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The Relationship Between Glottal Area at Release and Voice Onset Time in Stop Production

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1. Introduction

Several investigations have shown that there is a functional relationship between the degree of glottal opening at the stop release and voice onset time. Kim (1970), for example, claimed that "Aspiration is defined as a function of the glottal opening at the time of release of the oral closure of a stop" (p.115). This has been in agreement with other findings (e.g. for Korean isolated nonsense word-initial stops, see Kagaya, 1974; Hirose, Lee, and Ushijima, 1974; for Icelandic word-initial stops, Petursson, 1976; for German intervocalic stops in connected speech, see Butcher, 1977; for Danish word-initial stops, see Hutters, 1984). Kim (1970) also claimed that the main difference between aspirated and unaspirated stops seems to lie in the degree of glottal opening stops seems to lie in the degree of glottal opening at release. However, Lofqvist (1980) argued that "the main difference between aspirated and unaspirated stops seems to be one of interarticulator timing, and timing also appears to be the way in which the articulatory system solves the problem of controlling glottal opening at release in aspirated stops" (p.475) and that "degree of glottal opening at release which, as was noted by Kim (1970), is one of the chief determinants of degree of aspiration in voiceless stops, at least in those instances where peak glottal opening precedes the release." (p.485-486). Thus there is agreement among investigators that the size of glottal opening at release is functionally or positively related to degree of aspiration in voiceless stops, at least in those cases where peak glottal opening precedes the release, although disagreement lies over the main difference between aspirated and unaspirated stops.

In a photo-electric glottographic experimental study on laryngeal control in Hindi with bilabial stops at normal speech (Dixit, 1987), however, "the degree of glottal opening was found not to relate systematically to either the duration of closure, (cf. Lofqvist (1980) and Andersen (1981)), or the duration of aspiration, (cf. Kim (1970)). Dixit (1987, p.62) found that "the degree of glottal opening at the time of oral release for the unvoiced aspirated plosives was much greater than for the voiced aspirated plosives, but the degree or duration of aspiration for the two types was about the same." For the voiced aspirated stops in Hindi, peak glottal opening occurred approximately 25 ms after the release and size of the peak glottal opening was much less than that of the voiceless aspirated stops, whereas for their voiceless cognates the peak glottal opening preceded the release, except for those in the word-final position. Thus, in Hindi aspirated stops also, the duration of aspiration appears to relate functionally or positively to the degree of glottal opening at release, at least in those instances where the peak glottal opening, determined by the coordination of laryngeal and oral articulations, occurs before the release. Kim's original theory (1970) was based on the assumption, supported by actual observations, that onset of glottal adduction occurred before the oral release.

There are some studies on the effect of speech rate on laryngeal articulation, such as the effect of tempo on amplitude and peak velocity of laryngeal articulation (Lofqvist and McGarr, 1986), on the interval from onset of tongue-palate contact to peak glottal opening versus duration of oral closure of voiceless stops and fricatives in various positions and under different stress conditions (Lofqvist and Yoshioka, 1981, 1984), on the degree and duration of the glottal abduction of the Danish stop /p/ (Andersen, 1981). Within a given voiceless post-aspirated stops, however, the systematic investigation of the effects of tempo and place of articulation on the relationship between glottal opening at the time of oral release and voice onset time has been relatively neglected, and an investigation to examine the relationship, using controlled speech materials, is required. Lofqvist (1980) noted that variability in voice onset time may correlate not only with glottal width at the moment of stop release, but also with stop occlusion duration, timing of the onset of the glottal abduction gesture, and overall duration and magnitude of the abdution gesture. In this study, however, in order to avoid making things too complicated I will confine my attentions mainly to the effect of tempo and place of articulation on the relationship between relative glottal area at release and voice onset time in aspirated stops with British English and Korean speakers.

2. Method

2.1. Subjects

Two male subjects were used in the study. One of the two subjects was British and the other was Korean. The British subject has English parents, but he had his school education at an American school in Africa. After school he had lived in England for most of his life. He said that he tried deliberately to avoid an American accent. He was adjudged to have a near RP accent. The Korean subject (the author) speaks a near Seoul accent, which is considered to be the standard Korean. None of subjects had any speaking defects.

2.2. Speech materials

In order to obtain natural data, an attempt was made to construct bisyllabic /'CVCVC/ English words in pairs of natural sentences where the C was a stop. The sentences are shown in Table 1. The English test items were structured such that they were similar syntactically and prosodically.

Table 1. Speech materials

British English

(a) / ɑ: ðeɪ 'mɒbɪŋ ðə 'stɔ:z /
Are they mobbing the stores?

(b) / ɑ: ðeɪ 'mɒpʰɪŋ ðə 'flɔ: /
Are they mopping the floor?

(c) / ɑ: ju 'hi:dɪŋ maɪ əd'vaɪs /
Are you heeding my advice?

(d) / ɑ: ju 'hi:tʰɪŋ maɪ 'bɑ:θ /
Are you heating my bath?

(e) / ɑ: ju 'bægɪŋ maɪ 'si:t /
Are you bagging my seat?

(f) / ɑ: ju 'bækʰɪŋ mɪ 'ʌp /
Are you backing me up?

