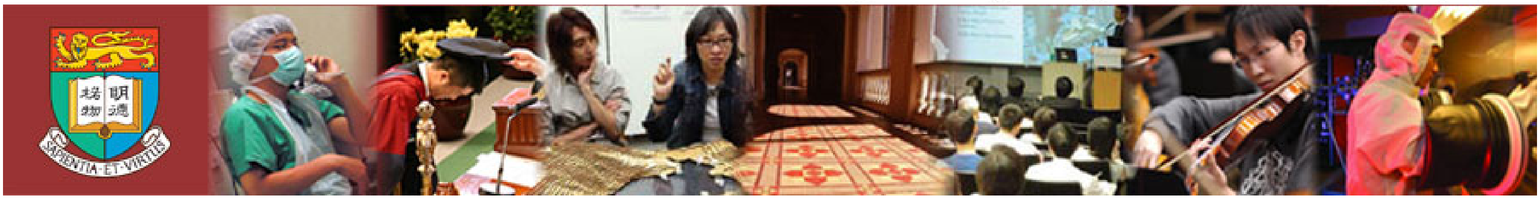

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Coupling between the Laryngeal and Supralaryngeal Systems

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Abstract

The present study investigated the coupling between the laryngeal and supralaryngeal systems in speech production. The interrelationship between the two systems was examined by studying the possible interaction between tone production (laryngeal system) and articulation (supralaryngeal system). Sixty (30 male and 30 female) native Cantonese speakers participated in the study. The first and second formant frequencies (F1 and F2) associated with the four vowels /i, u, ɛ, ɔ/ produced at six Cantonese lexical tones (high-level, high-rising, mid-level, low-falling, low-rising and low-level tones) were obtained. Results revealed that, regardless of vowels, significant articulatory changes were found when produced at different tones. However, the difference pattern across each vowel was not systematic. Gender difference was also noted; male and female speakers showed different patterns in articulatory changes. These findings revealed the coupling effect between the laryngeal and supra-laryngeal systems.

Coupling between the Laryngeal and Supralaryngeal Systems

The source-filter theory lays the foundation for the study of speech production and it facilitates the development of techniques in speech analysis and synthesis (Fant, 1960; Fitch, 1994; Kent & Read, 2002; Stevens & House, 1961). The theory assumes that speech production mechanism can be linearly divided into two components, namely the laryngeal and supralaryngeal systems, which are functionally independent of each other (Stevens & House, 1961). Fant (1960) suggested that, during voice sound productions, the larynx serves as the source of acoustic sound waves while the supralaryngeal vocal tract acts as an acoustic filter. Such acoustic filter can also be described as a transfer function which serves to modify the source. Speech output can thus be viewed as a product of source signal and filter's transfer function. Mathematically, in the time domain, the source and the filter are related by a convolution relationship, while they are related by a multiplication relationship in the frequency domain (Pickett, 1999). Therefore, a modified form of sound spectrum is produced by the sound source and the specific transfer function.

During vowel production, a driving excitation signal generated by the larynx enters the vocal tract for resonance. The fundamental frequency (F0) of the signal, which directly reflects the rate of vocal fold vibration, determines the perceived pitch of the speech output signal. The vocal tract configuration corresponding to the positioning and shape of articulators determines the specific filter characteristics, known as the transfer function. The transfer function depicts the resonance characteristics of the incoming source signal and yields an output waveform with a specific spectral characteristic (Kent & Read, 2002; Stevens & House, 1961). As a result, different vowels are produced.

Each vowel is distinguished by its spectral characteristic. Linear predictive coding (LPC) analyzes vowels acoustically and visualizes the resonances of the vocal tract, also

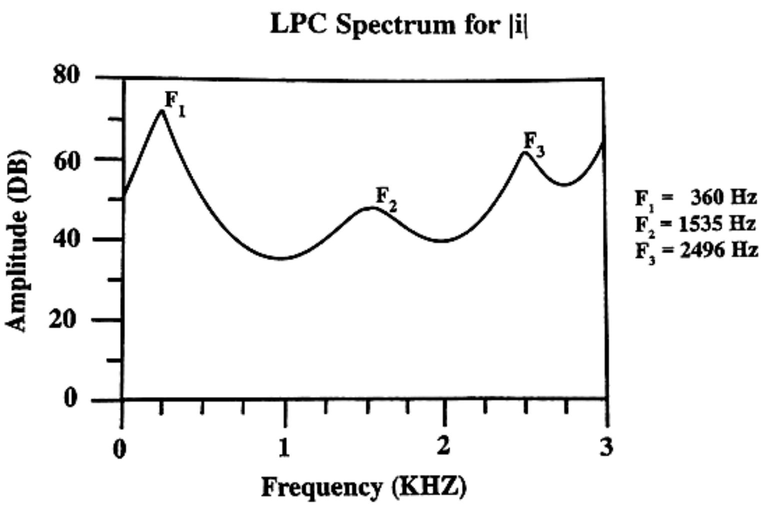

Figure 1. LPC spectrum of an /i/ vowel. First (F1), second (F2), and third (F3) formants frequencies listed at the right side. From *A basic introduction to speech perception* (p.30), by J. Ryalls, 1996, San Diego: Singular.

called the formants (Pickett, 1999) (Figure 1). Formant frequencies are closely related to vocal tract configuration, especially the first (F1) and second (F2) formants. Thus, in general, only F1 and F2 are of major interest for studying vowels (Pickett, 1999). Previous research studies have revealed the general relationship between the first two formants and tongue position (Chiba & Kajiyama, 1941; Hillenbrand, Getty, Clark & Wheeler, 1995; Stevens & House, 1955). High tongue position generally results in a low F1, while anterior tongue position generally leads to a high F2.

Validity of the source-filter theory lies in the assumption of independency between the laryngeal and supralaryngeal systems (Stevens & House, 1961). It is assumed that the vocal tract configuration never affects the voicing source, and vice versa. Acoustically put, F0 is independent of formants, where a change in F0 should not cause a change in formant frequencies. This provides an explanation to why speech can be intelligible regardless of pitch and loudness which are determined by the source (Kent & Read, 2002). However, such assumption of independency between the two systems has been challenged in recent studies.

Recent studies confirmed the interaction between laryngeal and supralaryngeal systems during speech production. They were based on the change in vocal tract configuration when using different vocal registers, pitches, and loudness (Huber, Stathopoulos, Curione, Ash & Johnson, 1999; Liénard & Di Benedetto, 1999; Story, Titze & Hoffman, 2001; Tom, Titze, Hoffman & Story, 2001). Vocal register, pitch and vocal loudness are mainly regulated by vocal fold activity (Colton, Casper & Leonard, 2006). Following the assumption of the source-filter theory, vocal quality should only vary with vocal fold behaviors, but not vocal tract. However, Story et al. (2001) and Tom et al. (2001) found that vocal tract configuration changed with vocal register when producing isolated vowels of a non-tonal language. Significant changes in formant frequencies associated with different vocal registers in both studies. However, only professional vocal performers were recruited in these studies. The generalization to untrained voice users might be questionable.

In addition to vocal register, pitch variation may result in changes in vocal tract shape (Tom et al., 2001). Pitch varies directly with changing F0 (Colton et al., 2006). Tom et al. (2001) found that supraglottic widening reduced in low-pitch falsetto register and it increased in medium- and high-pitch falsetto conditions. This implies an active coupling between the two systems to achieve a particular vocal condition. Similarly, interactions between the larynx and supralaryngeal systems were found in association with various vocal intensities. Formant frequencies, particularly F1, were found to be correlated with vocal intensity (Huber et al., 1999; Liénard & Di Benedetto, 1999; Tom et al., 2001).

The finding of intrinsic pitch in different languages also supports the presence of laryngeal and supralaryngeal interaction (Honda, 1995; Torng, 2000). Intrinsic pitch of vowels refers to the F0 differences between vowels produced with different tongue heights (Lehiste, 1996). Honda (1995) summarized that this phonetic phenomenon is related to the tongue and hyoid bone, whereas Torng (2000) suggested that jaw position can be more predictive for intrinsic pitch. Both suggested supralaryngeal involvement in F0 variation. Intrinsic pitch is a universal phenomenon (Torng, 2000). The universal pattern of intrinsic pitch suggested relationship of tongue height and the F0 of vowel, where high vowels are associated with higher F0 and low vowels with low F0 (Honda, 1995). Its inverse effect can be observed in tonal languages as well. Tonal effect on vowel articulation was found in several studies (Chen, Ng & Vrabilk, 2005; Erickson, Iwata, Endo & Fujino 2004; Hoole & Hu, 2004; Hu, 2004; Torng, 2000). Many Asian languages, for example, Cantonese, Mandarin, and Thai are tone languages. Different from non-tonal languages, the lexical tone in tonal languages is phonemic and lexically contrastive. It helps to convey different meanings even with the same syllable. Lexical tone is acoustically determined by the F0 contour which is generally perceived as the lexical pitch. Therefore, F0 variation in tonal languages should be more precise in order to maintain lexical intelligibility (Torng, 2000).

