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ACOUSTIC AND AERODYNAMIC EFFECTS OF INTERARTICULATOR TIMING IN VOICELESS CONSONANTS*

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Interarticulator timing is a mechanism for producing linguistic contrasts that is widely used in different languages. This paper explores acoustic and aerodynamic effects of variations in laryngeal-oral coordination in voiceless consonants. Measurements of voice onset time and interarticulator phasing for individual tokens of stop consonants show weak correlations, indicating that interarticulator timing is only one factor determining voice onset time. Other factors most likely involved are glottal opening, transglottal pressure and air flow, and vocal fold tension. Taken together, these observations suggest that speakers may only have limited control of voice onset time. This could explain why languages do not seem to make fine-grain use of VOT for linguistic contrasts. Measurements of peak and minimum air flow during individual source pulses, obtained by inverse-filtering oral flow, show a pattern of decrease and increase in vowels following voiceless consonants. Subtle differences in the time course of these patterns occur following different consonants, suggesting that interarticulator phasing may be partly responsible for them. Closer examination reveals consistent correlations with interarticulator phasing for one speaker but inconsistent results for another. The results are discussed in terms of speech motor control and controlled variables in speech.

Key words: speech motor control, interarticulator timing, voice onset time, voice source aerodynamics

INTRODUCTION

Interarticulator timing is a mechanism for producing linguistic contrasts that is widely used in different languages. One well known example is the coordination of oral and laryngeal articulatory gestures in the production of stop consonants. For their production, stop consonants require a momentary build-up of oral pressure during the period of oral closure. The pressure behind the closure is then released, which creates the transient burst. For the pressure build-up to occur, a closure is made in the oral cavity, and the velum is elevated to seal off the entrance to the nasal cavity. If the stop is voiceless, a glottal abduction-adduction gesture is made to arrest glottal vibrations and

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assist in the build-up of oral pressure by decreasing laryngeal resistance to air flow.

The oral and laryngeal articulations in voiceless stop production have to be coordinated in time. Variation in their timing is used to produce contrasts of voicing and aspiration. For example, if the onset of the glottal gesture precedes the formation of the oral closure, the last part of the preceding vowel is produced with a voice source that is breathy. That is, the glottal area progressively increases before the oral closure, resulting in a pattern of voicing where the source spectrum is dominated by the fundamental and the lower harmonics, since the amplitude of the higher harmonics decreases rapidly (*cf.* Klatt and Klatt, 1990; Childers and Lee, 1991); in addition, noise may be created in the incompletely closed glottis. This pattern of coordination is observed in languages that have preaspirated stops, such as Icelandic and Irish (Pétursson, 1976; Ní Chasaide, 1987; Löfqvist and Yoshioka, 1981). The opposite pattern occurs in voiced aspirated stops, as in Hindi (Dixit, 1989). Here, the glottis begins to open near the end of the oral closure; the closure is thus voiced. The abduction-adduction gesture is then completed after the release of the closure, thus making the onset of the vowel characterized by breathy voicing. Yet another timing pattern is observed in voiceless postaspirated stops. For these sounds, the onset of glottal abduction occurs around the onset of the oral closure; the closure is thus voiceless. Glottal adduction starts around the release of the oral closure. After the release, the vocal folds are thus being adducted while there is a high rate of airflow out of the vocal tract. As a consequence, the onset of voicing relative to the oral release is delayed and the first part of the following vowel is characterized by breathy voicing. The onset of voicing relative to the release is commonly referred to as Voice Onset Time (VOT, *cf.* Lisker and Abramson, 1964).

There has been some controversy about the nature of control of aspiration and VOT in stop consonants (for reviews, see Abramson, 1977; Löfqvist, 1980; Dixit, 1989). The arguments have centered around the roles of laryngeal-oral timing and the size of the glottal opening. The currently received view would seem to suggest that differences in interarticulator timing are always found between stop categories differing in VOT, but that differences in the size of the glottal opening can also occur. At the same time, we must acknowledge that there are several other factors that condition the occurrence of glottal vibrations and hence VOT. Among these are the glottal area, transglottal air pressure and air flow, and the tension of the vocal folds (*cf.* Stevens, 1977; Titze, 1988).

Most of the evidence for the role of interarticulator timing in the control of aspiration and VOT has been collected in studies comparing different stop categories, e.g., unaspirated *vs.* aspirated stops. In addition, average values have mostly been used. In order to further clarify the relationship between interarticulator timing and VOT, it would seem preferable to look at this relationship across individual tokens. Thus, one goal of the present research was to examine in more detail interarticulator timing and its relationship to voice onset time.

A second goal was to examine possible aerodynamic effects of variations in laryngeal-oral timing. These aerodynamic effects are related to changes in voice source pulse properties after vowel onset following different voiceless consonants. Löfqvist and McGowan (1992) used inverse filtering of the oral air flow to study source properties at vowel onset after different consonants. One of their findings is shown in Figure 1.

