule (5)).

Thirdly, comparisons between [an] and [ɑŋ] followed by the same C_2 shows that the vowels are significantly different in VF2 ($p<0.001$). This result may suggest that the categorical distinction in the backness feature of /a/ in [an] and [ɑŋ] remains despite the nasal coda variations in different contexts. It is worth noting that VNTRF2 of /a/ is significantly different in [an].KV_2 sequence as compared to that in [ɑŋ].KV_2 sequence, which suggests that the place of constriction for the assimilated /n/ coda is very different from canonical /ŋ/.

Fourthly, the results of comparison in VNTRF2 and in the first three formants are similar across the four phonemic tones in MC. This result is expected because tone is recognized as having little effect on vowel quality.

Finally, the duration of [an] and [ɑŋ] in V_1N.V_2 sequence are in many cases significantly longer than that in V_1N.C_2V_2 sequence. This result suggests that nasal coda deletion in V_1N.V_2 sequence does not result in a reduction of the nasal rhyme. Instead, the nasalized vowel lengthens to fill in the time slot of the deleted nasal coda.

2.1.2 Results for vowel /e/

The results of the comparison of vowel /e/ in different contexts that show significant differences are presented in Table 2 below, taking Tone 1 as the example.

Table 2: *T values for comparisons of vowel /e/ with T1*.

	VF2		**VNTRF2**		**RDUR**	
	n.C2~ n.T	**ŋ.C2~ n.C2**	**n.C2~ n.T**	**ŋ.C2~ n.C2**	**n.C2~ n.V2**	**ŋ.C2~ ŋ.V2**
p	-3.864	-13.139	-4.207	-8.893	1.563	0.098
t	---	-21.49	---	-14.856	-1.901	0.166
k	-9.455	-7.729	-9.366	-4.482	2.565	0.567
ts	-0.759	-18.467	-0.206	-16.166	-1.829	1.157
tʂ	-0.92	-19.163	3.861	-18.11	1.799	1.913
tɕ	1.78	-22.089	3.719	-22.05	1.696	0.091
Ø	2.674	-22.135	---	---	---	---

It can be seen that the results for vowel /e/ are very similar to those for /a/. Firstly, VF2 of /e/ in [en] is significantly different when C_2 is /P, K/ ($p < 0.001$) or the zero onset ($p < 0.01$) as compared with the baseline when C_2 is /T/. Secondly, VNTRF2 of /e/ is significantly different in [e**n**] preceding all C_2s except for /ts/ as compared with the baseline. Thirdly, VF2 and VNTRF2 of /e/ in [e**n**] are significantly different from those in [ə**ŋ**] when followed by the same C_2. Fourthly, rhyme duration of [en] and [ə**ŋ**] in the V_1N.V_2 context is not significantly different from that in the V_1N.C_2V_2 contexts, except in the /en.KV_2/ context. Last but not the least, the results mentioned above are similar across the four tones in MC.

2.1.3 Interim summary

In general, the statistical results in Experiment I show that: firstly, the change of coda /n/ in the place of articulation has significant effects on the VF2 of vowels /a/ and /e/ in the V_1n.C_2V_2 context, especially when C_2 is a bilabial or a velar; secondly, the weight of the initial syllable in the V_1N.V_2 context remains constant despite the deletion of the nasal coda.

2.2 Experiment 2: Perception

2.2.1 Research questions

A perception experiment is designed to examine whether the phonetic differences observed in Experiment 1 have phonological consequences. Specifically:

(8) a. Is V_1 categorially different in backness in the V_1**n**.C_2V_2 sequence when /n/ is phonetically realized with different places of articulation?
b. Is V_1 categorially different in backness in V1**n** as compared with that in V_1**ŋ** when followed by the same C_2?

2.2.2 Experiment design

An Identification Task (IT) and an Oddity Discrimination Task (ODT) were administered to examine the two research questions. The audio-stimuli used in both tasks came from the recordings made in Experiment 1. We randomly chose the recordings from two subjects participating in Experiment 1, which were made into two copies of stimuli sets for each task to be administered twice. The initial syllables (from the onset of V1 to the end of the nasal coda) of the disyllabic words were separated from the second and used as the audio stimuli in both tasks.

In both tasks, we focused on the perception of V_1 in V_1n.PV_2 and V_1n.KV_2 sequences because the VF2 of V_1 in these sequences showed significant differences from that in the other V_1n.C_2V_2 sequences in Experiment 1. Thus, for each vowel, the target syllables included 11 minimal pairs of V_1n followed by different C_2s, including the zero initial (e.g. /n.P/~/n.T/, /n.K/~/n.Ø/). In addition, seven minimal pairs of V_1**n** and V_1**ŋ** followed by the same C_2s and the zero initial (e.g. /n.P/~/ŋ.P/, /n.Ø/~/ŋ.Ø/) were included because VF2 of V_1 in these pairs also showed significant differences in Experiment 1. So altogether there were 18 minimally contrastive pairs of target rhymes, tone being constant.

For the IT, three types of trials were designed: (1) "different" trials that contained two minimal pairs contrasting in either C_2 or the nasal coda (e.g. /an.T/-/an.K/, /an.K/-/aŋ.K/. Each trial was identified twice, as /an/ or /aŋ/, respectively. 36 in all); (2) "catch" trials where two stimuli are the same syllable (e.g. /an.P/-/an.P/, /aŋ.K/-/aŋ.K/. Each trial was identified twice, as /an/ or /aŋ/, respectively. 28 in all); (3) "distractor" trials, where the distinction involved a non-target contrast (e.g. /ta-tai/. 8 in all). Though it is recognized that tone does not affect vowel quality in MC, we kept tone constant for each trial so as to keep the rhymes of the stimuli minimally contrastive in the coda. So altogether 72 trials were constructed for this task.