In studying Mandarin and Ningbo Chinese using electromagnetic articulography (EMA), Hoole and Hu (2004), and Hu (2004) suggested that the type of lexical tone affects vowel articulation differently. One native speaker was recruited in each of the studies. The results of Hoole and Hu (2004) suggested tongue retraction in production of vowels in low tones. These results were consistent with data reported by Erickson et al. (2004), who concluded that low-falling tone in Mandarin would accompany more retracted tongue than high tones in two native Mandarin speakers. In addition, data reported in Chen et al. (2005) supported the notion of interaction between laryngeal and supralaryngeal systems, as significant difference in voice onset time (VOT) across four Mandarin tones was observed from eight native Mandarin-speaking adults. Torng's (2000) study also supported the interaction as well. However, contradictory finding was reported where no universal pattern of the tonal influence on articulation of isolated vowels in six native Mandarin speakers was found.

The present study was to extend our understanding of laryngeal and supralaryngeal interaction in Cantonese. The spectral characteristics of Cantonese vowels produced at different tones (F0 contours) were investigated. As suggested, only small sample sizes were involved in the previous studies of tonal effect on articulation (see Chen et al., 2005; Erickson et al., 2004; Hoole & Hu, 2004; Hu, 2004; Torng, 2000; Zee, 1980). However, individual difference was observed from Erickson et al. (2004) and Torng (2000). Studies of small sample size inevitably limited the external validity. Seeing this limitation, the present study further investigated the coupling between laryngeal and supralaryngeal systems using Cantonese.

Cantonese is a tonal language which consists of six lexical tones, including (a) Tone 1: high-level (55), (b) Tone 2: high-rising (35), (c) Tone 3: mid-level (33), (d) Tone 4: low-falling (21), (e) Tone 5: low-rising (23), and (f) Tone 6: low-level (22) (Chao, 1947; Fok, 1974). Same as other tonal languages, pitch variation in Cantonese is responsible to serve the linguistic purpose to produce contrastive tones. Possible tonal effect on the articulation of different Cantonese vowels was studied.

Method

Participants

Sixty adults (30 males and 30 females) who were native Hong Kong Cantonese speakers participated in the study on a voluntary basis. Their ages ranged from 18 to 25 (M = 21 years, SD = 1.56 years) with no known history of speech, language and hearing problem.

Speech material

A list of 24 target words (4 vowel contexts x 6 tones) was adopted in the study (Appendix A). Four vowel contexts including the high front unrounded vowel /i/, high back rounded vowel /u/, mid-low front unrounded vowel /ɛ/ and mid-low back rounded vowel /ɔ/ were used for investigation. CV syllables in the four vowel contexts (/ji/, /fu/, /sɛ/ and /tsʰɔ/) and six Cantonese tones were included in the list of target words. As /tsʰɔ$_6$/ is not a real Cantonese word, it was presented with the phonetic symbols. The target words were embedded in a carrier phrase “/ji$_1$ kɔ$_3$ hɐi$_6$/ target ” (“This is ___”). The use of a carrier phrase was to avoid abrupt intensity fluctuations, which was found to influence the pitch between trials (Lau & James, 2004), and ensure more natural productions. In addition, speaking rate was controlled at approximately two syllables per second. According to Xu (1997), speaking rate can affect the degree of carry-over of tone in the preceding tone context. By controlling the speaking rate, the effect of tone coarticulation in different trials was minimized.

Data Collection

Prior to the experiment, the participants were allowed to rehearse for a brief period of time in order to familiarize themselves with the experiment setting and the speech materials. Each phrase was repeated three times, yielding a total 72 carrier phrases produced by each speaker. To avoid possible order effect, block randomization was used. Three random orders of the 72 speech samples were generated and the participants were randomly assigned to one of the three orders. The number of participant in each order was equal.

During recording, the participants were instructed to read the carrier phrase with the target word from the computer screen at a comfortable pitch and loudness. The speech rate was controlled through visual cue where the participant read aloud the word upon the transition of colors of the corresponding word in the stimuli.

Recordings were made in a soundproof booth of the Speech Science Laboratory of the University of Hong Kong. The speech samples were recorded via a high-quality microphone

(SM58, Shure), a USB bus-powered preamp and audio interface (MobilePre USB, M-AUDIO) and a laptop computer. The mouth-microphone distance was kept constant at 5 cm to avoid the effect of vocal intensity on vowel articulation (Huber et al., 1999; Liénard & Di Benedetto, 1999; Tom et al., 2001). It was maintained by having the participant touch the middle of his/her chin lightly with a rod, of which the top was 5 cm from the microphone.

Data Analysis

The vowel segments of the target words were extracted for acoustic analysis by Praat (version 5.1.01) (Boersma & Weenink, 2009) which is a signal analysis software. To avoid discrepancy at vowel initiation and termination, and possible transition effects, F1 and F2 values were measured from the medial 80% of the vowel segments. F1 and F2 values were calculated using LPC algorithm of Praat (Boersma & Weenink, 2009), and based on which average F1 and F2 values of each vowel segment were obtained.

The present study was a multi-factorial mixed design with three independent variables (vowel context, tone and gender). Two three-way repeated-measures Analysis of Variance (ANOVAs) (4 vowel contexts x 6 tones x 2 genders) were used to analyze F1 and F2 respectively. Vowel contexts and tones were the within-subjects factors while gender was the between-subjects factor.

Results

Reliability measurements

Intra- and inter-rater reliabilities were measured by using Pearson product-moment correlation. Ten percent of the data corpus (i.e., 432 vowel segments) was randomly selected and analyzed for a second time by both the primary investigator and a second rater. The two measurements obtained from the primary investigator were used to evaluate for intra-rater reliability, and the measurements obtained from the primary and second investigators were used to measure inter-rater reliability.

For intra-rater reliability, the Pearson's correlation coefficient (*r*) for F1 and F2 values were 0.998 ($p < .01$) and 0.999 ($p < .01$) respectively. For inter-rater reliability, the Pearson's correlation coefficient (*r*) for F1 and F2 values were 0.997 ($p < .01$) and 0.999 ($p < .01$) respectively. Both intra- and inter-rater reliability measures suggested that measurements obtained from the primary investigator were reliable and consistent.

The first formant (F1)

Mean F1 values of the four vowels produced at six Cantonese lexical tones by Cantonese males and females are summarized in Table 1 and plotted in Figure 2. Results of a repeated-measures ANOVA indicated significant interaction effects between tone and gender ($p < .01$), vowel context and gender ($p < .01$), vowel context and tone ($p < .01$) and vowel context, tone and gender ($p < .01$). Subsequently, tests of simple main effects of F1 of the six tones of each vowel context and each gender were carried out.

One-way repeated-measures ANOVA with dependent variable (F1) and independent variable (tone with six levels) was done for each vowel context and gender. For male speakers, significant main effects for tone were found in vowel /ɛ/, $F(5,145) = 7.37$, $p < .01$, and in /ɔ/, $F(5,145) = 6.22$, $p < .01$. For female speakers, significant main effects for tone were found in all vowel contexts including vowel /i/, $F(5,145) =3.54$, $p < .01$; vowel /u/, $F(5,145) = 34.1$, $p < .01$; vowel /ɛ/, $F(5,145) = 28.2$, $p < .01$; vowel /ɔ/, $F(5,145) = 18.6$, $p < .01$.

Post-hoc multiple comparisons revealed significant differences between mean F1 values of some of the tone pairs (detailed statistical results in Appendix B). For males, F1 of Tones 2 and 5 were significantly higher than that of Tones 1, 3 and 6 for vowel /ɛ/; F1 of Tones 1, 2, 3 and 5 were significantly higher than that of Tone 6 for vowel /ɔ/.

Table 1
Summary of Means, Standard Deviations (SD) and Range for F1 (in Hz) of vowels produced by Cantonese males and females.