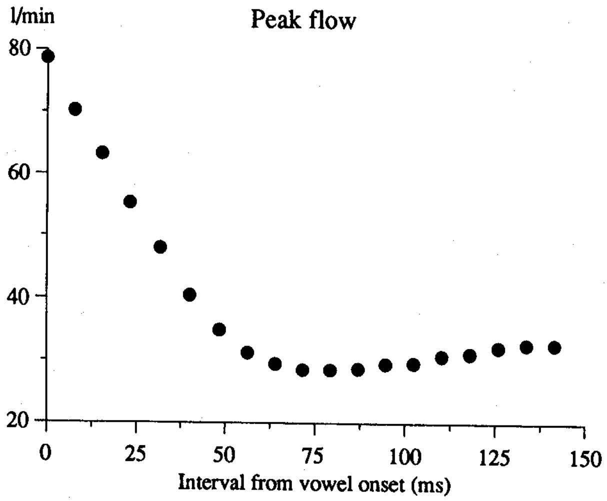

Fig. 1. Changes in peak flow during individual glottal pulses after onset of a vowel following a voiceless aspirated stop /p/ produced by a male speaker. The data points represent the mean of 12 measurements.

This figure plots the peak flow during individual glottal pulses after the onset of a vowel following a voiceless aspirated bilabial stop [$\mathrm{p^h}$] produced by a male speaker; the data points represent the mean of 12 observations. The peak flow is high at vowel onset and then decreases. Note, in particular, that a minimum of peak flow occurs around 75 msec. After the minimum, peak flow shows a small increase. This pattern of decrease followed by an increase was also found following other voiceless consonants, albeit with subtle differences in the time course. One possible explanation for this pattern is that the adduction gesture results in a momentary increase in the degree of glottal adduction, i.e., the force of contact between the folds, after glottal closure; the degree of glottal adduction then returns to a value suitable for the vowel. However, at a meeting where some of these results were presented, John Ohala suggested another possible explanation for this pattern. He hypothesized that it could be related to the decrease in subglottal pressure which is commonly observed at the onset of vowels following voiceless consonants (e.g., Löfqvist, 1975; Ohala, 1990). This decrease is due to a momentary reduction in glottal, and oral, resistance to air flow due to the fact that the glottis and the vocal tract are open immediately after the release of the oral closure/constriction. Thus, the second study reported in this paper was designed to further examine the mechanisms responsible for variations in the aerodynamic properties of the voice source following voiceless consonants.

INTERARTICULATOR TIMING AND ACOUSTICS

Material and method

The material for the first study was taken from Löfqvist and Yoshioka (1984). It consists of voiceless alveolar stops under different stress conditions occurring in nonsense words and spoken at two different rates by two native speakers of American English, one female (FBB) and one male (TB). Recordings were made of the acoustic signal, tongue-palate contact using an artificial palate, and glottal opening using transillumination. From the acoustic recording, voice onset time was measured. The interval between peak glottal opening and the release of the oral closure (offset of tongue-palate contact) was taken as an index of interarticulator timing. Since peak glottal opening represents the onset of glottal adduction, this interval is a suitable measure for the problem under investigation. The stops were divided into the categories 'stressed' and 'unstressed'. The 'stressed' category included stops occurring in the syllable carrying the main stress of the word produced. The 'unstressed' category contained stops occurring in other syllables. Linear correlations and regressions were used to assess the relationship between articulation and acoustics.

Results

The results of the measurements are shown in Figure 2. This figure plots the interval from peak glottal opening to release of the oral closure along the x-axis. A negative number indicates that the onset of glottal adduction occurred before the oral release. Voice onset time is plotted along the y-axis.

Overall, there is a positive relationship between the interval from peak glottal opening to oral release and VOT. The relationship is significant for both speakers within stress and speaking rate ($p < 0.05$ in all cases), suggesting that interarticulator timing is at least partly responsible for variations in voice onset time. However, the correlations are generally low. The squared r values never exceed 0.45, indicating that this particular measure of interarticulator timing explains less than 50% of the variance within stress and rate conditions. Thus, other factors are clearly involved.

However, if we look at correlations for the same articulatory/acoustic variables across stress conditions, but within speaking rates, the results are slightly different. Here, the correlations are generally higher, and the squared r values exceed 0.50 for the normal rate of both speakers.

Discussion

The present results suggest that interarticulator timing is one factor used in the control of voice onset time. Given that other aerodynamic and myodynamic factors are also involved, one might argue about the possibility of controlling VOT other than in a gross, categorical fashion. Published data clearly indicate that interarticulator timing is used to produce the distinction between aspirated and unaspirated voiceless stops. The present results for stops across stress conditions suggest that timing is used to control VOT variations related to stress, but for the control of VOT within stress conditions, timing

