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Effects of speaking rate on voice-onset time and vowel production: Some implications for perception studies

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An examination of studies investigating effects of speaking rate on speech production and speech perception reveals an apparent conflict between acoustic data from speech production and the acoustic parameters typically manipulated in speech perception experiments. This note is intended to address the apparent conflict in the literature by examining both production and perception studies in the extant literature, and by analyzing new data on the effects of speaking rate on voice-onset time (VOT) production in English. Subjects were asked to read CVC words in context at both slow and fast rates of speech, and the relationship between VOT and vowel duration across changes in speaking rate was then examined. The data for voiceless stop plus sound sequences indicate that as speaking rate slows both VOT and vowel duration increase in almost equal proportions. Importantly, there is no evidence that VOT and vowel length vary inversely such that as VOT increases, vowel length decreases. In contrast, most perception experiments examining the effects of speaking rate on VOT use stimulus parameters that do vary inversely VOT and vowel length. Thus, the perceptual the effects obtained under such conditions may not be appropriately attributable to perceptual effects of speaking rate on phonetic categorization, but rather may be due to other perceptual effects.

1. Introduction

Studies have shown that the acoustic properties corresponding to specific phonetic segments of speech are influenced by numerous sources of variability such as phonetic context, syllable position, speaker, and speaking rate (Liberman, Cooper, Shankweiler & Studdert-Kennedy, 1967; Pickett, 1980; Miller, 1987). One such source of contextual variability, speaking rate, has been found to affect the duration of acoustic properties specifying phonetic dimensions of speech (Miller & Liberman, 1979; Summerfield, 1981; Miller & Baer, 1983; Shinn, 1984). The effect of speaking rate on voice-onset time, which serves as a measure to categorize voicing in stop consonants, provides one such example.

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Voice-onset time (VOT) refers to an articulatory event related to voicing in stop consonants, and has a number of acoustic manifestations including the presence of F1 cutback, amplitude changes in the noise burst, and quasi-periodic energy following the burst release (cf. Lisker & Abramson, 1964). For the purposes of this paper, we refer to VOT as the time interval between the burst release and the onset of quasi-periodic energy. Studies have shown that changes in speaking rate affect the range of values associated with VOT (Summerfield, 1981; Miller & Baer, 1983; Miller, Green & Reeves, 1986; Miller & Volaitis, 1989; Volaitis & Miller, 1992; Kessinger & Blumstein, 1997). Specifically, in English, as speaking rate slows, the VOT values of voiceless stop consonants increase substantially.

In addition, studies examining the effect of speaking rate on perception suggest that listeners may process certain properties of the speech signal in a rate-dependent manner (Summerfield, 1981; Miller *et al.*, 1986; Miller & Volaitis, 1989; Volaitis & Miller, 1992). In the case of VOT, for instance, it has been found as syllable duration is increased (signifying slower speech), the perceptual boundary between voiced and voiceless stop consonants shifts toward longer VOT values (Summerfield, 1981; Miller *et al.*, 1986; Miller & Volaitis, 1989; Volaitis & Miller, 1992).

Considering speech production and speech perception studies together, however, there appears to be a conflict between the acoustic data from speech production and the acoustic parameters manipulated in speech perception experiments. Speech perception experiments exploring the effects of speaking rate on the perception of VOT typically use stimuli with a constant syllable duration (Green & Miller, 1985; Miller & Volaitis, 1989; Volaitis & Miller, 1992; Green, Stevens & Kuhl, 1994; Flege, Schmidt & Wharton, 1996; but cf. Summerfield, 1981, in a study of extrinsic rate effects on VOT). In these studies, two syllable durations, one "long" and one "short", are used to reflect slow and fast speaking rates, respectively, and each of the two syllable durations is held constant as VOT is varied. Thus, within each syllable duration, VOT and vowel length vary inversely, such that as VOT is lengthened, vowel length is shortened. In the extreme, when VOTs are longest, vowel durations are the shortest, and for some stimuli vowel length has been reduced to as little as 5 ms. However, the data from speech production studies indicate that most of the change in syllable duration as a function of speaking rate is due to a change in vowel duration and not to a change in VOT (Kozhevnikov & Chistovich, 1965; Gay, 1978; Port, 1981; cf. also Port & Rottuno, 1979, for similar findings for syllable-final voicing). If VOT and vowel length do not vary inversely in speech production, then the perceptual shifts which have been shown to occur when VOT is lengthened as syllable duration is held constant may not relate to changes in speaking rate per se, but may be due to other perceptual effects.

