



<b>Title</b>	<b>A kinematic study of coarticulation of Cantonese fricative /s/ using electromagnetic articulography (EMA)</b>
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A kinematic study of coarticulation of Cantonese fricative /s/ using  
electromagnetic articulography (EMA)

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Abstract

The present study investigated the coarticulation during production of Cantonese alveolar fricative /s/ in /sV/ syllables, and the effects of vowel contexts on the coarticulatory behavior. A total of 10 native speakers of Hong Kong Cantonese with ages between 20 and 25 years participated in the study. Kinematic information of tongue and lip movement during production of /s/ in various phonetic contexts (/sa/, /si/, /su/ and /sy/) was obtained using a three-dimensional electromagnetic articulography (EMA) system. Results indicated the presence of coarticulation during /sV/ production and differential effects of coarticulation in different vowel contexts. For both male and female speakers, the upper lip showed no coarticulatory activity regardless of the vowel context. The findings of the present study provided new kinematic information of the tongue and lips during the production of Cantonese fricative /s/ in different vowel contexts.

## Introduction

Among the 19 consonants in Cantonese, three are classified as fricatives: the labiodental fricative /f/, alveolar fricative /s/, and the glottal fricative /h/ (Cheung & Abberton, 2000). Within the alveolar-palatal region, there are two fricatives in English /s, ʃ/ while there is only one in Cantonese /s/. The Cantonese alveolar fricative /s/ is produced by placing the tongue tip behind the upper incisors, and with the tongue blade in contact with the alveolar ridge (Bauer & Benedict, 1997). Simultaneously, a central groove is created along the midline which directs the airflow from the tongue to the teeth through the constriction. This results in the production of a hissing and high-pitch sound (Borden, Harris, & Raphael, 2003).

There have been articulatory studies examining English fricative consonants by using magnetic resonance imaging (Narayanan, Alwan & Haker, 1995), lateral x-ray (Badin, 1991; Subtelny, Oya, & Subtelny, 1972), ultrasound (Stone, Faber, Raphael, & Shawker, 1992), and dynamic electropalatography (Fletcher, McCutcheon, & Wolf, 1989; Hardcastle & Clark, 1981; Hoole, Ziegler, Hartmann & Hardcastle, 1989). Acoustic studies have also been conducted on English fricatives (Hughes & Halle, 1956; Jongman, Wayland & Wong, 2000) to confirm various places of articulation. These studies of English fricatives generally agreed that the frication noise was generated at an articulatory constriction and that alveolar fricatives /s, z/ are characterized by high-energy and high-frequency noise (Borden et al., 2003). The palatographic studies reported by Hardcastle and Clark (1981), and Fletcher et al. (1989) also revealed that the groove formed for /s, z/ is more anterior and narrower than /ʃ, ʒ/.

Compared to English fricative consonants, relatively fewer studies had been conducted on Cantonese fricative consonants. Lee (1999) carried out an acoustic and perceptual study examining the production of /s/ before and after orthognathic surgery. Production of /s/ by children with cleft palate has also been investigated by Chan (2004) by means of

electropalatography and perceptual study, and Lau (1994) using acoustic and perceptual analyses. To study normal production of Cantonese /s/, Kwok and Stokes (1997) conducted an articulatory study examining /s/ produced by normal individuals using dynamic electropalatography. Perceptual and acoustic studies of allophonic variation of Cantonese /s/ have also been reported (Cheng, 2006; Cheung, 2005). These studies generally suggested variability in Cantonese /s/ production among individuals, including normal individuals, participants with cleft palate and orthognathic surgery in terms of acoustic, perceptual and articulatory analyses.

### *Coarticulation*

According to Borden et al. (2003), coarticulation occurs when two articulators move at the same time for different phonemes. It implies that the production of a phonetic segment is strongly dependent of the context (Katz & Bharadwaj, 2001). Based on spectrographic data of VCV syllable productions, Öhman (1966) postulated that the articulatory system already prepared for the production of subsequent consonants in VCV syllables. This results in a slightly discrepant realization of the same segment in different phonetic contexts known as allophonic variation (Kühnert & Nolan, 1999).

Studies have been done on the dynamics of vowel-fricative-vowel sequences and the effect of different vocalic contexts on fricative production (Shadle, Moulinier, Dobelke, & Scully, 1992; Shadle & Scully, 1995). Shadle and Scully (1995) studied the effects of different vowel contexts /a, i, u/ on fricatives /s, z/ in VCV sequences produced by a single subject using articulatory, acoustic and aerodynamic measurements. Both acoustic and aerodynamic data supported that some lip rounding feature from the vowel /u/ was extended to the fricative /s/ in the /su/ context. Yet, aerodynamic and acoustic data regarding how much vocalic context influences production of the fricative /s/ production was contradictory. Acoustic data suggested a strong contextual effect whereas minimal effect of context was concluded from the aerodynamic

data. With the limited articulatory data, it was assumed that lip rounding, rather than changes in constriction formed by tongue attributed to the acoustic differences that were interpreted.

However, to confirm the above assumption made on the tongue shape and exploring the possible lingual and labial coarticulation during the production of /sV/ syllable, a dynamic study of articulatory movement including the lips and tongue is needed.

Similarly, it has been reported that the Cantonese alveolar fricative /s/ can be realized as an alveolar fricative [s], alveo-palatal fricative [s<sup>j</sup>] or palatal fricative [ʃ] depending on the following vowel. According to Bauer and Benedict (1997), the Cantonese /s/ may be produced as a palatal fricative [ʃ] or a palatalized alveolar fricative [s<sup>j</sup>] when followed by a high front rounded vowel /y/. It is speculated that the lips may be rounded and tongue be raised toward the hard palate to produce /y/, extending these into the fricative [s], resulting in a [ʃ]. Cheung (as cited in Bauer & Benedict, 1997) however pointed out that Guangzhou Cantonese speakers tended to palatalize /s/ to [s<sup>j</sup>] before both /i/ and /y/. Based on these speculations, coarticulation may affect the realization of the alveolar fricative [s] in Cantonese.

