The Raising Effect of Aspirated Prevocalic Consonants on F_0 in Taiwanese

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1. Introduction

The interaction between consonants and tones is well documented. As consonants generally influence the quality and pitch of surrounding vowels (Li, 1980), this is not surprising. The well-known model of tonogenesis proposed by Haudricourt (1954) argues that, as consonants play a central and direct role in pitch assignment, they are consequently responsible for triggering tonal split. In his model, prevocalic segments determine tone height, while postvocalic segments determine tone contour. In refining this model, Li (1980) further concluded that the perturbation of tones is affected by both voicing and aspiration contrasts in prevocalic position.

Studies investigating onset perturbation effects have focused primarily on the perturbation effect of voiced onsets. It has been repeatedly demonstrated that F_0 at the onset of vowels is significantly higher after voiceless onsets than after voiced onsets. This process has been documented in Thai, Chinese, and other tonal languages (Hombert, 1978 and references therein). The same perturbation effect has also been documented in non-tonal languages (e.g., Fischer-Jørgensen, 1968; Mohr, 1971; Hombert, 1975; Löfqvist, 1975). Data comparing the effect of voiceless aspirated and unaspirated stops on the F_0 of following vowels are less clear, however, with conflicting results in tonal as well as non-tonal languages (cf. Hombert, 1975 for a detailed review). The purpose of the present study is to investigate whether and how F_0 is affected by prevocalic aspiration, how far the effect reaches along the tonal contour, and what factors contribute to the effect. Finally, some attempt will be made at explaining why results from other studies continue to conflict.

1.1 Literature Review

1.1.1 Perturbation by syllable-initial voicing contrast

Early studies on the perturbation effect of consonant voicing (Mohr, 1971) have shown that F_0 at the onset of a vowel is significantly higher after a voiceless stop than after a voiced stop. This effect is widely considered to have triggered tonogenesis in Chinese, as well as many other tonal languages. It is thought that Middle Chinese went through a process of tonogenesis through the loss of the voicing distinction in prevocalic position, in the following way.

At some point in the past, Middle Chinese had four phonemic tones. Due to the lower F_0 of vowels after voiced consonants, a lower pitch became associated with voiced prevocalics, and a higher pitch associated with voiceless prevocalics, in a purely allophonic relation. Later on the conditioning environment - the voicing contrast in prevocalic position - was lost. As a result, the distribution of high register tones and low register tones was no longer predictable, and each of the original four tones split into two - one with a higher pitch, and one with a lower pitch. A new eight-tone system was developed from the proto four-tone system.

The inherent lowering of F_0 following voiced consonants is caused by laryngeal and aerodynamic factors. When producing a voiced prevocalic segment, the subglottal pressure contributes to the voicing of the voiced consonants; thus, when voicing of the vocalic segment starts, there is less of a transglottal pressure difference, causing F_0 after voiced consonants to be consistently lower (Ladefoged, 1967; Klatt, 1968). It has also been documented that the lowering effect voiced consonants have on vowels with higher F_0 is greater than the raising effect of voiceless consonants on vowels with lower F_0 (Hombert and Ladefoged, 1977). This can be posited as a systematic minimization of the effect to avoid broadening the register range of the tonal system given that voiced segments have a lowering effect on tones.

1.1.2 Perturbation by syllable-initial aspiration contrast

Compared to voicing, the perturbation effect caused by aspiration has received rather less attention, and studies in this area have yielded conflicting results. It is generally assumed that F_0 after voiceless aspirated stops is higher than after voiceless unaspirated stops (Hombert, 1975). This claim is supported by studies from non-tonal languages: Korean (Han and Weitzman, 1970) and Danish (Jeel, 1975), along with tonal languages: Cantonese (Zee, 1980) and Thai (Ewan, 1976). However, conflicting results are found among the four languages mentioned above. In Danish, Fischer-Jørgensen (1968) reported that there is no difference in the F_0 onset depending on the preceding consonant (cited by Hombert and Ladefoged, 1977). A higher F_0 after unaspirated stops was reported in Korean (Kagaya, 1974), Thai (Gandour, 1974; Erickson, 1975), and Hindi (Kagaya, 1975).

1.1.3 Research in non-tonal languages

Jeel (1975) investigated Danish aspirated and unaspirated stops and found that F_0 after aspirated stops was consistently higher than after unaspirated stops. Han and Weitzman (1970) examined acoustic features of the three-way contrast (weak-strong-aspirated) of Korean stop consonants. Results indicated that the onset value of F_0 is highest after aspirated stops, followed by strong stops, and finally weak stops. Hombert and Ladefoged (1977) investigated the effect of aspiration on F_0 in English and French. They compared the perturbation effect on F_0 between English aspirated stops /p^h, t^h, k^h/ and French unaspirated stops /p, t, k/. Results indicated no direct correlation between aspirated and unaspirated stops and the onset F_0 of following vowels. They discussed the results in terms of how the determinants of F_0 might be influenced by the aspiration of preceding stops. They concluded that the determinants controlling F_0 are not significantly different between aspirated and unaspirated stops; therefore, aspirated and unaspirated stops have similar effects on F_0.