This note is intended to address the apparent conflict in the literature by examining both production and perception studies in the extant literature, as well as by providing additional data on the effects of speaking rate on the production of VOT in English. The analysis of this new data will focus primarily on the relationship between VOT and vowel duration as speaking rate changes.

2. Production

Previous studies have shown that as speaking rate slows, VOT and syllable duration increase systematically (Miller *et al.*, 1986; Miller & Volaitis, 1989; Volaitis & Miller, 1992). Miller *et al.* (1986) elicited the syllables /bi/ and /pi/ at eight rates of speech. Considering the mean VOT values for /bi/ and /pi/ as a function of syllable duration, they found that as overall syllable duration increased there was a considerable increase in VOT values for /pi/, but only a minimal increase in VOT values for /bi/. That is, for both voiced and voiceless stop consonants, syllable duration increased as speaking rate slowed, but VOT values for voiced and voiceless stops were affected asymmetrically (cf. also Kessinger & Blumstein, 1997; Pind, 1995). Thus, speaking rate had a greater effect on VOT values for voiceless stops than for voiced stops.

The increase in syllable duration found for syllables beginning with both voiceless and voiced stops, however, is attributable only in part to increases in VOT. Evidence indicates that increases in vowel duration at slower speaking rates also contribute to the increased syllable duration (Kozhevnikov & Chistovich, 1965; Gay, 1978; Port, 1981; Amerman & Parnell, 1981). Data from Volaitis & Miller (1992), e.g., show that for the voiceless stop /p/, the average VOT for syllables with a duration of 500–799 ms (slow speech) was 23 ms longer than that for syllables with a duration of 300–499 ms (medium speech), and that the average VOT for syllables with a duration of 300–499 ms was 35 ms longer than the average VOT for syllables with a duration of 100–299 ms (fast speech) (p. 732). Thus, it appears that as average syllable duration increased by 200 ms, VOT increased on average only between 23 and 35 ms. In contrast, for the voiced syllable /bi/, VOT increased on average only 0.7–3.5 ms as average syllable duration increased by 200 ms (cf. data from Volaitis & Miller, 1992: 732). These data suggest that while increases in voice-onset time contribute to the increased syllable duration at slower speaking rates (particularly for voiceless stops) they are not solely accountable for this increase, and in fact they may constitute a smaller part of the total duration increase. Evidence from Gay (1978) is consistent with this observation. Gay measured the duration of the initial consonant, vowel, and final consonant in CVC syllables produced by speakers in a carrier phrase at slow and fast speaking rates. The results showed that for both voiced and voiceless stop consonants, decreases in syllable duration at the faster speaking rate resulted primarily from decreases in vowel duration, although the consonant segments were also consistently shorter in this condition.

3. New production data

To investigate more closely the relationship between VOT and vowel length across changes in speaking rate, the production of voice-onset time and vowel duration were examined at slow and fast speaking rates for CVC words beginning with the initial voiceless stop consonant /p/. Since it has been demonstrated that voice-onset time values for voiced stop consonants do not vary greatly as a function of speaking rate (Summerfield, 1981; Miller *et al.*, 1986, Miller & Volaitis, 1989; Volaitis & Miller, 1992; Kessinger & Blumstein, 1997), the voiced stop /b/ was not included in this study.

3.1. *Method*

3.1.1. *Subjects*

The speech for four native speakers of American English was recorded. Two speakers were male and two female, and their mean age was 23.8 years (range 21–27). Each subject was recorded in a single session and was paid for their participation in the experiment.