#### *Purpose of the current study*

Regarding the issue of different realizations of /s/ in Cantonese and the factors causing such differences, perceptual and acoustic studies were carried out to examine the allophonic variation of Cantonese /s/. Cheung (2005) suggested that the phonemic variation were strongly associated with age, gender and vowel context. For example, a lip-rounded vowel following the target /s/ would be more likely to cause variation. An acoustic study conducted by Cheng (2006) also quantified the variation's physical properties.

Due to the limited access to moving articulators during speech, studies of articulatory movements during speech production have not been easy. Researchers have relied on acoustic measurements, magnetic resonance imaging (MRI), x-ray and x-ray microbeam (e.g., Engwall &

Badin, 2000; Soli, 1981) to study the articulatory movements during speech production. However, coarticulation is a dynamic event which cannot be captured using MRI, whereas using x-rays or x-ray microbeam for real-time articulatory movements unavoidably accompanies radiation hazard. Acoustic measurement could only provide objective data concerning few dimension of change with many to one relationship between acoustic data and articulatory movements (Kartz & Bharadwaj, 2001).

As an alternative, a three-dimensional electromagnetic articulography (EMA) system provides real-time kinematic measurements of articulator movement during speech production. A 3-D EMA system has the advantages of capturing substantial lateral deviations of the tongue from midline without error and lessens the unnaturalness of speech during the measurement (Hoole, Zierdt, & Geng, 2003; Yunusova, Green, & Mefferd, 2008). In a combined EPG, EMA and acoustic study, West (1999) proved the presence of coarticulatory effects in two syllables prior to English liquids in a sentence. Hoole, Nguyen-Trong, and Hardcastle (1993) studied English fricative coarticulation based on EMA, EPG and acoustic measurements. Results revealed different coarticulatory direction on /s/ and /ʃ/ by some speakers. Other studies examined French fricatives by using EMA (Nguyen-Trong, Hoole, & Marchal, 1991) and dynamic coarticulation in Swedish fricatives using EMA and EPG (Engwall, 2000). In these studies, kinematic data of different articulators were obtained by using EMA or/and EPG during the production of fricatives in different vowel contexts. Engwall (2000) found different coarticulatory patterns of the articulators caused by different vowel contexts.

Despite the relatively many studies on English fricatives, little examined Cantonese fricative consonants and their coarticulatory behaviors. Allophonic variation in Cantonese fricative /s/ production was examined perceptually and acoustically. As cross-language

difference is present in coarticulation of phonemes, such difference might be characterized by analyzing the extent of effects caused by different contexts (Hoole et al., 1993).

The present study attempted to examine the possible coarticulatory effects of different vocalic contexts on the production of Cantonese alveolar fricative /s/. The possible anticipatory coarticulation effects (both lingual and labial) brought by different upcoming vowels on the production of Cantonese /s/ were explored using kinematic measurements of the tongue and lips during 100 ms, 30 ms before vowel onset, the fricative-vowel boundary, and vowel mid-point of the /sV/ production. Kinematic measurements were obtained from tongue and lips highlighting the coarticulatory behavior of Cantonese /s/ due to four vowel contexts /i, y, a, u/. It was predicted that coarticulation is present during /sV/ production and different coarticulatory effects of different vowel contexts yielding different realizations of the Cantonese /s/ would be found.

#### *Electromagnetic Articulography (EMA)*

Developed by the University of Munich, the 3D EMA system (AG500, Carstens Medizinelektronik GmbH) allows the real-time measurement of movement of various articulators. With the EMA system, there are six transmitter coils which are fixed within the EMA cube, each of which produces an alternating magnetic field at different frequencies. To assess articulatory movement, up to twelve receiver coils (sensors) could be fixed onto the relevant articulator points. According to the theory of electromagnetism, an alternating current is induced by a moving receiver coil, with a magnitude directly corresponding to the rate and direction of movement of articulator points. Based on the induced electrical signals, instantaneous location and movement of each sensor during speech production can be interpreted. Hoole et al. (2003) and Yunusova et al., (2008) evaluated and assessed the 3D EMA system and found that articulatory data obtained with the system was both accurate and reliable when steps were taken to ensure the quality of recordings.



## Methods

### *Participants*

A total of 10 speakers (five males and five females) were recruited for the study. They were native speakers of Hong Kong Cantonese with ages between 20 and 25 years. All speakers were literal monolingual speakers who were recruited from the family and social circles of the researcher and those of the fellow students. Participants were excluded from the study if they had a reported history of speech or hearing problem.

### *Speech materials*

The speech materials consisted of four CV syllables which were formed by the Cantonese alveolar fricative /s/ followed by one of the four vowels /i, a, y, u/. Vowels /i/ and /a/ are unrounded whereas vowels /y/ and /u/ are rounded (Matthews & Yip, 1994). Among the four CV syllables, /su/ is a non-sense syllable. /i, a, u/ were chosen as test stimuli since they represent the corner vowels of Cantonese and are supposedly more stable, and /y/ might cause possible coarticulation and affects realization of /s/ as suggested by Bauer and Benedict (1997).

During the experiment, the participants were instructed to read aloud the CV syllables upon the spoken examples provided by the researcher who was a native speaker of Hong Kong Cantonese. Imitation rather than reading was chosen due to the use of a non-sense syllable /su/. The participants repeated each CV syllable for 10 times. To avoid any order effect, the order at which the speech materials were produced was randomized.

### *Instrumentation*

A 3-D electromagnetic articulography (EMA) system was used to acquire real-time kinematic measurements of articulator movement during speech production in the electrically shielded Speech Science Laboratory. It tracked articulators' movement in three Cartesian planes

(X, Y, & Z) and two angles. A microphone was used to obtain the acoustic signals of participant's speech.

#### *System Preparation*

Prior to the experiment, the EMA system was turned on for two hours to warm up the coils and to achieve an appropriate working temperature. After that, the AG500 system was calibrated according to the operating manual before each recording began. Calibration was considered acceptable only if the measured amplitudes were between 2100 and 2400 digits with the random distribution of alpha-zeros between  $\pm 0.5$ mm and the root mean square (rms) values below 20 digits (Yunusova et al., 2008). Sensors were visually inspected for damage if any of the calibration factors fell outside the acceptable range and calibration was re-conducted until the calibration quality improved to reach the expected range.

