Coarticulation Resistance of American English Consonants and its Effects on Transconsonantal Vowel-to-Vowel Coarticulation *

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KEY WORDS

coarticulation

coarticulation
resistance

electro-
magnetography

locus equations

tongue body

ABSTRACT

We explored the variation in the resistance that lingual and nonlingual consonants exhibit to coarticulation by following vowels in the schwa+CV disyllables of two native speakers of English. Generally, lingual consonants other than /g/ were more resistant to coarticulation than the labial consonants /b/ and /v/. Coarticulation resistance in the consonant also affected articulatory evidence for transconsonantal vowel-to-vowel coarticulation, but did not show consistent acoustic effects. As for effects of coarticulation resistance in the following vowel, articulatory and acoustic effects were quite large at consonant release but much weaker farther into the following stressed vowel. Correlations between coarticulation resistance effects at consonant release and locus equation slopes were highly significant, consistent with the view that variation in coarticulation resistance explains differences among consonants in locus equation slopes.

INTRODUCTION

Öhman (1966) and, following him, Perkell (1969) and Fowler (1977; 1980) proposed that, in production of VCV sequences, vowels are produced continuously, with consonants super-imposed on vowel-to-vowel sequences. Öhman's proposal was based on his observation of effects of V2 in a V1CV2 sequence on the shape of formant transitions from the first vowel to the consonant. This implied initiation of a postconsonantal vowel at approximately the same time as initiation of the consonant. He proposed that separate articulatory control systems, involving overlapping sets of muscles, control the tongue's role in production of vowels, apical consonants, and dorsal consonants. Coarticulation of vowels with either class of consonants is possible because production of a consonant leaves subsets of muscles

free to be governed by the vowel articulatory system. Compatibly, Perkell (1969) suggested that vowel movements, which are relatively slow and do not require the precision of consonants, might be expected to be achieved by the large extrinsic muscles of the tongue; whereas the faster consonants, requiring more precision than vowels, would be achieved by the intrinsic as well as some extrinsic muscles. Fowler (1977; 1980) proposed that a single, continuously active, parameterizable, control structure (coordinative structure) was responsible for vowel production; distinct, discretely active coordinative structures produced distinct consonants.

Although these characterizations capture the coarse-grained observations of vowel-consonant coarticulation, they paint a highly oversimplified picture, and, as Recasens (1985) has pointed out, too general a picture of vocal tract control during speech. None explains the detailed kinds of variability in coarticulatory overlap that researchers observe.

More recently, Recasens (e.g., Recasens, 1984a; 1984b; 1985; 1989; Recasens, Farnetani, Fontdevila, & Pallarès, 1993) has suggested that a major factor affecting the magnitude and perhaps temporal extent (but see Recasens, 1984b) of coarticulatory effects of one phonetic segment on another is the mutual compatibility of the gestures constituting the segments. Phonetic segments, whether consonants or vowels, may differ in the extent to which they resist coarticulatory overlap, with the magnitude of resistance determined by the mutual incompatibility of their gestures with those of sequentially adjacent or nearby segments.

Recasens' research (e.g., 1984a,b) has revealed that a major source of variation in "coarticulation resistance" is the level of constraint that gestures of a consonant or vowel place on the tongue dorsum. In his first study (1984a,b), he used an electropalatograph to examine consonant-to-vowel (1984a) and vowel-to-vowel (1984b) coarticulation in a single native speaker of Catalan. Utterances were VCVs in which vowels were /i/, /a/ and /u/, produced in all combinations in the two vowel slots. Consonants were the palatal consonant /j/, the alveopalatals /ɲ/ and /ʎ/, and the alveolar /n/. Looking at tongue-palate contact at the point of maximum contact (PMC) in production of these consonants averaged over contexts, Recasens determined that tongue dorsum contact for the speaker was greatest during /j/ and decreased monotonically in the series as listed above.

Based on these differences in tongue-dorsum contact, Recasens (1984a) predicted and found that magnitudes of anticipatory and carryover effects of vowels on contact area during PMC covaried with each consonant's requirement for tongue dorsum contact. In particular, the smallest effects of flanking vowels were found in VjV utterances, with effects increasing in the order VɲV, VʎV, VnV. In a subsequent analysis of vowel-to-vowel coarticulation in the same data set (1984b), he generally found, as predicted, that the magnitude of vowel-to-vowel anticipatory and carryover coarticulation also reflected the coarticulation resistance of the intervening consonant.

In subsequent investigations, Recasens and colleagues have extended their investigation to include examination of coarticulation resistance in a wider range of consonants (Recasens, 1985), of differences in coarticulation resistance between the vowels /i/ and /a/ (1989), and of coarticulation resistance in other speakers of Catalan (e.g., Recasens, 1985, 1989, Recasens et al., 1993), in speakers of Italian (Recasens et al., 1993) and in speakers of English (Recasens, 1989). Findings are generally consistent with the idea that a major factor affecting the extent to which a consonant or vowel resists coarticulatory

overlap is the extent to which it places constraints on the tongue dorsum.