3.1.2. *Stimuli*

Stimuli consisted of four CVC real words beginning with the voiceless stop consonant /p/, and were part of a larger data set used in Kessinger & Blumstein (1997). The four words used were “peak”, “peep”, “pat”, and “patch”. The words were printed in large letters on 3×5 inch cards.

3.1.3. *Procedure*

The stimuli were elicited in a carrier phrase at both slow and fast rates of speech. The carrier phrase was constructed such that the sound immediately prior to the onset of the stimuli was a voiceless stop consonant. The phrase used was “Speak ([spik])—again.” In the fast rate, subjects were encouraged to speak as quickly as possible without forsaking accuracy, as if speaking to a friend about to leave the room. The slow rate was illustrated as clearly enunciated speech. Speaking rates were demonstrated by the experimenter prior to each recording session, and before recording began subjects practiced speaking at both rates.

The stimuli were randomized within each speaking rate and were produced five times each. Each subject read all of the stimuli in each of the two speaking rate conditions. The order of the two rate conditions was counterbalanced across subjects.

Stimuli were recorded onto a DAT tape in a sound-treated room using a Sony DAT TCD-D7 recorder and a Sony ECM-909A stereo microphone. The microphone was placed on a table approximately 8 inches from the speaker’s mouth.

3.1.4. *Acoustic analyses*

The speech was sampled onto a MicroVAX computer at a rate of 10 kHz with a 4.5 kHz low-pass filter and 12-bit quantization using the BLISS speech system (Mertus, 1989). Using the waveform display, three measures were taken: VOT, vowel duration, and syllable duration. Voice-onset time was determined by measuring the time in milliseconds (ms) from the onset of the stop consonant burst to the onset of voicing, as determined by placing the zero crossing at the start of the first glottal pulse. Vowel duration was measured from voicing onset to voicing offset; voicing offset was determined by the absence of glottal excitation corresponding to the onset of the closure for the final consonant. Syllable duration (CV) was operationalized by measuring the time in milliseconds from the onset of the stop consonant burst to the offset of voicing. Thus, this measure included the duration of VOT plus the duration of the vowel (it did not include the closure duration and consonant release corresponding to the final consonant). Because the final consonant was different for each of the four stimuli, the CV duration, not the word duration (CVC), was used in the analyses.

Three tokens were excluded from analysis due to factors such as line noise or coughing. The total number of syllables included in the analysis was 157: 39 from speaker AD, 39 from speaker EK, 40 from speaker SB, and 39 from speaker CM.

3.2. *Results*

In order to explore the relationship between VOT and syllable duration (CV) as a function of speaking rate, the VOT values of the four speakers were averaged and plotted in relation to successive 50 ms bin intervals of syllable duration. These measures were made for the syllables /pi/ and /pæ/ separately and are presented graphically in Fig. 1. Separate analyses of VOT functions across the different final consonants revealed similar patterns of VOT. An examination of Fig. 1a reveals that, as found previously (Miller *et al.*, 1986; Volaitis & Miller, 1992), voice-onset time for /pi/ increased systematically and nearly monotonically with an increase in syllable duration. A similar pattern emerged for /pæ/, as illustrated by Fig. 1b, with the exception of the VOT values for /pæ/ in the 251–300 ms range.

In order to provide a more detailed view of the relationship between VOT and syllable duration, scatter plots of the individual tokens were made (see Fig. 2). In this way, it is possible to determine whether the increase in VOT as a function of syllable duration occurs across the range of both fast and slow rates of speech, and to determine the extent to which tokens with the same syllable duration are produced with a range of VOT values. As the figure shows, at both fast and slow speaking rates, overall syllable duration increased as VOT values increased, although there is a greater dispersion of scores for the