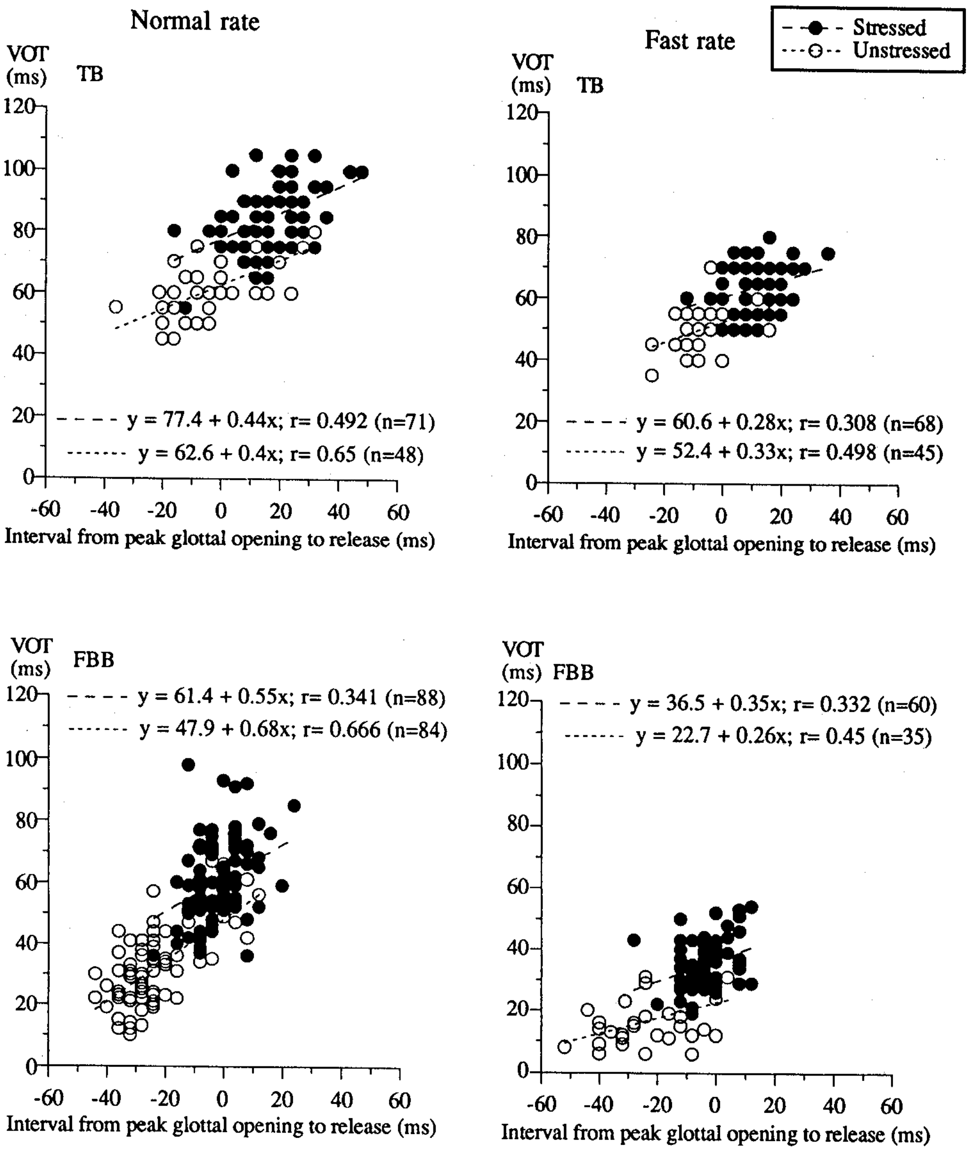

Fig. 2. Voice onset time plotted against the interval from peak glottal opening to release of the oral closure for stops spoken at normal (left) and fast (right) rates.

may not allow fine-grained control. Moreover, this is most likely not necessary, since languages do not appear to use fine-grained contrasts of VOT for making linguistic distinctions. In the well-known case of Korean stops, where there is a three-way distinction of VOT (short, medium, and long), an additional dimension of tensity appears to be used (*cf.* Hirose, Lee, and Ushijima, 1974; Dart, 1987). The dimension of tensity is related to force of glottal contact and is indexed by the activity of the vocalis muscle. I should make the obvious qualification that it may indeed be possible, in the laboratory, to produce finely controlled variations in VOT with practice.

Our knowledge of the conditions necessary for voicing to occur in normal speech is limited by current experimental techniques. Modelling studies are helpful for sorting out possible theoretical relationships in this respect. For example, Titze (1988) presents a theory of vocal fold vibrations which predicts that the subglottal pressure required to initiate vibrations depends on vocal fold thickness, the damping coefficient of vocal fold tissue, the velocity of the mucosal wave, and the glottal width. A few experimental studies have also addressed this issue.

Hirose and Niimi (1987) examined transglottal pressure and glottal width at offset and onset of phonation in voiceless stops and fricatives. At phonation offset, vibrations continued at larger glottal openings and reduced pressure ranges compared to conditions at onset of phonation. They found no difference between stops and fricatives at phonation onset. Increased vocal fold stiffness, manipulated by changing fundamental frequency, tended to require higher pressures for vibrations to occur.

Verdolini-Marston, Titze, and Druker (1990) directly examined the effect of dehydration on the phonation threshold pressure by manipulating environmental humidity and fluid intake. As predicted by theory, the subglottal pressure necessary for vibrations to occur increased in the dehydrated condition. In addition, fundamental frequency of phonation interacted with the degree of dehydration in its effect on phonation threshold pressure.