		Male[a]			Female[a]		
Vowel	Tone	Mean	SD	Range	Mean	SD	Range
/i/	1	273	28.8	228 - 346	304	34.0	256 - 391
	2	259	21.1	210 - 298	312	35.4	240 - 382
	3	263	24.4	204 - 311	312	38.4	234 - 375
	4	259	23.9	214 - 307	302	23.8	252 - 355
	5	261	23.6	204 - 316	312	34.9	236 - 368
	6	264	35.5	199 - 402	316	36.2	240 – 382
/u/	1	339	23.8	280 - 385	421	45.2	333 – 498
	2	338	23.7	277 - 394	374	30.4	310 – 437
	3	339	26.8	276 - 390	387	29.4	336 – 446
	4	335	18.9	298 - 365	367	22.1	313 – 411
	5	343	21.7	279 - 389	365	25.7	305 – 407
	6	338	24.1	271 - 401	364	26.5	318 – 414
/ ɛ /	1	566	64.0	438 - 745	738	72.2	602 – 887
	2	589	68.2	488 - 766	750	75.3	600 – 884
	3	553	62.8	448 - 706	679	88.1	512 – 846
	4	574	89.2	450 - 821	726	93.1	552 – 895
	5	585	73.0	468 - 770	736	72.8	614 – 872
	6	556	67.1	448 - 705	680	86.3	465 – 822
/ɔ/	1	503	50.7	367 - 619	588	82.6	400 – 775
	2	496	50.9	387 - 621	557	67.1	410 - 692
	3	489	66.8	265 - 603	550	65.6	415 - 670
	4	488	53.1	368 - 588	550	63.8	462 - 674
	5	499	53.4	380 - 609	535	67.0	394 - 692
	6	470	63.3	273 - 590	502	62.9	395 - 646

[a] $n = 30$
Note. 1 = high-level tone; 2 = high rising tone; 3 = mid-level tone; 4 = low-falling tone; 5 = low-rising tone; 6 = low-level tone.

For females, F1 of Tone 4 was significantly lower than that of Tone 6 for vowel /i/; F1 of Tones 1, 2 and 3 were significantly higher than that of Tones 5 and 6, where F1 of Tones 1 and 3 was significantly higher than that of Tones 2 and 4 and that of Tone 1 was significantly higher than that of Tone 3. For the vowel /ɛ/ produced by females, F1 of Tones 1, 2, 4 and 5 was significantly higher than that of Tones 3 and 6, where that of Tone 2 was significantly higher than that of Tone 4. For vowel /ɔ/, F1 of Tone 1 was significantly higher than that of all other tones, where F1 of Tones 1, 2, 3 and 5 was significantly higher than that of Tone 6 and that of Tone 2 was higher than that of Tone 5.

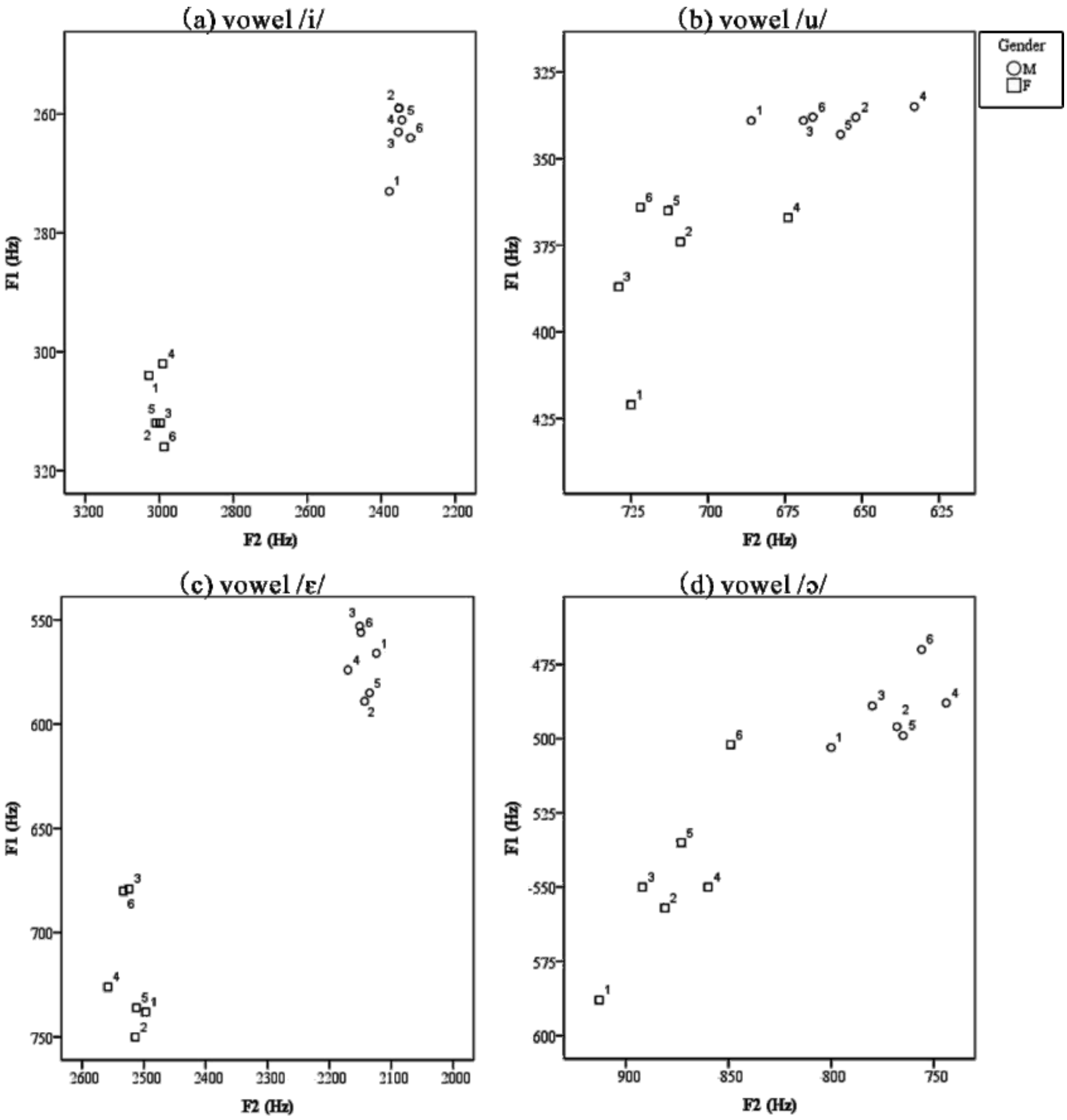

Figure 2. F1-F2 plot showing the formant frequencies of different tone of the males and females for (a) vowel /i/; (b) vowel /u/; (c) vowel /ɛ/; and (d) vowel /ɔ/.
Note. 1 = high-level tone; 2 = high rising tone; 3 = mid-level tone; 4 = low-falling tone; 5 = low-rising tone; 6 = low-level tone. The scales of x- and y-axes are not the same in each plot.

The second formant (F2)

A summary of mean F2 values of the four vowels at six tones is given in Table 2. The relative tongue frontness of each gender and vowels with respect to F2 was shown in Figure 2. Results of a repeated-measures ANOVA for F2 indicated significant interaction effects for vowel context and gender ($p < .01$), and tone and vowel context ($p < .01$). Therefore, test of simple main effect of F2 of the six tones for each vowel context and gender was implemented.

Table 2.
Summary of Means, Standard Deviations (SD) and Range for F2 (in Hz) of vowels produced by Cantonese males and females.