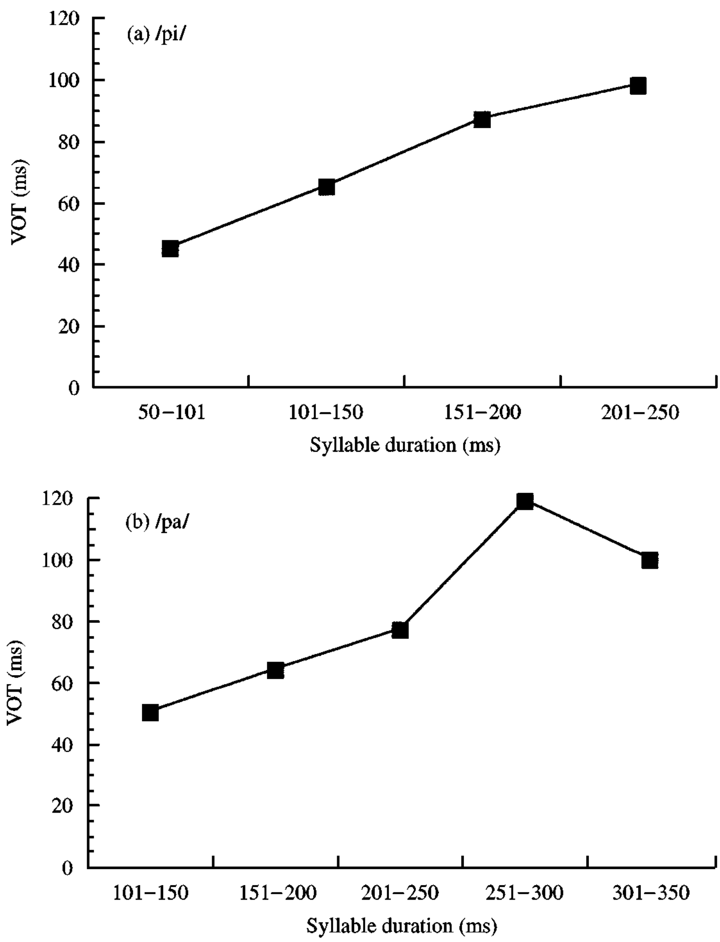

Figure 1. Mean VOT values for (a) /pi/ and (b) /pæ/ within successive 50 ms bin intervals of syllable duration.

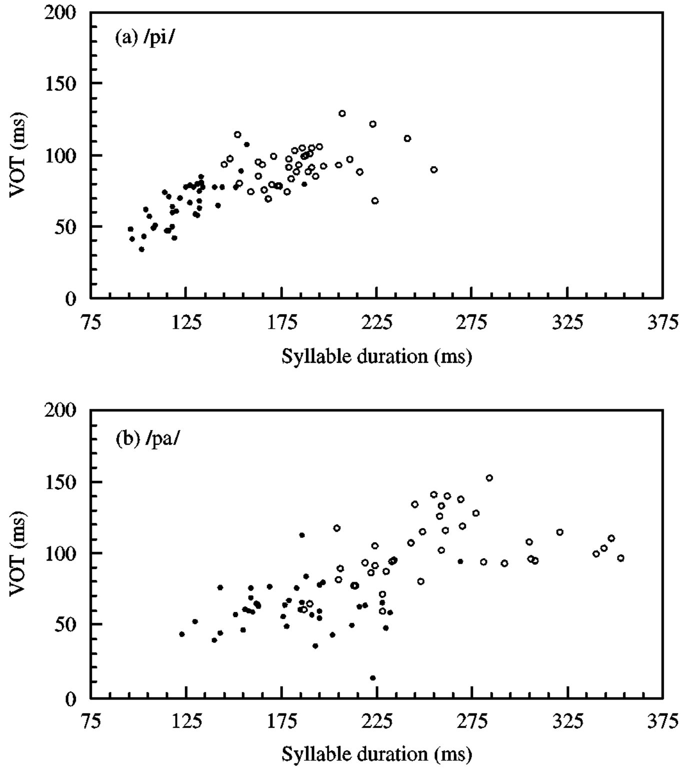

Figure 2. VOT values for (a) /pi/ and (b) /pæ/ plotted as a function of syllable duration for both the slow and fast speaking rates (/pi/: $r = 0.737$, /pæ/: $r = 0.645$). The figure collapses across speaking rate for the two /pi/ words and the two /pæ/ words, respectively, resulting in 40 slow and 40 fast tokens in each frame. The filled squares represent tokens produced at the fast rate, and the unfilled circles tokens produced at the slow rate.