An experiment by Finkelhor, Titze, and Durham (1987) using excised larynges, manipulated glottal width, viscosity, and vocal fold strain (elongation divided by rest length) to examine the effects of these variables on the phonation threshold. They found that increased strain and increased viscosity raised the threshold of oscillation. The effect of glottal width was inconsistent.

A further example of the interaction between these factors is the glottal condition during the laryngeal fricative /h/ and the voiceless fricative /s/ (*cf.* Yoshioka, 1981). For the laryngeal fricative the vocal folds are abducted, but voicing often continues uninterrupted during the abduction/adduction gesture. For the voiceless fricative /s/, voicing is usually interrupted. The degree of glottal opening may be similar for these sounds, but the aerodynamic conditions differ, since there is a pressure build-up in the oral cavity during the /s/ but not during the /h/. In addition, electromyographic results presented by Löfqvist, Baer, McGarr, and Seider-Story (1989) suggest that the longitudinal tension of the vocal fold, indexed by the activity of the cricothyroid muscle, is increased in voiceless consonants to contribute to the cessation of voicing.

INTERARTICULATOR TIMING AND AERODYNAMICS

Material and method

The material for this second study was taken from Löfqvist and McGowan (1992). It consists of the syllables /pa/, /sa/, and /spa/. The syllables occurred in a reiterant nonsense utterance (e.g., Ma pa ma ma *spa* ma), where they carried the sentence stress. Two subjects participated, one female (RSS), a native speaker of American English, and one male (AL), a native speaker of Swedish. They both produced the /p/ as a voiceless aspirated stop in initial position, and as an unaspirated voiceless stop in the cluster /sp/; this is in accordance with the phonetics of both American English and Swedish. Recordings were made of air flow using a face mask according to the method described by Rothenberg (1973). Oral pressure was sensed by a catheter-tip transducer introduced through the nose and placed in the pharynx. Glottal opening was recorded using transillumination, and an acoustic recording was also made. The flow signal was inverse-filtered to recover the glottal pulse; for details see Löfqvist and McGowan (1992). Peak flow, minimum flow, and the open quotient were measured for 19 periods following vowel onset. Twelve repetitions were used for averaging.

Results

Since we are interested in aerodynamic effects of interarticulator timing, it is useful to start by considering Figure 3, showing air flow, air pressure, glottal opening, and the acoustic signal for one token of each of the syllables produced by the two subjects. For all tokens, there is a glottal abduction-adduction gesture, as evidenced by the record of glottal opening. Concentrating on the onset of glottal adduction, we see that it occurs close to the release of the oral closure for the aspirated stop in /apa/. In the sequence /aspa/ where the stop is unaspirated, glottal adduction starts during the fricative for subject RSS, and close to the boundary between the fricative and the stop for subject AL; this boundary can be identified by the drop in airflow that occurs at stop closure. For the single fricative /s/, glottal adduction occurs approximately in the middle of the constriction. We should also note that the glottal vibrations following the /s/ and the /p/ start before the glottis is completely adducted. That is, the glottal opening continues to decrease following onset of voicing.

Figure 4 plots the changes in peak and minimum flow after vowel onset following the different consonants. From this figure, it is evident that a similar pattern of decrease and increase occurs following the stop, the fricative, and the fricative+stop cluster. This pattern is found for both subjects, and for both peak flow and minimum flow. A closer inspection of the curves for peak flow of subject AL in Figure 4 reveals that their time courses differ. That is, the minimum value occurs around 25 msec in /spa/, around 60 msec in /sa/, and around 75 msec in /pa/. The locations of the minima are identified by the arrows. A similar pattern is found for subject RSS. Moreover, a similar pattern of change was found for another source pulse property, the open quotient, i.e., the ratio of open phase to period time.

If different patterns of laryngeal-oral coordination are responsible for the differences in the time course of the curves in Figure 4, we would expect a correlation between