		Male[a]			Female[a]		
Vowel	Tone	Mean	SD	Range	Mean	SD	Range
/i/	1	2378	183	2059 - 2855	3028	170	2617 - 3406
	2	2352	184	2059 - 2830	3009	187	2574 - 3402
	3	2354	188	2066 - 2872	2998	172	2578 - 3353
	4	2353	176	2086 - 2781	2991	196	2602 - 3374
	5	2344	185	2098 - 2832	2997	182	2616 - 3401
	6	2321	222	1719 - 2857	2987	189	2589 - 3356
/u/	1	686	41.3	594 - 752	725	84.6	480 - 901
	2	652	39.6	566 - 725	709	60.9	580 - 849
	3	669	45.9	571 - 778	729	111	477 - 924
	4	633	42.9	550 - 701	674	45.3	581 - 756
	5	657	48.2	551 - 762	713	55.5	612 - 838
	6	666	50.7	562 - 803	722	60.1	603 - 835
/ ɛ /	1	2124	141	1870 - 2441	2497	173	2027 - 2856
	2	2143	142	1872 - 2458	2514	170	2026 - 2858
	3	2151	142	1867 - 2470	2524	170	2052 - 2926
	4	2170	132	1965 - 2449	2558	178	2093 - 2923
	5	2135	137	1845 - 2423	2512	161	2051 - 2883
	6	2149	127	1888 - 2450	2533	159	2131 - 2904
/ɔ/	1	800	49.4	692 - 943	913	74.0	780 - 1086
	2	768	47.5	679 - 877	881	63.5	704 - 978
	3	780	45.6	683 - 879	892	65.9	732 - 1026
	4	744	47.0	658 - 829	860	61.4	674 - 945
	5	765	49.4	666 - 857	873	59.9	735 - 957
	6	756	45.6	673 - 866	849	69.8	677 - 961

[a] $n = 30$

Note. 1 = high-level tone; 2 = high rising tone; 3 = mid-level tone; 4 = low-falling tone; 5 = low-rising tone; 6 = low-level tone.

One-way repeated-measures ANOVA with dependent variable (F2) and independent variable (tone with six levels) was done for each vowel context and gender. For male speakers, there were significant main effect of tone in vowel /u/, $F(5,145)=17.2$, $p < .01$, vowel /ɛ/, $F(5,145)=4.69$, $p < .01$, and vowel /ɔ/, $F(5,145)= 18.0$, $p < .01$. For female speakers, significant main effect of tone was found in all the vowel contexts including vowel /i/, $F(5,145)= 3.14$, $p < .01$; vowel /u/, $F(5,145)= 4.42$, $p < .01$; vowel /ɛ/, $F(5,145)= 5.21$, $p < .01$; vowel /ɔ/, $F(5,145)= 14.5$, $p < .01$.

Post-hoc multiple comparisons revealed significant differences between mean F2 values of some of the tone pairs (detailed statistical results in Appendix B). For males, F2 of Tone 4 was significantly lower than all other tones while that of Tone 1 was significantly higher than all other tones for vowel /u/; that of Tones 1, 3 and 6 was significantly higher than that of Tone 2. For vowel /ɛ/, F2 of Tone 4 was significantly higher than that of Tone 5 while that of Tone 1 was significantly lower than that of Tones 3, 4 and 6. For vowel /ɔ/, F2 of Tone 1 was significantly higher than that of all other tones where F2 of Tones 1, 2, 3 and 5 was significantly higher that that of Tone 4 and that of Tones 5 and 6 was significantly lower than that of Tone 3.

For females, F2 of Tone 1 was significantly higher than Tones 3, 4 and 5 for vowel /i/ while that of Tones 4 was significantly lower than that of all other tones for vowel /u/. For vowel /ɛ/, F2 of Tone 4 was significantly higher than that of Tone 5 while that of Tones 4 and 6 was significantly higher than that of Tone 1. For vowel /ɔ/, F2 of Tones 1, 2 and 3 was significantly higher that that of Tones 4 and 6, and that of Tone 5 was significantly higher than that of Tone 6; F2 of Tone 1 was significantly higher than that of Tone 2, 4, 5 and 6.

Discussion

Vowel specific tonal effect on articulation

High front unrounded vowel /i/. For the female speakers, the results indicated lower tongue position in low-level tone than in low-falling tone, and more retracted tongue position was found in high-level tone than mid-level, low-falling and low-rising tones. Compared with results obtained by Hoole and Hu (2004), who recruited a female native speaker of Mandarin, the pattern of vowel /i/ by the female speakers upon tone change was similar. Hoole and Hu found that the vowel /i/ produced with a low-falling tone by the single female participant was more retracted than that of high tone, despite the weak significance. Hu (2004) also reported that the EMA results indicated a slightly retracted tongue in low-rising tone compared with high-rising tone in vowel /i/ produced by the male Ningbo Chinese speaker. Although gender difference may exist, female speakers in the present study and the male speaker in Hu's study showed more retracted tongue in vowel /i/ of low-rising tone. This may suggest a general pattern of tonal effect on high front unrounded vowel /i/, where low-rising tone would company a more retracted tongue position. However, it should be noted that this may not be a universal pattern as Torng (2000) suggested significantly different pattern in production of vowel /i/ among individuals. The articulatory adjustment may vary among individuals.

Despite the similar results compared with previous studies, some opposing results were also shown. Hu (2004) suggested articulatory changes in male speaker in the production on /i/ at different Ningbo Chinese tones. However, the present study yielded a contradictory finding: no significant change in the articulation was found upon the change in tone in male speakers. Since only one male speaker was recruited in Hu's studies, individual differences might be pronounced in the observed tone effect for one speaker. In fact, other studies including Erickson et al. (2004), Perkell, Matthies, Svirsky and Jordan (1993), and Torng (2000) reported differences among individuals. Individual differences may account for the inconsistent results between Hu (2004) and the current study.

In addition, no significant difference in F1 or F2 was found between the high- and low-rising tones in both male and female speakers in the present study. Compared with the result of Hu (2004), in which tongue movement at the tongue tip position was noticed in the production of Ningbo Chinese /i/, tongue tip during production of vowel /i/ by the male speaker was in a higher position in low-rising tone than in high-rising tongue. This posts the question of direct comparison between different measurements.

Hu (2004) made use of EMA to indicate the movement of various articulators including the lower lip, jaw and three tongue positions from the tongue tip to tongue dorsum

(6 cm from the tongue tip). However, in the present study, F1 and F2, which were presumed to reflect the tongue positions, were used to infer the articulatory movement during vowel production. As suggested by Perkell et al. (1993), vowel articulation could be of acoustic goal where different movements of articulators can exert similar effect on the formant frequencies. Similar F1 or F2 can be yielded from slightly different articulatory gestures, although the difference should be limited. There appears to be a lack of one-to-one mapping between acoustics and articulation.

Reflecting the articulatory gesture by F1 and F2 might seem to have missed out the movement of certain parts of articulators, for example, tongue tip, jaw and lips, peripherally. However, it actually possessed a more holistic measurement on the vocal tract shapes taking all the locations above the glottis into account. Wood (1979) suggested that resonance characteristic is sensitive to vocal tract configuration. Formants are determined by movement of lips, tongue blade, tongue root, larynx and degree of oral and labial constrictions (Wood, 1979). In the EMA studies, only tongue movements at the front part of the tongue were measured (Erickson et al., 2004; Hu, 2004) as sensors were only attached to the front of the tongue, possibly within the tongue tip and blade region. Information regarding the movement and location of the tongue root, which can heavily affect the configuration in pharyngeal cavity, was overlooked. It follows that interpreting articulatory gesture based on EMA data obtained from these limited sensors may be limited, and sometimes erroneous.

Although the present data did not show any significant change in tongue movement as indicated by F1 and F2 values of /i/ by both male and female speakers, this did not totally contradict with Hu's (2004) results. It was possible that the effect of the tongue movement at different part neutralized their effect on F1. According to Lindblom and Sundberg (1971), and Pickett (1999), the change of F1 and F2 can be further explained by the oral and pharyngeal constrictions and the position of the constriction. The greater the oral constriction, the lower is the F1; the greater the pharyngeal constriction, the higher is the F2. Hu (2004) suggested higher tongue tip in low-rising tone, which increased oral constriction, in turn, lowered F1 value. It could be possible that difference in tongue tip movement also existed between the two tones but were masked by other articulatory movements along the vocal tract. If the pharyngeal constricted simultaneously with the raised tongue tip, their effects would cancel out each other acoustically and the change would be masked by F1 (Lindblom & Sundberg, 1971; Perkell et al., 1993; Pickett, 1999). Apparently, further investigation is required to confirm this hypothesis.

High back rounded vowel /u/. The results revealed no significant difference in tongue frontness when producing vowel /u/ at different tones by the male speakers. However, the vowel /u/ of low-falling tone showed the most retracted tongue position and of the high-level tone showed the most anterior tongue position in males. The level tones were generally more anterior than glide tones (high-rising, low-falling and low-rising tones). This reveals that the tongue height across different tones in male speaker was maintained at a similar position, but the anterior-posterior movement of the tongue occurred which resulted in F2 variation.