/æ/ vowel context compared to the /i/ vowel context. That VOT values increase as syllable duration increases indicates that, overall, both VOT and vowel length increase (and thus do not vary inversely) over the range of values encompassed by the two speaking rates. Nonetheless, it is also clear that at a particular syllable duration there may be a set of exemplars produced with a range of VOT values. These exemplars are typically (although not exclusively) produced at the same speaking rate. Furthermore, scatter plots of the VOT values of the individual utterances as a function of syllable duration (Figs. 2a and 2b for /pi/ and /pæ/, respectively) show that, as expected, syllable duration increased as speaking rate slowed.

Analogous to the VOT analyses, vowel length was plotted as a function of syllable duration. Fig. 3 shows the mean vowel duration for /pi/ and /pæ/ within 50-ms syllable duration intervals. The figures reveal that, similar to VOT, vowel length increased as a function of syllable duration. The magnitude of the vowel length change across syllable duration is similar to that for VOT, although it is somewhat larger for the vowel /æ/, with the exception of the vowel length values at 251–300 ms.

Scatter plots shown in Fig. 4 of the vowel length of the individual utterances as a function of syllable duration for /pi/ and /pæ/, further indicate that vowel length and

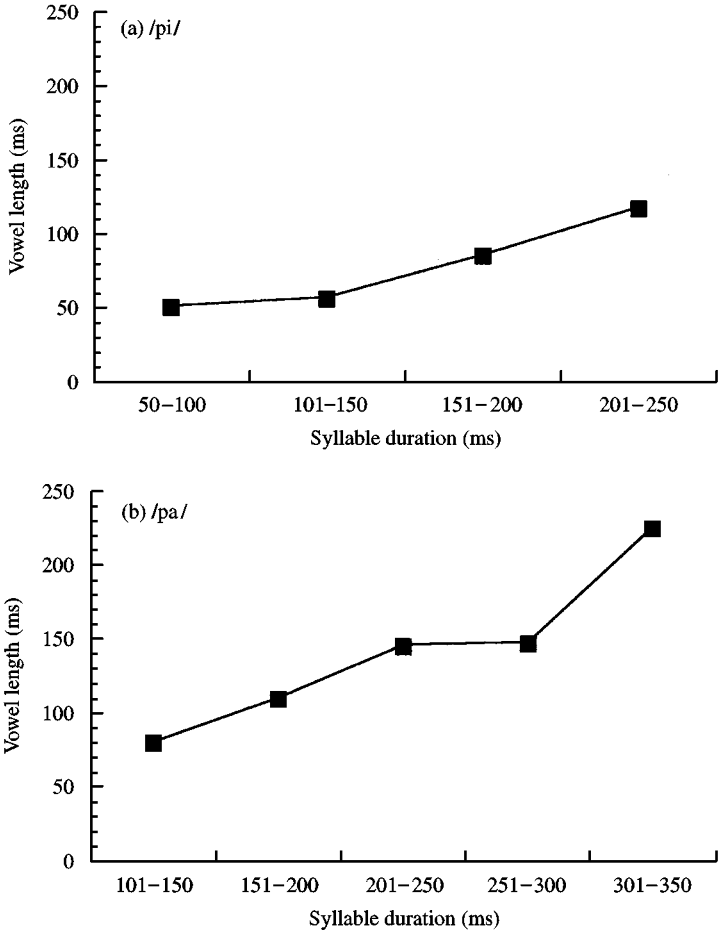

Figure 3. Mean vowel length for (a) /pi/ and (b) /pæ/ within successive 50 ms bin intervals of syllable duration.

syllable duration tended to increase together. This effect emerged most clearly for /pæ/ at both fast and slow speaking rates and for /pi/ at the slow speaking rate. The vowel length values are more tightly clustered at the fast speaking rate for the vowel /i/, although the trend for vowel duration to increase as syllable length increased is still apparent.

The previous analyses considered separately the duration of VOT and vowel length as a function of overall CV duration. Table I compares the relationship between VOT and vowel length as a function of speaking rate. The table shows that for both /pi/ and /pæ/ the overall increase in syllable duration at the slow speaking rate results from increases in both VOT and vowel duration. As the data in Table I show, when speaking rate slows, subjects lengthen both VOT and vowel in equal proportions: at the slow speaking rate the VOT for /pi/ increased by 25 ms (from 66 to 91 ms) and the vowel by 35 ms (from 60 to 95 ms), and for /pæ/ the VOT increased by 39 ms (from 61 to 100 ms) and the vowel by 37 ms (from 120 to 157 ms). These findings differ from Kozhevnikov & Chistovich (1965), Gay (1978), and Port (1981), who showed a greater change in vowel duration than in

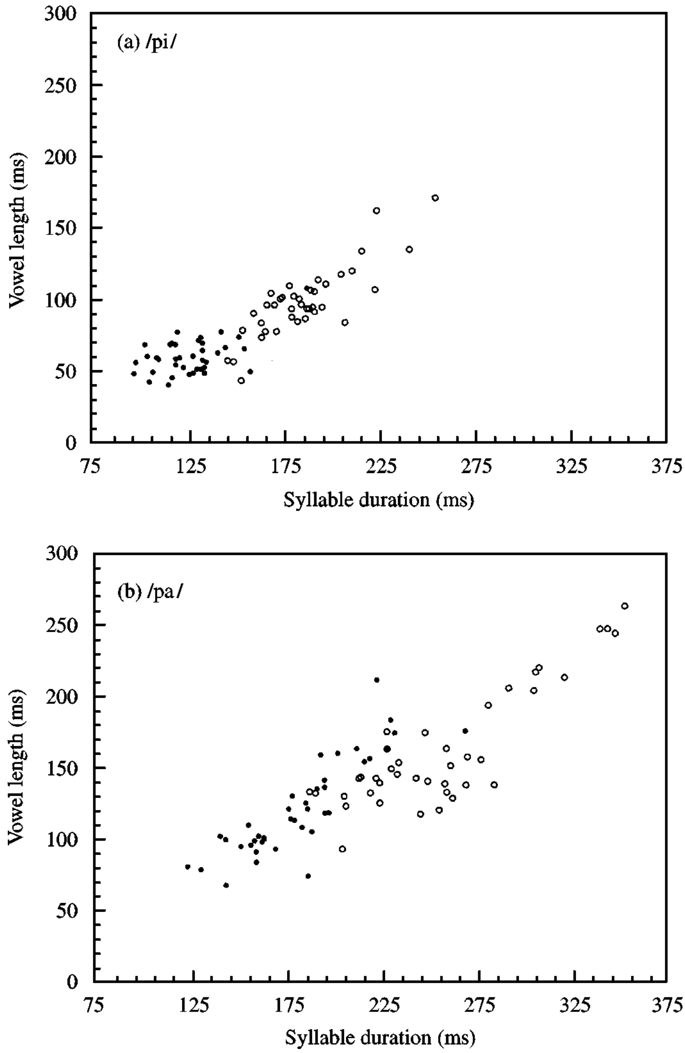

Figure 4. Vowel length for (a) /pi/ and (b) /pæ/ plotted as a function of syllable duration for both the slow and fast speaking rates (/pi/: $r = 0.866$, /pæ/: $r = 0.857$). The figure collapses across speaking rate for the two /pi/ words and the two /pæ/ words, respectively, resulting in 40 slow and 40 fast tokens in each frame. The filled squares represent tokens produced at the fast rate, and the unfilled circles tokens produced at the slow rate.

TABLE I. Relation between VOT and vowel duration

	Mean VOT (ms)	Mean vowel length (ms)	C/V ratio
/pi/ fast	66	60	1.10
/pi/ slow	91	95	0.96
/pæ/ fast	61	120	0.51
/pæ/ slow	100	157	0.64

VOT as speaking rate slowed. The increase in mean vowel duration as speaking rate slowed (35 and 37 ms, respectively, for /pi/ and /pæ/) is similar to that noted by Gay (1978). The mean VOT change as a function of speaking rate (25 to 39 ms, respectively, for /pi/ and /pæ/), however, is larger in the current study than that observed by Gay (1978), but is not inconsistent with other findings (cf. data from Lisker & Abramson, 1964). Specifically, Lisker & Abramson (1964) found that the mean VOT for word-initial /p/ in English was 30 ms shorter in running speech (fast) than in isolation (slow). Furthermore, Table I shows that within each of the two vowel environments the consonant/vowel ratio remained fairly stable across speaking rate, again indicating that both VOT and vowel duration increased in a similar manner as speaking rate slowed.

4. Conclusions and implications for perception studies

The current production study investigated the effect of speaking rate on the production of voice-onset time, vowel length, and overall CV duration for the English voiceless stop consonant /p/. In accord with evidence from previous studies (Kozhevnikov & Chistovich, 1965; Gay, 1978; Amerman & Parnell, 1981; Port, 1981), the present findings indicate that changes in speaking rate affect both voice-onset time and vowel duration: as speaking rate slowed, both VOT and vowel duration increased. The data also showed that the C/V ratio in each of the two vowel environments remained relatively constant across speaking rate.

The systematic increase in VOT and syllable duration as speaking rate slowed is consistent with previous research on voiceless stop consonants in English (Miller *et al*., 1986; Volaitis & Miller, 1992). As the present data show, however, the increase in syllable duration resulted not only from an increase in VOT, but also from increases in vowel length as speaking rate slowed. Consistent with Gay's (1978) findings and with data from Volaitis & Miller (1992), this further suggests that changes in syllable duration as a function of speaking rate do not result solely from an increase in voice-onset time, but rather are due to increases in both VOT and vowel length. In fact, as displayed by the mean VOT and vowel durations at the two speaking rates, increases in VOT and vowel were almost equally accountable for the increase in overall syllable duration as speaking rate slowed. Importantly, there is no evidence that VOT and vowel length vary inversely within any speaking rate such that as VOT increases, vowel length decreases.

The findings from the current and previous production studies have important implications for perception studies exploring the effects of speaking rate on VOT. Most particularly, they indicate that in order to provide a true test of speaking rate effects on perception, it is necessary to utilize stimuli that increase both VOT and vowel length. As indicated earlier, in most studies purporting to explore rate effects on the perception of VOT the two parameters vary inversely within each speaking rate such that as VOT becomes longer, vowel length is reduced. Namely, a lengthened VOT signals speech produced at a slow rate, but a shortened vowel signals speech produced at a fast rate. While the increases in VOT in these stimuli are consistent with slower speech, the concomitant decrease in vowel duration is not, and in fact is compatible with the opposite—namely a faster speaking rate. Thus, such stimuli provide potentially conflicting cues to listeners. While it is evident that VOT judgments and perception are affected when the duration of vowel length and VOT vary inversely, they cannot be considered measures of the effect of speaking rate on the perception of voicing. In fact, Utman (1998) has shown that when presented with stimuli in which VOT and vowel length vary inversely, listeners' identification responses and goodness judgments are based more on changes in the perception of the following vowel and not on the voicing of the initial stop consonant, particularly when the duration of the vowel may ultimately be reduced to one or two glottal pulses. Thus, the perception effects of VOT across speaking rate may have been due more to changes in vowel perception than to changes in voicing as a function of VOT.

Notably, perception experiments using stimuli in which VOT and vowel duration do not vary inversely fail to show robust shifts in the perception of voicing. Summerfield (1981), for example, investigated the effect of speaking rate on the perception of voicing using stimuli in which vowel length increased as VOT increased. Although perceptual effects on the VOT boundary did emerge, they were small, with only a 1.4 ms boundary shift, and the data were not tested for statistical significance. Moreover, the magnitude of the change in vowel duration as VOT increased in Summerfield's (1981) study was substantially smaller than that found in natural speech. More recently, in a study exploring the effects of speaking rate on voicing in Icelandic, Pind (1995) failed to find a VOT $\times$ Rate interaction using a series of synthetic stimuli in which the duration of the rime (VC) was increased as speaking rate slowed. In fact, Pind showed that the shift in the locus of the voicing phonetic boundary in the perception experiment was appreciably smaller than would be predicted from the production data. Additionally, there is some evidence that when stimuli are constructed in such a way that VOT and vowel length parameters are based on natural speech values, the perceptual effects of speaking rate on the perception of VOT disappear (Utman, 1998). Utman presented naturally produced exemplars of voiceless stop consonants in the context of syllables produced either at a slow or fast rate of speech. No effects of speaking rate context on the perception of VOT emerged in any of a number of perceptual tests, including phoneme discrimination, identification, and goodness ratings. Thus, studies that have used stimuli with more natural speech values or stimuli in which VOT and vowel length do not vary inversely, have found either reduced or no effects of speaking rate on the perception of voicing.

Nonetheless, it is still important to consider what the basis is for the perceptual shifts which have been shown to emerge when VOT and vowel length vary inversely. One possibility is that the VOT effects are due primarily to the duration changes in the vowel, particularly as they may change the relationships between normal duration values of consonants and vowels in syllables. In many studies examining the effects of speaking rate on perception, stimuli with the longest VOT values have the shortest vowels: stimuli representative of a fast speaking rate (with a syllable duration of 125 ms), for example, have VOTs ranging from 10 to 120 ms, resulting in vowels as short as 5 ms (Miller & Volaitis, 1989; Volaitis & Miller, 1992; Flege *et al.*, 1996). Thus, although the stimuli on the continuum are all of 125 ms duration and presumably "spoken" at the same rate, they include stimuli in which the voiceless stop has, for example, a VOT of 120 ms and a vowel of 5 ms, a VOT of 110 ms and a vowel of 15 ms, a VOT of 75 ms and a vowel of 50 ms. Not only is the relationship between consonant and vowel within these stimuli unnatural, but perhaps most importantly, these vowel duration differences will produce vowel stimuli that are noticeably different not only in their length but also in vowel quality, for example, [i] would sound like [I] at the shortest duration.

Perceptual effects of vowel duration on the preceding and following consonants has been shown in a number of experiments. These experiments indicate that changes in vowel duration affect not only the perceptual identity of the vowel (Ainsworth, 1972;

Gottfried, Miller & Payton, 1990), but also affect the perception of neighboring consonants (Summerfield, 1981; Luce & Charles-Luce, 1985). For instance, one acoustic cue for syllable-final stop consonants is the consonant/vowel ratio, and changes in the duration of the vowel are accountable for changes in the perception of final stop consonants (Port & Dalby, 1982; Luce & Charles-Luce, 1985). Interestingly, vowel duration in a CVC syllable also has been shown to affect the perception of word-initial stop consonants (Summerfield, 1981, experiment 5; cf. also Pind, 1995). Using four different vowel durations which were held constant as VOT was varied, Summerfield (1981) found that the voicing boundary between /b/ and /p/ shifted monotonically to longer VOT values as the duration of the vowel in the test syllables increased (cf. Pind, 1995, for similar results). These results suggest that vowel duration not only influences the perception of syllable-final stop consonants, but also can influence the perception of word-initial stops.

In sum, findings from studies using stimuli in which VOT and vowel length vary inversely are not necessarily attributable to perceptual effects of speaking rate on phonetic categorization, but rather may be due to other perceptual effects. In order to provide a true test of the effects of speaking rate on perception, it is necessary to utilize stimuli which more closely reflect the changes observed in production, where voice-onset time and vowel length do not vary inversely within a speaking rate, and where both voice-onset time and vowel length increase as speaking rate slows.

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