Korean

(a) / apa-nin taril pomjə ap'a ap'a han-ta/

Apa is saying 'dad' 'dad' looking at the moon.

(b) / pam-i ap^ha ap^ha hamjə on-ta /

The night comes saying pain, pain.

(c) / aka-nɨn $ap^hɨ$ta-rɨl at'a at'a han-ta /

The child says at'a at'a for pain.

(d) / at^ha-ka musɨn t'ɨsija/

What do you mean by 'at^ha'?

(e) / we: tataiksən-ɨl ataiksən ira-he /

Why do you say 'ataikson' for tataikson?

(f) / dʒə: pupu-nɨn mak^hao-esə manna-s-ta /

We met that couple at Makao.

(g) /ak'a-pon saram-i ak^h ino-ja /

The man who you saw just now is Akyno.

(Where /p,t,k/ are lax unaspirated stops,/p^h,t^h,k^h/ tense aspirated stops, and /p',t', k'/ tense unaspirated stops.)

In Korean, however, it was almost impossible to design such sentence pairs differing only in the location of stop consonants in question, maintaining /VCV/ structures where the vowel was /a/ and the consonant was an oral stop. As seen in the test items, four of the nine words with the type stop consonants were in sentence-initial position, and the rest of them were positioned within sentences.

The number of syllables of the words containing the type stop consonants was not always consistent, such as /ataiksən/,/at'a/, /at^ha-ka/, etc. It is conceivable that the position in the sentence and the number of following syllables may affect the duration of a preceding vowel in Korean as they are known to do in English. In order to justify the constructed Korean speech items, therefore, an informal experiment was taken with an electro-palatograph and laryngograph using /ataiksən/, /ata ata/, /at'a-ka/ /at'a at'a/, etc. in sentence pairs. The results of the experiment showed that the effect of the number of syllables on the duration of the preceding vowel followed by the alveolar stops was not only insignificant but also inconsistent. This may be due mainly to the fact that Korean is a syllable timed language where each syllable has more or less regular stress on it (Martin, 1951). It also was demonstrated that the position effect on the duration of the preceding vowel followed by the bilabial stops was insignificant, although overall sentence-initial stops gave a 4% decrease of the preceding vowel than sentence-medial stops. Thus, on the basis of the results of the informal experiments, it was judged that the constructed Korean speech materials are generally reasonable.

2.3. Procedures

The speakers produced the sentences with a rise-fall intonation. Each sentence was produced five times at a normal or moderately slow speech rate and five times at a fast speech rate, giving 2 (tempi)×5 (the number of repetition)×3 (the place of articulation)×2 (the manner of articulation)=60 utterances in English and 2 (tempi)×5 (the number of repetition)×3 (the place of articulation)×3 (the manner of articulation)=90 utterances in Korean.

Simultaneous measurements were made from an electro-palatograph and a lip sensor (both manufactured by the Phonetics Laboratory, University of Reading) and a photo-electric glottograph (F-J electronics). The photo-electric glottograph was used for sensing the relative glottal area. Their outputs were synchronized with an electro-laryngograph (manufactured by the Phonetics Laboratory, University College London), accelerometer (Knowles electronics BU-1771) and audio microphone. The electro-palatograph (EPG) was interfaced to a Commodore micro-computer (CBM 3032). For print-outs of EPG data, the Commodore microcomputer was used. for more detailed discussion of the instrumentation and the characteristics of the devices, see Kim (1987, p.163-168). Mingograms were made of signals of the devices and of the EPG synchronization pulse. Duration measurements were made for intervals corresponding to the voice onset time (VOT) from laryngograms synchronized with electro-palatograms and lip sensor signals. For measuring the relative glottal area at the onset of the release of oral stop closure, a base line indicating a complete closure of the vocal folds (i.e. glottal stop) was constructed on the basis of the photo-electro-glottographic signal on the mingograms. At the onset of the release of oral closure, the amplitude of the photo-electrical trace was measured to obtain the relative glottal area (GRA) in mm (arbitrary unit). For alveolar stops, the onset of the release of oral closure was defined as the beginning of a gap in the full lingual contact pattern in the electropalatogram (see Figure 1).