Our research is designed to investigate coarticulation resistance in speakers of English. We have three main reasons for making our investigation.

First, there are very few investigations of coarticulation resistance in English. Bladon and Al-Bamerni (1976), who coined the term "coarticulation resistance," reported a greater resistance of "dark" /l/ ([ɫ]) than of clear [l] to coarticulation. This finding is consistent with those of Recasens for Catalan, because [ɫ], according to Bladon and Al-Bamerni, is velarized as compared to alveolar [l]. (Compatibly, Sproat, & Fujimura (1993) report that [ɫ]s have greater retraction and lowering of the tongue body than do [l]s.) Recasens (1989) found largely consistent evidence of greater resistance of /ʃ/ than /t/ and of /i/ than /a/ to coarticulation in the speech of one Catalan and two American English speakers. Our research examines vowel-to-consonant and vowel-to-vowel coarticulation in əCV utterances in which C is one of seven consonants and V one of three vowels in the speech of two native speakers of American English. We predicted that our two nonlingual consonants, /b/ and /v/, and the lingual consonant /g/ would resist vowel-to-consonant coarticulation less than the remaining four lingual consonants. We expected /b/ and /v/ to be low resistant, because they do not require that a constriction be made with the tongue. We expected /g/ to be low resistant in the front-back dimension, because previous evidence has shown that its place of articulation varies with vowel fronting (e.g., Öhman, 1966). In fact, phoneticians sometimes have described /g/ as being allophonic (e.g., Abercrombie, 1961; Ladefoged, 1975) with one allophone having a more front (perhaps palatal) and one a more back (velar) place of articulation. This may or may not be the most useful way to look at variation of the point of constriction during closure for English /g/ or /k/. We are not aware that it has been established that there are in fact just two places of articulation for /g/. An alternative possibility, suggested by microbeam findings of Dembowski, Lindstrom and Westbury (1998), is that the point of constriction for /k/ (and so probably /g/ as well) varies continuously over variation in coarticulatory context. In that case, it might be more accurate to think of the constriction location during /g/ closure in a VCV as something like a vector sum of the (invariant) location for velar /g/ and those for the coarticulating vowels.

A second reason for conducting our research is to pursue findings of Recasens (1984b) on vowel-to-vowel coarticulation across consonants varying in coarticulation resistance. Although, in general, as we have indicated, he found smaller magnitudes of anticipatory and carryover coarticulation across high as compared to low resistant consonants, he obtained two other findings as well. First, in that study, the temporal extent of carryover of V1 during V2 and of anticipation of V2 during V1 was not less in the context of high than low resistant consonants. Carryover of V1 extended throughout V2 regardless of the intervening consonant; likewise, anticipation of V2 was always at V1 onset for vowels produced in the context of the highest resistance consonant. Accordingly, whatever the effect of resistance of the consonant may have been on vowel-to-vowel coarticulation, for this speaker, it was not to block it in the carryover direction or even to delay it in the anticipatory direction. In a subsequent investigation (Recasens, 1989), an American English speaker showed approximately this pattern. However, the two other subjects (an American English speaker and the Catalan speaker who was the speaker in Recasens, 1984b) showed less temporally extensive anticipation and carryover of vowel articulation in the context of the high resistant consonant, /ʃ/, than in the context of the lower resistant consonant, /t/.

A second finding (Recasens, 1984b), also observed in both the anticipatory and the carryover directions, was an absence of vowel-to-vowel coarticulatory effects in parts of the vowel close to a high resistance consonant, but the presence of effects farther away. That is, in the anticipatory direction, for example, effects of V2 might be observed on a row or two of the electropalate at V1 onset in the context of high resistant consonants, but, in some utterances, no vowel-to-vowel effects were observed there closer to the consonant. Of course, the differences reappeared on the other side of the consonant when V2 emerged as the predominant segment being produced.

These findings are intriguing because of what they may imply about the means by which coarticulation resistance has its effects. It is highly unlikely that, in a plan to produce a V1CV2, speakers plan to begin producing V2 during V1, then plan to stop producing it during a following high resistant consonant, and then, finally, plan to begin producing it again following the consonant. There is no obvious motivation for the first step; why produce V2 during V1 at all if production will have to cease in the consonant? An alternative way to look at coarticulation resistance (Fowler & Saltzman, 1993) is to see it, at least in part, as a consequence of the way that a consonant or vowel is implemented in the vocal tract periphery. A high resistant consonant serves as a kind of articulatory barrier to other gestures that may be ongoing simultaneously.