1.1.4 Research in tonal languages

Gandour (1974) investigated the effect of preceding consonants on F_0 in Thai. He used nonsense CV syllables (C = p, p^h, b, t, t^h, d, s, n; V = a, i, u; Tone = 1, 2, 3, 4, 5), and measured the perturbation of prevocalic segments on the following tones, testing just a single male participant. This study focused on the effect triggered by the voicing contrast, but mentioned briefly that the onset F_0 after voiceless unaspirated stops was eight percent higher than after aspirated stops. Zee (1980) compared the effect of voiceless aspirated and unaspirated stops on the F_0 of the following diphthong [ei] in Cantonese. He utilized one minimal pair, /pei/ vs /phei/, and one tone (high level) as stimuli, and tested only three speakers – all of which were male. In contrast to the findings of Gandour (1974), he found that syllables with aspirated stops have a higher F_0 than those with unaspirated stops. Also, the intensity of voicing after aspirated stops is lower than after unaspirated stops. Zee has suggested that the intensity difference indicates lower subglottal pressure after aspirated stops. However, the result that the F_0 onsets of aspirated stops are higher indicates that a higher F_0 may be produced even with lower subglottal pressure. He further suggests that data about airflow, subglottal pressure, larynx height, glottal aperture, and vocal fold length at the onset of the following vowel should be collected to explore this phenomenon. He surmised that this effect could be language-specific, and sometimes may even differ from speaker to speaker.

Ewan (1979) used a computer-controlled photoelectric device to track vertical larynx movement in 2ms steps. Laryngeal activity was studied in English, French, German, Hindi, Arabic, Thai, Vietnamese, Mandarin, Taishan Chinese, Taiwanese, and Japanese. The results showed a positive correlation between F_0 and larynx height. The larynx, as well as F_0, is higher after voiceless obstruents than after voiced obstruents. Moreover, the larynx and F_0 are higher after voiceless aspirated stops than after voiceless unaspirated stops in Thai (Ewan 1976). Several studies have reported that the airflow rate is faster after voiceless aspirated (relative to unaspirated) stops (Ladefoged, 1974, 1967). A higher airflow rate intensifies the Bernoulli effect and decreases the pressure perpendicular to the vocal folds. This decreased pressure causes the vocal folds to adduct and tighten more rapidly, thus raising F_0 after aspirated stops.

More recently, in a study of Mandarin, Xu and Xu (2003) compared the effect of aspiration on F_0 for Mandarin tones in continuous speech. One minimal pair of syllables /ta/ and /t^ha/, carrying the four Mandarin tones, were embedded in two different carrier sentences (though as /t^ha2/ is lexically absent from Mandarin, Xu and Xu used /p^ha2/ instead). Eight native speakers were tested, all of which were female. They combined the target with another syllable to form a disyllabic word, in order to explore the effect of tonal coarticulation. The target was either in the first or the second syllable in a disyllabic word. A five-way ANOVA was conducted to evaluate the effect of consonant, lexical tone, syllable position, tonal context and carrier sentence on onset F_0, end F_0 and F_0 contour. Xu and Xu found, in conflict with Zee's (1980) work in Cantonese, that the onset F_0 of a tone is (much) higher following unaspirated consonants than following aspirated consonants. They also showed that this effect disappears toward the end of the syllable. In addition, the effect is claimed to be greater for the rising and dipping tones than for the high level and high falling tones. In terms of tonal context, when the preceding tone is high or rising, the effect seems to be stronger. Since in their experiment, subjects produced /ta/ and /tʰa/, and F_0 was measured for each production, a repeated measures ANOVA rather than the regular ANOVA used in the study would, perhaps, have been more appropriate. Xu and Xu (2003) have inferred that the raising effect of unaspirated initials which they found is due to the fact that subglottal air pressure is lower after aspirated stops. However, Zee (1980) has pointed out, "That the intensity onset of the diphthong [ei] following [pʰ] is always lower in Cantonese seems to imply that the subglottal pressure at the onset of the diphthong is also lower. The fact that the F_0 onset of the diphthong following [pʰ] is always higher indicates that a higher F_0 may be produced even with a decreased subglottal pressure." Unfortunately, Xu and Xu (2003) did not measure intensity in their experiments. Xu and Xu (2003) documented an onset F_0 difference of around 20 Hz, which is higher than they expected. Figures from their study indicate that the onset F_0 difference is about 15 Hz for the high tone, 30 Hz for the rising tone, 50 Hz for the low tone and 8 Hz for the falling tone.

