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The syllable's rhyme affects its P-center as a unit

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The P-center, or psychological moment of occurrence, of a syllable does not correspond to any obvious acoustic marker in the speech signal, nor can it be determined solely with reference to the phonetic composition of syllable. Syllable structure however, does play a role in explaining this timing phenomenon. It has been well established that the duration of the syllable onset (i.e., of the prevocalic consonants) behaves as a unit in its effect on P-center location; the same has been proposed for the syllable rhyme, although previous evidence on this point has been insufficient. The present two experiments confirm that the syllable rhyme behaves as a unit in its effect on P-center location, with a magnitude much less than that of the onset. Algorithms based only on an acoustic center of gravity cannot account for the present data. We conclude that descriptions of P-center location in speech stimuli must make crucial reference to the phonological structures, onset and rhyme, together with the duration of their acoustic realizations.

1. Introduction

A wide array of research has shown that the perceptual moment of occurrence (P-center) of a syllable does not correspond to any obvious acoustic marker in the speech signal (Rapp, 1971; Allen, 1972; Morton, Marcus & Frankish, 1976; Marcus, 1976, 1981; Cooper, Whalen & Fowler, 1986). Nor is it sensitive to the phonetic quality of vowels (Fox & Lehiste, 1987) or the number of syllable-initial consonant (Cooper *et al.*, 1986). It is, however, affected by the duration of syllable-initial consonants and, to a lesser extent, by the duration of subsequent segments (Marcus, 1981; Cooper *et al.*, 1986). Marcus (1981) proposed a two-parameter model to account for these findings. Specifically, his

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model divides the syllable into onset and rhyme (a phonological distinction) with a separate weighting factor applied to the acoustic durations of each of those components.

While the relevant data in the literature are in general agreement with Marcus's description of P-center location, support for collapsing the vowel and following consonant of the rhyme into a unit is weak. It consists of a comparison across experiments (numbers 3 and 4 of Marcus, 1981) and the effect of a single manipulation in another (Experiment 8 of Marcus, 1976). In the first case, the effect on the P-center of lengthening a vowel was about the same as that of changing the closure for a final stop. In the second case, a change in vowel duration of the word "one" had an almost identical effect on P-center location as an equal change in the duration of the nasal murmur. The predicted changes matched the actual P-center measurements within a few milliseconds. While the differences between predicted and actual changes were rather small in magnitude, they translate into errors of −41% to +38%. To be confident that variations in different components of the rhyme are interchangeable in their effects on the P-center, we need to enhance manipulations of rhyme constituents so that differences can be easily found.

Note that while Marcus (1981) describes his theory as an acoustic one, its division of a syllable into its initial consonant(s) on the one hand, and the vowel and following consonant(s) on the other, is phonological.[1] Thus, Marcus's theory is best described as one that uses the acoustic durations of the phonologically defined units, onset and rhyme. From this perspective, Marcus's conclusion that members of the rhyme are interchangeable in their effects on the P-center is interesting because it provides independent justification for the rhyme as a unit of the language. However, for reasons we have given, the conclusion may be premature.

Other proposed accounts of the P-center treat the entire signal as a unit. The threshold model of Vos and Rasch (1981), for example, requires only that amplitude envelopes pass a certain intensity threshold with respect to the peak intensity of the signal. This account however, does not handle P-center experiments in speech where manipulations of the signal after the intensity peak change the P-center. Howell (1984, 1988) attempts to use only the midpoint of the amplitude envelope (the center of gravity) to describe a syllable's timing characteristics. This approach however, fails to account for previously published results (cf. Fowler, Whalen & Cooper, 1988). Nevertheless, it seems possible that a revised acoustic center-of-gravity algorithm that weights the earlier part of the signal more heavily than the latter part, might provide a better account for the published data. For weighted center-of gravity algorithms, changes in segment durations would have less impact the farther those changes are from the acoustic onset of an utterance. We will test three versions of center of gravity accounts: (1) unweighted, (2) weighted by a linearly falling amplitude decrement over the entire utterance, and (3) weighted by a linearly falling amplitude decrement over the last half of the