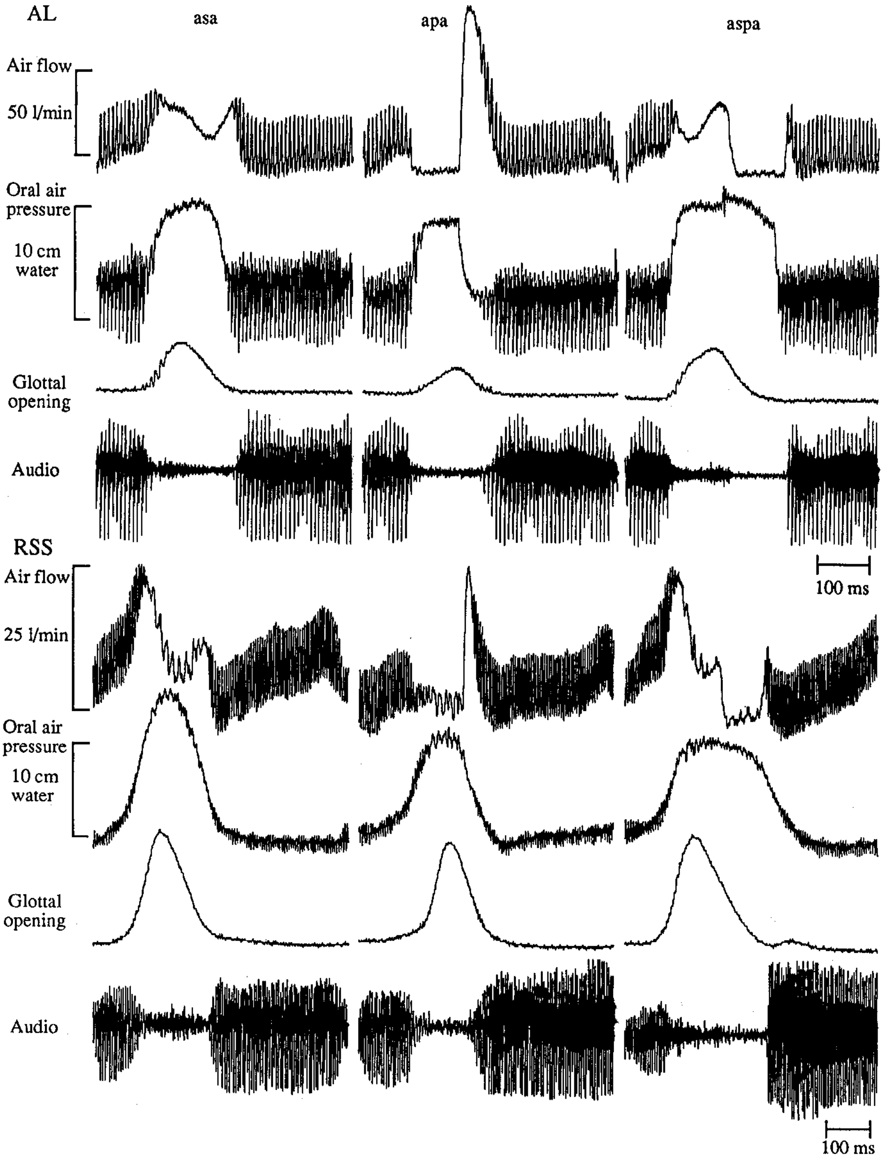

Fig. 3. Air flow, oral air pressure, glottal opening, and audio signal during productions of the sequences [asa], [$\mathrm{p^h}$a], and [aspa] by subject AL (top) and RSS (bottom).