#### *Placement of receiver coils.*

Eight receiver coils were used in this study. Each sensor was coated with plasty-late and sterilized with alcohol pad before it was attached to the participants. Three sensors were placed on the participant's tongue along the midline, and they were positioned 1 cm (T1), 2 cm (T2) and 3 cm (T3) inward from the tongue tip (see Figure 1). Another sensor was attached to the upper lip (UL) and one on the lower lip (LL). Three sensors were used as references: one on the nasal bridge, one on the mastoid process of the left ear, and one on the gingiva above the upper incisor. The coil on the nasal bridge, mastoid process and upper incisor acted as anatomical references for correcting head movement. The tongue-tip coil (T1) was placed 1 cm behind the tongue apex to prevent tongue irritation which might be felt by the participants (Hoole & Nguyen, 1997). All sensors were attached to the participants using biologically-safe adhesive. Their positions were visually inspected before and during the experiment periodically to ensure recordings were made on the mid-sagittal plane. All participants were grounded to avoid effects of static electricity.

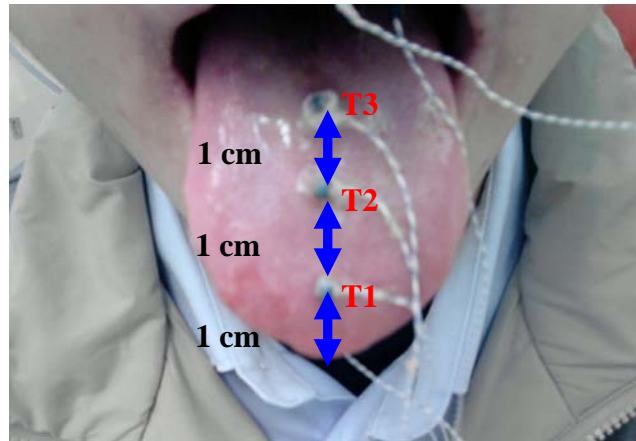


Figure 1. *Placement of coils on tongue*

### *Procedures*

Prior to the experiment, the participants were informed of the purpose of the study. Informed consent and personal information were also obtained from each participant. To prepare for the EMA experiment, participants sat on a straight-back seat inside the EMA cube. Eight sensors were attached to the different articulators of the participant. To avoid interference, sensors were separated by a distance of at least 1 cm. To familiarize with the format and setup of the experiment, and speaking with sensors attached, the participant was allowed to practice with the speech materials and engaged in casual conversation with the experimenter for about 30 minutes. Only those who could produce the speech materials naturally and comfortably with the sensors attached were allowed to continue with the study. During the EMA recording, participants were instructed to read aloud the CV syllables upon the researcher's modeling. They repeated the CV syllables 10 times in a randomized order. Acoustic recordings of speech materials were made simultaneously. The entire recording session including CV syllables reading and attachment/ removal of sensors for each participant lasted for approximately one hour.

### *Data Analysis*

With the EMA system, the signals were amplified and digitized at 200 Hz, and evaluated by a processing unit. As a result, amplitude data were obtained from each sensor. After that, the recorded data were further evaluated by the CalcPos program with both temporal and geometric parameters for determining the sensors' motion. Since the EMA data contained both the head and articulators' movement, head movement was adjusted by means of reference sensors by using the NormPos program, after which, the X (anteroposterior), Y (transversal), Z (vertical) coordinates and two angles (tilt and yaw) were evaluated.

To examine the anticipatory lingual and labial coarticulatory effects of /s/ due by different vowels, kinematic data were analyzed in both X (anteroposterior) and Z (vertical) coordinate planes of movement over time. A total of 400 productions were used for analysis (10 speakers x 4 vowels x 10 tokens), of which three were discarded due to measurement failure. The kinematic data indicating the distance between the measured sensor's position and the referenced sensor was obtained by subtracting the measured sensor's position from that of the nasal bridge's sensor. By so doing, the separation between the sensors and the nose (anteroposteriorly indicated by X and superoinferiorly indicated by Z) could be described.

To depict coarticulatory activity, only kinematic data at four measurement windows were considered: at 100 ms (point 1) and 30 ms (point 2) before vowel onset, fricative/vowel boundary (point 3), and the vowel mid-point (point 4). The measurement windows of 100 ms and 30 ms before vowel onset were used as they help show the existence of anticipatory coarticulation (symbolized as -100 ms and -30 ms). All the measurement windows were identified by measuring the time from the corresponding waveform and narrow-band spectrogram of the acoustic speech sample. Using the time tags, the kinematic data of the tongue and lips were obtained and used for later analyses.

In order to identify the main effect of vowel contexts and different points of production on speakers' articulatory movements, and the interaction effect of vowel contexts by time windows, 4 (vowel contexts) x 4 (measurement windows) repeated measure factorial ANOVAs were used. Analyses were done separately for the identified kinematic data of five sensors (T1, T2, T3, UL and LL) in X and Z planes for speakers of each gender.

## Results

A two-way repeated measure ANOVA was conducted for each sensor in X and Z planes. Due to the small number of male and female participants, gender was not considered as an independent variable and data obtained from male and female speakers were analyzed separately. Since the effect of vowel context on coarticulation was the focus of the present study, one way repeated measure ANOVAs with vowel as the independent variable and post-hoc pairwise comparisons were conducted if needed. Their results were summarized in Table 1.