[1] Marcus attempts to reduce this division to an acoustic one, defined as "the most rapid increase in energy in the region of the first two formants" (1981, p. 253). This delimitation however, is only valid for syllables produced in isolation, and would probably fail even in some of those cases. As an example of the difficulties the definition would face in broader contexts, consider Mermelstein's (1975) automatic segmentation procedure. This reasonably successful algorithm not only depends explicitly on phonological rules to help predict how many syllables ought to have been in the utterance, but it also requires the inclusion of *higher* frequencies to determine the boundary between liquids and vowels. [Other automatic segmentation systems exist, but Marcus's algorithm would not be relevant to most of them. Most approaches to automatic speech recognition, including Marcus's (e.g., 1985), do not retain real-time information, which is critical for Marcus' algorithm.]

utterance.[2] (These versions will be called untapered, tapered, and half-tapered, respectively.) The untapered version predicts that changes in segment durations will be equally effective in all positions. The two tapered versions, however, predict that changes in the duration of utterance-initial segments would have a larger effect on P-center location than the same changes in non-initial segments. In Experiment 1 we test these predictions (including the onset-rhyme proposal) directly. In Experiment 2 we look for firmer evidence that the rhyme is, in fact, a unit.

2. Experiment 1

The purpose of the first experiment was to determine whether the weak effect of vowels on P-center location (Marcus, 1981; Cooper *et al.* 1986) is due to their syllable constituency (in the rhyme rather than in the onset of the syllable), or instead, to their distance from the acoustic onset of a syllable. Two continua were used in which vowel duration was varied. The continua were identical except for the presence or absence of a syllable-initial consonant. According to the onset-rhyme proposal, the effect of vowel duration should be equal and weak in both continua because the vowel is always in the syllable rhyme. In the tapered center of gravity proposals, the effects of vowel duration should be stronger without than with an initial consonant because the vowel with an initial consonant is farther away from the acoustic onset of the syllable.

2.1. *Method*

2.1.1. *Stimuli*

The stimuli consisted of two continua (/a/ and /sa/) in which vowel duration was varied. Using the pulse-code-modulation system at Haskins Laboratories, a seven-step acoustic continuum was created by excising successive pairs of pitch pulses from a digitized naturally spoken /a/ syllable 534.3 ms in duration. One pitch pulse, located 201.2 ms into the vocalic segment, was excised from the original syllable to create the initial stimulus of the continuum. This location was both within the steady-state portion of the vowel and beyond the peak intensity of the vowel. Six additional members of the continuum were made by excising pairs of pitch pulses from 7.7–7.9 ms in duration. A total of 102 ms was excised to create the final stimulus of the continuum.

The second continuum was created by appending the frication of a natural spoken /sa/ syllable, totaling 201.5 ms in duration, to the beginning of each member of the continuum described above. The authors perceived all of the resulting /sa/ syllables as natural. The lack of transitions on the vowel in /sa/ may have caused the syllables to lose coherence after repeated presentation, but the subjects were instructed to stop listening whenever this happened (see below).

[2]Two different methods were used to compute the center of gravity. In the first method, the rectified amplitude of the pressure waveform was summed up, and then the location in the signal at which half of that amplitude came before and half after, was established as the center of gravity. In the second method, the waveform was first rectified and then low-pass filtered at 50 Hz, resulting in an amplitude envelope (as outlined in Fant, 1959, and urged by Howell, 1984). Again, the center of gravity was established at the midpoint of the amplitude envelope. The difference between the two methods ranged from -1.0 ms to 0.6 ms, with a mean of -0.1 ms for the present stimuli. (For stimuli which include infinite peak clipping, such as in Fowler *et al.*, 1988, the difference is even less.) For computational simplicity, the first method of computing the center of gravity was chosen.