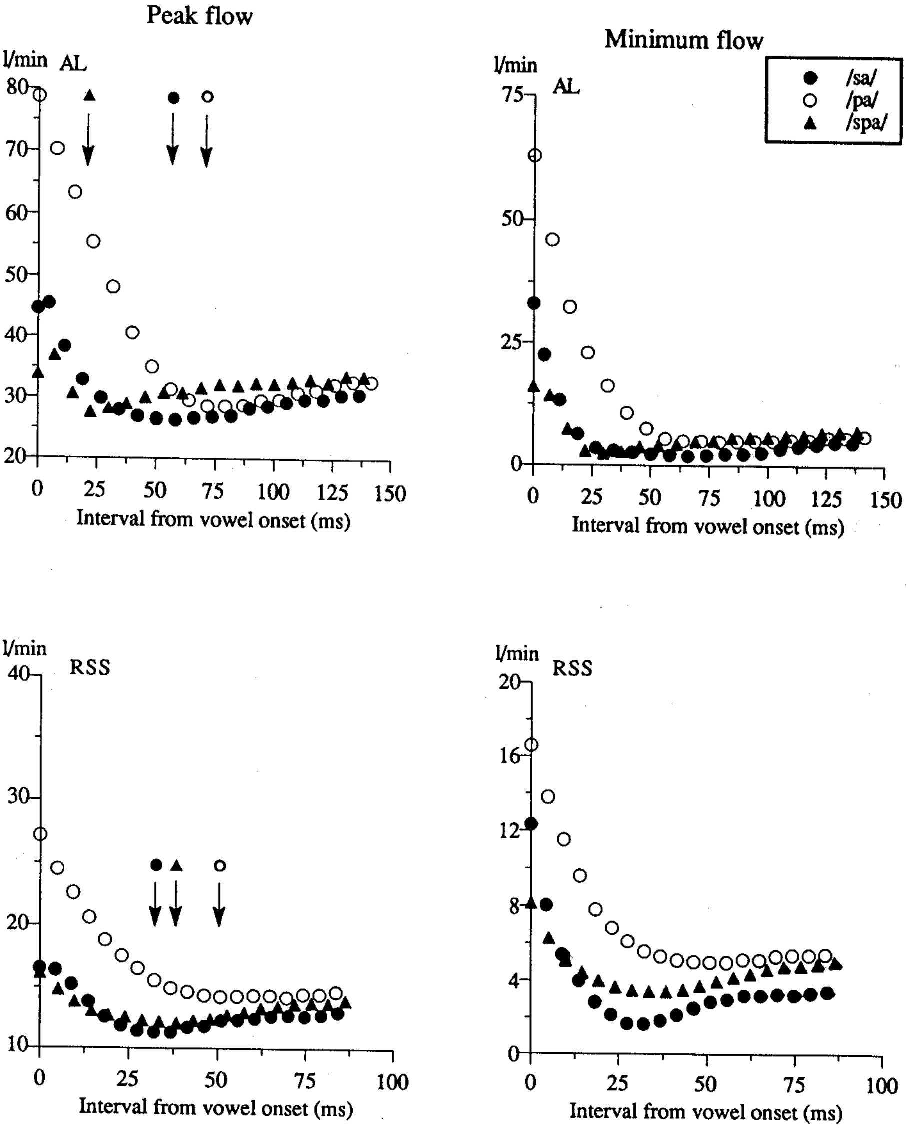

Fig. 4. Peak flow (left) and minimum flow (right) during individual glottal pulses after vowel onset following three different voiceless consonants. The arrows point at the location of the minima in the curves.

interarticulator phasing and the point in time after vowel onset where the minimum occurs in the curve. As an index of interarticulator phasing, we can use the interval between peak glottal opening (onset of glottal adduction) and vowel onset, defined by onset of voicing in the audio signal. The relevant plots are shown in Figure 5. For subject AL, we find a clear negative relationship between the two intervals. That is, as the interval between onset of glottal adduction and vowel onset decreases, the minimum in the curves moves further away from vowel onset. This is true for peak flow, minimum flow, and the open quotient. In addition, the location of the minima is very close for the different parameters. For subject RSS, on the other hand, the relationship is not as clear. Although there is a large difference in the interval from adduction onset to vowel onset between /sa/ and /spa/, the minimum in the curves for peak and minimum flow occurs approximately at the same point in time following vowel onset.

In addition to the difference in laryngeal-oral timing between the three consonants shown in Figure 3 and discussed so far, there may also be differences in the speed and duration of the adduction gesture that may account for the differences between the two speakers. In particular, it is possible that a higher velocity of the adduction gesture could make the duration of the gesture shorter, and also cause the folds to make a more forceful contact. Measurements of peak velocity and duration of the adduction gesture for the two speakers showed variable results, however. These measures were made from the derivative of the signal representing glottal opening; onset and offset of movement were identified as points of zero velocity. For subject AL, the peak velocity of the gesture was negatively correlated with the interval from vowel onset to the minimum value in the curves; the order of decreasing peak velocity for the three consonants was /sp/, /s/, and /p/. For subject RSS, however, the correlation was positive and the ordering of peak velocities was /p/, /sp/, /s/. The duration of the adduction gesture showed inconsistent results for the two speakers. While there is thus a similar pattern of laryngeal-oral coordination for the two subjects, the results for velocity and duration of the adduction gesture indicate that these properties can vary between speakers.

Discussion

The present results suggest that interarticulator timing is in part responsible for how some source properties change after vowel onset following different voiceless consonants. Detailed measurements of source properties in different consonantal contexts have been published by Löfqvist and McGowan (1992). The minimum observed in the curves for peak flow, minimum flow, and the open quotient could thus be explained by a momentary increase in the degree of glottal adduction following vowel onset. If this increase reflects the folds being brought together by the adduction gesture, we would expect the location of this momentary increase to differ between consonantal contexts. The reason is that different voiceless consonants are produced with different patterns of laryngeal-oral coordination (Figure 3). Hence, the point in time where the vocal folds make contact with each other differs depending on the onset of the adduction gesture but appears also to be sensitive to the speed and duration of the gesture. For example, in the cluster /spa/, the onset of adduction occurs during the fricative and most of the adduction gesture is completed when phonation starts. For the stop /p/, on the other