Table 1. *Summary of the major findings for coarticulation in female and male speakers during the production of [sV] syllable. \*  $p < 0.05$*

Major findings from repeated measure ANOVAs
<p><b>Front versus back vowels</b></p> <p>Males demonstrated sig. diff between /i/ and /u/ across window 1, 2, 3, 4 for T1 and across window 2, 3 for T2 in plane X</p> <p>Females demonstrated sig. diff between /i/ and /u/ across window 4 for T1, across window 1, 2, 3, 4 for T2 and across window 4 for T3 in plane X</p> <p>Males demonstrated sig. diff between /i/ and /a/ across window 4 for T1 and across window 1 for T2 in plane X</p> <p>Females demonstrated sig. diff between /i/ and /a/ across window 4 for T1 and across window 2, 3, 4 for T2 in plane X</p> <p>Males demonstrated sig. diff between /y/ and /u/ across window 2, 3, 4 for T1, across window 1, 2, 4 for T2, and across window 2, 3, 4 for T3 in plane X</p> <p>Males demonstrated sig. diff between /y/ and /a/ across window 1 for T2, across window 1, 2 for T3 in plane X</p>
<p><b>High versus low vowels</b></p> <p>Males demonstrated sig. diff between /i/ and /a/ across window 1, 2, 3 for T1 and across window 1 for T2 in plane Z</p>

Males demonstrated sig. diff between /y/ and /a/ across window 1, 2 for T1, across window 1 for T2 and T3 in plane Z

Males demonstrated sig. diff between /u/ and /a/ across window 1, 2, 3 for T1, across window 1, 2 for T2 and T3 in plane Z

### **Rounded versus unrounded vowels**

Males demonstrated sig. diff between /y/ and /i/ across window 1, 2, 3, 4 for LL for both plane X and Z

Females demonstrated significant differences between /y/ and /a/ across window 4 for LL in plane X and across window 1, 2, 3, 4 for LL in plane Z

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### ***Male Speakers***

#### *Tongue tip (1cm inward from the tongue tip)*

For the anteroposterior plane X, because of the significant interaction between vowel context and measurement window ( $F = 20.565, p < 0.01$ ), one-way repeated measure ANOVAs and post-hoc pairwise contrasts were carried out for measurement windows. Significant differences ( $p < 0.05$ ) were found: sensor T1 for /u/ was consistently more posterior than that for /i/ measured at -100 ms, -30 ms, fricative-vowel (FV) boundary, and vowel mid-point. T1 for /u/ was more posterior than that for /a/ at -100 ms, -30 ms, and fricative-vowel boundary. At vowel midpoint, T1 for /a/ was more posterior than /i/, and at -30 ms, FV boundary and vowel midpoint, T1 for /u/ was more posterior than that for /y/.

Similarly for the vertical plane Z, significant interaction effect ( $F = 10.879, p < 0.01$ ) was found. The subsequent one-way ANOVAs and post-hoc pairwise contrasts revealed that, at -100 ms, -30 ms, and FV boundary, T1 for /i/ and /u/ were lower than that for /a/. At -100 and -30 ms, T1 for /y/ was lower than that for /a/.

#### *2 cm inward from the tongue tip*

For the anteroposterior plane X, because of the significant interaction ( $F = 7.784, p < 0.01$ ), one-way repeated measure ANOVAs and post-hoc pairwise contrasts were conducted for each measurement window. Significant differences ( $p < 0.05$ ) were found: sensor T2 for /u/ was consistently more posterior than that for /a/ measured at -100 ms, -30 ms, FV boundary, and

vowel mid-point. T2 for /u/ was more posterior than that for /y/ at -100 ms, -30 ms and vowel mid-point. At -30 ms and FV boundary, T2 for /u/ was more posterior than that for /i/ and at -100 ms, -30 ms and FV boundary, T2 for /i/ was more posterior than /y/. T2 for /i/ and /y/ were more posterior than that for /a/ measured at -100 ms.

For the vertical plane Z, significant interaction effect ( $F = 16.393, p < 0.01$ ) was revealed. The following one-way ANOVAs and post-hoc pairwise contrasts found that at -100 ms and -30 ms, T2 for /u/ was lower than that for /a/ and at -100 ms, T2 for /i/ and /y/ were lower than that for /a/. At vowel mid-point, T2 for /u/ was lower than that for /i/.

### *3 cm inward from the tongue tip*

For the anteroposterior plane, with significant interaction effect ( $F = 19.269, p < 0.01$ ), one-way repeated measure ANOVAs and post-hoc pairwise comparisons were conducted for each window. Significant differences ( $p < 0.05$ ) were revealed: T3 for /u/ was constantly more posterior than that for /a/ at -100 ms, -30 ms, FV boundary and vowel mid-point, and T3 for /u/ was more posterior than /y/ at -30 ms, FV boundary and vowel mid-point. At -100 ms and -30 ms, T3 for /y/ was more posterior than that for /a/.

For the vertical plane, significant interaction effect ( $F = 21.138, p < 0.01$ ) was found, one-way repeated measure ANOVAs and post-hoc pairwise contrasts revealed significant differences ( $p < 0.05$ ): T3 for /u/ was lower than /a/ at -100 ms and -30 ms and /y/ was lower than /a/ at -100 ms.

### *Upper lip*

Results of 2-way ANOVA revealed no significant interaction effect (X:  $F = 1.077, p > 0.01$ , Z:  $F = 1.444, p > 0.01$ ) in both the anteroposterior and vertical planes.

### *Lower lip*

For X plane, due to the presence of significant interaction ( $F = 20.703, p < 0.01$ ), one-way repeated measure ANOVAs and post-hoc pairwise comparisons were conducted. Significant differences ( $p < 0.05$ ) were found: at -100 ms, -30 ms, FV boundary and vowel mid-point, LL for /i/ and /u/ were more posterior than that for /y/ and at FV boundary and vowel mid-point, LL for /a/ was more posterior than that of /y/.

Comparably for plane Z, one-way repeated measure ANOVAs and post-hoc pairwise comparisons were performed due to the presence of significant interaction effect ( $F = 25.583, p < 0.01$ ). They revealed significant differences ( $p < 0.05$ ): LL for /i/ was lower than that of /y/ at -100 ms, -30 ms, FV boundary and vowel mid-point. LL for /i/ was also lower than that for /a/ at -100 ms, -30 ms and FV boundary.

### ***Female Speakers***

#### *Tongue tip (1cm inward from the tongue tip)*

For the anteroposterior plane, significant interaction effect ( $F = 9.604, p < 0.01$ ) was revealed. Subsequently, one-way repeated measure ANOVAs and post-hoc pairwise comparisons followed found significant differences ( $p < 0.05$ ): T1 for /u/ was more posterior than that of /a/ at -30 ms, FV boundary and vowel mid-point whereas at vowel mid-point, T1 for /u/ was more posterior than /i/ and /y/ and /a/ was more posterior than /i/.