2.1.2. *Procedure*

The experiment consisted of an alignment test (cf. Marcus, 1981; Cooper *et al.*, 1986) designed to measure the relative P-center location of the test stimuli. Listeners heard syllable pairs played in a continuous sequence under computer control. The temporal position of the second syllable relative to the first was adjustable within a 1400 ms window. Each of the stimuli was paired with a reference syllable, /ba/ (329 ms in duration). Initially, on each trial there was a 50 ms gap between the offset of the first syllable and the onset of the other. The listener's task was to adjust the timing of the sequence until it was perceived as isochronous. Listeners adjusted the second syllable in steps of 15 ms, 5 ms of 1 ms in either direction, relative to the fixed syllable by pressing designated keys on a computer terminal keyboard. When they were satisfied with an adjustment they pressed the carriage return, thereby ending the trial. Twelve alignment measures were obtained for each member of each continuum in random order.

Under the conditions of this experiment, with syllables presented repeatedly, listeners occasionally experienced streaming of the consonantal segments from the vocalic segments of the stimuli, or other transformations, so that the stimuli no longer sounded like speech. Listeners were instructed not to make judgments under these conditions. Rather, they were to stop the sequence, wait a few minutes, and then resume listening.

2.1.3. *Subjects*

Three subjects participated in the experiments. One subject (MRS) was naive as to the purposes of the experiment. The other two subjects were two of the authors. These were the same subjects from Cooper *et al.* (1986) who had shown reliability in their adjustments in those experiments (traits that were not exhibited in pre-tests on naive subjects).

2.2. *Results and discussion*

Figure 1 shows the mean results of the alignment test for each subject. The abscissa represents the duration of the pitch pulses excised from the vowel (in milliseconds). The ordinate represents the displacement from acoustic isochrony of the test stimuli relative to the reference syllable in milliseconds. This measure is the interval from the acoustic onset of the reference syllable to the acoustic onset of the test stimulus minus one half of the window size. Thus, this measure would be zero for stimuli aligned at their acoustic onsets. As the offset from acoustic isochrony increases, the P-center shifts earlier in the stimulus and vice versa. In order to facilitate comparison of the continua, the measure for /sa/ syllables was taken at the onset of the vocalic segment rather than at the onset of the fricative noise.

The general increase in the functions indicates that, as expected, the P-center is judged to occur earlier as the duration of the vowel decreases, that is, as the duration of the excised segment increases. Separate analyses were performed for each listener because an overall analysis of variance with listener as a factor showed an interaction between continuum type and listener. For each listener, analyses had the factors continuum type (/sa/ vs. /a/) and vowel duration.

Listener MRS [Fig. 1(a)] showed significant main effects for both continuum type ($F(1, 154) = 12.16, P < 0.001$) and vowel duration ($F(6, 154) = 6.92, P < 0.001$), but no interaction between the factors ($F < 1$). The mean offset from isochrony for the /sa/ continuum was -6 ms and for the /a/ continuum, -13 ms. A linear trend test on the effect of vowel duration was highly significant ($F(1, 154) = 30.84, P < 0.001$). As

