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How the Components of Speaking Rate Influence Perception of Phonetic Segments

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In two studies we investigated the way in which the components of speaking rate, articulation rate and pause rate, combine to influence processing of the silence-duration cue for the voicing distinction in medial stop consonants. First, we replicated the finding that the articulation rate of a carrier sentence, that is, the rate at which the speech itself is produced, influences how the duration information is used to assign voicing values. Second, and more importantly, the assignment of voicing values was also influenced by the pause rate of the sentence. Thus, the listener adjusts for both articulation rate and pause rate when processing the phonetically relevant information. Finally, the two rate components did not function in an equivalent manner, since changes in articulation rate had considerably more effect on phonetic judgments than did changes in pause rate. Alternative explanations for the relative weighting of the two variables are discussed.

It is well-known that there is a complex relation between the perceived phonetic segments of speech and the acoustic properties of the speech waveform that specify those segments. One reason for this complexity is that the acoustic properties that provide information for phonetic distinctions vary considerably with such factors as phonetic context, speaker, and rate of speech (cf. Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Studdert-Kennedy, 1976). A critical issue for any theory of speech perception is the specification of how the speech signal varies with particular contextual factors and how the listener processes the context-dependent information.

Most of the research on this issue has focused on the influence of phonetic context on the information specifying segmental distinctions. Recently, however, there has been increasing interest in the effects of prosodic factors on segmental contrasts, in particular, the effect that changing speaking rate has on the production and perception of speech. It has become apparent that speaking rate exerts a systematic influence on a variety of temporal (and possibly spectral) parameters and that the listener compensates for this variation when making phonetic judgments. (See Miller, in press, for a recent review of this literature.)

The segmental distinction that has been studied most extensively with respect to rate is that of voicing. For example, in a series of studies, Port (1976, 1978, 1979) examined the influence of rate on the production and perception of the voicing distinction in medial stop consonants, as in the contrast between *rabid* and *rapid*. More specifically, he studied two acoustic variables, the duration of intervocalic silence and the duration of the preceding vowel. As a consequence of the dynamics of speech production, a voiced stop

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typically has both a shorter closure duration and a longer preceding vowel than its voiceless cognate, and each of these acoustic parameters provides sufficient information for the perceived voiced–voiceless distinction: A relatively long closure duration specifies a voiceless consonant, whereas a relatively long preceding vowel specifies a voiced consonant (cf. Denes, 1955; House & Fairbanks, 1953; Lisker, 1957). Port (1976) found that as speaking rate increased, there was a decrease in the duration of the vowel and the duration of the silence for both voiced and voiceless medial stops. Moreover, at faster rates of speech, relatively less silence was required to hear the voiceless, as opposed to the voiced, consonant; the perception of vowel duration as a function of rate was not measured (Port, 1976, 1978, 1979). A similar pattern of results for another voicing cue, voice onset time (VOT), was reported by Summerfield (1975). Concentrating on initial rather than medial consonants, he showed that VOT decreased at faster rates of speech and, furthermore, that a lower VOT value was sufficient to cue the voiceless stop at faster rates of speech.

To study the influence of speaking rate on segmental processing, most investigators have manipulated the rate of a carrier sentence containing the phonetic contrast of interest (e.g., Minifie, Kuhl, & Stecher, 1976; Pickett & Decker, 1960; Port, 1976; Summerfield, 1975).[1] In natural conversation, a change in sentence rate typically involves both a change in articulation rate, the rate at which the speech itself is articulated, and a change in pause rate (Goldman-Eisler, 1968; Lane & Grosjean, 1973). However, in the studies of phonetic perception, the carrier sentences were relatively short and contained no pauses. Since the change in overall sentence rate was due entirely to a change in articulation rate, the role of pauses remains unknown. That is to say, when making a phonetic judgment, does the listener adjust only to the rate of the speech itself, ignoring pauses, or alternatively, does he or she adjust to both articulation rate and pause rate?

In an attempt to answer this question, we designed an experiment on the perception of the silence duration cue for voicing, in which we changed overall rate of the carrier sentence by independently manipulating articulation rate and pause rate. This design dissociates articulation rate and pause rate from their natural covariation with the overall rate, thereby permitting us to assess whether both aspects of rate influence the voicing judgment.[2]

Experiment 1

Method

Subjects. Fourteen undergraduate students with no history of speech or hearing disorders served as subjects in this experiment. All were volunteers who were paid for their participation.