In females, unlike the male speakers, significant difference in tongue height was observed in certain tones. Vowel /u/ of high-level tone tended to show the lowest tongue position and that of low tones showed higher tongue position that the high tones as reflected from F1 values. While this is comparable with the results of Torng (2000), and van Lieshout and Alfonso (2001) (as cited in Hoole & Hu, 2004), which suggested high vowels had low F0 and vice vresa, the current data reversed the pattern of intrinsic pitch suggested by Honda (1995) and Hoole and Hu (2004).

Honda (1995) explained the inverse effect of intrinsic pitch by comparing the vowel height with the corresponding F0 and suggested further higher tongue position is resulted when a high vowel is provided at high tones. In the study of Torng (2000), results suggested different effect of intrinsic pitch across different vowels and at different portion of the F0 contours. Measurements of the intrinsic pitch were made by comparing the articulatory differences between different vowels at each particular tone. The current data questioned on the universal pattern of intrinsic pitch suggested by Honda (1995), and Hoole and Hu (2004). The incoherent results implied that the interaction between the vocal tract and laryngeal source may not simply follow the universal pattern of intrinsic pitch. Or the question comes with the over-simplified interpretation of F1 and F2 in relation to the tongue height and frontness.

The constriction rules for F1 and tongue position rule for F2 may explain the discrepancy (Lindblom & Sundberg, 1971; Pickett, 1999). Although the classic tongue pull theory (Lehiste, 1970) suggested that increase of F0 is correlated with the posterior fibers of the genioglossus muscle pulling the tongue further to front and high position, other muscular activities in the oral and pharyngeal cavities are not completely excluded. Constrictions of pharyngeal cavity may also contribute to the overall increased F1 values in high tones. Therefore, acoustically, the F1 and F2 values may not directly reflect the tongue height and frontness to yield a comparable pattern with the intrinsic pitch.

In addition, the vowel /u/ produced at low-rising tone showed higher tongue position than that at high-rising tone in female speakers, this was incoherent with the results in Hu (2004), in which vowels at low-rising tone generally showed lower tongue position than high-rising tone. The pattern of vowel /u/ in the present study reversed the result of Hu (2004), who studied vowels /i/ and /a/ produced by one male speaker. However, Torng (2000) and

Zee (1980) suggested vowel specify tonal effect. The patterns of the tonal effect in the present study were different across vowels as well (see Figures 3 and 4). Therefore, direct comparison with the results obtained from a different vowel may not be appropriate. When comparing Hu's results with the pattern of vowel /u/ produced by male of the present study, similar pattern would be observed. Although /u/ produced by male in this study showed no significant difference in the statistical analysis. From the F1-F2 scatterplot (Figure 2), it was shown that male did employ lower tongue position to produce /u/ at low-rising tone than high-rising tone. This further supported the vowel specific tonal effect.

Despite the different pattern found between different vowels, the tonal effect on articulation of vowel /u/ in females shared some similarities with males. In both males and females, vowels /u/ produced at low-falling tone showed the most retracted tongue position than at other tones. This is consistent with the findings in Hoole and Hu (2004), where more retracted tongue was observed in vowel /u/ of low-falling tone. More anterior tongue position was observed in high-level tone in vowel /u/ in both male and female speakers. This was supported by the study in Hoole and Hu (2004) as well. This implies that, for vowel /u/, high-level tone is usually accompanied with more anterior tongue position while the low-falling tone usually accompanied with more retracted tongue position.

Mid-low front unrounded vowel /ɛ/. For both males and females, production of vowel /ɛ/ at rising tones showed significantly lower tongue position than the mid- and low-level tones which showed the highest tongue position. This implies that when producing the mid-low unrounded vowel /ɛ/ at mid- and low-level tones, the tongue is placed at a higher tongue position. Also, both male and female speakers showed a higher tongue position in low-rising tone than in high-rising tone in spite of insignificant difference statistically (see Figure 2).

For the anterior-posterior movement of tongue when producing vowel /ɛ/ upon tone change, both male and female speakers exhibited more anterior tongue position in low-falling tone than high-level and low-rising tones, where high-level tone associated with the most retracted tongue position. Low-level tone also showed more anterior tongue position than high-level tone. The pattern found from the present study reversed the pattern of vowel /a/ in the study of Erickson et al. (2004) and Hu (2004). This supported the suggestion from different studies that tonal pattern was not systematic across different tones and vowel context (Hoole & Hu, 2004; Torng, 2000; Zee, 1980). However, study on vowel /ɛ/ in different tones was limited. The current data was unable to compare with similar studies at this stage.

Mid-low back rounded vowel /ɔ/. The results showed a more consistent and systematic pattern between male and female speakers. For the high-level tone, both males and females showed the lowest and most anterior tongue position, while low-level tone showed highest tongue position and more retracted tongue than high tones. Producing vowel /ɔ/ at low-falling tone resulted in a retracted tongue position reflected by F2 in both genders. This pattern was consistent with the findings in the study of Erickson et al. (2004), in which most retracted tongue position was observed in production of /a/ of low-falling tone.

Relationship of vowel articulation and tone change

Vowel height. From the above discussion, high vowels in high-level tone showed more anterior tongue position, while mid-low vowels of rising tones usually showed lower tongue position than low-level tone. However, as only two vowels at each vowel height were included in the present study. Lip rounding and spreading of the vowels was also a factor confounding the pattern of tonal effect of different vowel height. Therefore, the relationship of vowel height and tonal effect was not drawn from this study.

Front unrounded vowels. No consistent relationship between tonal effect across different vowels and across genders can be drawn from the results, suggesting absence of pattern observed across the two vowels /i, ɛ/. It is not known whether vowel specificity can account for this phenomenon as comparison between front vowels or unrounded vowels. However, the present results preliminarily suggest that if a vowel is articulated with an anterior tongue position with a retracted lip, no systematic tonal effect on articulation upon tone change is expected.

Back rounded vowel. The tonal effect on mid-low back rounded vowel /ɔ/ shared certain patterns with the high back rounded vowel /u/. In terms of tongue height, both vowels showed the lowest tongue position at high-level tone and highest tongue position at low-level tone, except for vowel /u/ produced by male speaker. For tongue frontness, a high-level tone with the most anterior tongue position and a low-falling tone with more retracted tongue were found. This implies that when back-rounded vowels are produced at high-level or low-falling tones, more extreme articulatory adjustment occurs, where a high-level tone gives lower and a more anterior tongue position while low-falling tone gives a higher and more retracted tongue position. However, it is uncertain whether the pattern can be generalized to rounded vowels and/or back vowels. Further research examining the rounded front vowel /y/ may help investigate the pattern of tonal effect on round vowels and back vowels.

Gender differences in tonal effect on vowel articulation

Gender difference was observed from the results. For the high vowels, male speakers tended to show insignificant tongue movement, except anterior-posterior movement in vowel /u/ regardless of tones. Compared with the results obtained from female speakers, significant tongue movement was noted across the four vowel contexts used, despite the non-systematic tonal effect. This implies different response in male and female speakers in articulation upon tone change in certain vowel contexts. The underlying difference may come from the overall length and resting shape of the vocal tract (Rosner & Pickering, 1994). Rosner and Pickering (1994) quoted the evidence of different ratio of pharyngeal size to mouth cavity size, i.e., the resting shape of the vocal tract, in males and females. This physical difference resulted in a different vowel spaces between males and females. This may result in the different tonal effect in certain vowel context between males and females.

The vocal tract size difference may lead to an underlying physiological difference between males and females in producing certain vowels. In the present study, the F1 change observed in vowel /i/ and /u/ by males differed from that by females. Males generally exhibited a more consistent tongue height when producing the high vowels /i/ and /u/, while females varied the articulation more significantly across tones.

Despite the incoherent pattern between males and females for F1 of vowel /i/ and /u/, similar pattern in the change of articulation across the tones were observed in F1 of vowel /ɛ/ and /ɔ/ (Figure 3) and F2 of vowel /i/, /u/, /ɛ/ and /ɔ/ (Figure 4). This further supports the hypothesis of vowel specific tonal effect on vowel articulation. Therefore, gender can be a factor affects the tonal effect while different vowel context respond to the tonal effect differently.