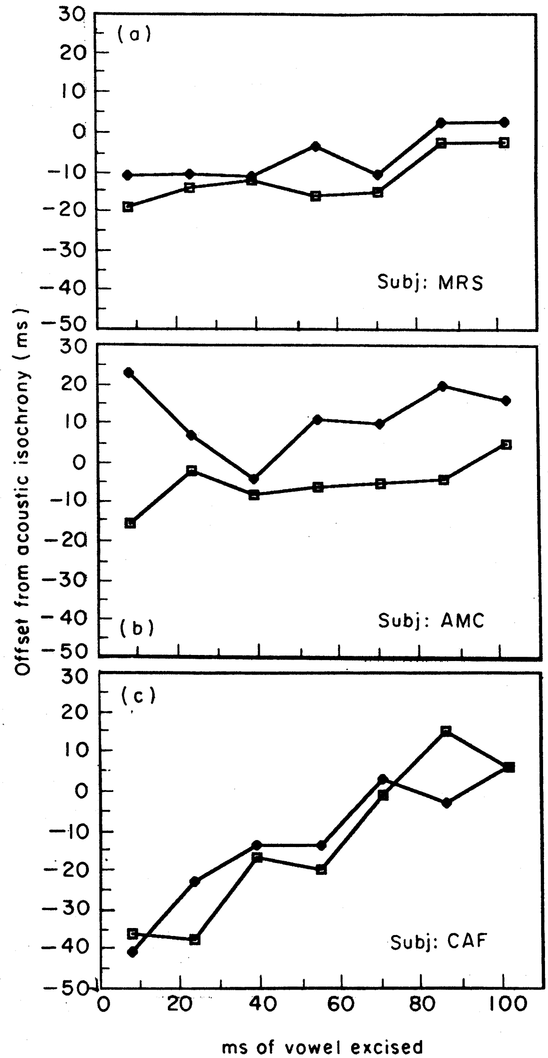

Figure 1. Mean P-center alignment functions for the three subjects in Experiment 1. Measurements for /sa/ (—◆—) are made from the onset of voicing, making them more comparable to /a/ (□) judgments.

stimulus duration decreased, the P-center was perceived earlier in the syllable by 17 and 14% of the change in vowel duration for the /a/ and the /sa/ continua, respectively.

Listener AMC [Fig. 1(b)] showed a significant difference between continuum types ($F(1, 154) = 16.5, P < 0.001$), but no effect of vowel duration and no interaction. The mean offset from isochrony for the /sa/ continuum was 12 ms and for the /a/ continuum, −6 ms. A linear trend test applied to the duration factor proved to be non-significant ($F(1, 154) = 2.21, P = 0.13$).

Listener CAF (Fig. 1(c)] showed no significant difference between the /sa/ and the /a/ continua. There was an effect of vowel duration ($F(6, 154) = 7.79, P < 0.001$), but no interaction. A linear trend test on the effect of the vowel duration was highly significant ($F(1, 154) = 44.5, P < 0.001$). As stimulus duration decreased, the P-center was perceived earlier in the syllable by 40 and 46% of the change in vowel duration for the /a/ and the /sa/ continua, respectively.

The main effect of continuum type is in the direction predicted by Marcus's model (1981). The base line for the function was shifted (for two of three subjects) by the addition of an initial consonant. However, the size of the shift was much smaller than that predicted by Marcus. His model predicts a 70 ms difference between the continua while the obtained differences were 7, 18 and 0 ms for MRS, AMC, and CAF, respectively. (Some of the fricative noise may have been below the amplitude threshold required for inclusion, but even if half of the noise were excluded from the P-center computations, Marcus's prediction only decreases to a 25 ms difference between continuum types, which is still too large.) According to the center of gravity models, the difference between the continua is small, due to the low amplitude of the fricative noise. The untapered version predicts a 4 ms difference between the continua, the tapered version, a 6 ms difference, and the half-tapered version, a 25 ms difference. For this effect, a version of the center of gravity measure fits the data reasonably well. Thus, in this instance, modified center of gravity accounts and the onset-rhyme account, both come close to predicting the outcome of the experiment. Since the modified center of gravity accounts underestimate the differences and the onset-rhyme account overestimates them, it should be possible to differentiate the two models further.

No subject shows an interaction of continuum type with vowel duration. This finding indicates that the effect of vowel duration on P-center location, where present, is not affected by the temporal position of that vowel within a stimulus. This is predicted by the onset-rhyme account because a vowel is in the syllable rhyme whether it is syllable-initial or not. However, distance from acoustic onset does play an important role for the tapered center of gravity accounts. The reason this did not show up clearly in this experiment is the low amplitude of the fricative noise, which left the vowel as the primary determinant of the center of gravity. Experiment 2 will distinguish between these theories in a different way.