As previous studies on the aspiration perturbation effect have indicated, the effect can vary from speaker to speaker (Zee, 1980), and even by gender (Lai, 2004). Lai examined two male and two female speakers of Taiwanese, and found a significantly higher F_0 after aspirated stops only in females, while male differences were not significant. In their studies, Xu and Xu and Zee tested only females and males, respectively, and this should be taken into account. The large F_0 differences found by Xu and Xu, as well as the fact that only females were tested, suggests that these results for Mandarin should not be regarded as conclusive without further testing, preferably with some degree of gender balance.

1.2 Introduction to Taiwanese

Taiwanese has 7 phonemic tones: Tone 1 - High Level (HL), Tone 2 - High Falling (HF), Tone 3 - Low Level (LL), Tone 4 - High Falling short (Fs), Tone 5 - Low Rising (LR), Tone 6 - Low Falling short (Fs), and Tone 7 - Low Falling (LF). Numeric tone marking here follows the general tone marking convention, as shown in Figure 1. Taiwanese tones can be divided into two groups according to the onset register of the tones: high register (includes HL, HF, HFs), and low register (includes LL, LF, LR, and LFs) (Chiang, 1967). They can also be categorized by duration: HL, HF, LL, LF, and LR are long tones and HFs and LFs are short tones. The short tones are always pronounced with voiceless stops in coda position and are drastically shorter than long tones. For the purposes of this study, only the five long tones (Tones 1, 2, 3, 5, and 7) are included.

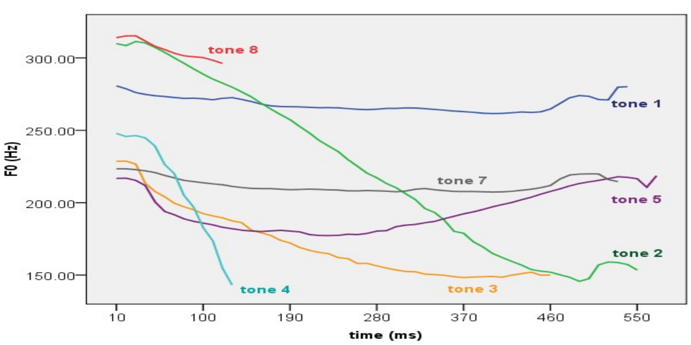

Figure 1: The seven tones of Taiwanese from a female native speaker.

1.3 The present study

It is posited that the conflicting results from other acoustic studies on aspiration perturbation are due to the fact that the stimuli were not constructed systematically and in a balanced fashion with respect to place of articulation, gender, and tone (including tones with different height). We hypothesize that aspirated stops will have a raising effect on following vowels, though we are also interested in further determination of the roles gender, place of articulation, and tone play in this raising effect. And, following the same reasoning as Hombert, it seems reasonable to speculate that aspirated segments will have a stronger effect on lower tones than on higher tones.

2. Methodology

Stimuli: The recorded syllables were 30 consonant-vowel (CV(N)) word pairs, contrasting in aspiration (voiceless aspirated and voiceless unaspirated) of initial stop consonants. The syllables consist of tokens from three places of articulation (bilabial, alveolar, and velar) with the five full tones in Taiwanese: Tone 1 - High Level (HL), Tone 2 - High Falling (HF), Tone 3 - Low Level (LL), Tone 5 - Low Rising (LR), Tone 7 - Low Falling (LF).

Participants: 10 adult native speakers of Taiwanese, 5 females and 5 males, were recruited from Taipei, Taiwan. Their ages ranged from 35 to 70 years old. The participants also speak Mandarin Chinese, and have no known history of speech or hearing impairments.

Procedure: Recording was done in a quiet room using a Marantz solid state recorder model PMD671. Stimuli were presented in Chinese characters on a laptop computer screen. Participants were allowed first to practice the entire word list until they were comfortable with all of the words. Three repetitions of the stimuli were displayed in random order, the speed of which was controlled by the subject. There were a total of 180 tokens: 2 words x 5 tones (tones 1,2,3,5, and 7) x 3 places of articulation (bilabial, alveolar, and velar) x 2 aspiration (aspirated and unaspirated) x 3 repetitions = 180. Each session lasted approximately 20 minutes.

Acoustic Measurements: The recordings were recorded digitized at 44.1 kHz and analyzed using the speech analysis software program Praat (By Paul Boersma and David Weenink) at the Phonetics and Psycholinguistics Lab at the University of Kansas. Each token was displayed and measured on Praat with waveform, spectrogram, and pitch contour. Two sets of measurements were made on each token: VOT (voice onset time) and F_0 (at onset, and every 10% of the tonal contour). Voice onset time was measured from the release of stop closure to the F1 onset of the following vowel. All measurements were averaged over three repetitions of a given syllable. SPSS was used for statistical analyses.