Similarly, for the vertical plane, one-way repeated measure ANOVAs and post-hoc pairwise contrasts were conducted due to the significant interaction effect ( $F = 36.568, p < 0.01$ ) found. One-way ANOVA and pairwise contrasts followed revealed significant differences ( $p < 0.05$ ): at -100 ms, -30 ms, FV boundary and vowel mid-point, T1 for /i/ was lower than that of /y/, T1 for /u/ was consistently lower than that of /y/ measured at -30 ms, FV boundary and vowel mid-point. At vowel mid-point, T1 for /a/ was constantly lower than that of /i/, /u/ and /y/.

#### *2 cm inward from the tongue tip*



For the anteroposterior plane, due to the presence of significant interaction effect, ( $F = 34.408$ ,  $p < 0.01$ ), subsequent one-way repeated measure ANOVAs and post-hoc pairwise contrasts revealed significant differences ( $p < 0.05$ ): T2 for /u/ and /y/ was constantly more posterior than that for /i/ measured at -100 ms, -30 ms, FV boundary and vowel mid-point, T2 for /a/ was more posterior than that for /i/ at -30 ms, FV boundary and vowel mid-point. At FV boundary and vowel mid-point, T2 for /u/ was more posterior than that of /a/ and /y/ and at vowel mid-point, /a/ was more posterior than /y/.

Similarly, one-way repeated measure ANOVAs and post-hoc pairwise contrasts were performed after significant interaction effect ( $F = 60.724$ ,  $p < 0.01$ ) was found in the vertical plane. Significant differences ( $p < 0.05$ ) were revealed: sensor T2 for /i/ was lower than that for /y/ measured at -100 ms, -30 ms, FV boundary and vowel mid-point, /a/ and /u/ were consistently lower than that for /y/ at FV boundary and vowel mid-point. At vowel mid-point, T2 for /a/ was lower than /i/ and /u/, and /u/ was lower than that for /i/.

### *3 cm inward from the tongue tip*

For the anteroposterior plane, since significant interaction effect, ( $F = 2.709$ ,  $p < 0.01$ ) was found, one-way repeated measure ANOVAs and pair-wise contrasts were conducted. Significant differences ( $p < 0.05$ ) were revealed: T3 for /u/ was more posterior than that for /a/ at -100 ms, -30 ms, FV boundary and vowel mid-point and at vowel mid-point, /u/ was more posterior than /i/. For the vertical plane, no significant interaction effect, ( $F = 1.679$ ,  $p > 0.01$ ) was noted.

### *Upper lip*

No significant interaction effect (X:  $F = 0.604$ ,  $p > 0.01$ , Z:  $F = 1.732$ ,  $p > 0.01$ ) was found for both the anteroposterior and vertical planes.

### *Lower lip*

For the anteroposterior plane, one-way repeated measure ANOVAs and post-hoc pairwise contrasts were performed after significant interaction effect ( $F = 45.649$ ,  $p < 0.01$ ) was found. They revealed significant differences ( $p < 0.05$ ): at FV boundary and vowel mid-point, sensor LL for /a/, /i/ and /y/ were more posterior than /u/ whereas LL for /a/ was more posterior than that for /y/ measured at vowel mid-point.

Similarly, with the presence of significant interaction effect ( $F = 113.836$ ,  $p < 0.01$ ), one-way repeated measure ANOVAs and post-hoc pairwise contrasts were conducted for the vertical plane. Significant differences were revealed ( $p < 0.05$ ): sensor LL for /a/ was lower than that for /y/ measured at -100 ms, -30 ms, FV boundary and vowel mid-point, /a/ was also lower than /u/ at FV boundary and vowel mid-point. At vowel mid-point, LL for /a/ was lower than that for /i/.

### Discussion

The present data appears to confirm the presence of coarticulation during the production of /sV/ syllables, and the differential coarticulatory effect caused by different vowel contexts. Another important finding is the lack of interaction between vowel and measurement window for the upper lip. This is true for both male and female speakers. Previously, allophonic variation of Cantonese fricative /s/ has been studied only by means of perceptual and acoustic analyses, or physiologically using EPG. According to Cheung (2005), older adults and males showed significantly lower percentages of alveolar fricative /s/ in passage reading, especially when the alveolar /s/ was followed by high front rounded vowel /y/, in both word list and passage reading. Results of the present kinematic study of the lingual and labial movement during production of Cantonese fricative /s/ seem to confirm the perceptual findings reported by Cheung (2005).

### ***Presence of coarticulation***

To assess the presence of coarticulation, the location of various sensors at different articulators was measured for different vowels at different measurement windows. Results revealed significant differences in T1, T2, T3 and LL at measurement windows 1 and 2 (-100 ms and -30 ms) among different vowels for both genders. This suggests the presence of both anticipatory lingual and labial coarticulation in different vowel contexts.

### ***Males vs. Females***

Similarities and differences were found in the coarticulation pattern between male and female speakers. For example, the vertical and anteroposterior location of T1 and T2 was found to be different among different vowels measured at -100 ms, -30 ms, FV boundary and vowel midpoint for both male and female speakers, as well as the anteroposterior plane for T3 and the vertical plane for LL. Yet, significant differences were revealed in the vertical plane for T3 and anteroposterior plane for LL only for males.

### ***Vowel contexts vs. Timing of Coarticulation***

The present results suggested that vowel context might affect the onset of coarticulation. According to the data obtained from male speakers, the significant differences between /i/ and /u/, and /a/ and /u/ were found earlier than between /y/ and /u/ in the anteroposterior location (X) of T1. Also, differences between /a/ and /u/, /u/ and /y/, /i/ and /y/, /a/ and /i/, and /a/ and /y/ occurred significantly earlier than /i/ and /u/ anteroposteriorly for T2, and /a/ and /u/, and /a/ and /y/ differed significantly earlier than /u/ and /y/ anteroposteriorly for T3. For female speakers, /i/ and /y/ differed significantly earlier than /u/ and /y/ in vertical location for T1 whereas significant differences between /i/ and /u/, /i/ and /y/ were existed earlier than /a/ and /i/ in anteroposterior location for T2. Generally, the significant differences between rounded and

unrounded/neutral lip position vowels existed earlier than those between both rounded/unrounded vowels for T1, T2, and T3, yet, similar observation were not made in UL and LL.