A final outcome of interest in Experiment 1 is the presence of substantial individual differences across subjects. AMC showed no shift in P-center location across either continuum, MRS showed the expected very weak effect and CAF shifted the P-center by 40 and 46% of the change in vowel duration for the /a/ and /sa/ continua, respectively. Fox and Lehiste (1987) report analogous differences among speakers asked to produce isochronous syllable pairs that differed in inherent vowel duration. The variability in the present experiment contrasts sharply with measures from the same subjects on stimuli differing in prevocalic segments (Cooper *et al.*, 1986). There we found a one millisecond shift in P-center location for each millisecond change in initial consonants or consonant cluster duration for all three of the subjects. Similarly, Marcus (1981) found a high degree of uniformity in subjects' P-center judgments for the digits 1–9, leading him to use only himself as a subject in later experiments (including his experiments involving manipulations of vowel durations). This difference in variability seems to be a real one since it has been consistently found across a number of experiments, reported by a number of researchers in different laboratories (Marcus, 1981; Cooper *et. al.*, 1986; Fox and Lehiste, 1987). Thus, it seems clear that the effects of the onset are both larger than those of the rhyme and more reliable across subjects, although the causes of variability cannot be determined from this or from previous experiments. Whether this indicates an important variable in the speech community, or a particular weakness of our experimental method, remains to be determined.

3. Experiment 2

Our next aim was to determine whether the effect of vowel duration on the P-center of the stimuli in the first experiment is peculiar to vowels or whether it is typical of any segment, vocalic or consonantal, in the syllable rhyme. Marcus (1981) found that changes in the durations of vowels (in CV syllables) and syllable-final consonants (in CVC and VC syllables) all have weak effects on the P-center of a syllable. Similarly, in Experiment 8 of Marcus (1976), changes made in the steady-state of the vowel of "one", and in the nasal murmur, had equivalent effects. From these results Marcus concluded that the syllable rhyme behaves as a unit in its effect on P-center location. The present experiment compares durational effects of vowels and consonants in the syllable rhyme across a broader range of changes, allowing us to see if the effects are in fact equivalent.

To this end we obtained alignments for syllables from two continua—one in which the vowel in a VC syllable decreased in duration, and the other in which syllable duration was held constant by lengthening final stop consonant closure duration to offset decreases in vowel duration. If the rhyme behaves as a unit, P-center shifts in the first duration-varying continuum should resemble those of Experiment 1, while there should be no shift in the constant-duration continuum. For the center of gravity accounts, there should be little difference between the two continua since the silence and release burst add little to the amplitude profile of the utterance.

3.1. *Method*

3.1.1. *Stimuli*

The continua were based on a naturally spoken /at/ syllable totaling 556.2 ms in duration: the vowel was 255.5 ms in duration, the closure, 234.2 ms, and the burst, 66.5 ms. For the length-varying continuum, pairs of pitch pulses were excised from a base stimulus beginning 86 ms into the vowel. This location was both within the steady-state portion of the vowel and beyond the peak intensity of the vowel. The individual pitch pulses ranged from 7.5 to 7.8 ms in duration. One pitch pulse, 7.7 ms in duration, was excised from the base to create the first step of the continuum. Thirteen pitch periods, totaling 98.9 ms, were excised from the base to create the final stimulus of the continuum. The continuum consisted of seven members. For the constant-duration continuum, a compensatory amount of silence was inserted between the vowel and the release burst.

3.1.2. *Procedure*

The procedure of Experiment 1 was used.

3.1.3. *Subjects*

The subjects of Experiment 1 participated again.

3.2. *Results and discussion*

The data were analysed separately for each listener as in Experiment 1. Figure 2 shows the mean results of the alignment test for each subject individually. The abscissa represents the duration of the pitch pulses excised from the vowel (in milliseconds). The ordinate represents the displacement (in milliseconds) from acoustic isochrony of the reference syllable relative to the test stimuli.