3. Results

3.1 Fundamental frequency (F_0)

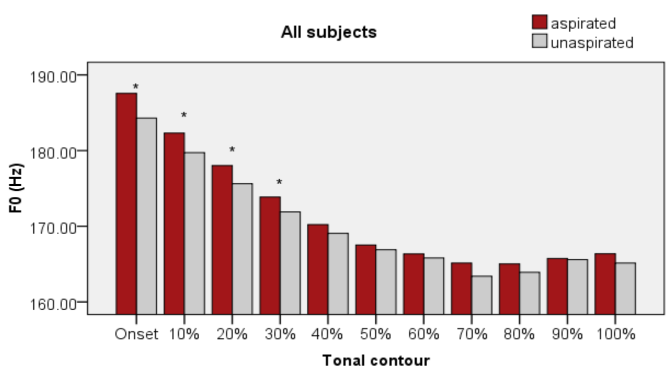

Figure 2: F_0 measurements in 10% increments over the duration of the tonal contour. Asterisks indicate that the difference between aspirated and unaspirated conditions is significant.

A series of one-way repeated measures analyses of variance (ANOVAs) were conducted to compare F_0 after aspirated and unaspirated stops in 10% intervals along the tonal contour. As shown in Figure 2, the onset, 10%, 20%, and 30% measurements have higher F_0 when following aspirated stops. These differences were not significant beyond 30% (c.f. Table 1).

Table 1: Mean F_0 after aspirated and unaspirated stops, as well as the F and p values of pair-wise comparisons between aspirated and unaspirated stops at each F_0 measurement.

measurement	aspirated (Hz)	unaspirated (Hz)	significance	F	p
Onset	187.6	184.3	*	(1, 8)= 11	.011
10%	182.3	179.7	*	(1, 8)= 12.27	.008
20%	178	175.6	*	(1, 8)= 12.91	.007
30%	173.8	171.9	*	(1, 8)= 7.63	.025
40%	170.2	169.1	n.s.	(1, 8)= 3.67	.092
50%	167.5	166.9	n.s.	(1, 8)= 1.11	.323
60%	166.3	165.8	n.s.	(1, 8)= 1.11	.322
70%	165.1	163.3	n.s.	(1, 8)= 3.05	.119
80%	165	163.9	n.s.	(1, 8)= .839	.387
90%	165.7	165.6	n.s.	(1, 8)= .013	.914
100%	166.3	165.1	n.s.	(1, 8)= .781	.403

To test the robustness of the gender effect found in Lai (2004), a four-way repeated measures ANOVA was conducted at onset F_0. The within-subjects factors were aspiration (aspirated and unaspirated), place (bilabial, alveolar, and velar), and tone (tones 1, 2, 3, 5, and 7). The between-subjects factor was gender (female and male). These results are listed in Table 2.

Table 2: The F and p values for the four way repeated measure ANOVA conducted on onset F_0.

	significance	F	p
aspiration	*	(1,8)= 11.03	.011
place	*	(2, 16)= 41.58	<.001
tone	*	(4, 32)= 82.79	<.001
gender	*	(1, 8)= 13.2	.007
aspiration*gender	*	(1, 8)= 7.01	.029
place*gender	n.s.	(2, 16)= 2.27	.135
tone*gender	n.s.	(4, 12)= .81	.196
aspiration *place	n.s.	(2, 16)= .367	.698
aspiration*place*gender	n.s.	(2, 16)= 1.35	.286
aspiration*tone	n.s.	(4, 32)= 1.16	.348
aspiration*tone*gender	n.s.	(4, 32)= .965	.44
place*tone	*	(8, 64)= 5.71	<.001
place*tone*gender	n.s.	(8, 64)= 2.00	.06
aspiration*place*tone	n.s.	(8, 64)= .461	.879
aspiration*place*tone*gender	n.s.	(8, 64)= .782	.62

The results indicate that onset F_0 is significantly higher after aspirated stops (187.6 Hz) than after unaspirated stops (184.3 Hz) when data from all speakers are included. As expected, the main effect of gender was significant - females were found to have higher onset F_0 (213.1 Hz) than males (158.7 Hz). The main effect of tone was also significant. As expected, post hoc analysis showed that onset F_0 for tone 2 (high falling) is significantly higher than for tone 1 (high level), which is significantly higher than both tone 3 (low falling) and tone 7 (low level). Tone 5 (low rising) has a significantly lower onset F_0 when compared to all other tones. Interestingly, the main effect of place was also found to be significant. Post hoc analyses revealed that onset F_0 after velars (193Hz) is significantly higher than after bilabials (186Hz), which in turn are significantly higher than alveolars (179Hz).

The interaction of aspiration and gender (as shown in Figure 3) was significant. A post hoc analysis showed that higher F_0 values after aspirated stops were observed in females, but not in males. While an overall significant effect was observed for aspiration (F_0 for aspirated stops higher than for unaspirated stops), this effect was mainly due to female participants. The interaction between place and tone was also significant - onset F_0 was found to be highest after velar stops, followed by alveolar and then bilabial stops. This effect, however, was only found in the two high tones (1 and 2) (c.f. Figure 4). Tone 1: velar – 202Hz, alveolar – 189Hz, bilabial – 187Hz. Tone 2: velar – 239Hz, alveolar – 214Hz, bilabial – 229Hz.

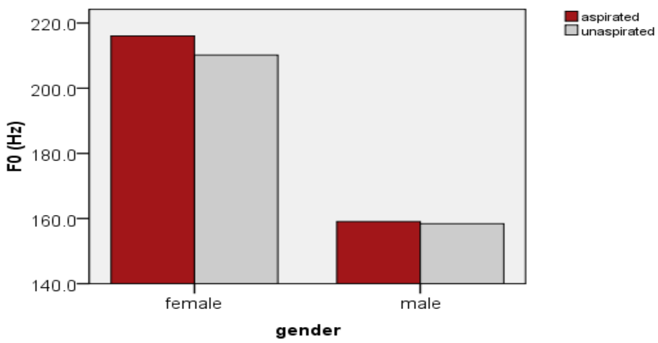

Figure 3: Onset F_0 after aspirated and unaspirated stops in females and males. The significant interaction indicates that the raising effect is significant in females but not in males.

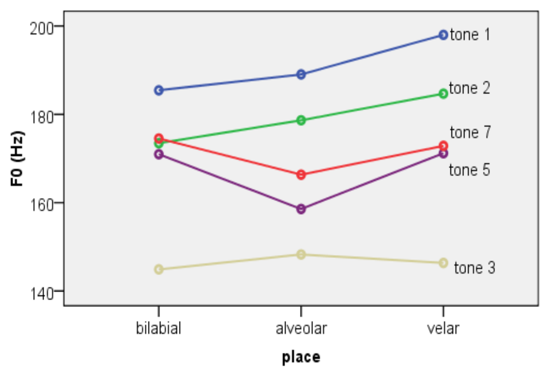

Figure 4: Onset F_0 for the five tones tested (all subjects), at bilabial, alveolar and velar place of articulation.

To further investigate the factors which may have caused the effect of gender, a series of three-way repeated measures ANOVAs (within subject factors: aspiration, place, and tone) were conducted for each gender separately. The female results are shown in Table 3, while males are shown in Table 4.

Table 3: The F and p values for females at onset F_0. The main effects of aspiration, place, and tone are all significant.

Female	significance	F	p
aspiration	*	(1, 4)= 13.7	.021
place	*	(2, 8)= 20.8	.001
tone	*	(4, 16)= 69.3	< .001
aspiration *place	n.s.	(2, 8)= .720	.516
aspiration * tone	n.s.	(4, 16)= 1.4	.288
place *tone	n.s.	(8, 32)= 1.6	.160
aspiration*place *tone	n.s.	(8, 32)= .568	.796

Table 4: The F and p values for males at onset F_0. The main effects of place and tone are significant, as well as the interaction between place and tone.

Male	Onset F_0	F	p
aspiration	n.s.	(1, 4)= .326	.599
place	*	(2, 8)= 23.8	.001
tone	*	(4, 16)= 25.3	< .001
aspiration *place	n.s.	(2, 8)= 1.6	.252
aspiration * tone	n.s.	(4, 16)= .5	.734
place*tone	*	(8, 32)= 10.7	< .001
aspiration*place *tone	n.s.	(8, 32)= .836	.578

Females showed a main effect of aspiration (F_0 for aspirated stops higher than for unaspirated stops), place (velar is significantly higher than bilabial, and close to significance with alveolar), and tone. Tone 2 is significantly higher than all other tones (260Hz). Tone 1 (222Hz) is significantly higher than tone 5 (181Hz), and close to significance with tones 3 (201Hz) and 7 (202Hz).

Results from male participants showed that place and tone were significant, but that aspiration was not. The main effects of place and tone are both significant. Post hoc analyses showed that velars have significantly higher F_0 (166Hz) than alveolars (153Hz) and are close to significance with bilabials (157Hz). As was expected from the overall analysis including gender, females showed differences between aspirated and unaspirated stops, while males did not. As shown in Figure 5, which summarizes the results of both genders across tones, F_0 after aspirated stops was found to be higher across all five tones in females, but this effect was not observed in males.

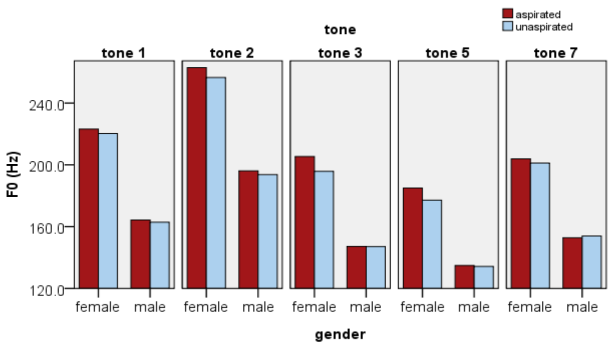

Figure 5: Onset F_0 for aspirated and unaspirated stops for all five tones (1, 2, 3, 5, and 7), for male and female speakers. Females have higher F_0 after aspirated stops, and this effect is consistent across all test tones. The raising effect can also be found in tones 1 and 2 in the male data.