The inter-trial interval was set at 2.8s and the inter-stimulus interval was set at 1.3s, following [16]. The trials were randomized to minimize the ordering effect. Only the different and the catch trials were analyzed.

Twenty native speakers of MC (with different Chinese dialectal background) participated in this experiment. They were all sophomore students in college when taking part in this experiment. None reported any hearing impairment, and none had participated in Experiment 1.

The participants were randomly assigned a copy of the stimuli set and received an answer sheet which listed all the target rhymes that the participants were asked to identify. They were required to indicate the sound that they thought was the target rhyme by circling A, B, C or D, where A referred to the first stimulus in the trial, B the second, C both and D neither. The task was carried out in a regular classroom at Shanghai International Studies University (SISU) in China with each subject having an individual earphone headset. All the participants were paid a token fee to take the test twice, with a three-minute interval in between.

The target syllables used in the ODT were the same as those in the IT. Also, three types of trials were designed: (1) "different" trials appearing in the form of AXB which contained an odd item (e.g. /an.P/-/an.P/-/an.T/, /an.K/-/aŋ.K/-/aŋ.K/. 36 in all); (2) "catch" trials where all the stimuli were the same (e.g. /an.P/-/an.P-/an.P/, /aŋ.K/-/aŋ.K/-/aŋ.K/. 14 in all); (3) "distractor" trials, where the distinction involved a non-target contrast (8 in all). Tone was kept constant for each trial. So altogether there were 58 trials in this task, each consisting of three monosyllabic words. Only the different and the catch trials were analyzed. The inter-trials interval was set at 2.8s, and the inter-stimuli interval was set at 1.3s.

The participants in the ODT were the same as those in the IT. They were given an answer sheet and required to indicate the odd item in each trial by circling "A", "B", "C", referring to the first, second and third stimuli, and "D", if they heard no odd item. The experiment was carried out in the same classroom as that in the IT, but one week later. All the participants were paid to take the test twice, with a three-minute interval in between.

2.2.3 Experiment Results

The results for the IT are presented in Table 3 below, in which the percentage results were obtained by averaging the identified rhyme by the total number of trials containing that rhyme in both repetitions.

Table 3: *Results for the IT.*

	V1n.K		**V1n.C2[non-K]**	**V1ŋ.C2**
	an.K	en.K		
V1n	632 (98.75%)	608 (95%)	100%	0%
V1ŋ	8 (1.25%)	32 (5%)	0%	100%

Results in Table 3 show that the initial rhymes of the V_1ŋ.C_2V_2 sequence were uniformly identified as V_1ŋ; whereas those of the $V_1n.C_2V_2$ sequence were all identified as V_1n except for the $V_1n.KV_2$ sequence. Specifically, /an.K/ was identified as /aŋ/ 8 times (8/640=1.25% in percentage) in total, and that of /en.K/ sequence was identified as /eŋ/ 32 times (32/640=5% in percentage) in total. We can conclude from these results that /a, e/ in the $V_1n.C_2V_2$ sequence are still categorized as the non-back vowels by native MC speakers.

The results for the ODT are presented in Table 4 below. The table only presents the discrimination for trials consisting of the $V_1n.KV_2$ stimuli because they have different results of discrimination. That is, some of the $V_1n.KV_2$ stimuli were considered to be the same as V_1n, whereas others as V_1ŋ. Trials that consist of stimuli other than $V_1n.KV_2$ have consistent discrimination results. The percentage difference (diff.) and similarity (same) was obtained by averaging the number of trials discriminated as different or same by the total trials that feature one specific contrast in the two repetitions of the task.

Table 4: *Results for the ODT.*

	an.C2-an.K	**aŋ.K-an.K**	**en.C2-en.K**	**eŋ.K-en.K**
diff.	8 (1.67%)	77 (96.25%)	18 (3.75%)	73 (91.25%)
same	472 (98.3%)	3 (3.75%)	462 (96.25%)	7 (8.75%)

Table 4 shows that the results of ODT are very similar to those of IT, i.e. the initial rhymes of the /an.K/ and /en.K/ sequences were overwhelmingly more likely to be perceived as the same as those of the other /an.C_2/ and /en.C_2/ sequences, and as different from those of the /aŋ.K/ and /eŋ.K/ sequences, respectively. This result suggests that non-high vowels /a, e/ as V_1 in $V_1n.C_2V_2$ sequences are categorized as non-back vowels by native MC speakers, which echoes the finding in the IT.

3. General discussion and conclusion

The results of the perception experiment discussed in Section 2 show that the phonetic changes in VF2 and VNTRF2 of V_1 in the V_1**n**.C_2V_2 sequence does not affect the categorial perception of V_1 by native MC speakers as a non-back vowels. In other words, the contrast in vowel backness between [a, e] in the V_1**n**.C_2V_2 sequence as opposed to [ɑ, ə] in the V_1**ŋ**.C_2V_2 sequence is maintained in perception despite the change of coda /n/ in the place of articulation.

Based on this finding, we conclude that the vowel backness feature of V_1 in the $V_1N.C_2V_2$ sequence is not re-specified even though the Nasal Place Assimilation process sets up the appropriate environment for the VBS Rule to re-apply. In terms of Lexical Phonology [17][18][19], the VBS rule can only apply within the mono-syllable once, but not again. That is, the VBS rule is not cyclic.

As to the $V_1N.V_2$ sequence, the deletion of the nasal coda destroys the environment for all the rules applied in the first cycle, i.e.V_1N, although it does not affect the weight profile of the initial syllable, and thus constitutes a typical case of phonological opacity, in particular, one of counter-bleeding.

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