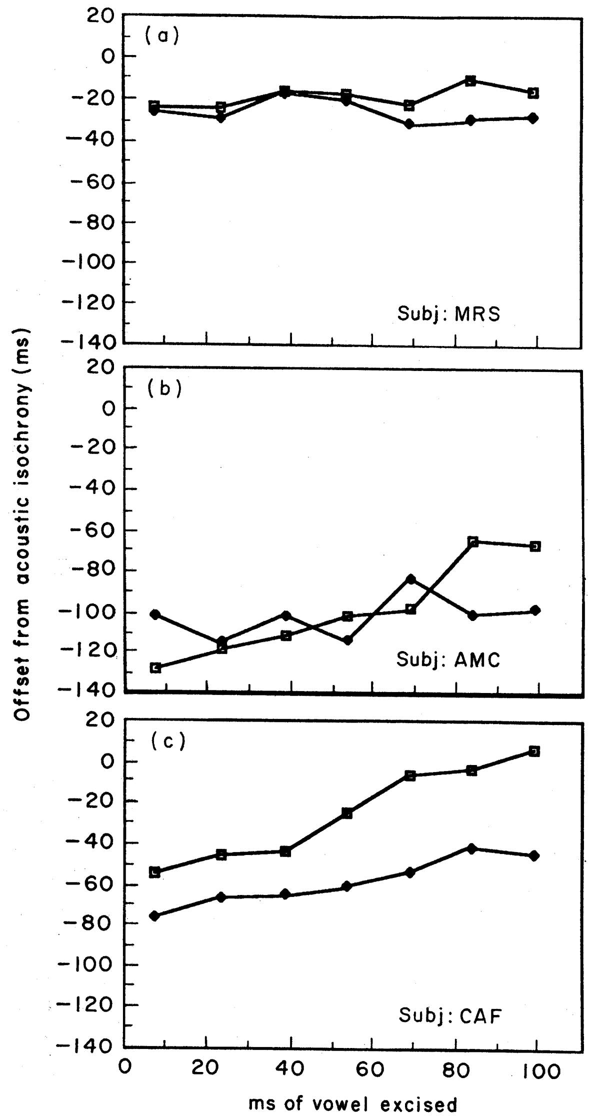

Figure 2. Mean P-center alignment functions for the three subjects in Experiment 2. In the "constant" (—◆—) stimuli, the /t/ closure gap is lengthened as the vowel is shortened. In the "variable" stimuli (□), syllable duration changes because gap duration is held constant while vowel duration decreases.

The overall results for each listener separately show shifts in the P-center toward stimulus onset as vowel duration decreases for the length-varying continuum (for all listeners); but for two listeners, there were no shifts along the continuum in which rhyme duration was held constant.

Listener MRS [Fig. 2(a)] showed a marginal effect of continuum type ($F(1, 154) = 2.00$, $P = 0.001$), but no interaction. Although there was no interaction, linear trend tests on the effect of vowel duration performed separately on the two continua were significant for the length-varying continuum ($F(1, 154) = 4.76$, $P = 0.03$) but not for the constant continuum ($F(1, 154) = 1.53$, ns). As stimulus duration decreased in the length-varying continuum, the P-center shifted toward stimulus onset by 8% of the change in vowel duration.

Listener AMC [Fig. 2(b)] showed no effect of continuum type but a significant main effect of vowel duration ($F(6, 154) = 3.08$, $P < 0.007$). The interaction was marginal ($F(6, 154) = 2.00$, $P = 0.068$). A linear trend test on the effects of vowel duration was significant for the length-varying continuum ($F(1, 154) = 23.21$, $P < 0.001$) but not for the constant continuum ($F(1, 154) < 1$). As stimulus duration decreased in the length-varying continuum, the P-center shifted 61% of the change in vowel duration toward stimulus onset.

For listener CAF [Fig. 2(c)] effects of continuum type ($F(1, 154) = 53.54$ $P < 0.001$), vowel duration ($F(6, 154) = 8.61$, $P < 0.001$) and the interaction ($F(6, 154) = 2.54$, $P = 0.02$) were all significant. The constant continuum showed smaller offsets from acoustic isochrony than the length-varying continuum. Linear trend tests on vowel duration showed a significant trend for both the length-varying continuum ($F(1, 154) = 56.12$, $P < 0.001$) and the constant continuum ($F(1, 154) = 5.3$, $P = 0.02$). Decreases in vowel duration shifted the P-center toward syllable onset by 63% and 33% of the change in duration for the length-varying and the constant continua, respectively.

For the length-varying continuum, all three listeners showed the expected shifts in P-center location toward stimulus onset as the vowel decreased in duration. Marcus's algorithm predicts a 25 ms change, while the actual changes were 8, 60 and 63 ms for MRS, AMC and CAF, respectively. The center of gravity accounts predict changes of 51, 41 and 51 for the untapered, tapered, and half-tapered versions, respectively. In addition, as in Experiment 1, the effect of vowel duration on P-center location varied somewhat across listeners. Here, the P-center shifted by about 62% of the change in vowel duration for AMC and CAF but only about 8% for MRS.

For the constant-duration continuum, where increases in consonant duration offset decreases in vowel duration, P-center shifts were eliminated for two listeners and substantially weakened for the third. Marcus's algorithm predicts no change at all, while the center of gravity accounts predict changes of 51, 40, and 51 for the untapered, tapered, and half-tapered versions, respectively. That is, the center of gravity accounts wrongly predict that the weak amplitude of the release burst is ignored in the computation. Since even the one subject (CAF) who did show a change showed less of a change than in the variable-duration continuum, the center of gravity accounts fail to account for these data.

The results of the present experiment suggests that the components of the syllable rhyme have equal or near equal effects on P-center location.

4. General discussion and conclusions

The results of this study support an onset-rhyme view of the P-center and disconfirm a variety of center-of-gravity accounts. The account proposed by Marcus (1981) and modified by Cooper *et al.* (1986) that syllable constituency is an important factor in determining the P-center, receives more support. In addition, the present study showed that the contribution of segments in the rhyme to P-center location varies across listeners in the method-of-adjustment procedure. This stands in marked contrast to effects of the syllable onset (Cooper *et al.*, 1986). In the light of evidence that the P-center effect for initial segments occurs in languages of different rhythmic types (e.g., Hoequist, 1983), it would be interesting to see whether syllable rhymes have weak and more variable effects in all languages, or more substantial effects in languages, such as Thai or Hungarian, in which vowel length is distinctive and therefore may be more salient perceptually. Indeed, the strong evidence for the importance of syllable constituency may be specific to languages such as English which allow both complex onsets and complex rhymes. Further experimentation with languages that exhibit explicit contrasts in vowel duration would establish the limits on the generality of our results. Alternatively, the productions of children might be examined, since the acoustic evidence of the vowel has been shown to be more prominent within the fricative noise of children than in adult noises (McGowan & Nittrouer, 1988). These and other examinations of the reasons for this change in variability deserve direct attention.

While our definition of rhyme is traditional (and still used by, e.g., Harris, 1983), it has been challenged by Clements & Keyser (1983, pp. 19–24). They find no compelling evidence that the rhyme is a unit, as opposed to, say, a grouping of the initial consonants and the vowel. However, the stimuli of our experiment contain a unit that Clements and Keyser argue is essential, namely the syllable nucleus. In their formulation, the vowel and final consonant together form a syllable nucleus. To find parallel cases where part of the signal would be outside the nucleus but within the rhyme, we would either need to add a consonant (e.g., "cost") or change the vowel to a diphthong (e.g., "bout"), both of which have a [t] outside of the nucleus. If the nucleus were the only post-onset factor in P-center determination, then manipulations of these [t]'s would not affect the P-center. Conversely, if these effects were identical to those in the nucleus, we would have one piece of solid evidence that the rhyme exists as a unit.

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