While the interaction of place and aspiration was not significant in males or females, the magnitude of the effect is larger in female data for all places of articulation (c.f. Figure 6).

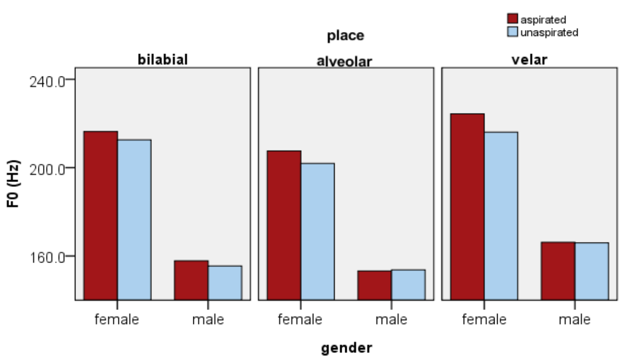

Figure 6: The onset F_0 for aspirated and unaspirated stops for three places of articulation (bilabial, alveolar, and velar) for male and female speakers.

To examine the effect of aspiration on each tone by gender, the 11 measurements across the tonal contours in Figure 7 (females) and Figure 8 (males) were plotted. In general, higher F_0 values are associated with aspirated stops for all tones in females. Results from male data were not statistically significant, but show a general trend of F_0 being higher after aspirated stops.

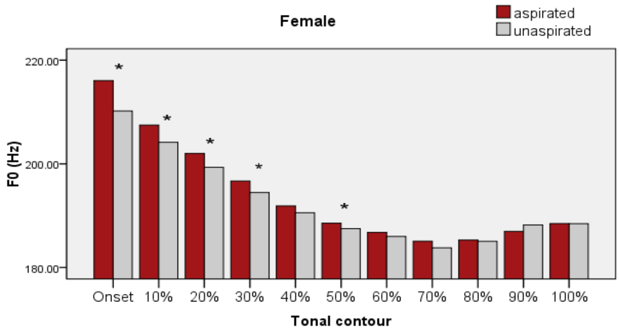

Figure 7: F_0 after aspirated and unaspirated stops in female speakers (from all five tones). Aspiration shows a raising effect across the tonal contour.

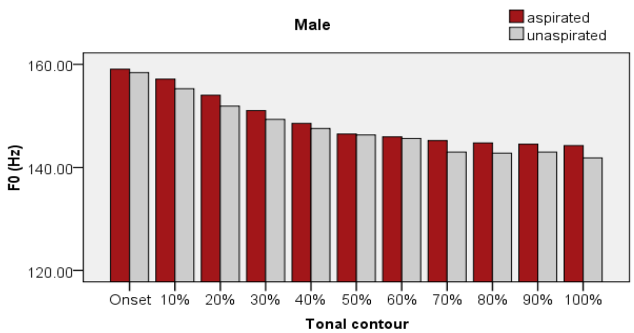

Figure 8: F_0 after aspirated and unaspirated stops in male speakers. Aspiration shows a raising effect across the tonal contour, though the differences are smaller than for female speakers. Aspiration also shows a raising effect across the tonal contour but none of the pair-wise comparisons was significant.

3.2 Voice Onset Time

A four-way repeated measures ANOVA was also conducted on VOT. The within-subjects factors were aspiration (aspirated and unaspirated), place (bilabial, alveolar, and velar), and tone (tone 1, 2, 3, 5, and 7). The between-subjects factor was gender (female and male). These results are listed in Table 5.

Table 5: The F and p values for the four-way ANOVA on VOT.

	significance	F	p
aspiration	*	(1,8)= 162.58	<.001
place	*	(2, 16)= 31.26	<.001
tone	*	(4, 12)= 9.46	<.001
gender	n.s.	(1, 8)= .03	.864
aspiration*gender	n.s.	(1, 8)= .148	.71
place*gender	n.s.	(2, 16)= .281	.758
tone*gender	n.s.	(4, 12)= .81	.530
aspiration *place	n.s.	(2, 16)= 1.68	.218
aspiration*place*gender	n.s.	(2, 16)= 1.68	.217
aspiration*tone	*	(4, 32)= .737	<.001
aspiration*tone*gender	n.s.	(4, 32)= .482	.749
place*tone	n.s.	(8, 64)= .511	.843
place*tone*gender	n.s.	(8, 64)= .443	.891
aspiration*place*tone	n.s.	(8, 64)= 1.24	.29
aspiration*place*tone*gender	n.s.	(8, 64)= 1.11	.364

A significant main effect of aspiration serves to demonstrate the longer VOT associated with aspirated stops (aspirated = 90ms; unaspirated = 19ms). Unsurprisingly, the main effect of place is significant, and a posthoc analysis indicated that velars (68ms) have significantly longer VOT than bilabials (47ms) and alveolars (48ms). The VOT difference between bilabials and alveolars was not found to be significant (c.f. Figure 9).