***Previous hypothesis on labial and lingual coarticulation***

Cheung (2005) suggested that lip rounding of /s/ in /sy/ attributing to the allophonic variation of Cantonese fricative /s/, instead of a change in lingual constriction, is likely affected by the lip-rounding feature of the following vowel /y/. To confirm this suggestion, labial and lingual coarticulation as indicated by the presence of significant differences between rounded, unrounded and neutral vowels measured at -100 ms and/or -30 ms of the measured T1, T2, T3, UL, LLs' position in both X and planes were investigated. Results of the current study revealed diverse findings between males and females regarding this issue.

***Lip movement***

With regard to labial coarticulation, significant differences between rounded and unrounded vowels measured at -100 ms and/or -30 ms existed in LL between /i/ and /y/ in both the anteroposterior and vertical planes. But this was not true for UL for male speakers. EMA values obtained from /i/ were greater than that of /y/ in both X and Z planes. Recall that EMA values of X and Z planes indicated the anteroposterior and vertical distances between the reference point which was the nasal bridge and the location of sensors on articulators. The consistently negative values obtained for the X plane indicated the measured articulator located more anterior than the point on nasal bridge whereas smaller value in the Z plane indicated higher measured articulators' points.

For instance, interpretations made from EMA values measured at -100 ms and -30 ms indicated the LL's location during the production of /s/ was more anterior when it was followed by /y/ than /i/ in the anteroposterior plane. While in the vertical plane, the values indicated higher

lip position during the production of /s/ preceding /y/ than /i/. Results from male speakers suggested protrusion and rounding of the LL in preparation of the following /y/ when producing /s/.

For female speakers, interpretations were also made from the values measured at -100 ms and -30 ms; they revealed no coarticulation between rounded and unrounded vowels in both anteroposterior and vertical planes for UL and LL. Yet, coarticulation was present between neutral lip position /a/ and rounded /y/. The values indicated higher height of the LL during the production of /s/ preceding /y/ than /a/, indicating some degree of lip rounding was observed during production of /s/ as a preparation for the following /y/.

Another major finding from the present study was the lack of interaction between vowels and measurement window for the sensor at the upper lip. This was true for both male and female speakers in the anteroposterior and vertical planes. In addition, no effect of vowel contexts was noted. However, the sensor from the lower lip exhibited an opposite pattern. This finding may imply that the upper lip's contribution to lip rounding, protrusion or lip spreading is considerably smaller than the lower lip's. Upper lip seems to be less sensitive to any coarticulation effect. According to Green, Moore, Higashikawa and Steeve (2000), upper lip's contribution to oral closure was significantly less than the lower lip and jaw in both children and adults. Similarly, the UL's movement will be less affected by the vowel contexts and attributed to the results obtained.

### ***Confirmation with previous hypothesis on labial coarticulation***

As a coarticulatory behavior, lip protrusion appears to have occurred before for the onset of high front rounded vowel /y/, and the contribution made by the lower lip was evident in both male and female speakers. According to cross-language studies reported by Faber (1989, 1990), post-alveolar fricatives were produced with protrusion of lips in all the languages studied

(Catalan, English, German, Italian). In the present study, lip protrusion found in the Cantonese alveolar fricative /s/ may have contributed to listeners' perception of alveo-palatal fricative [s<sup>j</sup>] or palatal fricative [ʃ]. Therefore, the present results are consistent with Cheung (2005) who assumed lip rounding for production of /y/ had affected the production of preceding /s/ that might contribute to allophonic variation of Cantonese fricative /s/.

### ***Tongue movement***

With regard to tongue movement during /s/ production preceding a lip-rounded vowel, Cheung (2005) suggested that /s/ and /y/ have comparable place feature which might not contribute to the allophonic variation of /s/. In the present study, the measurement taken at anteroposterior location of the three lingual sensors for /su/ and /sy/ were different for male speakers. Values indicated more anterior position of the tongue during production of /s/ when it was followed by /y/ than /u/. Also, the values taken at anteroposterior location of T2 and T3 for /sy/ and /sa/ were different, indicating more posterior position of the tongue during /s/ production when preparing for following /y/ than /a/. This might account for the perception of alveolar fricative /s/ into the palatalized fricative [ʃ] when /s/ was followed by /y/ as found in the study conducted by Cheung (2005) since [ʃ] showed more posterior constriction when compared to the alveolar /s/ as found out by Faber (1989, 1990). To conclude, for male speakers, assumption made by Cheung (2005) did not agree with the results as more anterior/ posterior position of tongue was observed and might result in allophonic variation of /s/.

For female speakers, both the anteroposterior and vertical locations of the three lingual sensors for /sy/ and /sa/ were not different. This was true for measurements taken at -100 ms and -30 ms. Since the lower lip was found to be protruded during /s/ in /sy/ at 100 ms and 30 ms before the onset of /y/, but not the tongue which demonstrated no significant differences between high and low, front and back vowels. Such findings appear to agree with Cheung (2005) that lip

rounding rather than changes in constriction formed by tongue contribute to the perception of alveolar /s/ that were followed by /y/ to alveo-palatal fricative [s<sup>j</sup>] or palatal fricative [ʃ].

***Cross-language differences in production of alveolar fricative /s/***

Shadle and Scully (1995) made assumption concerning the tongue shape based on acoustic data obtained from a French speaker producing /pasa, pisi, pusu/. It was assumed that during /s/ production, tongue shape was independent of the vowel contexts and that the acoustic differences interpreted between them was attributed to the lip rounding. However, the current study revealed different findings. For both male and female speakers, the anteroposterior location of UL and LL were not different between the rounded and unrounded vowel /u/ and /i/, /u/ and /a/ obtained from windows 1 and/or 2. This suggests that lip rounding might not attribute to acoustic differences which do not agree with the findings by Shadle and Scully (1995).