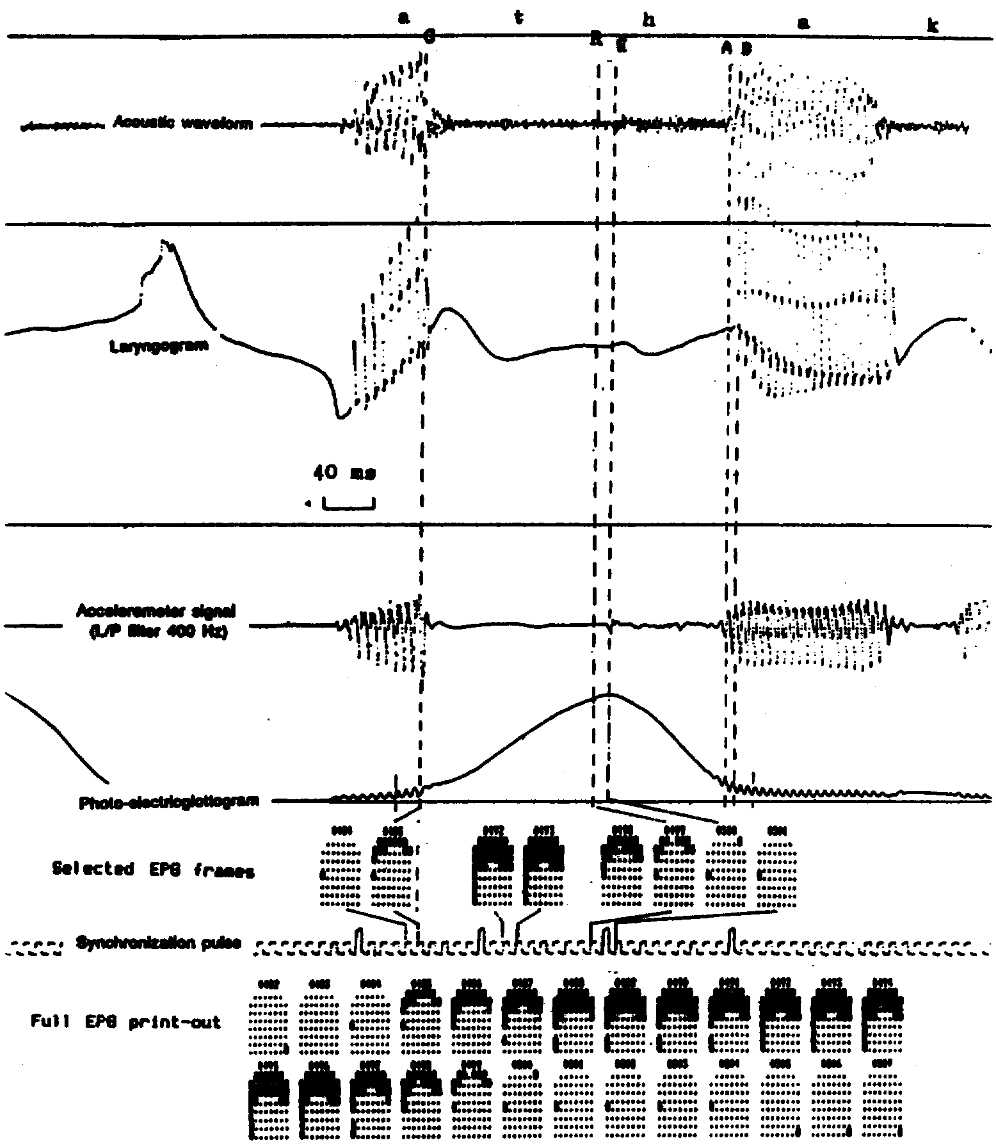

Figure 1. Mingograf print-out synchronized with selected EPG frames and full EPG print-out for the /atʰa/ sequence in the Korean word /atʰa-ka/ in connected speech. The synchronization pulse is set at 133 Hz. Vertical line "C" indicates the onset of oral closure, "R" the moment of oral release on the electro-palatogram, "E" the moment of oral explosion on the accelerometer signal, "A" the onset of the vocal fold vibration on the accelerometer and on the audio signal, and "B" the onset of the vocal fold vibration on the laryngogram.

The lip sensor was used for bilabial stops. An abrupt fall in signal from the lip sensor was considered to be clear indication of the onset of the release of the bilabial stops (see Figure 2).

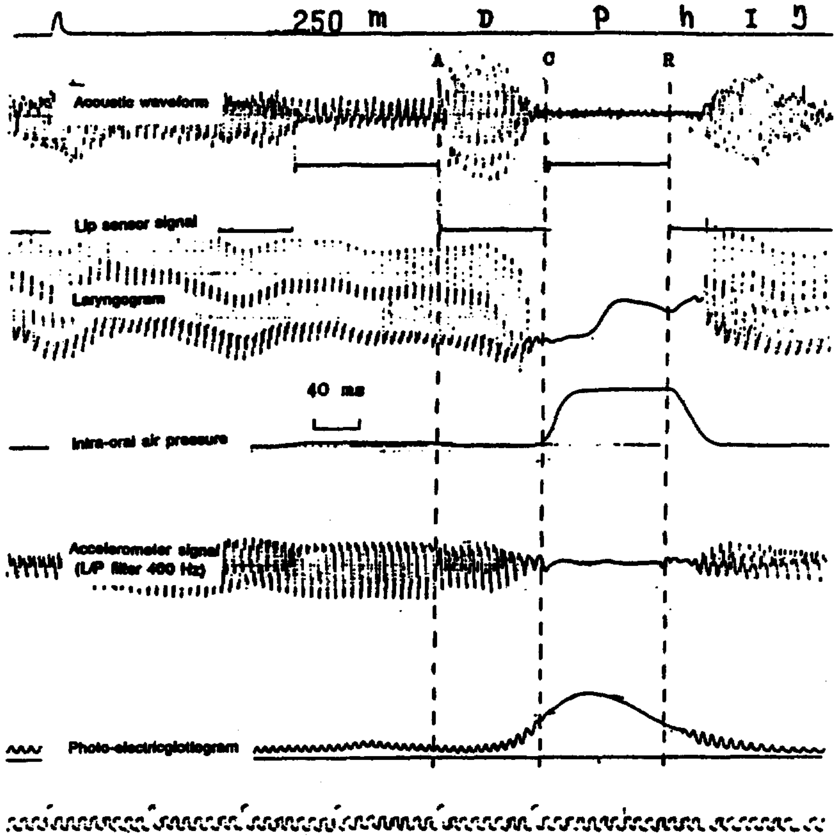

Figure 2. Mingograf print-out for /mɒpɪŋ/ sequence in the BrEng sentence "Are you mopping the floor?" Vertical line "A" indicates the beginning of oral release for the preceding vowel, "C" the onset of oral closure for /p/, and "R" the moment of oral release for the following vowel.