The main effect of tone is also significant, with tone 1 = 52ms, tone 2 = 48ms, tone 3 = 56ms, tone 5 = 56ms, and tone 7 = 58ms. A posthoc analysis showed that Tone 2 has a significantly shorter VOT than tones 3, 5, and 7, but not tone 1. There are no significant differences among tones 1, 3, 5, and 7. The interaction between aspiration and tone was found to be significant. As shown in Figure 10, the high tones have smaller VOT differences (tone 2 – 64ms; tone 1 – 70ms) than tone 3 (74ms), tone 5 (76ms), and tone 7 (71ms) between aspirated and unaspirated stops.

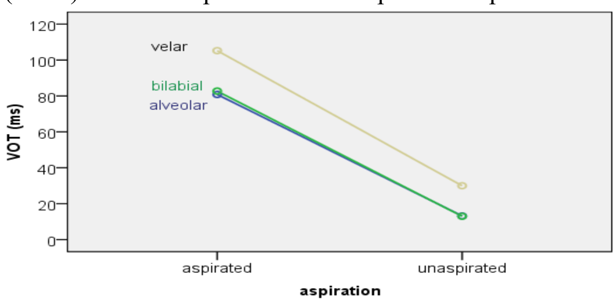

Figure 9: VOT as a function of aspiration and place of articulation. Velars have significantly longer VOT, while no difference was found in bilabials and alveolars.

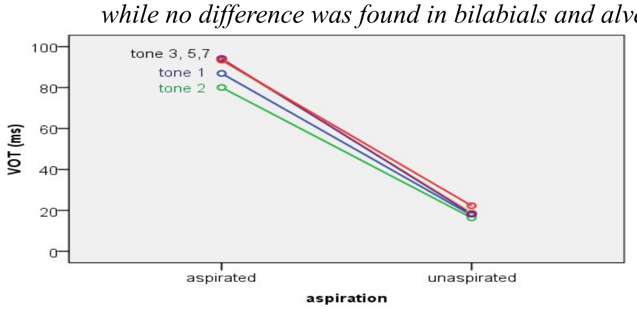

Figure 10: VOT as a function of aspiration and tone. High tones (1 and 2) were found to have shorter VOT than other tones.

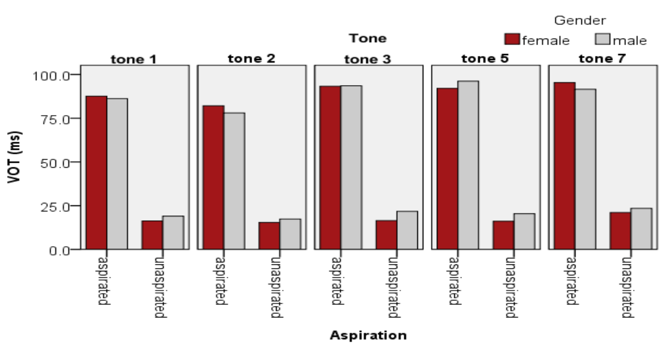

Figure 11: VOT as a function of aspiration, gender, and tone.

As shown in Figure 11, although not significant, males seem to have a longer VOT in unaspirated stops. In terms of aspirated stops, males have either equal or shorter VOT except in tone 5.

4. Discussion and Conclusion

4.1 Summary of the results

Results from the current study demonstrate that the F_0 of tones following aspirated stops is higher than tones following unaspirated stops, corresponding to the findings of Lai (2004). The mean tone duration for all tokens was 465ms, with a general tapering off of the raising effect occurring at around 140ms, or about

30% of the way through the tonal contour. Interestingly, F_0 after velar stops was found to be significantly higher than after either bilabial or alveolar stops. A significant interaction between place and tone was also found – velar stops were found in correlation with higher F_0 in tones 1 and 2, but not in tones 3, 5, or 7. A significant interaction was found between aspiration and gender in which, though in general both genders exhibited a trend for higher F_0 following aspirated stops, only female values were significantly higher. Given previous research we expected to find differences in the magnitude of the aspiration perturbation effect by tone height (Hombert and Ladefoged, 1977), however no significant differences were observed.

Results from VOT measurements demonstrate a clear, significant effect in terms of aspiration, with aspirated stops having a mean 90ms VOT, in comparison to 19ms in unaspirated stops. Additionally, velar stops demonstrated significantly longer VOT values (68ms) than either bilabials (47ms) or alveolars (48ms). The effect of tone on VOT was found to be significant, with tone 2 having significantly shorter VOT (48ms) than tone 3 (56ms), tone 5 (56ms), and tone 7 (58ms), but not tone 1 (52ms). The interaction between tone and aspiration was also found to be significant, with greater VOT differences between aspirated and unaspirated stops in tones 3, 5, and 7, and lesser differences in tones 1 and 2 (see Figure 11).