Effect of coupling between laryngeal and supralaryngeal systems

Based on the above discussion of the pattern tonal effect on vowel articulation, one question was unresolved: why laryngeal and supralaryngeal interactions exist? Studies on tonal production of whispered and alaryngeal speech may provide insights to the question (Cheung, 2003; Ching, Williams & van Hasselt, 1994). In whispered and alaryngeal speech, lexical tone can be conveyed, though, with less efficiency. This implied varying F0 by the glottis was not the only factor for tone production. Other mechanisms, for example, the

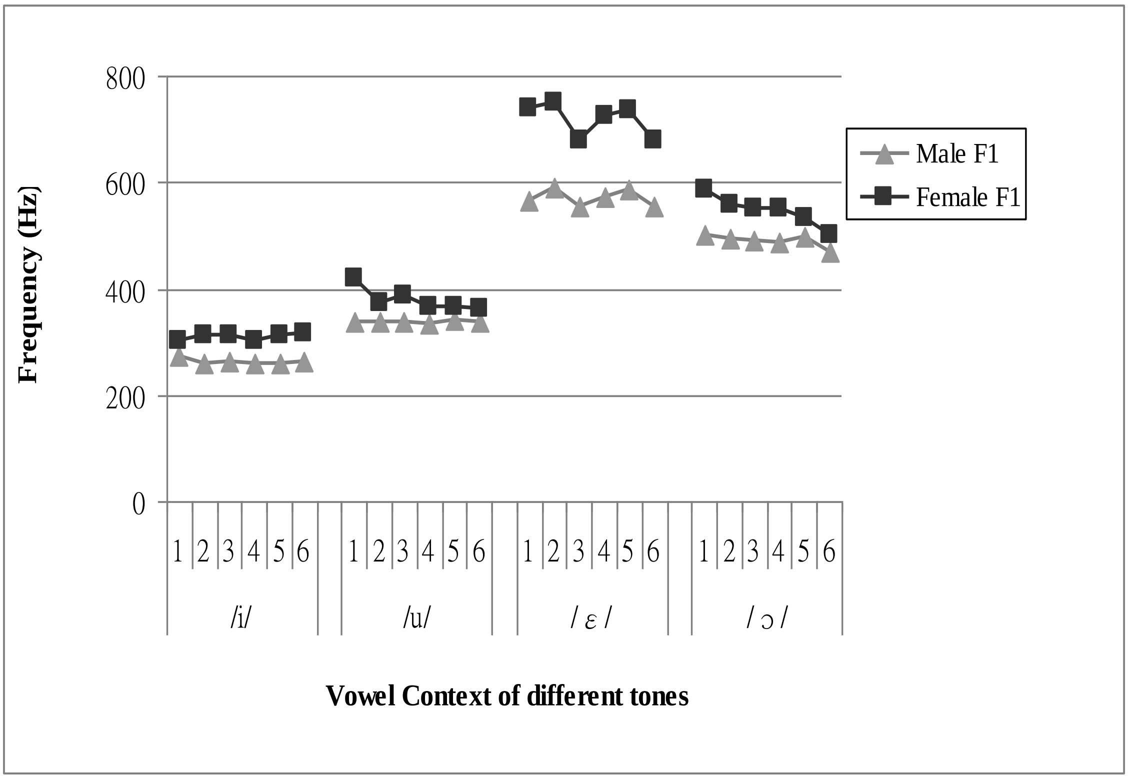

Figure 3. Graph showing the pattern of tonal effect on F1 (in Hz) for vowel /i, u, ɛ, ɔ/ produced by Cantonese males and females.
Note. 1 = high-level tone; 2 = high rising tone; 3 = mid-level tone; 4 = low-falling tone; 5 = low-rising tone; 6 = low-level tone.

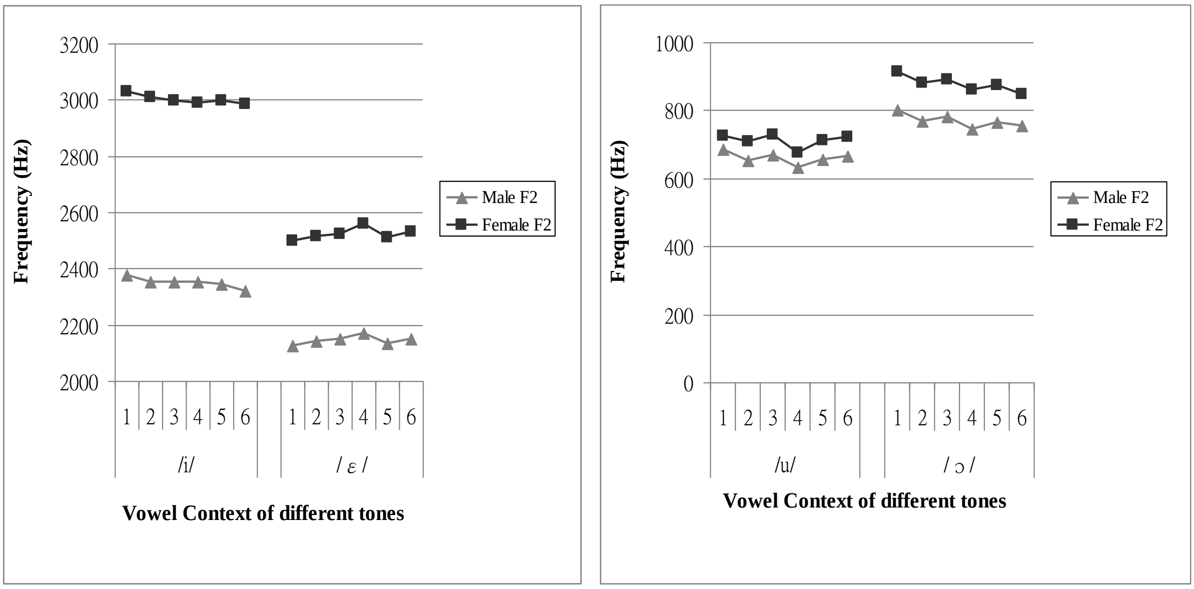

Figure 4. Graphs showing the pattern of tonal effect on F2 (in Hz) for vowel /i, u, ɛ, ɔ/ produced by Cantonese males and females.
Note. 1 = high-level tone; 2 = high rising tone; 3 = mid-level tone; 4 = low-falling tone; 5 = low-rising tone; 6 = low-level tone.

respiratory and/or articulatory systems may account for tone production. For the respiratory system, it is unknown whether it is involved in the interaction between the two systems. Although the loudness was controlled at a constant level and no abrupt change of respiratory effort, which can lead to loudness and pitch change (Colton et al, 2006), was not observed, subtle aerodynamic changes might exist. This may be explained by the relatively poor tone recognition in electrolaryngeal speech than the other such as the esophageal speech (Ching et al., 1994). However, the change in vocal tract configuration should not be overlooked as this was evident in the current studies and the previous ones (Chen et al., 2005; Erickson et al., 2004; Hoole & Hu, 2004; Hu, 2004; Torng, 2000).

Upon these changes in articulation for different tones, lexical tones were conveyed clearly. Speech production should meet the acoustic goal. The tonal and segmental (vowel) information is required to be conveyed clearly. Therefore, the interaction of the articulation during tonal production may be viewed as the ways to maintain the speech naturalness (Honda, 1995) and to ensure the precise transmission of both lexical tone and vowel information.

Limitations of the study

One of the limitations of the present study is that F1 and F2 were used as the primary measurement of the articulatory change upon tone change. Although Chiba and Kajiyama (1941), Hillenbrand et al. (1995) and Stevens and House (1955) suggested how F1 and F2 reflect tongue position in a simple relationship, it should be noted that the effect of articulation on F1 and F2 can be more complicated (Lindblom & Sundberg, 1971; Pickett, 1999). Any small local changes along the vocal tract can affect the F1 and F2 to different extent. Therefore, this limited the comparison of the current studies to the EMA studies (Erickson et al., 2004; Hu, 2004) to draw a universal pattern.

Another limitation is that F1 and F2 values were averaged in the statistical procedures. Under the hypothesis that tonal effect may affect the vocal tract shape, the articulation in the glide tones, i.e. high-rising and low-rising tones, may show a continuum in the articulatory movement during the gliding of F0 in the tone. However, the possible articulatory change in the gliding tones was averaged out when the average F1 and F2 values were obtained from the three trials of each target word. Therefore, the changes within the vowel segment in the F0 contour might have been overlooked.

Future studies

In the present study, only four vowel contexts were investigated. As suggested before, tonal changes showed a vowel specific effect on the tongue position. However, the vowels selected were not contrastive regarding vowel roundedness, vowel height and vowel frontness. It is suggested that further studies on the tonal effect on vowel articulation can include other vowels such as high front rounded vowel /y/ for comparison. This helps determine the tonal effect on vowel roundedness, height and frontness.

