AERODYNAMIC CONSTRAINTS ON SOUND CHANGE: THE CASE OF SYLLABIC SIBILANTS

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ABSTRACT

High vowels are known to assimilate in place of articulation and frication to a preceding sibilant. Such an assimilation process is found in a historical sound change from Middle Chinese to Modern Mandarin (e.g., */si/ became [sz̩] 'poetry'). However, such assibilation is systematically absent when the vowel is followed by a nasal consonant. This paper investigates the co-occurrence restriction between nasalization and frication, demonstrating that when pharyngeal pressure is vented significantly during the opening of the velic valve, the necessary pressure buildup behind the constriction of a fricative is severely diminished, resulting in no audible turbulence. It reports the aerodynamic effects of nasalization on vowels, as spoken by a native speaker of American English (presumed to parallel the phonetic conditions present in Middle Chinese). The results reveal that in comparison to oral vowels the pharyngeal pressure, volume velocity and particle velocity decrease dramatically when high vowels are nasalized. Based on this study, a physical motivation for the phonological patterns with respect to the interaction between syllabic sibilants and nasal is advanced.

1. INTRODUCTION

High vowels are known to assimilate in place of articulation and frication to a preceding sibilant. Such an assimilation process is found in the historical sound change from Middle Chinese to Modern Mandarin and several other phonological patterns found in languages such as Yuchi and Fante.

In this paper, we will provide aerodynamic evidence to demonstrates that when pharyngeal pressure is significantly vented during the opening of the velic valve that the necessary pressure buildup behind the constriction of a fricative is severely diminished, resulting in no audible turbulence.

This paper begins with a brief discussion on the basic facts about syllabic sibilants. In section 3, an investigation of the aerodynamic properties of oral vowels, vowels before a nasal and nasalized vowels is presented. This investigation reveals that the anticipatory velic opening during the production of a vowel before a nasal bleeds the pharyngeal pressure build-up. Based on this, a physical explanation of the non-fricativizing property of vowel before nasal is advanced.

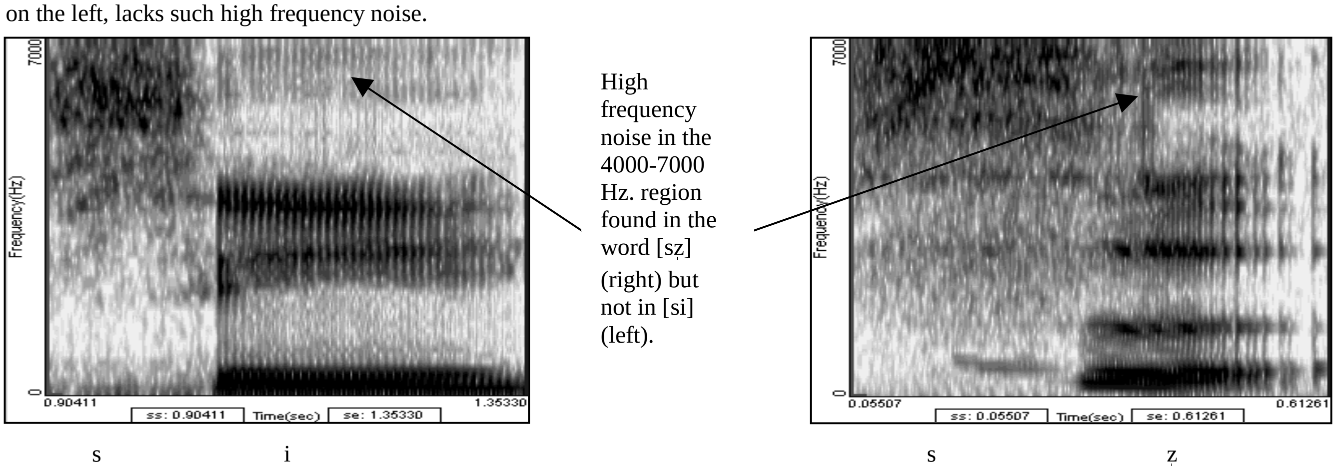
2. SYLLABIC SIBILANTS?

2.1. Some facts about syllabic sibilants

Syllabic sibilants are generally rather uncommon among the world's language. Bell [2] reports in his survey that of the 182 languages of major language families and areas of the world 85 of them possess syllabic consonants while only 24 of them have syllabic continuants. In many Chinese dialects (e.g. Hakka, Hsiang(Chang-sha), Hsiang(Hankow), Kan, Mandarin, Wu(Suchou), Wu(Wenchou)) [7] and Lolo-Burmish languages (e.g. Ahi, Lahu, and Nyi) [9], the high front vowel /i/ and its rounded counterpart in some dialects are often pronounced as fricativized.

Many researchers have studied the acoustic structures of fricative vowels, most notably Svantesson [18]. These fricative vowels display distinct formant structure as often found in vowels, however, the definitive indication of its sibilant property is the high frequency energy noise in the 4000 Hz - 6000 Hz region, most typical of fricatives and sibilants (see figure 1).

Figure 1. The spectrogram of the word 'silk' [si] in Cantonese (left) and [sz̩] in Mandarin (right). The vowel /i/ in Mandarin is fricativized, indicated by the concentration of high frequency noise in the 4000-7000 Hz. region. The non-fricative counterpart, presented on the left, lacks such high frequency noise.



2.2. Phonological patterns

Chen [5], in his 1976 comprehensive study of the historical sound change from Middle Chinese (MC) to Modern Mandarin (MM), points out that MC sibilant-high front vowel sequences becomes MM sibilant-syllabic sibilant sequences. For example, */si/ → [sz̩] ‘poetry’; */ʂi/ → [ʂʐ̩] ‘lion’. However, the high front vowels in MC sibilant-high front vowel sequences when followed by any nasal segment, the vowels remain oral vowels in MM. Thus, the assibilation of the vowel fails to occur in the presence of nasalization. For example, */ʂiəm/ → [sən] ‘forest’ but not [sz̩n]. Phonological patterns similar to those found in MM are also found in other languages. For example, in Fante [16], /hI/ ‘border’ → [çi] but /hĨ/ ‘where’ → [hĩ] not [çĩ]. In Yuchi [19], voiceless spirants appear predictably between all vowels and following lingual stops but not if the vowel is nasalized. Recent research [6, 13, 14] suggest that the feature [nasal] rarely co-occurs, if at all, with continuant obstruents. In the next section, I will introduce an aerodynamic study of vowels in nasal and oral environment.

3. THE STUDY

3.1. An aerodynamic hypothesis

Fricatives are produced by making a tight constriction somewhere in the vocal tract with the constriction area of the order of 0.1 cm^2. The volume flow-rate of voiceless fricatives range from 200 to 400 cm^3/s [17]. According to Fant [8: 272-279], “sustainable sounds of noise character are produced from a turbulent source located at or near a constricted passage within the vowel tract. The contraction of the flow causes the air particles to accelerate, forming a jet of air shot at high speech through the passage. The jet associated with circulation effects and eddies, partially of a random nature… The turbulent noise is a secondary effect of the airflow.”

The non-co-occurrence between nasalization and frication has been noted by various researchers [6, 12, 13, 14, 15]. Ohala et al. [15] provide instrumental evidence demonstrating that frication is hard to maintain in the presence of nasalization. They argue that such a constraint has its origin in the basic aerodynamic properties of human physiology. They assert that pharyngeal pressure is so significantly vented during the opening of the velic valve that the necessary pressure buildup behind the constriction of a fricative is consequently severely diminished and results in no audible turbulence.

This impacts on the fate of the [i] in the [s_n] context for the following reason:

Many researchers [3, 10, 11] have pointed out that there is an anticipatory velic opening during the production of the segment preceding a nasal. Such velic opening should theoretically decrease the pharyngeal pressure during the articulation of the vowel. Thus, assuming that the configuration of the tongue and other resisting bodies remain constant, the only variable that affects the formation of turbulence is the amount of airflow passing through the constriction. Hence, the higher the airflow, the more chance turbulence is generated. Since volume velocity is proportional to the intraoral pressure and to particle velocity, theoretically then, a decrease in the intraoral pressure should decrease volume velocity and particle velocity. Ali et al. [1], in their study of intrusive stops in nasal-fricative clusters, also observe that the co-articulatory velopharyngeal opening may shunt the oral air pressure, delaying air pressure build up. Although they conclude that the intrusive stops in nasal-fricative clusters are the result of the timing and release characteristics of nasal stops, they acknowledge that the nasal “bleeding” may also have been a contributing factor. This aerodynamic constraint with respect to nasal "bleeding" imperils the frication in syllabic sibilants even more directly since the generation of voicing already compromises the frication. In order to produce enough vocal cord vibration for audible voicing, pressure in the pharyngeal area must be lower than the subglottal pressure. Yet, the pharyngeal pressure must be higher than the atmospheric pressure in order to create enough intraoral pressure for frication to happen. The anticipatory velopharyngeal opening will invariably offset the precarious balance of pharyngeal pressure in satisfying both the voicing and frication requirement.

The working assumption behind the experimental findings reported in the following section is that phonological phenomena that recur across geographically distant languages have a phonetic basis and stem from the same mechanisms of speech production and perception that all humans share. This evidence may be drawn from the speaker of a language that may have no overt phonological pattern involving nasalization and its effects on frication and on adjacent vowels should further strengthen this universalistic interpretation of phonology. In the remainder of this paper, instrumental measurements of pharyngeal pressure and airflow in oral and nasalized environment produced by a native English speaker are presented. The implications of these data are discussed in the final remarks in section 4.

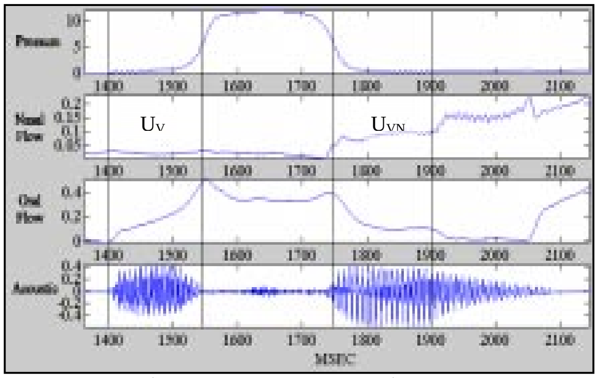
3.2. Method

To attempt to verify this hypothesis, a trained phonetician, who is a native speaker of American English, uttered [isi, ise, isa, isin, isen, isan, i, e, a, ĩ, ẽ, ã] seven times. Audio was recorded by a high quality microphone place within 15-20cm. of the speaker's mouth. Pharyngeal pressure was sampled by a 3mm inner diameter and 21cm long catheter inserted into the pharynx via the nasal cavity and connected to a pressure transducer. A Rothenberg mask with oral and nasal separation was placed on the subject's mouth and nose. Oral and nasal flows were collected by connecting plastic tubes from the respective chambers of the mask to the transducer. All signals were digitized and logged directly onto a PC hard drive at a sampling rate of 4.8kHz. A Khron-Hite filter was used to 50 Hz low-pass filter the pressure and nasal flow signals in order to minimize the effect of microphonics created by voicing.

3.3. Results

Figure 2 is a tracing of the filtered air pressure (channel 1), nasal (channel 2)/oral flow (channel 3) and acoustic signal (channel 4) from the production of [isin]. The onset of the rise phase of the nasal flow (U_{VN}) is far anterior to the actual production of the nasal segment. This provides evidence of anticipatory velum lowering during the production of the vowel. This contrasts remarkably with the oral vowel (U_V) preceding the fricative where little, if any, nasal flow is found. Since the two vowels under comparison are the same, namely [i], the difference observed cannot be attributed to variation in vowel production. The amount of nasal flow is significantly higher during the production of the nasal segment than during its preceding vowel [i].

Figure 2. The tracing of the pressure, nasal/oral flow and the acoustic signals of the word [isin].



i s i n

The results of this study for the effect of nasalization on vowels are best shown in Tables 1, 2, and 3. The calculation is based the average of the seven sets of measurements collected. As can be seen in Table 1, air pressure is highest in high vowels and lower in the mid and low vowels.[1]

		/isV/	/isVn/	Diff.
/i/	M	0.492	0.394	-20%
	SD	0.080	0.070	
/e/	M	0.167	0.183	10%
	SD	0.020	0.030	
/a/	M	0.204	0.277	36%
	SD	0.050	0.030	

		/V/	/∇/	Diff.
/i/	M	0.667	0.513	-23%
	SD	0.060	0.080	
/e/	M	0.198	0.193	-3%
	SD	0.010	0.040	
/a/	M	0.290	0.294	2%
	SD	0.050	0.040	

Table 1. Mean and standard deviations in centimeter of water of the air pressure values in various oral and nasalized environments.

The flow difference between vowels in oral and nasalized environments is most dramatic in the high front vowel [i], yielding a 26% drop when followed by a nasal segment and a 40% drop in flow when fully nasalized. Little effect or even reverse effect in the case of the non-high vowels followed by a nasal.

Table 2 reveals that the intraoral flow is highest in the high vowel [i], lower in the mid vowel [e] and lower yet in the low vowel [a]. Nasal vowels, in general, suffer greater aerodynamic change than contextually realized vowels in nasal environments, that is, when the vowel is followed by a nasal segment. As expected, pharyngeal pressure is greater in high vowels than the other two non-high ones, since the constriction created the tongue body is tighter for high vowels than low ones. The values of the low back vowel [a] are higher than the mid front vowel [e] in most dimensions.

		/isV/	/isVn/	Diff.
i	M	149	111	-26%
	SD	7	9	
e	M	116	114	-2%
	SD	18	12	
a	M	77	91	19%
	SD	14	18	

		/V/	/∇/	Diff.
i	M	166	102	-40%
	SD	18	2	
e	M	159	115	-30%
	SD	10	17	
a	M	120	72	-40%
	SD	32	7	

Table 2. Mean and standard deviations in milliliter of air per second of the volume velocity in various oral and nasalized environments

The mean particle velocities during the production of vowels in various environments are calculated and the values and their percentage of difference between oral and nasalized vowels are given in Table 3. Assuming a constant aperture, the particle velocity is calculated using the formula given below:

$$\text{Particle velocity} = \text{Intraoral flow}/412(\text{Pressure})^{½}$$

This formula is derived from various formulas given in Catford [4: 31, 34].

		/isV/	/isVn/	Diff.
i	M	901	816	-10%
	SD	76	76	
e	M	537	558	4%
	SD	38	47	
a	M	591	677	15%
	SD	67	39	

		/V/	/∇/	Diff.
i	M	1069.7	933.3	-13%
	SD	50	73	
e	M	584.3	572	-2%
	SD	14	50	
a	M	734.7	698.7	-5%
	SD	63	41	

Table 3. The calculated mean and standard deviations in centimeter per second of the particle velocity in various oral and nasalized environments

3.3. Discussion

This study points to velopharyngeal opening as a factor in inhibiting turbulence, at least when the constriction is small (i.e. [i]). Typologically, vowel fricativization, resulting in syllabic fricatives and sibilants, is found mainly in high vowels. Comparison of the values of each aerodynamic dimension measured permits us to form a rough idea of the relative impact of the velopharyngeal opening on aerodynamic conditions during the production of vowels and, presumably, to other continuants such as fricatives and glides. The normal particle velocities of flow being of the order of 1000 to 4000 cm/s through the articulatory channels for fricatives. A 20% drop in particle velocity during a fricative with a minimal particle velocity of 1000 cm/s would result in a particle velocity of 800 cm/s. Such a value of particle velocity coincides with the particle velocity during the production of a high vowel as shown in Table 3. This suggests that, given the proper circumstance, frication is endangered, if not extinguished all together, when followed immediately by a nasal segment. As mentioned above, syllabic sibilants are especially vulnerable to the bleeding of pharyngeal pressure since the aerodynamic condition for voicing requires the pharyngeal pressure to be lower than in voiceless fricative. As a result, the already low pharyngeal pressure diminishes even further. This further jeopardizes the generation of turbulence, as the intraoral pressure is invariably lower than under normal condition.

4. Final Remarks

In this paper, a partial phonological distribution of the fricative vowels is presented which reveals that syllabic sibilants are rarely, if at all, appear before nasal segments. This non-co-occurrence restriction is observed in several phonological patterns of several genetically and geographically unrelated languages. However, this restriction is most salience in the historical sound change of sibilant-high front vowel sequence from Middle Chinese to Modern Mandarin and in the general distributional property of syllabic sibilants in several Chinese dialects.[2] An aerodynamic investigation of nasalization on vowels is reported based the production of a speaker of English. Despite the fact that English has no productive phonology or attested phonological distribution biased against sibilants-nasal sequence, the finding reveals that anticipatory velum opening generally result in a decrease of pressure, oral flow and particle velocity. Such reduction effect is most apparent in segment with high degree of constriction, such as high vowels, suggesting that the intrinsic human physiological aerodynamic constraints disfavor the adjacency of strident and nasal segments. The results of this study also demonstrates that such gaps in the phonological distribution of syllabic sibilants should not be viewed as accidental, but have sound physical grounding for the co-occurrence restriction on syllabic sibilants and nasalized segments.

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NOTES

1. A peculiar phenomenon occurs in the pressure value of the low back vowel [a]. The intraoral pressure of this low back vowel is unexpectedly higher than the mid vowel [ɘ]. A plausible explanation for this fact can be that the location of the catheter might be lower in the pharyngeal area than the back constriction created by the back vowels. Thus during the production of a back vowel, the back constriction might create a buildup of pharyngeal pressure below the back tongue body. Since the judgement of the location of the catheter cannot be observed without additional instrumental study, e.g. by X-ray imagining, we can only rely on an impressionistic judgement on this matter.

2. There are also other suggestive motivations for the observed pattern in Mandarin. For example, the historical development of the word ‘forest’ is */s̩iəm/ → [sən]. The modern pronunciation suggests that possibility that the schwa might have been lowered before the assibilation be introduced into Mandarin, thus effectively eliminating the condition for assibilation since the fricativization only applies to high vowels. Larry Hyman also points out that the distribution of the syllabic sibilants in Mandarin might have to do with the syllable structure, that is, syllabic sibilants only occur in open syllable and not the closed ones. All these alternative explanations are plausible. However, I should stress that the purpose of this paper is merely to empirically demonstrate one of the many possible motivations for the asymmetric distribution of the syllabic sibilants in Mandarin.

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