4.2 Discussion

The current study replicates the findings of Lai (2004) in finding higher F_0 after aspirated stops than after unaspirated stops, in the context of an expanded participant pool. The duration of the perturbations caused by the voicing of prevocalic consonants on the F_0 of following vowels has been shown to be shorter in tonal languages than in non-tonal languages (Hombert, 1977). However, contrary to previous arguments put forward on the subject by Hombert (1978) and Francis et al (2006), which claim that speakers of tonal languages inhibit the perturbation effect on F_0 to around the first 30-50ms of a vowel in order to maintain maximum perceptual difference between tones (c.f. Gandour 1974 and Hombert 1977), the present study found that the perturbation effect did not diminish until around 140ms into the vowel. This duration exceeds those suggested in non-tonal languages, with an upper limit set at 100ms or more (English – Whalen et al. 1990; Swedish - Lofqvist et al. 1989).

In Lai (2004), the perturbation effect of aspiration was found to disappear between 55 and 83ms into the long tones, in a tonal contour with a mean duration of 278ms (20-30% of the way through the contour). A comparison of this value with the findings of the present study (30% of tonal contour), suggests that the duration of the perturbation effect of voicing may be associated with a percentage of the total tonal contour rather than an absolute duration, and subject to considerations of speaking rate. In light of these findings, previous research needs to be carefully re-examined with an eye to percent duration, and possibly intonation systems, rather than simply looking at absolute duration.

It has been reported that rates of airflow are faster after voiceless aspirated stops than after voiceless unaspirated stops (Klatt et al, 1968), and that faster airflow rates trigger raised F_0 (Ladefoged, 1967 and Ohala, 1973). The larynx has also been reported as being higher after voiceless aspirated stops than voiceless unaspirated stops (Ewan, 1976). In light of these assertions, the present findings that onset consonant aspiration has a raising effect on F_0 in Taiwanese tones may be caused by the faster airflow rates and greater larynx heights associated with such aspiration. The higher F_0 values which were found to be associated with both aspirated and unaspirated consonants at the velar place of articulation have, to our knowledge, not been reported in any previous research. Evidence from Ohala et. al. (1978) has shown that the production of high vowels requires a higher tongue height, which raises larynx height, as well as requiring greater tongue muscle tension, both of which raise F_0. Velar stops require similar mechanisms in production, involving greater tongue back height and subsequent larynx raising, and we hypothesize that this could be the cause of higher F_0 values following velar stop consonants.

Previous studies on the effect of aspiration of F_0 have tended to be restricted in terms of stimuli with regard to place of articulation, with Zee (1980) testing only bilabials and the high level tone in Cantonese, and Xu and Xu (2003) testing only alveolars, with the exception of bilabial replacements in accidental gaps, in Mandarin. Our results suggest that place of articulation may indeed be a factor, and that more care ought to be taken in balancing stimuli in this regard. Additionally, there is a significant interaction between place and tone on onset F_0, in which tones 2 and 1 have higher F_0 after velar stops, followed by alveolar, and then bilabial stops. This phenomenon should be further investigated in future research.

Results from separate analyses of the male and female data further support the existence of the gender differences found in Lai (2004). F_0 after aspirated stops was found to be significantly higher in females, though the general trend of higher F_0 after aspirated stops was also found in males, albeit not statistically significant. We theorize that the difference between aspirated and unaspirated stops generates a consistent drop in transglottal pressure. Other things being equal, the same degree of aerodynamic force could trigger a greater increase in vibration rate for females, which have shorter/lighter vocal folds. As a result, the raising effect is more obvious in female speakers or speakers with shorter/lighter vocal folds. It is clear that given the gender differences which were found in this study, it is imperative for experiments to balance subject gender. Xu and Xu (2003) only tested 8 female speakers, and Zee (1980) only 1 male speaker. The existence of possible gender bias suggests their conclusions be treated with caution. This brings us to the essential question regarding why there are conflicting results from previous studies. The determinants of F_0 are many – gender, place of articulation, and tone – all of which need to be taken into consideration when managing experimental design and conducting statistical analysis.

Although it has not been discussed thoroughly before, Tse and Lai (2005) have demonstrated that high tones tend to have shorter VOT than low tones. The current study also found that high tones (tone 1 and 2) have shorter VOT when compared to low tones (3, 5, 7). The VOT data confirm the well-known phenomenon that aspirated stops have longer VOTs than unaspirated stops, as well as that velar stops have a longer VOT than either labial or alveolar stops.

4.3 Conclusion

The present study developed a systematic design to study the effect of prevocalic aspiration on the F_0 of following vowels, and showed that aspiration has a raising effect. While this effect was observed in males, the differences in onset F_0 values for aspirated as compared to unaspirated stops were significantly greater in females. The present study, in examining F_0 and VOT values due to aspiration perturbation, shows sizeable gender differences in addition to the systematic effect of place of articulation and tone.

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