However, for the lingual sensors, differences were found across windows 1 and/or 2 between /u/ and /i/, /u/ and /a/ in both anteroposterior (X) and vertical (Z) planes. /i/ was more anterior than /u/ and /u/ was lower than /i/. This does not agree with the assumption made by Shadle and Scully (1995) that tongue shape was independent of the vowel contexts. This discrepancy in findings may be explained by the cross-language difference in coarticulation behaviors (Hoole et al., 1993; Öhman, 1966). Also, the difference may also be due to the different effect size caused by different vowel contexts and different languages.

***Gender differences in the production of alveolar fricative /s/***

Cheung (2005) reported that gender did not have significant effect on the /s/ production in disyllabic word level. The present results, however, suggested that the pattern of coarticulation in different articulators would be different for male and female speakers even in /sV/ syllable. The discrepancy may be explained by the fact that differences in coarticulation pattern may not

be significant enough to cause allophonic variation of /s/, and the limited number of subjects recruited for the present study did not give us a detailed picture of gender effect on articulation of alveolar fricative /s/.

### ***Methodological limitation and research implication***

A number of methodological limitations might have affected the results and data should be interpreted with caution. One potential problem of using EMA is related to the high sensitivity of the equipment. Measurements may be affected by the nearby magnetic field or presence of metallic object near the equipment. Another potential problem is the existence of variation between subjects and between productions by the same subject. In fact, alveolar fricatives have been found to show more variation across and within speakers (Farnetani, 1999; Hughes & Halle, 1956). In addition, due to the limited number of subjects, the present study is not able to investigate gender's effects on coarticulation. Future studies should include more participants (both males and females) in order to examine the possible effect of gender on coarticulation. Furthermore, only young adults aged between 20 and 25 were participated in the current study. Studies involving subjects of larger age range is suggested to reduce the effects of coarticulation caused by age differences. Lastly, the current study only investigated speaker's coarticulation at /sV/ syllable level. Further studies could increase the stimuli corpus to include meaningful disyllabic words, sentences and passage, so that coarticulation could be further investigated at different levels.

The current study confirmed with the hypothesis of the presence of coarticulation in producing Cantonese fricative /s/. In the future, EMA data should be correlated with information obtained from perceptual experiment of /s/ produced in different vowel contexts. Through such, whether it is an allophonic variation or not could be answered. Acoustic study is also suggested to be carried out simultaneously with kinematic measurements, since comparison of the



coarticulation pattern between acoustic and articulatory level is important (Hoole et al., 1993). Perhaps EPG could be used simultaneously with EMA to obtain information regarding both the tongue movement and lingual-palatal contact (Hardcastle, Jones, Knight, Trudgeon, & Calder, 1989), thus allowing comparison between the palatographic and EMA data.

### *Clinical implication*

As one of the most frequently occurring word-initial consonants in Cantonese (Ng & Kwok, 2004), the Cantonese alveolar fricative /s/ is of high importance in both normal and disordered speech (Whitehill & Ciocca, 2000). Among all fricatives in Cantonese, /s/ is the last to be acquired by children who speak Cantonese as the first language (So & Dodd, 1995). Cheung and Abberton (2000) also found /s/ to be the most difficult sound and had the highest error percentage in disordered speech. Second language speakers of Cantonese appear to show accent in /s/, as observed in accent modification therapy for the Mandarin speakers learning to speak Cantonese. Knowledge of coarticulation of the Cantonese fricative /s/ in different vocalic contexts helps nonnative speakers learn to produce context-appropriate /s/ correctly. To conclude, the current study provided first-hand, real-time kinematic data concerning the production of Cantonese alveolar fricative /s/ followed by different vowels /a, i, u, y/. Coarticulation was present and different vowel contexts were associated with different patterns of coarticulation. Results confirmed the assumptions made by Cheung (2005) with regard to the allophonic variation of Cantonese fricative /s/.

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## References

- Badin, P. (1991). Fricative consonants: acoustic and X-ray measurements. *Journal of Phonetics*, 19, 397-408.
- Bauer, R. S., & Benedict, P. K. (1997). *Modern Cantonese Phonology*. New York: Mouton de Gruyter.
- Borden, G. J., Harris, K. S., & Raphael, L. J. (2003). *Speech Science Primer – Physiology, Acoustics, and Perception of Sound* (4<sup>th</sup> ed.). Baltimore, MD: Lippincott Williams & Wilkins.
- Chan, C.-T. (2004). *An electropalatographic and perceptual investigation of /s/ productions in Cantonese children with cleft palate*. Unpublished B.Sc. Thesis, The University of Hong Kong.
- Cheng, T.-F. (2006). *An acoustic analysis of the variation in alveolar fricative /s/ production in Hong Kong Cantonese*. Unpublished B.Sc. Thesis, The University of Hong Kong.
- Cheung, P. & Abberton, E. (2000). Pattern of phonological disability in Cantonese-speaking children in Hong Kong. *International Journal of Language and Communicative Disorders*, 35, 451-473.
- Cheung, W.-K. (2005). *Variation in the production of alveolar fricative /s/ in Hong Kong Cantonese*. Unpublished B.Sc. Thesis, The University of Hong Kong.
- Engwall, O., & Badin, P. (2000). An MRI study of Swedish fricatives: coarticulatory effects. *Proceedings of the 5th Speech Production Seminar*, 297-300.
- Engwall, O. (2000). Dynamical aspects of coarticulation in Swedish fricative-a combined EMA & EPG study. *TMH-Quarterly Status and Progress Report*, 4, KTH, Stockholm, pp. 49-73.

- Faber, A. (1989). Lip protrusion in sibilants. *Journal of the Acoustical Society of America*, 86, S1, S113.
- Faber, A. (1990). The time-course of labial gestures for sibilant articulations. *Journal of the Acoustical Society of America*, 88, S1, S120.
- Farnetani, E. (1999). Labial Coarticulation. In Hardcastle, W.J. & Hewlett, N. (Ed.), *Coarticulation: theory, data and techniques*. Cambridge: Cambridge University Press, pp.144-163.
- Fletcher, S. G., McCutcheon, M., & Wolf, M. (1989). Palatometric specification of stop, affricate and sibilant sounds. *Journal of Speech, Language and Hearing Research*, 32, 736-748.
- Green, J.R., Moore, C.A., Higashikawa, M., & Steeve, R.W. (2000). The physiologic development of speech motor control: lip and jaw coordination. *Journal of Speech, Language, and Hearing Research*, 43, 239-255.
- Hardcastle, W. J., & Clark, J. E. (1981). Articulatory, aerodynamic and acoustic properties of lingual fricatives in English. *Speech Research Laboratory Work in Progress*. University of Reading, 3, 51-78.
- Hardcastle, W.J., Jones, W., Knight, C., Trudgeon, A., & Calder, G. (1989). New developments in electropalatography: a state-of-the-art report. *Clinical Linguistics and Phonetics*, 3, 1-38.
- Hoole, P., Ziegler, W., Hartmann, E., & Hardcastle, W. (1989). Parallel electropalatographic and acoustic measures of fricatives. *Clinical Linguistics and Phonetics*, 3, 59-69.
- Hoole, P., Nguyen-Trong, N., & Hardcastle, W. (1993). A comparative investigation of coarticulation in fricatives: electropalatographic, electromagnetic, and acoustic data. *Language and Speech*, 36, 235-260.

- Hoole, P., & Nguyen, N. (1997). Electromagnetic articulography in coarticulation research. In W.J. Hardcastle & N. Hewlett (Eds.), *Coarticulation: Theoretical and Empirical Perspectives*. Cambridge: Cambridge University Press.
- Hoole, P., Zierdt, A., & Geng, C. (2003). Beyond 2D in articulatory data acquisition and analysis. *Proceedings of the 15th International Congress of Phonetic Sciences*, 265-268.
- Hughes, G. W., & Halle, M. (1956). Spectral properties of fricative consonants. *Journal of the Acoustical Society of America*, 28, 303-310.
- Jongman, A., Wayland, R., & Wong, S. (2000). Acoustic characteristics of English fricatives. *Journal of the Acoustical Society of America*, 108(3), 1252-1263.
- Katz, W. F., & Bharadwaj, S. (2001). Coarticulation in fricative-vowel syllables produced by children and adults: a preliminary report. *Clinical Linguistics and Phonetics*, 15, 139-143.
- Kwok, I.C.-L., & Stokes, S.F. (1997). An electropalatographic description of Cantonese speech. *Asia Pacific Journal of Speech, Language and Hearing*, 2, 125-128.
- Kühnert, B., & Nolan, F. (1999). The origin of coarticulation. In Hardcastle, W. J. & Hewlett, *Coarticulation: Theory, Data and Techniques*. Cambridge: Cambridge University Press.
- Lau, S-H. (1994). *Temporal and Spectral variability of /s/ production by Cantonese-speaking cleft palate children*. Unpublished B.Sc. Thesis, The University of Hong Kong.
- Lee, S-Y. (1999). *An acoustic and perceptual analysis of /s/ before and after orthognathic surgery*. Unpublished B.Sc. Thesis, The University of Hong Kong.
- Matthews, S., & Yip, V. (1994). *Cantonese: A Comprehensive Grammar*. London; New York: Routledge.
- Narayanan, S. S., Alwan, A. A., & Haker, K. (1995). An articulatory study of fricative consonants using magnetic resonance imaging. *Journal of Acoustical Society of America*, 98, 1325-1347.

- Ng, M., & Kwok, I. C. L. (2004). Frequency of occurrence of Cantonese word initials, finals, and tones. *Asia Pacific Journal of Speech, Language, and Hearing*, 9, 189-199.
- Nguyen-Trong, N., Hoole, P., & Marchal, A. (1991). Articulatory-acoustic correlations in the production of fricatives. *Proceedings of the 9th International Congress of Phonetic Sciences*, 1, 18-21.
- Öhman, S. E. G. (1966). Coarticulation in VCV utterances: Spectrographic Measurements. *Journal of the Acoustical Society of America*, 39, 151-168.
- Shadle, C. H., Moulinier, A., Dobelke, C. U., & Scully, C. (1992). Ensemble averaging applied to the analysis of fricative consonants. In *Proceedings of ICSLP*, 53-56
- Shadle, C. H. & Scully, C. (1995). An articulatory-acoustic-aerodynamic analysis of [s] in VCV sequences. *Journal of Phonetics*, 23, 53-66.
- So, L.K.H. and Doss, B.J., (1995). The acquisition of phonology by Cantonese-speaking children. *Journal of Child Language*, 22, 473-495.
- Soli, S. D. (1981). Second formants in fricatives: Acoustic consequences of fricative-vowel coarticulation. *Journal of the Acoustical Society of America*, 70, 976-984.
- Stone, M., Faber, A., Raphael, L. J., & Shawker, T. H. (1992). Cross-sectional tongue shapes and linguopalatal contact patterns in [s], [ʃ] and [l]. *Journal of Phonetics*, 20(2), 253-270.
- Subtelny, J. D., Oya, N., & Subtelny, J. D. (1972). Cineradiographic study of sibilants. *Folia Phoniatica et Logopaedica*, 24, 30-50.
- West, P. (1999). The extent of coarticulation of English liquids: An acoustic and articulatory study. *Proceedings of the 14th International Congress of Phonetic Sciences*, 1901-1904.
- Whitehill, T. L., & Ciocca, V. (2000). Speech errors in Cantonese speaking adults with cerebral palsy. *Clinical Linguistics & Phonetics*, 14(2), 111-130.

Yunusova, Y., Green, J.R., & Mefferd, A. (2008). Accuracy assessment for AG500, electromagnetic articulograph. *Journal of Speech, Language, and Hearing Research*, 52, 547-555.

## Appendix A: A Cantonese vowel quadrilateral (Adapted from Bauer &amp; Benedict, 1997)