For velar stops, difficulties were experienced in constructing reference lines for the onset/offset of oral closure. The electro-palatographic data did not give a clear-cut indication of either the onset of the oral closure or the release of the oral closure. One possible reason for this may be that contact for the stops was made further back than the most posterior row of electrodes. They may have approximated uvular stops as the last row of electrodes was placed at the junction between the hard and the soft palates. Thus, the measurement of the velar stops was excluded. The experiment was undertaken in the phonetics laboratory, the University of Reading. For the statistical analysis, T-test and Pearson's correlation on Statworks were used on the Macintosh Plus computer.

3. Results

Table 2. Mean closure duration, aspiration, and the intervals from implosion to peak glottal opening and from peak glottal opening to release for speaker 1 (BrEng speaker)

stop consonant	closure duration	aspiration	Implosion to peak glottal opening	peak glottal opening to release
N/p/	x 107.6	32.8	58.0	49.6
	s 1.67	3.03	9.79	9.94
F/p/	x 73.2	35.2	48.8	24.4
	s 7.56	8.78	14.87	15.3
N/t/	x 56.0	65.2	56.0	0.00
	s 5.47	6.72	5.47	0.00
F/t/	x 50.0	43.2	50.0	0.00
	s 7.07	4.14	7.07	0.00

(ms, n=5)

Table 3. Mean closure duration, aspiration, and the intervals from implosion to peak glottal opening and from peak glottal opening to release for speaker 2 (Korean speaker)

stop consonant	closure duration	aspiration	Implosion to peak glottal opening	peak glottal opening to release
N/p^h/	x 263.2	56.0	240.4	22.8
	s 14.53	10.19	21.09	10.35
F/p^h/	x 178.8	48.4	147.6	31.2
	s 12.29	6.84	9.83	13.08
N/t^h/	x 140.8	98.8	148.4	-7.6
	s 7.15	12.21	13.81	9.31
F/t^h/	x 123.8	62.4	108.4	15.4
	s 8.95	8.17	12.83	4.98

(ms, n=5)

As seen in Tables 2 and 3, both in BrEng and in Korean aspirated stops the peak glottal opening preceded the oral release or occurred at the moment of the oral release, except for the three cases associated with the Korean alveolar stops in normal speech. As seen in Figure 1 associated with one of the three cases, the onset of oral closure in the electropalatogram occurred 10 ms earlier than that in the accelerometer signal which is corresponding to the audio signal in various aspects, including the onset of regular pulse after the release. In the accelerometer signal, peak glottal opening occurred at oral release. Thus, it would be possible to say that acoustically both in BrEng and in Korean voiceless tense aspirated stops peak glottal opening preceded oral release or occurred at the oral release. For these stops, the correlation between the duration of oral closure and VOT was insignificant, except for the single case associated with the Korean alveolar stops in fast speech. The duration or oral closure was inconsistently correlated to the interval from implosion to peak glottal area. Thus, it appears that the duration of oral closure does not systematically correlate either the degree of aspiration or the interval from implosion to peak glottal area (for a similar result, see Dixit, 1987). This is in contrast with the findings (Lofqvist, 1980 and Andersen, 1981).

Within a given place of articulation for the BrEng tense aspirated intervocalic stops and across tempi, the correlation of glottal area to VOT was observed to be insignificant at the 5% level. This was generally similar to the case with the Korean intervocalic stops, except for the tense aspirated bilabial intervocalic stops ($df=8$, $r=0.646$, $p<0.05$) (see Figs 4 and 5). Both in BrEng and in Korean, therefore, within a given place of articulation of an intervocalic stop and across tempi, VOT was generally independent of glottal area, except for the single case associated with the Korean tense aspirated bilabial intervocalic stops.

4. Discussion

4.1. The effect of tempo both on glottal area and on VOT.

As seen in Figure 3, in fast speech the BrEng tense aspirated bilabial intervocalic stops were manifested with a highly significant decrease (mean 62%) in glottal area at release, compared with normal speech: the mean ratio was 1 (F): 2.6 (N).