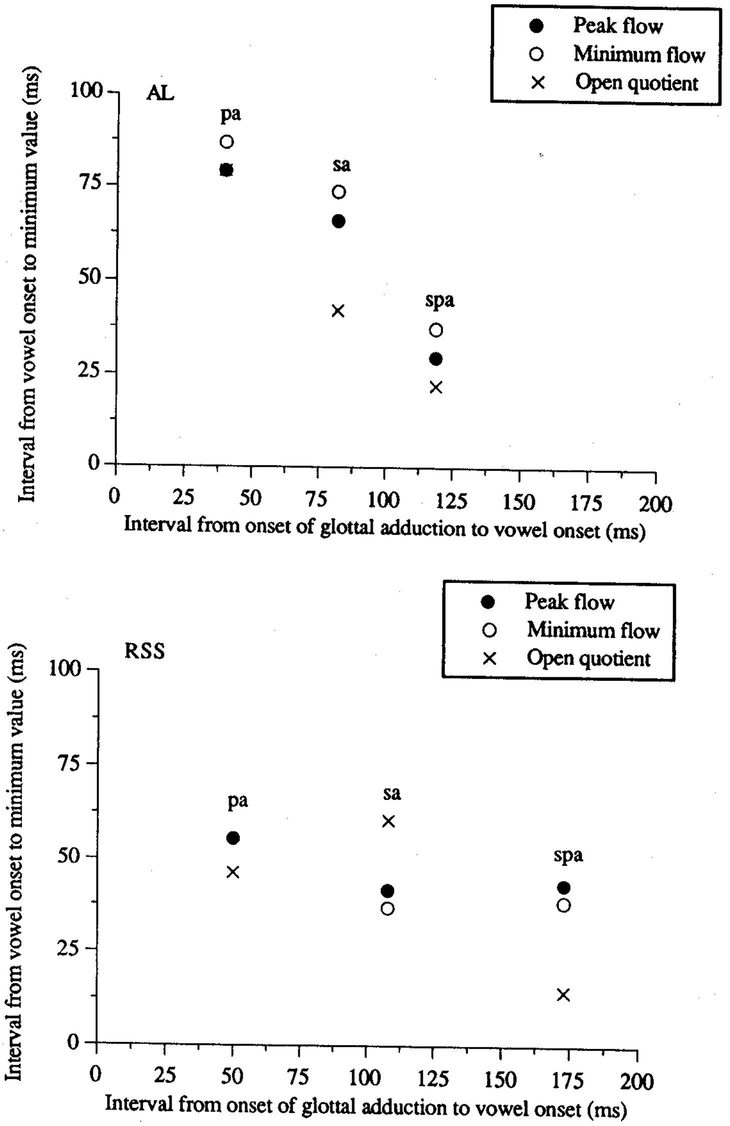

Fig. 5. The interval from vowel onset to minimum values of peak flow, minimum flow, and the open quotient plotted against the interval from onset of glottal adduction during the preceding consonant to vowel onset.

hand, the glottis begins to close around the release of the oral closure, and the adduction gesture is completed after the onset of voicing.

The reason why the pattern is not clearly observed for subject RSS appears to be due to differences in the speed and duration of the adduction gesture which interact with the difference in interarticulator timing. For subject AL, on the other hand, the duration of the interval from onset of glottal adduction to vowel onset covaried with the speed of glottal adduction. Hence, if both the interval and the velocity affect the location of the minimum in the curves, they would cooperate to give the same result for subject AL.

What about the other possibility suggested by John Ohala? While a momentary decrease in subglottal pressure following voiceless consonants would most certainly cause a reduction in peak and minimum flow, it is not clear what influence it would have on the open quotient. Moreover, following the release of the stop in the cluster /sp/, one would not expect subglottal pressure to be very much affected, since the stop is unaspirated and the glottis is in a position suitable for voicing. Records of lung volume changes presented by Ohala (1990) do not show any marked decrease following the release of a voiceless unaspirated stop. Published data on variations in subglottal pressure during vowels following different consonants do not appear to allow a detailed analysis of the time course of these variations similar to the one we have made here for peak and minimum flow during individual glottal pulses.

In addition, Löfqvist and McGowan (1992) present results showing a mirror pattern of change following a glottal stop. That is, following the glottal stop the curve for peak flow shows an increase to a maximum value, and then a decrease. Following the line of argument pursued here, this pattern could be explained by a tight glottal closure during the glottal stop. The degree of glottal adduction is then decreased at vowel onset and shows a slight overshoot before it returns to a value suitable for the vowel. Following a glottal stop, we would not expect subglottal pressure to be significantly increased after vowel onset. At the same time, we should acknowledge that several aerodynamic and myodynamic factors are rapidly changing at the consonant-vowel transition, so it may not be possible, or productive, to seek a single cause.

GENERAL DISCUSSION

The present results suggest that initiation of voicing following voiceless stops is partly determined by interarticulator timing, but that other factors, such as transglottal pressure, vocal fold tension, and degree of glottal opening must also be involved. Taken together, these considerations suggest that it may not be possible to have fine-tuned control of voice onset time. Given the categorical nature of speech perception, such control would not seem to be necessary. Hence, the existence of a limited number of stop categories differing in VOT may be rationalized with reference to the production and perception of variations in voice onset time. With training and under good listening conditions, however, the discrimination of VOT can be quite sensitive with a Weber ratio of approximately 0.2 for VOT values greater than 15 msec (Samuel, 1977; Kewley-

Port, Watson, and Foyle, 1988).

One further comment is in order here concerning the role of VOT in perception. Inspection of Figure 2 reveals that voice onset time is shorter at the fast rate than at the normal rate. Listeners are apparently aware of, and sensitive to, such rate-dependent changes in the acoustic signal. Summerfield (1981) examined the effect of speaking rate on the perception of the voiced/voiceless distinction cued by variations in voice onset time. When the test syllables were preceded by precursor phrases spoken at different rates, the VOT boundary for voiced and voiceless percepts changed. That is, when preceded by an utterance spoken at a fast rate, the boundary moved towards shorter values of VOT. This may be rationalized with respect to the shorter values of VOT commonly observed at fast rates of speech.