As suggested that information of the articulation change in tones, especially the glide tones was averaged out during the statistical analysis. It is suggested that further investigation comparing the articulation along the F0 contour at different point, for example, vowel beginning, mid and final, can be made. This can facilitate the understanding of the changes of articulatory gestures along the F0 changes in tones.

In future study examining the coupling between laryngeal and supralaryngeal systems, ultrasonic imaging (Qin, Carreira-Perpiñán, Richmond, Wrench & Renals, 2008) or dynamic real-time magnetic resonance imaging (MRI) (details of MRI in Echternach et al., 2008) can be applied which can supplement F1 and F2 values in measuring articulatory changes. This holistic measurement allows the investigation of articulatory adjustment upon tone change.

As suggested by Perkell et al. (1993), individuals showed compensatory articulation to limit changes in formant frequencies. In other words, articulators may change their position or location during speech production without changing the formant frequencies. Some articulatory change may yield no significant change in observed F1 and F2. Therefore, further investigation can provide a comprehensive understanding of coupling between laryngeal and supralaryngeal systems.

Clinical implications

It is suggested that coupling between the laryngeal and supralaryngeal systems is to maintain the speech naturalness. F1 and F2 change accordingly to a change in F0 but at the same time pose no effect on speech intelligibility. This may provide insights on speech synthesis to provide more natural speech in tonal languages.

Conclusion

Previous research revealed evidence for interaction between laryngeal and supralaryngeal systems in non-tonal languages and tonal languages. Results from the present study further support the coupling between the laryngeal and supralaryngeal systems. The interaction between the laryngeal and supralaryngeal systems may contribute to the speech naturalness. Patterns of tonal effect on vowels at different Cantonese tones were observed.

Acknowledgement

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References

Boersma, P., & Weenink, D. (2009) Praat: doing phonetics by computer (Version 5.1.01) [Computer program]. Retrieved Feb 22, 2009, from http://www.praat.org/

Chao, Y. R. (1947). *Cantonese primer*. Cambridge, MA: Harvard University Press.

Chen, Y., Ng, M., & Vrablik, K. (2005). *Coupling between laryngeal and supralaryngeal systems in Mandarin speech.* Poster presented at the 2005 Annual Convention of the American Speech-Language and Hearing Association, San Diego, CA, U.S.A.

Cheung, Y. M. (2003). Recognition of lexical tones in Cantonese whispered speech. Hong Kong: Division of Speech and Hearing Sciences, the University of Hong Kong.

Chiba, T., & Kajiyama, M. (1941). *The vowel, its nature and structure.* Tokyo: Tokyo-Kaiseikan.

Ching, T. Y. C., Williams, R. & van Hasselt, A. (1994). Communication of lexical tones in Cantonese alaryngeal speech. Journal of Speech and Hearing Research, 37, 557-571.

Colton, R., Casper, J., & Leonard, R. (2006). *Understanding voice problems: a physiological perspective for diagnosis and treatment.* Philadelphia: Lippincott Williams & Wilkins.

Fant, G. (1960). *Acoustic theory of speech production.* The Hague: Mouton.

Fitch, W. T. (1994). *Vocal tract length perception and the evolution of language*. Doctoral Thesis, Brown University. Retrieved from http://www.st-andrews.ac.uk/~wtsf/downloads/Fitch1994PhD.pdf

Fok, C. Y. Y. (1974). *A perceptual study of tones in Cantonese.* Hong Kong: Centre of Asian Studies.

Echternach, M., Sundberg, J., Arndt, S., Breyer, T., Markl, M., Schumacher M., & Richter B. (2008). Vocal tract and register changes analysed by real-time MRI in male professional singers: a pilot study. *Logopedics Phoniatrics Vocology, 33*, 67-73.

Erickson, D., Iwata, R, Endo, M., & Fujino, A. (2004). Effect of tone height on jaw and tongue articulation in Mandarin Chinese. International Symposium on Tonal Aspects of Languages (TAL-2004), Beijing, China. Retrieved from http://www.isca-speech.org/archive/tal2004/tal4_053.pdf

Hillenbrand, J., Getty, L., Clark, M. J., & Wheeler, K. (1995). Acoustic characteristics of American English vowels. *Journal of the Acoustical Society of America,97* , 3099-3111.

Honda, K. (1995). Laryngeal and extra-laryngeal mechanisms of F0 control. In F. Bell-Berti & L. J. Raphael (eds.), *Producing Speech: Contemporary Issues* (pp 215-232). New York: American Institute of Physics.

Hoole, P., & Hu, F. (2004). Tone-vowel interaction in standard Chinese. International Symposium on Tonal Aspects of Languages (TAL-2004), Beijing, China. Retrieved from http://www.isca-speech.org/archive/tal2004/tal4_089.pdf

Hu, F. (2004). Tonal effect on vowel articulation in a tone language. International Symposium on Tonal Aspects of Languages (TAL-2004), Beijing, China. Retrieved from http://www.isca-speech.org/archive/tal2004/tal4_053.pdf

Huber, J, E., Stathopoulos, E. T., Curione, G. M., Ash, T. A., & Johnson, K. (1999). Formants of children, women, and men: The effects of vocal intensity variation. *Journal of the Acoustical Society of America, 106*, 1532-1542.

Kent, R. D., & Read, C. (2002). *The acoustic analysis of speech* (2nd ed.). Albany, NY : Singular/Thomson Learning.

Lau, L. S. P., & James, C. J. (2004). A tonal language test of speech perception: Cantonese spondee lists. *Asia Pacific Journal of Speech, Language and Hearing, 9*, 200-219.

Lehiste, I. (1970). *Suprasegmentals*. Cambridge, MA: MIT Press.

Lehiste, I. (1996). Suprasegmental features of speech. In N. J. Lass (Ed.), *Principles of experimental phonetics* (pp. 226-244). St. Louis, Missouri: Mosby.

Liénard, J. S., & Di Benedetto, G. M. (1999). Effect of vocal effort on pectral properties of vowels. *Journal of the Acoustical Society of America*, *106*, 411-422.

Lindblom, B. E. F., & Sundberg, J. E. F. (1971). Acoustical consequences of lip, tongue, jaw, and larynx movement. *Journal of the Acoustical Society of America,* 50, 1166-1179.

Perkell, J. S, Matthies, M. L., Svirsky, M. A., & Jordan, M. I. (1993). Trading relations between tongue-body raising and lip rounding in production of the vowel/u/: A pilot "motor equivalence" study. *Journal of the Acoustical Society of America, 93,* 2948-2961.

Pickett, J. M. (1999). *Acoustics of speech communication.* Boston: Allyn & Bacon.

Qin, C., Carreira-Perpiñán, M. Á ., Richmond, K., Wrench, A. and Renals, S. (2008). Predicting tongue shapes from a few landmark locations. In *Interspeech-2008*, 2306-2309. Retrieved from http://www.isca-speech.org/archive/interspeech_2008/i08_2306.html

Rosner, B. S., & Pickering , J. B. (1994). *Vowel perception and production*. Oxford: Oxford University Press.

Ryalls, J. (1996) *A basic introduction to speech perception*. San Diego: Singular.

Stevens, K. N., & House, A. S. (1955). Development of a quantitative description of vowel articulation. *Journal of the Acoustical Society of America*, *27*, 401–493.

Stevens, K. N., & House, A. S. (1961). An acoustical theory of vowel production and some of its implications. *Journal of Speech and Hearing Research*, *4*, 303-320.

Story, B. H., Titze, I. R., & Hoffman, E. A. (2001). The relationship of vocal tract shape to three voice qualities. *Journal of the Acoustical Society of America, 109*, 1651-1667.

Tom, K., Titze, I. R., Hoffman, E. A., & Story, B. H. (2001). Three-dimensional vocal tract imaging and formant structure: Varying vocal register, pitch, and loudness. *Journal of the Acoustical Society of America*, *109*, 742-747.

Torng, P-C (2000). *Supralaryngeal articulator movements and laryngeal control in Mandarin Chinese tonal production*. Doctoral Thesis, University of Illinois, Urbana-Champaign. Retrieved from http://sunzi1.lib.hku.hk/ER/detail/hkul/2693692

Wood, S. (1979). A radiographic analysis of constriction locations of vowels. *Journal of Phonetics, 7*, 25-43.