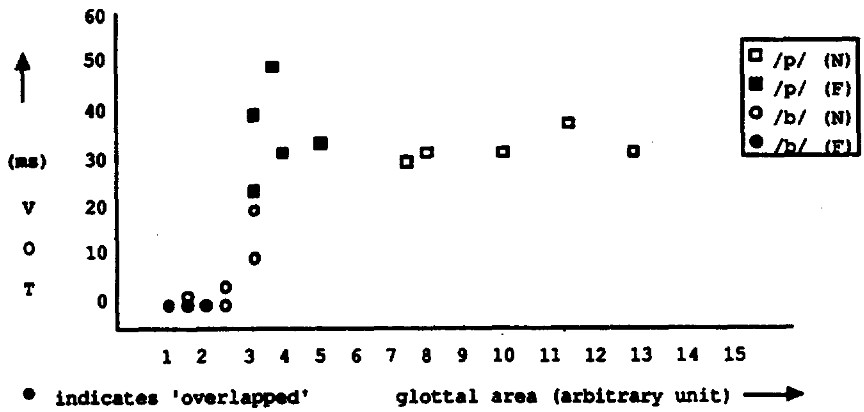

Figure 3. Scatter diagram of VOT against glottal area at release during BrEng intervocalic stops /b,p/ in /mɒbɪŋ/ and /mɒpɪŋ/ sequences in connected speech (N=normal speech, F=fast speech).

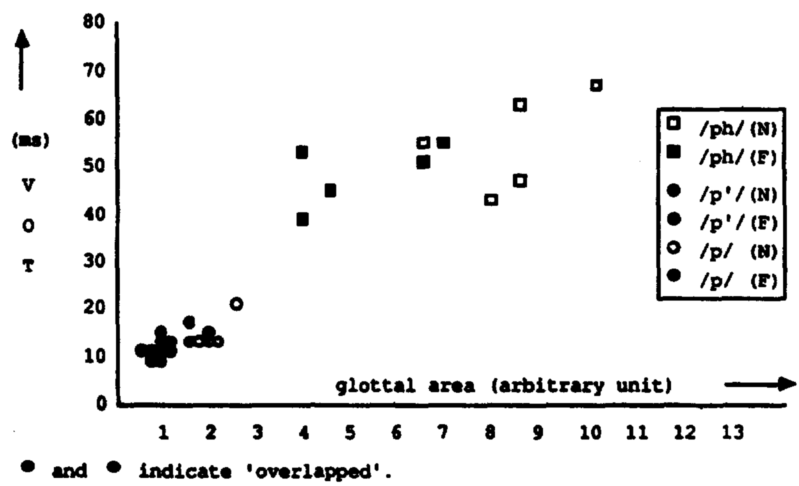

Figure 4. Scatter diagram of VOT against glottal area at release during Korean intervocalic stops /p, p', pʰ/ in real words in connected speech (/p/ indicates phonologically unaspirated lax stop, /p'/ unaspirated tense stop, /pʰ/ aspirated tense stop, N=normal speech, F=fast speech).

This was similar to the Korean tense aspirated bilabial intervocalic stops (mean 37%) : the mean ratio was 1 (F) : 1.6 (N), although the Korean tense aspirated bilabial stops showed less of a tempo effect on glottal area than did the BrEng aspirated bilabial stops (see Figure 4). This difference may be due to the differences in language, surrounding vowels, subject, etc. Both in BrEng and in Korean, on the other hand, for the tense aspirated bilabial stop the effect of tempo on VOT was insignificant, although the Korean tense aspirated bilabial intervocalic stops tended to have considerably shorter (13%) VOT in fast speech than in normal speech. Contrasted to this, both in BrEng and in Korean, the tense aspirated alveolar intervocalic stops were produced with a significantly shorter VOT in fast speech than in normal speech (see Figures 5 and 6).

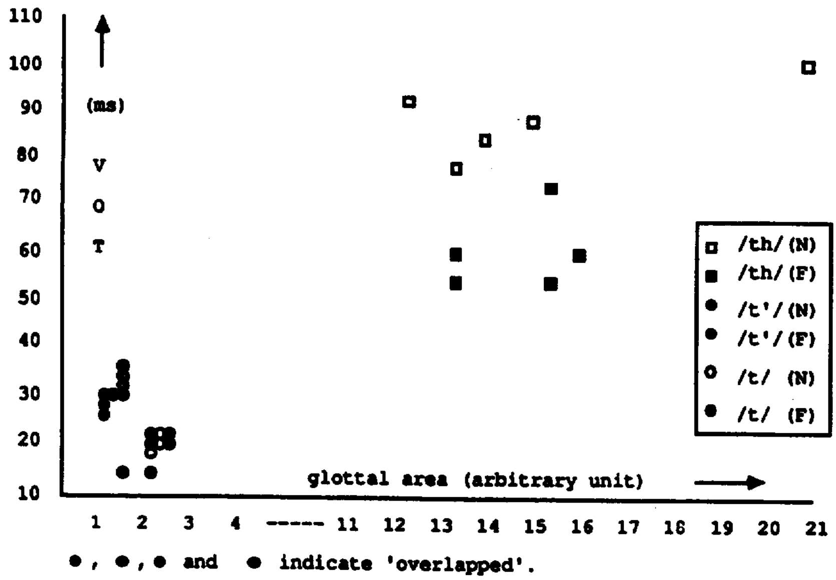

Figure 5. Scatter diagram of VOT against glottal area at release during Korean intervocalic stops /t, t', tʰ/ in real words in connected speech (/t/ indicates phonologically unaspirated lax stop, /t'/ unaspirated tense stop /tʰ/ aspirated tense stop.)

Overall, the tempo effect on VOT was 33% (BrEng) and 32% (Korean). For glottal area, however, there was no significant effect. Thus, both in BrEng and Korean the effects of tempo on VOT and glottal area were conditioned by the place of articulation. In other words, for the tense aspirated bilabial stops the tempo effect on glottal area was highly significant, whereas for their alveolar counterparts it was insignificant. For VOT, however, the reverse was true. All

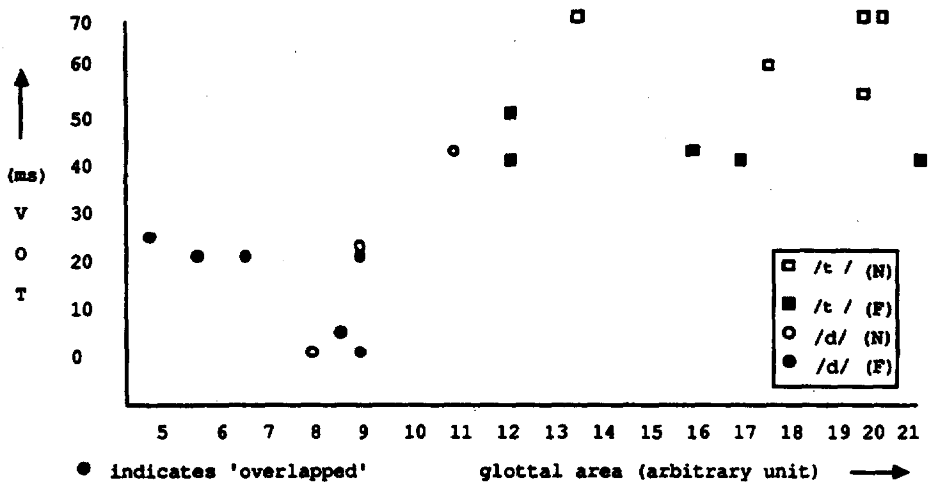

Figure 6. Scatter diagram of VOT against glottal area at release during BrEng intervocalic stops /d,t/ in the /hi:dɪŋ/ and /hi:tʰɪŋ/ sequences in connected speech (N=normal speech, F=fast speech.)

else being equal, this may be one of the main reasons for the fact that for the tense aspirated intervocalic stops, within a given articulatory place and across tempi, VOT was generally not significantly corelated to glottal area.

4.2. Possible underlying physiological mechanisms for the alveolar stop-related insignificant tempo effect on glottal area.

All else being equal, the BrEng alveolar stop-related insignificant tempo effect on glottal area may be due mainly to a combination of (1) the physiological connections between the tongue and the larynx (Hardcastle, 1976; Fink, Basek, and Epanchin, 1956), (2) the decreased thickness of the vocal folds caused by the surrounding high pitch vowel /i:/ (Hollien, 1962; Van Den Berg and Tan, 1959), and (3) the nature of the photo-electric glottograph which is designed to signal even the trans-illuminated light of the thin glottis affected by the vowel /i/. However, considering the case associated with the Korean tense aspirated alveolar intervocalic stops where the surrounding vowels were /a/, the alveolar stop-related negligible tempo effect on glottal area may be due mainly to the physiological connections between the tongue and the larynx. As quoted by Kirchner (1983), it is claimed by Fink, Basek, and Epanchin (1956) that widening of the glottis can be produced by the unfolding of the vestibular and vocal folds that results when the thyroid cartilage is pulled away from the hyoid bone. They also concluded that "opening and closure of the glottis during respiration is interpreted to be the result of up-and-down movements of the larynx as a whole, …" (p.423) and that "the role of the crico-arytenoid muscles [i.e. abductor] in glottis movements though essential is probably more indirect than usually supposed, …" (p.424). The anterior belly, because of the position of its origin, when contracting from a fixed mandible, will act to bring the hyoid and so the tongue, anteriorly and upwards into position for alveolar articulations such as [t], [s], [i] (Hardcastle, 1976, p.89-90). Thus it seems reasonable to speculate that during the alveolar stops, the hyoid bone will be pulled away from the larynx (especially the thyroid cartilage) to a certain extent which in turn results in unfolding the vestibular and vocal folds, thereby widening the glottis.

Considering the alveolar stop-related insignificant tempo effect on glottal area and the fact that during the tense aspirated alveolar intervocalic stops there was a highly significant difference in VOT between the two tempi, one can presume that during the tense aspirated alveolar intervocalic stops the speed of the glottal adduction following release for the following vowels was actively controlled by the speaker to meet aerodynamic requirements in relation to tempo. In other words, both in BrEng and in Korean the speed of the glottal adduction following release was conditioned by tempo: at the fast tempo it was greater than at the normal tempo, which in turn results in shorter VOT in fast speech than in normal speech.