The subtle variations in voice source aerodynamics that I have discussed in the present paper most likely owe their occurrence to several interacting factors following voicing onset. Interarticulator timing appears to be used to control overall properties of voice onset time and mode of phonation at vowel onset. However, the detailed structure of these properties would seem to result from interactions among the respiratory, laryngeal, and oral articulatory systems.

REFERENCES

ABRAMSON, A.S. (1977). Laryngeal timing in consonant distinctions. *Phonetica,* **34,** 295–303.

CHILDERS, D.G., and LEE, C.K. (1991). Vocal quality factors: Analysis, synthesis and perception. *Journal of the Acoustical Society of America,* **90,** 2394–2410.

DART, S.N. (1987). An aerodynamic study of Korean stop consonants: Measurements and modelling. *Journal of the Acoustical Society of America,* **81,** 138–147.

DIXIT, R.P. (1989). Glottal gestures in Hindi plosives. *Journal of Phonetics,* **17,** 213–237.

FINKELHOR, B.K., TITZE, I.R., and DURHAM, P.L. (1987). The effect of viscosity changes in the vocal folds on range of oscillation. *Journal of Voice,* **1,** 320–325.

HIROSE, H., LEE, C.Y., and USHIJIMA, T. (1974). Laryngeal control in Korean stop production. *Journal of Phonetics,* **2,** 145–152.

HIROSE, H., and NIIMI, S. (1987). The relationship between glottal opening and the transglottal pressure differences during consonant production. In T. Baer, C. Sasaki, and K.S. Harris (eds.), *Laryngeal Function in Phonation and Respiration* (pp. 381–390). Boston: College-Hill Press.

KEWLEY-PORT, D., WATSON, C.S., and FOYLE, D.C. (1988). Auditory temporal acuity in relation to category boundaries; speech and nonspeech stimuli. *Journal of the Acoustical Society of America,* **83,** 1133–1145.

KLATT, D., and KLATT, L. (1990). Analysis, synthesis, and perception of voice quality variations among female and male talkers. *Journal of the Acoustical Society of America,* **87,** 820–857.

LISKER, L., and ABRAMSON, A.S. (1964). A cross-language study of voicing in initial stops: Acoustic measurements. *Word,* **20,** 384–422.

LÖFQVIST, A. (1975). A study of subglottal pressure during the production of Swedish stops. *Journal of Phonetics,* **3,** 175–189.

LÖFQVIST, A. (1980). Interarticulator programming in stop production. *Journal of Phonetics,* **8,** 475–490.

LÖFQVIST, A., BAER, T., MCGARR, N.S., and SEIDER-STORY, R. (1989). The cricothyroid muscle in voicing control. *Journal of the Acoustical Society of America,* **85,** 1314–1321.

LÖFQVIST, A., and MCGOWAN, R.S. (1992). Influence of consonantal environment on voice source aerodynamics. *Journal of Phonetics*, **20**, 93–110.

LÖFQVIST, A., and YOSHIOKA, H. (1981). Laryngeal activity in Icelandic obstruent production. *Nordic Journal of Linguistics*, **4**, 1–19.

LÖFQVIST, A., and YOSHIOKA, H. (1984). Intrasegmental timing: Laryngeal-oral coordination in voiceless consonant production. *Speech Communication*, **3**, 279–289.

NÍ CHASAIDE, A. (1987). Glottal control of aspiration and voicelessness. In *Proceedings of the XIth International Congress of Phonetic Sciences*, Vol. 6 (pp. 28–31). Tallinn: Academy of Sciences of the Estonian S.S.R.

OHALA, J.J. (1990). Respiratory activity in speech. In W. Hardcastle and A. Marchal (eds.), *Speech Production and Speech Modelling* (pp. 23–53). Dordrecht: Kluwer.

PÉTURSSON, M. (1976). Aspiration et activité glottal. Examen experimental à partir des consonnes islandaises. *Phonetica*, **33**, 169–198.

ROTHENBERG, M. (1973). A new inverse filtering technique for deriving the glottal air flow waveform during speech. *Journal of the Acoustical Society of America*, **53**, 1632–1645.

SAMUEL, A. (1977). The effect of discrimination training on speech perception: Noncategorical perception. *Perception & Psychophysics*, **22**, 321–330.

STEVENS, K.N. (1977). Physics of laryngeal behavior and larynx modes. *Phonetica*, **34**, 264–279.

SUMMERFIELD, Q. (1981). Articulatory rate and perceptual constancy in phonetic perception. *Journal of Experimental Psychology: Human Perception and Performance*, **7**, 1074–1095.

TITZE, I.R. (1988). The physics of small-amplitude oscillation of the vocal folds. *Journal of the Acoustical Society of America*, **83**, 1526–1552.

VERDOLINI-MARSTON, K., TITZE, I.R., and DRUKER, D.G. (1990). Changes in phonation threshold pressure with induced conditions of hydration. *Journal of Voice*, **4**, 142–151.

YOSHIOKA, H. (1981). Laryngeal adjustments in the production of fricative consonants and devoiced vowels in Japanese. *Phonetica*, **38**, 236–251.