Materials. Following the lead of Port (1976), we concentrated on the silence duration cue for voicing in medial stop consonants and, in particular, on the contrast between *rabid* and *rapid.* We chose a carrier sentence that was semantically appropriate for both words and that was syntactically appropriate for a variable number of internal pauses—*Actually, the tiger, that the man, had to chase, was rabid/rapid* (cf. Grosjean & Collins, 1979). To obtain the experimental sentences, we asked a male speaker to produce numerous instances of this sentence (*with rabid*) at various articulation rates and pause rates. The variation in articulation rate was accomplished by a magnitude production technique that required the talker to produce rates ranging from approximately half of his normal rate to double his normal rate. To vary pause rate, the talker produced this range of articulation rates for three different pause structures: no pauses, two pauses (after *tiger* and *chase*), and four pauses (after *actually, tiger, man,* and *chase*), which correspond to fast, medium, and slow pause rate, respectively. Having the speaker himself produce the change in pausing ensured that those prosodic features that normally covary with pauses (e.g., intonation con-

[1] Perceptual effects have also been obtained by altering only the rate of the syllable containing the target phone, and, in fact, it has been shown that the rate of the target syllable has a more powerful influence on a phonetic judgment than the rate of adjacent context (e.g., Miller & Liberman, 1979; Port, 1978).

[2] It is important to keep separate the two different types of silence we have mentioned, pauses and closure duration. Pauses are the relatively long silences, inserted by speakers between words at various points in a sentence (or between sentences), especially at slower rates of speech. Distinct from these pauses are the relatively short silences in the speech signal that are the direct consequence of closure during the production of stop consonants. These silences are an integral part of the acoustic information specifying segmental distinctions and should be treated as any other acoustic cue.

Table 1
Overall Sentence Rate, Articulation Rate, and Pause Rate in Experiment 1

Sentence	Rate		
	Overall	Articulation	Pause
A_fP_f	.163	.163	.000
A_fP_s	.397	.183	.214
A_mP_m	.266	.212	.054
A_sP_f	.241	.241	.000
A_sP_s	.490	.276	.214

Note. Data are given in seconds per syllable for the five carrier sentences excluding the word *rabid.* A = articulation rate; P = pause rate; s = slow; m = medium; f = fast.

tour, prepausal lengthening) were appropriate for the pause structure of the sentence. Approximately 100 sentences were produced in all.

Five sentences that contained no hesitations or other aberrations were chosen from the set of 100 sentences for editing. They had the following characteristics: medium articulation rate and medium pause rate (A_mP_m), fast articulation rate and fast pause rate (A_fP_f), fast articulation rate and slow pause rate (A_fP_s), slow articulation rate and fast pause rate (A_sP_f), and slow articulation rate and slow pause rate (A_sP_s). The articulation rates aimed for were .172, .204, and .250 sec/syllable for fast, medium, and slow, respectively.[3] These values were based on earlier studies of speech production (Grosjean, 1972; Grosjean & Deschamps, 1975; Lane & Grosjean, 1973) and represent the average speaking rate and two standard deviations above and below average. From our corpus we chose those sentences that had rates closest to these target values. The actual articulation rates of the five sentences, as well as their pause rates and overall rates, are given in Table 1.

As indicated above, the variation in pause rate was due to an alteration in the number of pauses in the sentence—zero, two, or four. In addition, however, the pause durations were modified so that the resultant pause rates would, as far as possible, be in accord with pause rates found in the production studies cited above. Specifically, the average pause rate across those studies was chosen as the medium pause rate, two standard deviations above the average pause rate as the slow pause rate, and no pauses as the fast pause rate. (See Table 1 for the actual pause rates of the five sentences.) To modify the pause durations, we first digitized each of the sentences (10-kHz sampling rate with 5-kHz low-pass filtering) and then used an editing program to change the pause durations of the three sentences that contained pauses. (The two sentences that did not contain pauses were not altered.) In changing the pause durations, we distributed the total pause time allotted to a sentence according to the average distribution of pause time across 10 readings of the sentence by the talker. Specifically, pause time was evenly distributed across the two pause slots in the medium-rate sentence (each pause was .35 sec in duration), and, for each of the two sentences with four pauses, the percentage of total pause time per pause was 23, 24, 25, and 28, going from left to right in the sentence. (Actual pause durations were .65, .66, .69, and .78 sec, respectively.) Thus, whereas the variation in articulation rate was entirely naturally produced, the variation in pause rate was the joint result of naturally produced variation in the number of pauses (and accompanying prosodic features) and edited pause duration.

Computer editing procedures were used to generate the final test series in the following manner. First, the word *rabid* was removed from each of the five carrier sentences at a zero crossing in the waveform. Next, for the *rabid* from the medium-rate sentence, the closure interval was excised and in its place was inserted a variable amount of silence. Specifically, the silence duration was varied from 35 to 100 msec, in 5-msec steps, to create a 14-member series that varied from *rabid* to *rapid.* Finally, each of these 14 tokens was attached to each of the five versions of the sentence, yielding 70 sentences in all. Experimental tapes were created by recording five different random orders of these 70 sentences, with successive sentences separated by 3 sec of silence.

Procedure. Each subject was presented all five random orders on each of 4 days of testing, yielding a total of 20 responses to each of the 70 sentences per subject. The subject's task was to provide for each sentence a rating of the target consonant from one to six. Subjects were instructed that one indicated a very clear /b/ and six a very clear /p/, that two and five indicated a less clear /b/ and /p/, respectively, and that three and four signified a borderline /b/ and /p/, respectively. The stimuli were presented over earphones at a comfortable listening level (approximately 78 dB [SPL] measured for the first syllable of *rabid*).

Results

To obtain a summary measure of performance, we calculated for each subject the mean /b–p/ rating across the 14 tokens of each of the five sentences. Averaged across subjects, the mean ratings were: A_mP_m = 3.68, A_fP_f = 3.88, A_fP_s = 3.96, A_sP_f = 3.70, and A_sP_s = 3.58.[4] Given the rating scale

[3] Rate is typically defined in terms of units/time. However, we have elected to define rate in terms of time/units to facilitate a comparison of articulation rate and pause rate. Specifically, we define articulation rate as average speaking time/syllable and pause rate as average pause time/syllable.

[4] To assess the range of the effect in terms of the /b–p/ category boundary shift, we also used linear interpolation to estimate the duration of intervocalic silence at a rating equal to 3.5 for each group rating function. (Recall that a rating of three signified a borderline /b/ and a rating of four, a borderline /p/.) These values, in milliseconds of silence, were A_mP_m = 64.3, A_fP_f = 62.3, A_fP_s = 60.6, A_sP_f = 65.4, and A_sP_s = 66.3. Thus, the lowest and highest values differed by about

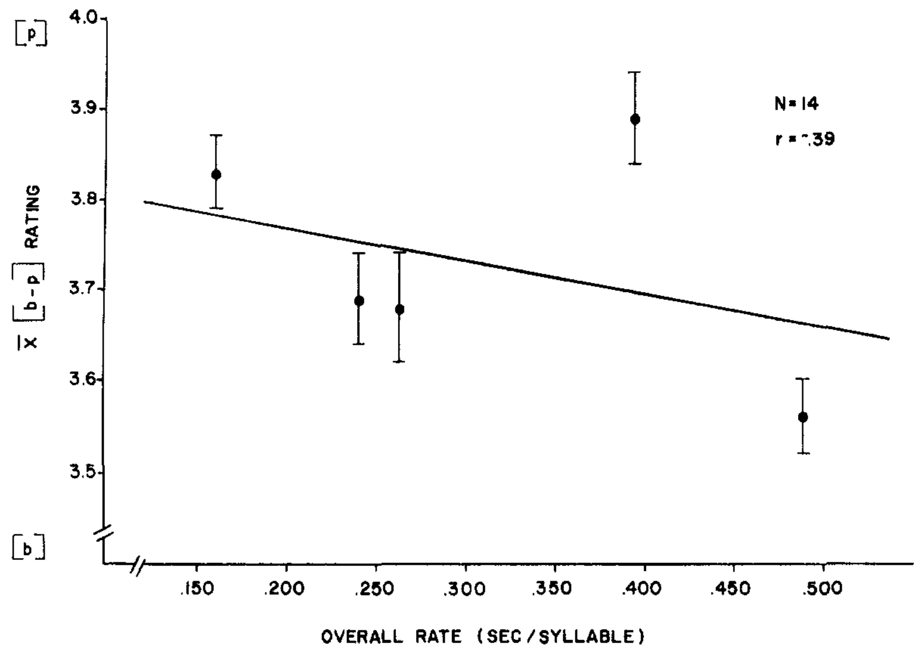

Figure 1. Mean /b–p/ rating as a function of overall sentence rate for the five sentences in Experiment 1. (Bars indicate 1 *SE* on either side of the mean.)

used, a lower /b–p/ rating indicates more /b/-like judgments across the series, and a higher /b–p/ rating indicates more /p/-like judgments. From previous research, we would predict that at slower rates of speech, more silence would be required to hear the voiceless stop, resulting in more /b/-like ratings (especially for stimuli near the /b–p/ category boundary) and, consequently, a lower overall rating for the series.

Consider first the relation between overall sentence rate and the voicing judgment. From Figure 1, it is apparent that overall rate was not systematically related to mean /b–p/ rating and, indeed, the correlation between the two variables was low (−.39) and not significant ($p > .10$). On the other hand, as can be seen from Figure 2, articulation rate alone was a relatively good predictor of mean /b–p/ rating: The slower the rate (the more time per syllable), the lower the rating, with a −.91 correlation between the two variables ($p < .05$). Moreover, there was a stronger correlation between articulation rate and voicing judgment than between overall rate and voicing judgment for 13 of the 14 listeners ($p < .002$ by a sign test). Finally, there was an extremely low correlation (−.08, $p > .10$) between pause rate alone and mean /b–p/ rating.

The data clearly show that the best predictor of voicing judgments was not overall rate, which treats pause time and articulation time equally, but articulation rate itself. This means that changing sentence rate by stretching and compressing the speech and by altering pause time were not equivalent. Rather, a change in the actual amount of time spent articulating had far greater influence than did a comparable change in the amount of time spent pausing. In fact, it is not clear from the present results whether pause rate had any systematic effect on the voicing judgments. Indeed, it may be that phonetic judgments are sensitive only to articulation rate and that pauses play no role. Alternatively, however, it may be that pause rate does exert some small influence on phonetic judgments but that the influence of pause rate was obscured in the present experiment by the large effect of articulation rate.

To determine more directly whether pause rate alone can influence voicing decisions, we conducted a second experiment in which we

6 msec, which is in close agreement with a shift of about 8 msec reported by Port (1979).

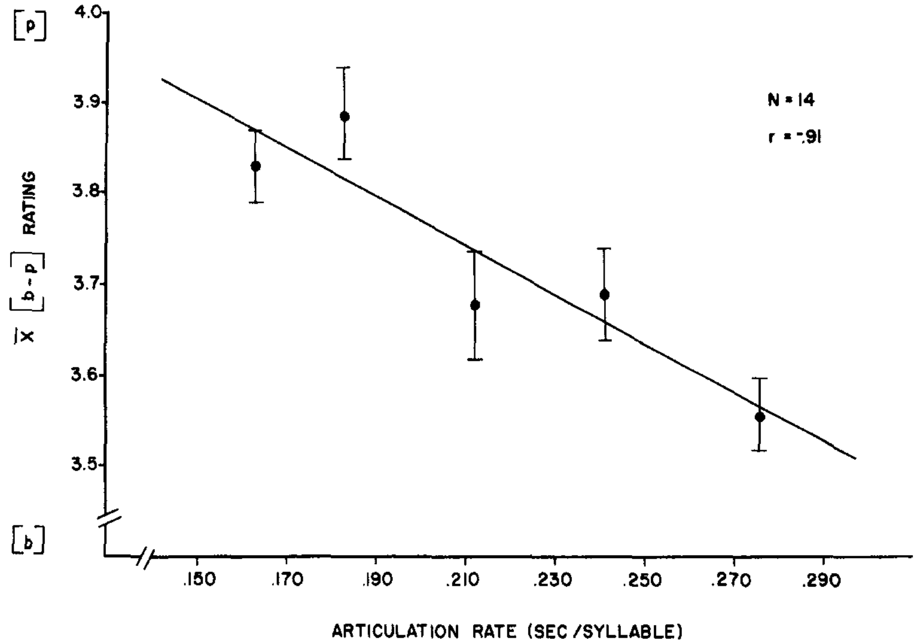

Figure 2. Mean /b–p/ rating as a function of articulation rate for the five sentences in Experiment 1. (Bars indicate 1 *SE* on either side of the mean.)

manipulated only pause rate by varying the pause time of a single naturally produced sentence. This procedure allowed us to assess whether the identical stream of speech, with different amounts of pausing, would differentially influence the /b–p/ judgment.[5]

Experiment 2

Method

Subjects. Seven undergraduate students with no history of any speech or hearing disorders were paid for their participation in this experiment. None had served as listeners in the previous study.

Materials. Three carrier sentences were used in this study. Two, A_mP_m and A_sP_s, were from the first study and were included as a test of the replicability of the finding that voicing judgments are affected by a change in sentence rate from medium to slow. To test for the effects of pauses, per se, a third sentence was created by deleting all pause time from sentence A_sP_s. This resulted in a sentence with a slow articulation rate and a fast pause rate, A_sP_f' (as distinguished from sentence A_sP_f from the first study).[6] Note that the original sentence, A_sP_s, and the modified sentence, A_sP_f', had the identical speech but radically different pause rates, permitting the evaluation of the role of pauses in voicing judgments.

Each of the three carrier sentences was attached to each of the 14 tokens of the *rabid–rapid* series, resulting in a total of 42 experimental sentences. Six different randomizations of these 42 sentences were recorded, with an intersentence interval of 3 sec.

Procedure. On each of 3 days of testing, the subjects listened to all six random orders, yielding a total of 18 responses to each of the 42 sentences per subject. In contrast to the first experiment, subjects were instructed to simply identify each target word as either *rabid* or *rapid*.[7] Stimuli were presented over earphones at a comfortable listening level, as in the previous study.

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[5] It is not possible to assess the influence of pauses by comparing sentences A_fP_f and A_fP_s or sentences A_sP_f and A_sP_s because the two sentences within each pair did not have the identical articulation rates (see Table 1). Consequently, any difference in /b–p/ rating could have been due to a difference in articulation rate, rather than to a difference in pause rate. Furthermore, we should point out that even if the articulation rates of the two sentences of a given pair had been identical, differences in articulation rate across different parts of the sentence may have resulted in differential effects on the /b–p/ rating (cf. Summerfield, Note 1), obscuring any possible small effect due to pause rate. It is because of such inherent variability in naturally produced sentences that we chose in Experiment 2 to alter the pause time of a single sentence.

[6] A consequence of deleting all pause time from the original sentence was that even though there were no pauses in the new sentence, the prosodic structure still specified pausing. If anything, however, this should have reduced the probability of finding a differential effect of these sentences on the voicing judgment.

[7] The reason for the change in task was that in the second experiment, listeners not only judged the voicing of the target consonant but also used a rating scale to estimate the apparent rate of the sentences. Asking subjects to give a binary /b–p/ response, rather than a rating of 1–6, eliminated any possible interference caused by performing two different rating tasks on sentences within a single session. The results of the rate estimation task are presented in the General Discussion.

Results

The summary measure of performance in this study was the /b–p/ phonetic boundary location on the *rabid–rapid* series attached to each of the three carrier sentences. These boundaries were calculated for each subject by first transforming the percentage data into z scores and then fitting a straight line to the transformed scores using a least mean squares solution, taking as the boundary that value at which $z = 0$. The three boundaries, in milliseconds of silence duration, averaged across subjects, were $A_mP_m = 61.2$, $A_sP_f' = 62.7$, and $A_sP_s = 64.9$. We should note that a higher boundary value signifies more /b/ responses across the series and is thus analogous to a lower /b–p/ rating in the first experiment.

The individual boundary values were entered into a repeated measures analysis of variance that showed a highly significant effect of carrier sentence, $F(2, 12) = 24.58$, $p < .001$. Post hoc analyses revealed first that the boundary for sentence A_mP_m was reliably different from that of sentence A_sP_s ($p < .01$); thus, the finding in Experiment 1 that the shift in voicing perception as rate was changed from medium to slow was replicated in this experiment. Second, and most important, the analyses revealed that sentences A_sP_s and A_sP_f', which had identical articulation rates, also had reliably different boundary values ($p < .01$). Thus, a change in pause rate alone affected the voicing boundary.

General Discussion

Our experiments provide yet another demonstration that phonetically relevant acoustic information, namely, the silence-duration cue for the medial-voicing distinction, is processed in relation to the rate of the sentence in which it occurs. More importantly, they have shown that the effective rate information includes both the articulation rate—the rate at which the speech is produced—and the pause rate. Consequently, any complete theory of the listener's adjustment for rate during phonetic processing will have to account for the role of pauses as well as the role of speech rate per se.

Our data indicated that when the two components of rate combine to influence the voicing judgment, they are not weighted equally, but rather that changes in articulation rate carry considerably more weight than do changes in pause rate. An important task for future research is to determine the underlying basis of this relative weighting of components. We can suggest three alternative explanations that should be investigated further.

First, it may be that listeners adjust more for articulation rate than for pause rate because they tacitly know that articulation rate, but not pause rate, directly affects the way in which the medial stop is articulated. More specifically, the listener is attuned to the fact that when articulation rate is changed, the closure duration of the medial stop is necessarily modified (cf. Port, 1976), whereas a change in pause rate does not necessarily alter the production of the consonant. Accordingly, the listener is especially sensitive to articulation rate when taking a particular value of silence duration as specifying a voiced versus voiceless stop.

A second possible explanation of the obtained result is based on the role of apparent speaking rate. Grosjean and Lane (1974, 1976) have found that when judging apparent rate, listeners use information about both articulation rate and pause rate and, moreover, that articulation rate is by far the more important variable. This of course mirrors the pattern obtained in the current experiment on phonetic judgments and raises the possibility that articulation rate played a greater role than pause rate in our study because the listeners adjusted for the apparent speaking rate when processing the silence information.

If listeners indeed adjust for apparent speaking rate, then we would expect that judgments of apparent rate and phonetic adjustments for rate would be highly correlated. To test this prediction, we asked seven of the listeners who participated in Experiment 1 to return for an additional session in which they used a magnitude estimation procedure to judge the apparent rate of the five experimental sentences (cf. Grosjean & Lane, 1976). The correlation between mean /b–p/ rating and estimate of rate was high (.92, $p < .05$). Similarly, the listeners in Experiment 2 provided rate estimates of the three sentences tested in that study, yielding a correlation of $-.99$ ($p < .05$) between phonetic boundary location and estimate of rate. These results are consistent with the hypothesis that when processing segmental information, the listener adjusts for apparent speaking rate, which is primarily a function of articulation rate and secondarily a function of pause rate.[8]

Finally, it may be that articulation rate was more influential than pause rate in our study not because of the nature of the two variables per se but because of the way in which they were combined in our particular sentences. That is, throughout this article we have defined rate over the entire carrier sentence. However, the listeners did not necessarily adjust for the rate of the entire sentence when processing the silence-duration cue. Related studies have shown that listeners tend to give increasingly more weight to those portions of the sentence in closer proximity to the target (e.g., Summerfield, Note 1). It is possible, then, that in our study, articulation rate was found to be more influential than pause rate because only the local context was taken into account, and the rate of the syllable adjacent to the target word, *was,* had more influence than the pause before the syllable *was.* We should point out, however, that since the earlier studies on the proximity effect did not use carrier sentences that contained pauses, their relevance to the current experiment is not straightforward. In particular, we do not know whether the proximity effect operates over sentences with interspersed speech and pauses in the same way it does over sentences with only speech. Clearly, determining the validity of this interpretation will involve an extended investigation of the effective domain for the influence of rate, the relative weighting given to various parts of the sentence within this domain, and the extent to which these interact with the speech–pause structure of the sentence. It should be emphasized that the issue of the domain over which rate is effective is important in its own right, apart from its possible role in accounting for the present finding.

In summary, we found, as have others before us, that the listener adjusts for speaking rate when using durational information to specify a phonetic distinction. Furthermore, we demonstrated that both components of overall rate, articulation rate and pause rate, comprise the effective rate information for the listener. Finally, our data indicate that the two components of rate do not carry equal weight, but rather that articulation rate has considerably more influence than pause rate. Future research must determine the reason for the relative weighting of the two components, as well as address the related question of the domain over which effective information is defined.

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[8] Grosjean and Lane (1974, 1976) suggest that the relative weight given by listeners to articulation rate and pause rate when estimating apparent rate may reflect the fact that speakers change pause rate considerably more than articulation rate when modifying overall rate of speech (e.g., Grosjean, 1972; Lane & Grosjean, 1973). According to this view, the listener, by assigning more weight to a given unit of change in articulation rate than in pause rate, is compensating for the pattern of change in production. (For an extended discussion of this issue, the reader is referred to Grosjean & Lane, 1976.)

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