4.3. Possible reasons for the BrEng tense aspirated bilabial stop-related negligible effect of tempo on VOT.

There are some phoneticians claiming that the amount of aspiration given to the English /p/ in the unstressed syllable will always tend to be less that that in the stressed syllable (e.g. Lofqvist and Yoshioka, 1984; Gimson, 1980; Jones, 1972). This agrees with Kim's (1987) findings. In a laryngographic study with eight BrEng speakers using isolated nonsense VCV words, Kim (1987) found that voiceless stops in the unstressed position generally gave a significantly shorter VOT than in the stressed position. Considering this, one may presume that in fast speech for the phonetic realization of the /p/ in the unstressed position, the English speaker may have three tasks to carry out simultaneously; (1) the fast speech-motivated reduction of VOT, (2) the unstressed position-related reduction of VOT, and (3) the production of a significantly greater VOT for the tense aspirated stop than for its lax unaspirated cognate. However, considering the fact that there was practically no difference in VOT between the two tempi, it seems that at the fast tempo the task (1) was cancelled for the tasks (2) and (3).

In this study, at the normal tempo the amount of VOT given to the BrEng untressed /p/ was observed to be an average 32 ms (SD=3.03). This is much less than the findings associated with VOT for the word-initial stressed /p/ in the existing literature. In a spectrographic study (Weismer, 1979), for example, the data obtained from nine AmEng speakers using a set of CVC words embedded in the frame "Say ___ instead." where C was one of the three voiceless stops /p,t,k/, showed that in normal speech the VOT of the word-initial /p/ in the stressed position was an average 52.8 ms (SD=14.59). Thus, although they are not directly comparable due to differences in dialect, speech item, speaker, the experimental devices used, etc., the value (i.e. 32 ms) for VOT associated with the present study was much less (39%) than that for the stressed position-related /p/ in the existing literature, and it was slightly longer than the phonemic boundary of VOT between /p/ and /b/. In English, the phonemic boundary of VOT between /p/ and /b/ was about 25 ms, ranging from 10 ms to 35 ms (Lisker and Abramson, 1970). Considering this, it seems that at the normal tempo the unstressed position-related reduction of VOT (i.e. the second task) was manifested as usually claimed in the existing literature. If this is the case, it seems reasonable to speculate that in the fast speech the speaker may have to avoid the tempo-motivated reduction of VOT to save the distinction between /p/ and /b/. If this assumption is true, this may be one of the possible reasons for the fact that in the fast speech for the BrEng aspirated bilabial stops the difference in VOT between the two tempi was insignificant.

At the level of physiology, however, there was a fast tempo-motivated significant reduction of glottal area (see Fig. 3). This was similar to the results of the Korean bilabial aspirated stops, although the Korean stops were produced with a considerably shorter VOT in fast speech than in normal speech. Both in British English and in Korean, however, at fast speech the bilabial aspirated stops were realized with a significant decrease of the duration of oral closure. For the alveolar stops, on the other hand, the reverse was true as seen above. At the normal tempo, the shortest VOT produced by the speaker was 56 ms which is much greater than the phonemic boundary of VOT for the alveolar stops. Thus, in the fast speech the speaker did not have to avoid the tempo-motivated reduction of VOT. For the alveolar stops, the phonemic boundary of VOT was about 35 ms (Lisker and Abramson, 1970). It seems, however, universal that in oder to save time the fast speech is expected to be manifested generally with a decrease of the phonetic variables of speech sounds, unless there are some inhibitive factors such as the unstressed position-related VOT reduction rule, the physiological connections between the tongue and the larynx, etc.

4.4. It also is worthwhile to note that the same amount of glottal area given to the BrEng bilabial intervocalic stops was observed to yield a clearly different VOT according to the phonological information, such as class (i.e. tense and lax, traditionally voiced and voiceless). Fig. 3 shows that the shortest glottal area (i.e. 3 mm) for the tense aspirated bilabial intervocalic stop yielded either 24 ms or 38 ms of VOT. For its lax unaspirated cognates, however, the same size of glottal area (i.e. 3 mm) gave either 8 ms or 20 ms of VOT. Thus, considering this and the results associated with the bilabial and alveolar stops, it seems reasonable to presume that during the tense aspirated intervocalic stops, the speed of the glottal adduction following release for the following vowel was conditioned either by tempo, by stress, or by class (i.e. tense/lax in English and aspirated/unaspirated in Korean). This means that the speed of the glottal adduction following release for the following vowel is actively controlled to meet aerodynamic requirements in relation to class, stress and tempo. This also means that speakers directly control VOT, that producing different VOT distributions for voiced and voiceless cognates is a task with the same status as producing compressed VOT distributions in unstressed syllables or at higher rates, and that the difference in VOT as a function of rate or stress are the result of direct manipulation. In other words, the duration of voiceless aspiration (i.e. VOT) is not simply a function of the glottal area at release in an aspirated stop, even in those instances where peak glottal area precedes the release, as it is normally defined in the existing literature (cf. Kim, 1970; Hutters, 1984; Kagaya, 1974; Petursson, 1976). This implies that VOT and glottal area are autonomously controlled receiving motor command from the high level neural-systems in the brain in relation to tempo, stress and class.

In general, other investigators did not take into consideration tempo and the place of articulation as affecting glottal area and VOT of the voiceless aspirated stops, and they usually made overall observations of the relationship between glottal area and VOT in normal speech only. Probably, this is the main reason why my results are different from others in the existing literature. My data also show that in normal speech, overall there is a significant relationship between glottal area and VOT, particularly in Korean. Overall (i.e. across tempo, class and the place of articulation), for the Korean intervocalic stops glottal area was significantly correlated to VOT: the greater the glottal area, the longer the VOT; the less glottal area, the shorter the VOT ($r=0.908$, $df=58$, $p<0.001$).