Xu, Y. (1997). Contextual tonal variations in Mandarin. *Journal of Phonetics, 25,*61-83.

Zee, E. (1980). Tone and vowel quality. *Journal of Phonetics, 8,* 247-258.

Appendix A

The word list of the targeted 24 monosyllabic words

Tone	High-level (1)	High-rising (2)	Mid-level (3)	Low-falling (4)	Low-rising (5)	Low-level (6)
/ji/	衣	椅	意	宜	耳	二
/fu/	夫	苦	富	扶	婦	負
/sɛ/	些	寫	瀉	蛇	社	射
/ts^{h}ɔ/	初	楚	錯	鋤	坐	/ ts^{h}ɔ$_6$/

Appendix B

Summary of the significant figures in the pairwise multiple comparisons of F1 between tones in each vowel context and each gender

	Male				Female			
Pairwise	/i/	/u/	/ɛ/	/ɔ/	/i/	/u/	/ɛ/	/ɔ/
1 – 2	---	---	0.006*	0.170	0.108	0.000*	0.167	0.004*
1 – 3	---	---	0.016	0.034	0.076	0.000*	0.000*	0.000*
1 – 4	---	---	0.515	0.072	0.696	0.000*	0.279	0.004*
1 – 5	---	---	0.007*	0.378	0.079	0.000*	0.816	0.000*
1 – 6	---	---	0.057	0.000*	0.034	0.000*	0.000*	0.000*
2 – 3	---	---	0.000*	0.252	0.911	0.001*	0.000*	0.366
2 – 4	---	---	0.165	0.231	0.026	0.161	0.002*	0.421
2 – 5	---	---	0.491	0.501	0.837	0.001*	0.019	0.000*
2 – 6	---	---	0.000*	0.001*	0.278	0.003*	0.000*	0.000*
3 – 4	---	---	0.070	0.897	0.053	0.003*	0.000*	0.947
3 – 5	---	---	0.000*	0.098	0.933	0.000*	0.000*	0.133
3 – 6	---	---	0.494	0.005*	0.334	0.000*	0.864	0.000*
4 – 5	---	---	0.283	0.134	0.011	0.490	0.195	0.111
4 – 6	---	---	0.088	0.064	0.005*	0.459	0.000*	0.000*
5 – 6	---	---	0.000*	0.000*	0.281	0.685	0.000*	0.000*

Note: no significant main effect was identified for vowel /i/ and /u/ in male speakers; 1 = high-level tone; 2 = high rising tone; 3 = mid-level tone; 4 = low-falling tone; 5 = low-rising tone; 6 = low-level tone.

*$p < .01$

Summary of the significant figures in the pairwise multiple comparisons of F2 between tones in each vowel context and each gender

	Male				Female			
Pairwise	/i/	/u/	/ɛ/	/ɔ/	/i/	/u/	/ɛ/	/ɔ/
1 – 2	---	0.000*	0.066	0.000*	0.020	0.201	0.315	0.006*
1 – 3	---	0.010*	0.003*	0.001*	0.000*	0.862	0.057	0.090
1 – 4	---	0.000*	0.001*	0.000*	0.001*	0.003*	0.005*	0.000*
1 – 5	---	0.000*	0.355	0.000*	0.001*	0.354	0.318	0.001*
1 – 6	---	0.007*	0.008*	0.000*	0.033	0.809	0.019	0.000*
2 – 3	---	0.002*	0.358	0.028	0.091	0.188	0.396	0.051
2 – 4	---	0.003*	0.013	0.001*	0.048	0.001*	0.002*	0.001*
2 – 5	---	0.242	0.337	0.376	0.049	0.520	0.814	0.057
2 – 6	---	0.006*	0.567	0.060	0.215	0.084	0.033	0.000*
3 – 4	---	0.000*	0.118	0.000*	0.481	0.008*	0.025	0.000*
3 – 5	---	0.041	0.139	0.008*	0.947	0.369	0.245	0.010*
3 – 6	---	0.628	0.837	0.000*	0.545	0.690	0.282	0.000*
4 – 5	---	0.001*	0.001*	0.002*	0.434	0.000*	0.004*	0.041
4 – 6	---	0.000*	0.062	0.141	0.844	0.000*	0.037	0.172
5 – 6	---	0.116	0.183	0.151	0.543	0.088	0.026	0.003*

Note: no significant main effect was identified for vowel /i/ in male speakers; 1 = high-level tone; 2 = high rising tone; 3 = mid-level tone; 4 = low-falling tone; 5 = low-rising tone; 6 = low-level tone.

*$p < .01$

Appendix C

参加研究者同意書
Informed Consent Form

「喉部與聲道的功能連合」研究
Coupling between the laryngeal and supralaryngeal systems

香港大學 – 言語及聽覺科學部誠意邀請閣下參與一項由吳民華博士監督，言語及聽覺科學部學生李宏婷主理的研究。
You are invited to participate in a research study conducted by Lee Wang Ting, Wendy, supervised by Dr. Lawrence Ng in the Division of Speech and Hearing Sciences at the University of Hong Kong.

研究目的
PURPOSE OF THE STUDY

研究目的是為証實人類言語系統中的喉部和聲道之間的功能連合
This study aims to find the coupling between the laryngeal and supralaryngeal systems in human speech mechanism.

研究程序
PROCEDURES

是項研究會在香港大學 - 言語及聽覺科學部舉行。
The study will be held at the Division of Speech and Hearing Sciences at the University of Hong Kong.

所有受試者都會依照電腦螢幕上的顯示讀出目標字句。研究員會在過程中進行錄音，以用作日後分析用途。整個過程需時約三十分鐘。
All participants will read the speech materials following the computer screen at the comfortable loudness and pitch. The speech materials will be recorded using microphone for data analysis. This will take about thirty minutes to complete.

潛在風險
POTENTIAL RISKS / DISCOMFORTS AND THEIR MINIMIZATION

沒有潛在風險
No potential risks or discomforts.

研究裨益
POTENTIAL BENEFITS

是次研究不會為閣下提供直接得益，但是項研究結果可提高對人類言語系統的了解。所以閣下的參與對日後研究有極大的貢獻。
There are no direct benefits to you. However, the study can provide valuable information for understanding the speech production mechanism.

個人私隱
CONFIDENTIALITY

閣下向研究人員提供的資料，只供作研究之用，個人資料將絕對保密。閣下的所有資料將以代碼記錄，以保障閣下的私穩。參加者的身份亦不會被公開。
All information obtained in this study will remain strictly confidential, will not be disclosed to any other people, and will be used for research purpose only. Codes, not names, are used on all test instruments and subject files to protect confidentiality. Participant will not be identified by named in any report of the completed study.

參與及退出
PARTICIPATION AND WITHDRAWAL

是次研究項目純屬自願性質，閣下可隨時查看研究紀錄，閣下亦可隨時提出終止參與此項研究，有關決定將不會引致任何不良後果。如有需要，閣下可要求銷毀測試結果。
Your participation is voluntary. This means that you can choose to stop at any time without negative consequences.

疑問
QUESTIONS AND CONCERNS

如你對是項研究有任何疑問，請現在提出。如日後你對是項研究有任何查詢，敬請聯絡研究員李宏婷小姐(電話：9032-1896；電郵：wendy30@hkusua.hku.hk)。如你想知道更多有關研究參與者的權益，敬請聯絡香港大學非臨床研究操守委員會(電話：2241-5267)
If you have any questions or concerns about the research, please feel free to contact Miss Lee Wang Ting at HKU, (Telephone number: 9032-1896; Email: wendy30@hkusua.hku.hk). If you have questions about your rights as a research participant, contact the Human Research Ethics Committee for Non-Clinical Faculties, HKU (2241-5267).

我們在此多謝閣下的參與。
We thank you for your interest and support.

簽署
SIGNATURE

本人 ________________________________ (姓名) 已有足夠機會詢問清楚明白有關這項研究的內容，並同意參加這項研究。

I ________________________________ (Name of Participant) have given opportunity to ask questions about this study and they have been answered to my satisfaction. I understand the procedures described above and agree to participate in this study.

____
參加者姓名 Name of Participant

____
參加者簽署 Signature of Participant

____
見証人姓名 Name of Witness

____
見証人簽署 Signature of Participant

____
日期 Date

Date of Preparation: Nov 6, 2009
HRECNCF Approval Expiration date: