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An examination of intra-articulator relative timing

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The relative timing of consonant and vowel related movements of the tongue dorsum across variations in stress patterns was examined in two subjects using a computerized pulsed ultrasound system. The patterns observed were similar to those reported by Tuller *et al.* [J. Exp. Psychol. H.P.P. **8**, 460–472 (1982)] for interarticulator timing. Correlations between the duration of a "period," defined as the interval between the onsets of movements associated with adjacent vowels, and the "latency," defined as the interval between the beginning of the period and the point in the period at which movement associated with the intervocalic consonant begins, were positive and reliable. The source of this correlation pattern was examined and found not to be due to a scaling of an invariant phase relation but rather due to a main effect for stress on the vowel-to-vowel articulatory period combined with an artifactual part–whole correlation within each stress level.

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INTRODUCTION

The identification of temporal invariances has long been an important research goal in the study of speech production (e.g., Kozhevnikov and Chistovich, 1965; Kent and Netsell, 1971; Löfqvist and Yoshioka, 1981). Recently, Tuller *et al.* (1982) have reported an invariance in the relative timing of vowels and consonants across changes in speech rate and stress. This invariance is shown as a linear relationship between the duration of a period, defined as the interval between the onset of activity associated with adjacent vowels, and the duration of a latency, defined as the interval between the beginning of the period and the point in the period at which movement associated with the intervocalic consonant begins. This correlation has been interpreted as indicating that the coordination between articulators in speech is marked by a relatively fixed phase relationship for a particular vowel–consonant–vowel utterance. To date, this relationship has proven reliable for lip–jaw and tongue–jaw kinematics, as well as for the timing of the electromyographic (EMG) concomitants of these movements (e.g., Harris *et al.*, in press; Tuller and Kelso, 1984; Tuller *et al.*, 1982, 1983). In addition to these data for American English speakers, the pattern has been observed in both kinematic and EMG measures from native speakers of French (Gentil *et al.*, 1984a,b).

In spite of these demonstrations, there appear to be persisting concerns about the nature of this regularity and its interpretation (Barry, 1983; MacNeilage, in press). These include questions about the statistical treatment of the data, as well as a suggestion that the linear relationship may, in part, result from variations in the overall tempo of production. The present paper examines these concerns about the relative timing phenomenon with particular reference to movements of the tongue dorsum. The data presented here were collected originally for other purposes (see Munhall *et al.*, 1985), but, as they involve a suprasegmental manipulation—a change in stress—they are appropriate for this analysis.

The analysis provided in this paper makes two distinct contributions to the relative timing literature. A series of statistical tests indicate how "true" relative timing invariances might be distinguished from artifactual relations. In addition, relative timing is tested in an articulatory environment in which a single articulator plays a major role in the production of both the vowels and consonants in the test utterance. Unlike the data analyzed by Tuller *et al.* (1983), both the period and latency are defined with respect to the activity of a single articulator. Thus the data presented here provide a test of relative timing under conditions in which the period and latency are potentially more constrained than when the movements associated with the consonants and vowels are produced by different articulators.

I. METHOD

A. Subjects

The subjects were two fluent speakers of Canadian English with no known speech abnormalities. Subject AP is a native Hebrew speaker; subject KM is a native Canadian English speaker.

B. Apparatus

The data were collected with the McGill University computerized pulsed ultrasound system that has been described in detail elsewhere (Keller and Ostry, 1983; Munhall and Ostry, 1985). For tracking movements of the tongue dorsum, the transducer is placed externally against the skin beneath the chin just anterior to the hyoid bone, and measurements are taken of the distance from the transducer to the tongue's surface. Details of transducer placement and verification, as well as a description of the holding apparatus, are provided by Keller and Ostry (1983) and Munhall and Ostry (1985). The signal-processing steps and data-scoring procedures are also described in these publications.

C. Stimuli and procedure

Both subjects produced the nonsense utterance /ka kak/ repetitively with either the first or second vowel receiving the primary stress. This particular sequence is used

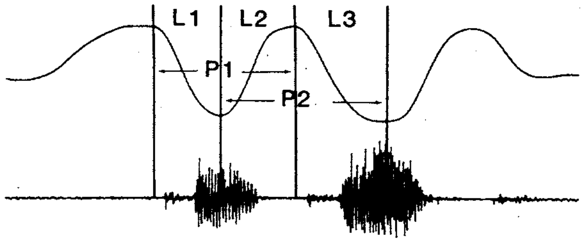

FIG. 1. Temporal intervals that mark the various periods and latencies. The upper trace shows the tongue height as a function of time.

because the principal movement component is parallel to the ultrasound measurement axis. Subjects produced each of the two stress conditions for fifteen 3.5-s trials at a self-paced rate.

II. RESULTS AND DISCUSSION

A. Replication of the Tuller *et al.* findings

The tongue data were first partitioned into a number of intervals (Fig. 1). The interval from the zero velocity point at the beginning of tongue lowering for the first vowel to the zero velocity point at the beginning of tongue lowering for the second vowel was designated the period (P1). The interval from the beginning of tongue lowering for the first vowel to the zero velocity point at the onset of tongue raising associated with the intervocalic consonant was designated the latency (L1). These intervals are the within-articulator counterparts to the period and latency measures used by Tuller *et al.* (see, for example, Tuller and Kelso, 1984). The linear regression of latency with period was computed for each subject without regard to stress level. As can be seen in Fig. 2, the relationship between these two variables is linear and highly reliable. Pearson correlation values were 0.92 and 0.88 for AP and KM, respectively ($p < 0.01$).

Tuller *et al.* (1983) have also shown that their particular period and latency correlation is reliably stronger than arbitrarily defined comparisons, which examine an interval composed of articulatory events associated with vowel and consonant subunits. A similar analysis was performed on the present data. In Fig. 1, alternate period and latencies are marked. Period 2 (P2) extends from the beginning of movement for the intervocalic consonant to the beginning of movement for the final consonant. The two parts of the new period are labeled latency 2 (L2) and latency 3 (L3). (Note that L2 is one of the parts of both P1 and P2.) In Table I(a), the correlations between the original period and latency (a la Tuller) and the two alternate periods and latencies are shown.

When the relative strengths of the overall correlations, calculated without regard to the stress manipulation, were tested using Fisher's r to Z transformation, the original period (P1) and latency (L1) were found to be more strongly related than either of the other two pairs of variables (P2/L2; P2/L3) for both subjects ($p < 0.01$).

B. Part–whole correlations

An alternate interpretation to that offered by Tuller *et al.* (1983) for the observed high correlations between latency and period is that they are due solely to a statistical artifact of correlating a whole with the subdivision of that whole that accounts for most of its variation (Barry, 1983). In this case, it is suggested that both the latency and period are largely determined by the vocalic portion of the measures. As it is well known that manipulations of variables such as stress

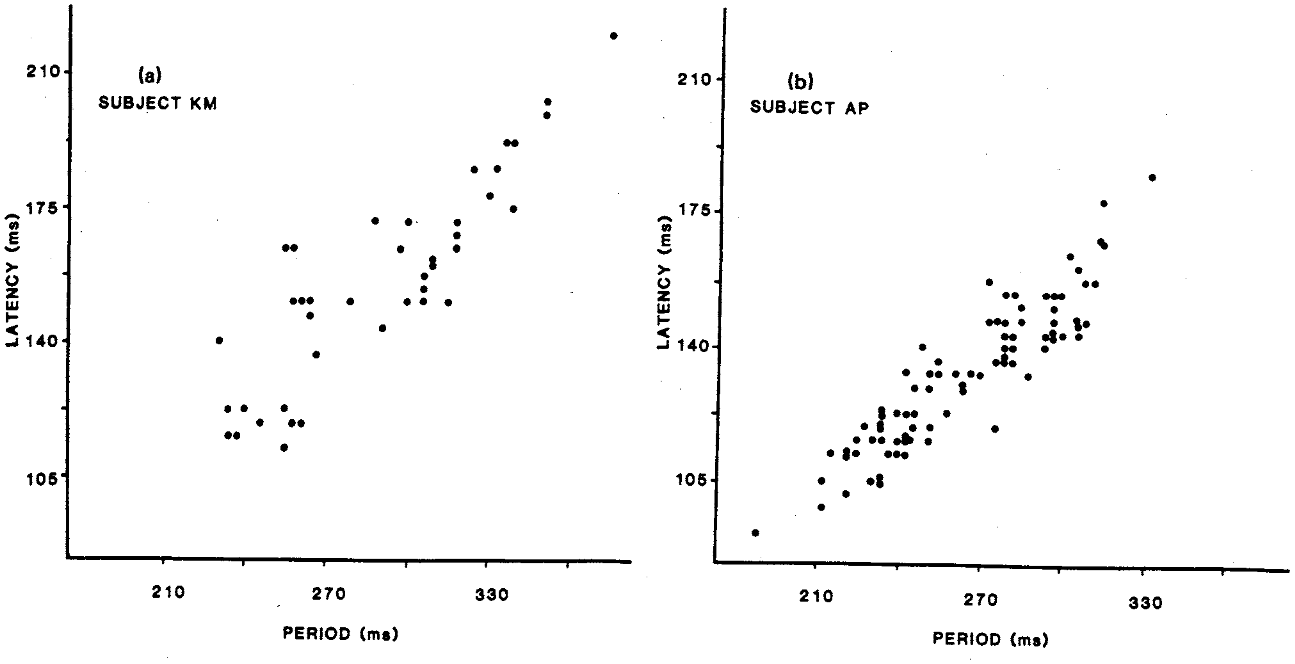

FIG. 2. (a) and (b)—Scattergrams showing the relationships between individual token period and latency (P1/L1) measures for subjects KM and AP, respectively.

and rate influence vowels more than consonants, the high correlations are to be expected.

Barry (1983) is certainly correct that the data presented by Tuller *et al.* and the data presented here are, by definition, part–whole correlations. But is that fact, *per se*, sufficient to account for the relative timing pattern? To evaluate this issue fairly, the observed correlations must be partitioned into the variance due to the inherent part–whole relationship and that due to the relative timing relationship. One way to do this is to calculate the expected correlation for a part–whole relationship when the whole is composed of two uncorrelated parts. The relative timing hypothesis predicts that both parts of the period should covary and thus the parts should be correlated (e.g., Tuller *et al.*, 1983). This falls from the suggestion that an invariant phase linkage is metrically scaled across rate and stress changes; the scaling should affect both parts similarly. The amount that the observed period/latency correlations exceed (or are less than) the expected correlation based solely on part–whole relations can thus be used as a measure of the size and direction of the correlation between the two parts of the whole. Since the two parts are supposedly covarying in the present case the successful demonstration of relative timing requires that the observed period/latency correlation exceed the uncorrelated-parts baseline correlation. Thus the correct null hypothesis for the relative timing hypothesis is that the observed correlation will be reliably greater than the expected part–whole correlation, not that the observed will be reliably greater than zero.

If N uncorrelated parts with equal standard deviations (s.d.) are added together, the correlation of one of the parts with the whole will equal $1/\sqrt{N}$. For the two-part case considered in the period/latency analysis, the expected correlation on a purely part–whole basis is $1/\sqrt{2} = 0.707$. This follows from the fact that each part's variance accounts for 50% of the overall (whole) variance. When the standard deviations are unequal, the expected correlation is $\text{s.d.}/\sqrt{\Sigma \text{s.d.}^2}$, where the s.d. in the numerator is for the part that is being correlated with the whole and the summation in the denominator is across the two parts (Cohen and Cohen, 1975). It is this latter case of unequal s.d.s, as suggested by Barry, that corresponds with the situation in the period/latency analysis.[1] The expected part–whole correlations on this basis for the present tongue data are 0.776 and 0.806 for subjects AP and KM, respectively. A confidence interval can be calculated around the expected correlation by using Fisher's r to Z transformation (Ferguson, 1981). The 95% and 99% confidence intervals for subject KM are 0.662–0.892 and 0.602–0.911, respectively. The 95% and 99% confidence intervals for subject AP are 0.674–0.818 and 0.635–0.870, respectively. As can be seen, the observed period/latency correlation for subject KM falls within even the 95% confidence interval of the part–whole correlation. The period/latency correlation for subject AP, on the other hand, exceeds both the 95% and 99% confidence intervals. Thus, at least for subject KM, the observed relative timing relationship could be due to a simple part–whole artifact.

A second way to examine this part–whole problem is to consider the pattern of correlations of both of the parts with the period. If a scaling of an invariant phase linkage is occurring, the correlation between either part and the whole should be equivalent. In Table I(a), the overall (across stress levels) correlations can be seen for the P1/L1 and P1/L2 correlations. For both subjects, the P1/L1 correlation is larger than the P1/L2 correlation. This suggests that a simple metrical scaling may not be occurring; however, the difference between the size of the correlation coefficients is not large for either subject ($p \approx 0.1$).

C. Within-condition effects

In the previous sections, both subjects were shown to produce P1/L1 correlations that reliably exceeded the values of correlations between alternate periods and latencies. As well, subject AP showed a P1/L1 correlation that was reliably larger than the baseline part–whole correlation. To tease out the source of these patterns in the data, information

TABLE I. Correlations for the within-condition and overall period/latency analyses.

	AP			KM		
	Str.	Unstr.	Overall	Str.	Unstr.	Overall
(a) Observed correlation coefficients (and partial correlation coefficients in parentheses) for the various period/latency combinations.						
P1/L1	0.748	0.768	0.920 (.918)	0.899	0.646	0.879 (.878)
P1/L2	0.644	0.783	0.876	0.418	0.573	0.760
P2/L2	0.725	0.305	0.167	0.620	0.371	0.020
P2/L3	0.667	0.745	0.626 (.534)	0.757	0.630	0.679 (.409)
(b) Expected part/whole correlation coefficients for the various period/latency combinations.						
P1/L1	0.754	0.700	0.776	0.900	0.732	0.806
P1/L2	0.657	0.714	0.630	0.436	0.681	0.591
P2/L2	0.737	0.510	0.586	0.640	0.658	0.557
P2/L3	0.676	0.860	0.810	0.768	0.753	0.831
(c) Correlation coefficients for the two parts of P1 and P2.						
L1/L2 (P1)	− 0.025	0.203	0.617	− 0.023	− 0.256	0.358
L2/L3 (P2)	− 0.030	− 0.103	− 0.571	− 0.44	− 0.332	− 0.667
N	42	43	85	21	20	41

about the correlations observed within conditions and the corresponding within-condition expected correlations must be considered. The correlations for the within-condition and overall period/latency analyses are shown in Table I.

A number of general trends are worthy of note in Table I. First, the original period and latency relationships (P1/L1) are always larger than the alternate period (P2) correlations. Second, the magnitude of that difference over the other relations is increased by calculating the overall correlation (i.e., across stress levels). Finally, the observed within-condition correlations do not reliably exceed the expected part/whole values for any of the periods and latencies for either subject; in fact, they tend to be somewhat smaller than the expected.

Part of the advantage of P1/L1 over other period/latency relationships may stem from the fact that the expected correlation is higher for some of the P1/L1 correlations than for the alternate period and latencies relations [Table I(b)]. This does not explain all of the differences, however. A second contribution to the P1/L1 advantage lies in the fact that all of the observed alternate period (P2) correlations fall below their expected values. This indicates that the two parts of P2 are negatively correlated [see Table I(c)]. In addition, stronger period/latency relationships are present within condition for P2/L2 and P2/L3 than are observed in the overall correlations. This is an example of an overall regression masking the relationship between two variables when their within-condition regression lines (slopes and/or intercepts) are different.

The opposite situation occurs for the original period/latency relationship (P1/L1); the value of the correlation coefficient is magnified by calculating the overall correlation. It is well known that the sampled range of variables can influence the magnitude of the correlation coefficient [see Smith (1981) for a formal discussion of this isssue], but Table I(c) suggests that something in addition to a range effect is occurring here. The correlations between the parts in the two periods are shown for the overall and within-stress level partitionings of the data. It can be seen that there is no significant relationship between the parts of either of the periods within a stress condition. This can also be seen in the fact that none of the within-condition period and latency correlations reliably exceed the expected part–whole values. When the correlations are calculated across conditions, however, reliable correlations between the two parts are observed for both periods.

This pattern of results suggests that there is no within-condition evidence for a period/latency linkage in either subject. Rather, what is present is a main effect for stress for both the period and latency.

A main effect on the duration of the vowel-to-vowel period will have a number of consequences for a period/latency correlation analysis. The correlation between the two halves of the period (P1) will not be reliable within conditions but both individual stress conditions will show artifactual part–whole correlations. The individual condition period/latency regressions may be different in slope and/or intercept since they do not derive from a single continuous function but rather from separate part–whole relationships. On the other hand, across conditions the correlation between the two halves of the period will be artifactually reliable due to the main effect. (Note that if the latency varied randomly somewhere within the period, the two parts of P1 would also show main effects across stress levels.) Finally, as a result of this across condition correlation between the two parts of P1, the overall period/latency regression can exceed the expected part–whole value and in some cases can be very strong. As can be seen in Table I, these descriptions fit the present data well. Further, the individual condition P1/L1 regression lines are reliably different for both subjects [AP: $F(2,81) = 13.92, p < 0.01$; KM: $F(2,37) = 13.65, p < 0.01$].

The latter finding, as well as the failure to observe any period/latency correlations within condition beyond those based on part–whole artifacts, argue against calculating an overall regression for these data for either subject. The calculation of an overall correlation using the trial-to-trial variation would provide an inflated estimate of the significance of the relation between the period and latency. This is due to the fact that the observations within condition serve only to increase the degrees of freedom for the overall correlation and do not contribute any evidence for a true relation between the two variables.

D. Effects of overall tempo

One further interpretation of the observed relative timing stability has been recently proposed by MacNeilage (in press) who suggested that the high correlation may reflect an overall tempo effect on the utterance as a whole. In spite of the above conclusion, it is still worthwhile to examine this notion. MacNeilage's suggestion was tested in the present data by partialing out the variance due to overall tempo and examining its effect. Tempo was estimated by the total acoustic duration of each /ka ka/ token. (The final /k/ was, in general, unreleased and therefore its duration could not be measured.) While rate was not directly manipulated, subjects spontaneously varied their token durations from token to token. Table I(a) shows, in parentheses, the partial correlations for the original and P2/L3 periods and latencies with the variation due to tempo partialed out.

It can be seen that the original period/latency relationship is virtually unaffected by the removal of overall tempo variation. While tempo accounts for a small but reliable portion of the period variance (6% and 8% for AP and KM, respectively), it is a portion of the variance that is largely independent of the relative timing relationship. In contrast, the tempo adjustment reduces the arbitrary P2/L3 relationship for both subjects. (Fisher's r to Z computations show these correlation differences for the arbitrary intervals to be reliable at the $p < 0.1$ and $p < 0.01$ levels for subject AP and KM, respectively.) Thus, as MacNeilage suggests, the correlation between two "arbitrarily" paired temporal units can be inflated by the overall tempo of production. However, this effect is not contributing to the observed high P1/L1 correlations. Tuller and Kelso (1984) have tested the tempo effect in a manner suggested by MacNeilage (in press) and also found that it did not contribute to the high correlations in their data.[2]

III. SUMMARY AND CONCLUSIONS

Tuller *et al.* (1982) have suggested that the relative timing pattern reflects a physiological coherence characteristic of coordinative structures in speech—that is, that the period/latency linkage reflects a constraint among potentially independent degrees of freedom in the control of the speech articulators. The strategy they have employed to support this interpretation has been three pronged: (1) The stability of the relationship across subjects, contexts, and linguistic bases has been demonstrated; (2) the relationship has been shown to be statistically stronger than other possible partitionings of the data; and (3) the ubiquity of the relationship across articulator systems has also been assessed—the lip–jaw and tongue–jaw systems have shown this relative timing pattern.

At first brush, the present data support this general pattern. Both subjects showed high period/latency correlations when the correlations were calculated across stress conditions. In addition, the P1/L1 correlations were reliably higher than other period and latency pairings. However, subsequent examination of these relationships suggested that a within-condition part–whole artifact and a main effect, rather than a true regression, were responsible for the observed high correlations. Only one of the subjects' P1/L1 correlations exceeded the expected part–whole correlation when the correlations were calculated across conditions and neither subject showed anything but an artifactual part–whole correlation within condition.

This pattern of results produces two conclusions—one methodological, the other concerning the implementation of stress. First, the results attest to the difficulties inherent in correlational data. Often these difficulties arise because all that is reported is the overall correlation coefficient. To overcome this problem, it is important to demonstrate the source of the observed high correlations. As shown in the above analysis, this should always involve the calculation of the expected part–whole correlations, as well as a consideration of within-condition effects. This will provide an appropriate null hypothesis for testing relative timing, as well as indicating whether a true regression or a main effect is present in the data. Note that the present analysis does not rule out the possibility of demonstrating true scaling of a period/latency linkage; however, more evidence than the observation of a significant correlation is required for the demonstration of relative timing (cf. Weismer and Fennell, 1985).

Second, although the tongue data analyzed here do not show evidence for a constant phasing of vowel- and consonant-related movements, they do suggest that a vowel-to-vowel articulatory period plays a significant role in speech production (e.g., Fowler, 1983). In Table I(c), it can be seen in the overall correlations that the stress manipulation affects the two halves of P1, the vowel-to-vowel interval, in the same manner. This is evidenced by the reliable positive correlations between L1 and L2 in the overall analyses with no relation being observed within stress conditions. In other words, both parts of P1 increased in duration with increased stress. On the other hand, in the overall correlation of the two halves of P2, the consonant-to-consonant interval, the relationship is negative. This suggests that a given stress level is manifested on the vowel-to-vowel period, while the tongue raising movement toward oral closure and the tongue lowering movement away from the consonant closure are distinct with respect to stress assignment (see Browman and Goldstein, 1984).

It should be pointed out that the present data differ from those of Tuller *et al.* (1982) in a number of ways. First of all, the speech sample differs from any previously examined and no direct rate manipulation was tested. Perhaps more importantly, the period and latency in these data are defined with respect to the same articulator, whereas Tuller and colleagues' data have always been defined on an interarticulator basis. It is not clear how these differences may influence the data; however, in light of the foregoing analysis, some caution is certainly warranted when interpreting any correlational evidence for the relative timing hypothesis. It is worth noting that the present intra-articulator data meet the criteria that have been used by Tuller *et al.* to show interarticulator relative timing (i.e., high overall correlations between the period and latency and significantly lower correlations for alternate periods and latencies). An analysis of interarticulator relative timing data similar to the analysis carried out for the present data is thus necessary to determine if the present pattern of results is due to constraints on intra-articulator gestural timing or is true of the relative timing correlations in general.

What kinds of intra-articulator constraints might limit the relative timing of a single articulator, or, in other words, what determines the shape of the movement period? While the data presented here do not point to any specific answer, at least two general types of constraints might be involved: dynamical constraints on the speech gestures and segmental constraints on the timing of consonants and vowels. Kelso *et al.* (1985) noted in their reiterant speech data that the period had a consistent shape in position-time plots; that is, the opening gestures tended to be longer in duration (and hence less stiff) than the closing gestures for the two speakers of English they tested. While this was modeled in the Kelso *et al.*'s data by changing the stiffness parameter every half-cycle, the period shape may ultimately prove to be some more general characteristic of the system responsible for gestural control in speech. The possibility exists that the speech motor system can exhibit only a limited range of dynamical states. If these states have characteristic space–time signatures (e.g., Kelso *et al.*, 1985; Munhall *et al.*, 1985; Ostry and Munhall, 1985), relative timing may be influenced.

The second possibility is that the timing of vowels and consonants as successive abstract segments imposes temporal constraints on the subsequent gestural timing. If the timing of such a consonant–vowel sequencing was based on the time course of a purely segmental process, the timing of the raising and lowering movements, and hence the period shape, could be influenced. This segmental suggestion, however, seems less likely to be implicated in any inter/intra-articulator differences since these articulator details are presumably irrelevant at an abstract level of description. In either case, it is probably premature to speculate on the exact nature of intra-articulator constraints until interarticulator relative timing data have been shown to have a different pattern when analyzed in a manner similar to the present data analysis.

Recently, Kelso and Tuller (1985; in press) have reported new procedures that avoid many of the pitfalls of a correlational analysis of relative timing.[3] When the onset of movement of one articulator for a consonant was measured on the velocity-position phase plane of another articulator, a constant phase angle was observed across stress and rate manipulations. This appears to be a promising technique that will hopefully shed some light on the nature of articulatory and segmental phasing.[4]

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[1] Note that it is not the relative size of the two parts that is important in this regard but the relative size of the variability.

[2] It is precisely because the period/latency relationship is a characteristic of a given stress level that it is uninfluenced by the independent tempo variation. Note that this implies that manipulating, whether the first or second syllable of a token is stressed, has little effect on the overall "word" duration. A direct rate manipulation which would simultaneously alter the "word" and period durations may have produced a different result.

[3] Phase angle constancy is tested by analysis of variance. This approach has the "new" problem that investigators are required to prove the null hypothesis that there are no differences between mean phase angles. Failure to find differences between means can occur for a variety of relatively uninteresting statistical reasons. Thus information, in addition to the analysis of variance statistics, is required to establish what degree of constancy is being observed. Kelso and Tuller (1985), for example, showed that the standard deviations around the mean phase angles were small, indicating that the failure to observe differences between conditions was at least not due to excessive production variability.

[4] Phase angle for the intra-articulator case, unfortunately, is not particularly informative as the beginning of the movement associated with the consonant always occurs by definition at exactly 180°.

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