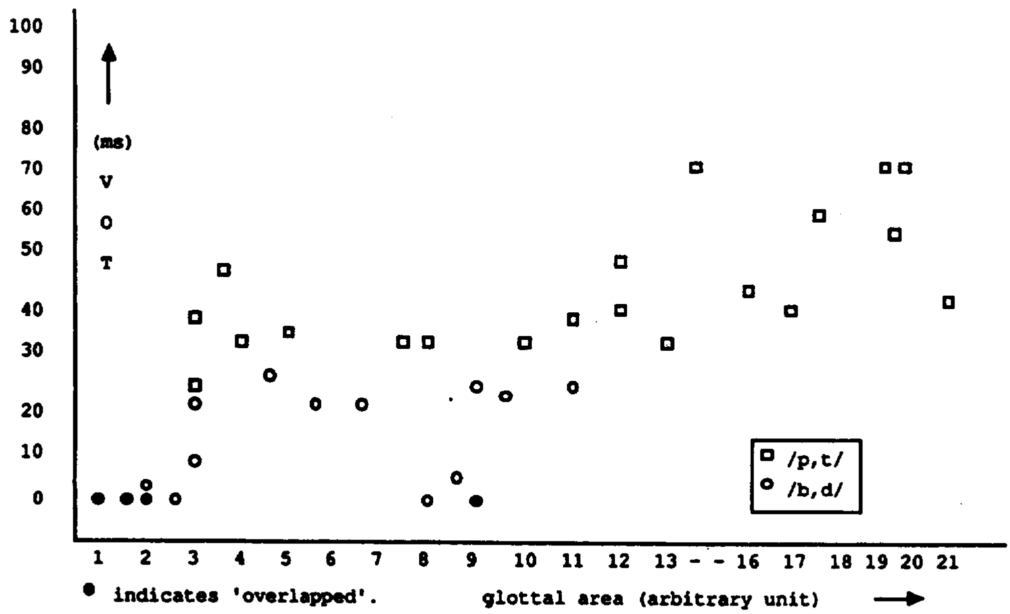

Figure 7. Overall scatter diagram of VOT against glottal area at release during BrEng intervocalic stops /b,p,d,t/ in connected speech.

Figures 7 and 8 show that for the BrEng intervocalic stops the overall relationship between glottal area and VOT was considerably less than that for the Korean intervocalic stops. One of the possible reasons for this would be the alveolar stop-related greater glottal area (see Figures 3 and 6). All else being equal, the alveolar stop-related greater glottal area, particularly for the lax unaspirated stops in English, may be due mainly to a combination of (1) the decreased thickness of the vocal folds caused by the surrounding high pitch vowel /i:/ (Hollien,

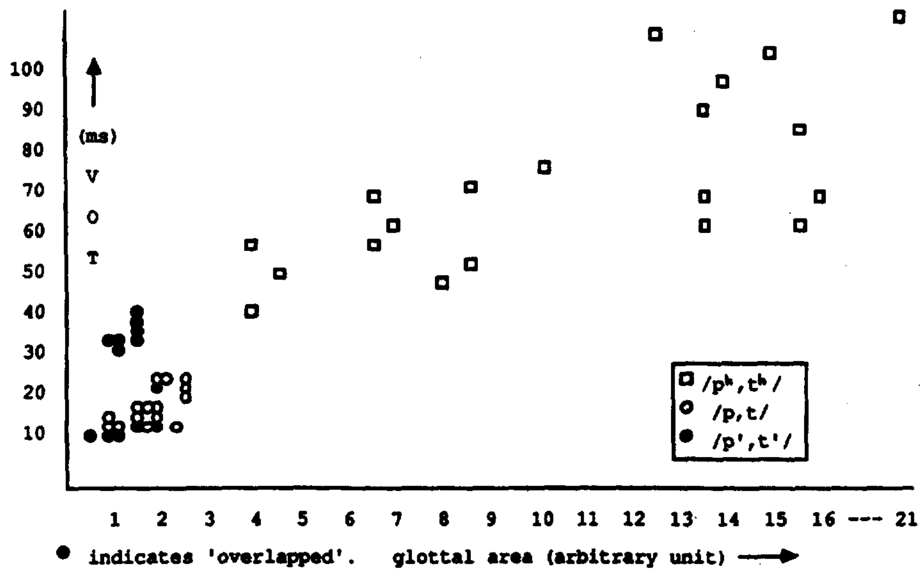

Figure 8. Overall scatter diagram of VOT against glottal area at release during Korean intervocalic stops /p, p', p^h, t, t', t^h/ in connected speech where /p, t/ indicate unaspirated lax stops, /p', t'/ unaspirated tense stops, and /p^h, t^h/ aspirated tense stops.

1962; Van Den Berg and Tan, 1959) and (2) the nature of the photo-electric glottograph which is designed to signal even the trans-illuminated light of the thin glottis caused by the surrounding high pitch vowel /i:/.

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