Conceivably, the planned phasing of V2 to V1 and so the extent of vowel-to-vowel coarticulation can be the same, say, for any VCV regardless of the coarticulation resistance of C. V2 is initiated during V1 independently of the coarticulation resistance of C. When C begins to be produced, it places either strong or weak constraints on the tongue dorsum that prevent or permit, to various degrees, the coarticulating V2 to have an effect on the dorsum.

It is perhaps premature, however, to speculate on the reasons for these findings. They were not characteristic of two of the three speakers in Recasens' later study. Moreover, because the electropalatograph only provides tongue position information for parts of the tongue that contact the palate, the data may be misleading. In our production study, we used an electromagnetic midsagittal articulometer (EMMA; Perkell, Cohen, Svirsky, Matthies, Garabieta, & Jackson, 1992), which provides tongue position information whether or not the tongue is in contact with the palate. (EMMA has the disadvantage, however, of only providing position information about discrete points on the tongue, which may or may not include the tongue portion used to make a consonantal constriction.)

A third reason we had for designing our investigation of coarticulation resistance was to attempt to determine whether it is appropriate to draw the link that Fowler (1994) and Brancazio and Fowler (1998) have proposed between coarticulation resistance and "locus equation" plots as presented most notably by Sussman and his colleagues (e.g., Sussmen, 1989).

Following pioneering work by Lindblom (1963; cited, e.g., in Sussman, McCaffrey, & Matthews, 1991), Sussman and colleagues have found a linear relation between F2 at vowel mid points and F2 at the transition onsets of CVs. The linear relation is present when the measures are from syllables in which the C is the same and the vowel varies. Slopes of the lines fit to the scatterplots typically differ for different consonants. For example, /b/ has a steeper slope (usually in the range of .7 to .9) and smaller intercept (approximately −100 to 300) than does /d/ (slope range: .3 to .5; intercept range: 900 to 1600).

$y = -0.112 + .002x$ $R^2 = 0.677$
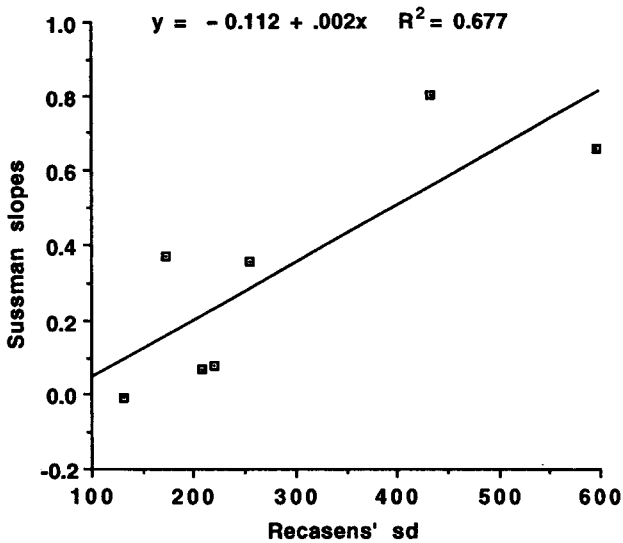
Figure 1

Scatterplot and regression line reflecting the relation between locus equation slopes and the coarticulation resistance for different consonants.

The findings raise two questions: Why do the scattered points form a line, and why do the slopes differ in the way that they do? Regarding the latter issue, it is generally agreed that a consonant's locus equation slope reflects the degree of coarticulation of the vowel with the consonant (Duez, 1992; Fowler, 1994; Krull, 1989; Sussman, Hoemeke, & McCaffrey, 1993); accordingly, /d/'s slope is lower than /b/'s because the magnitude of vowel-to-consonant coarticulation is less when the consonant is /d/ than /b/. Fowler (1994; see also Sussman, 1994; Brancazio & Fowler, 1998) has further argued that differences in coarticulation resistance underlie slope differences, so that the reason why vowels coarticulate less with /d/ than with /b/ (and hence, /d/ has a more shallow locus equation slope) is because the lingual consonant /d/ is higher in resistance than labial /b/. In fact, there is some indication of a relationship between coarticulation resistance and locus equation slope. Recasens (1985) collected əCV productions from three speakers of Catalan in which C was each of 18 consonants and V each of seven vowels. As one measure of coarticulation resistance, he looked at the standard deviation of formants at transition onset for a given consonant across the set of vowels. Standard deviations were computed for groups of related consonants: for labial consonants, dentals and alveolars, palatals, velars, and /r/, /l/, and /w/. The ranking of Recasens' standard deviations across these categories is similar to the ranking of locus equation slopes for consonants in these categories. Culling slopes for consonants as similar as possible to those studied by Recasens from values reported by Sussman et al. (1991) and Sussman (1994), we found a strong correlation across the seven categories between Recasens' measure and Sussman's ($r=.82$, $p=.01$). Figure 1 shows the scatterplot and regression line. The slope for bilabials is an average of male speakers' /b/ slopes from Sussman et al. (1991) and /v/'s slope from Sussman (1994). Dental/alveolars include male speakers' /d/ slope in Sussman et al. (1991) and /z/'s slope from Sussman (1994). /ʒ/'s slope (Sussman, 1994) served for the palatal category, and /r/, /l/ and /w/ (Sussman, 1994) for /r/, /l/ and /w/.

However, the basis for the linearity in F2 vowel-F2 onset scatterplots captured by locus equations is under dispute. At issue is whether the linearity can be an automatic

consequence of coarticulation. Sussman and colleagues (e.g., Sussman, Fruchter, Hilbert, & Sirosh, 1998a) have asserted that it cannot, and have proposed that the points form a line because speakers obey an innate constraint, the "orderly output constraint," that compels them to do so. According to this account, the speech production system has evolved in such a way that F2 at onset and vowel midpoint will be linearly related across utterances of a given consonant. In their view, invocation of the orderly output constraint is required because of the nonlinear relations between articulation and its acoustic consequences. To get linearity in the relations of F2 in the vowel and F2 at consonant release in sets of CVs that vary in the vowel, but not the consonant, the vowels would have to coarticulate to nonuniform extents with the consonant.

We have proposed (Brancazio & Fowler, 1998; Fowler, 1998) as an alternative to the orderly output constraint that coarticulation resistance underlies the linearity of locus plots, because the resistance of a consonant to coarticulation is roughly the same across the set of vowels with which it coarticulates (the uniform coarticulation resistance hypothesis; cf. Carré, 1998). This is because vowels use similar parts of the tongue; accordingly, their compatibility or incompatibility with requirements for forming a given consonantal constriction should be roughly the same. Accordingly, plots of tongue body position at vowel midpoint against tongue body position at consonant release for a consonant produced in the context of a variety of vowels should form a line. Therefore, acoustic linearity is the result of articulatory linearity. Some evidence supporting this position comes from modeling of VCV production and its acoustic consequences using Carré's Distinctive Region Model (e.g., Chenoukh & Carré, 1997; see also Sussman, Fruchter, Hilbert, & Sirosh, 1998b, Figure R1). When the onset of production of the second vowel in a VCV is fixed temporally relative to the onset of consonant closing for the production of a given consonant in the context of a variety of vowels, the acoustic consequences plotted as locus equation points are linear.

It should be noted there is evidence refuting the strong notion that coarticulation resistance of a consonant is completely invariant across vowel contexts (e.g., Recasens, 1984b; cf. Sussman et al., 1998). However, the claim here is that degree of resistance for a consonant is nearly invariant, and that deviations from this invariance will correspond to small deviations from linearity in the acoustic domain (see Brancazio & Fowler, 1998, for preliminary supporting evidence). Sussman et al. (1998b) have recently disputed the uniform coarticulation resistance claims and provide evidence ostensibly showing that the uniform coarticulation resistance account is wrong. The evidence shows different extents of the coarticulatory effects of different vowels on the tongue body configuration during the same consonant, Swedish /d/. We discount these findings for two reasons. Most importantly, according to Sussman et al., the data are not articulatory; rather they are reconstructions of articulation based on acoustic data. The reconstructions may be wrong. Second, the y-axis measure of coarticulation that Sussman et al. provide is "euclidean distance" in unspecified units between "a neutral tongue body configuration and that observed during coarticulation" (p. 292). However, there is no neutral tongue body configuration in nature, and so invoking one to measure magnitude of coarticulation gives an unrealistic measure. In any case, the failure to specify the units makes it impossible to know whether the unequal amounts of coarticulation exhibited in their data are big or small or even very small.

In our research below, we provide a direct test of the coarticulation-resistance account

of locus equation slopes and as direct a test as we are able of our account of the linearity of locus equation plots.

EXPERIMENT

One major purpose of the study was to investigate differences in the coarticulation resistance of consonants of American English. Accordingly, we first looked at articulatory and acoustic evidence for different magnitudes of anticipatory coarticulation by the final vowel in the domain of the preceding consonant as a function of the identity of the consonant.

A second interest was to explore the effects, if any, of the coarticulation resistance of a consonant on the magnitude of anticipatory vowel-to-vowel coarticulation. We can look at anticipatory vowel-to-vowel coarticulation by comparing tongue body positions during schwa produced in disyllables ending in different vowels. Then we can ask whether the magnitude of any coarticulation we see or whether its temporal extent is less in the context of high as compared to low coarticulation resistant consonants. In addition to looking at the position of the tongue body, we can look for acoustic evidence of systematic variation in vowel-to-vowel coarticulation.

Relating to our interest in the relation of coarticulation resistance of consonants to the slopes of locus equation plots, we will correlate variation in coarticulation resistance of consonants in the speech of our two talkers with variation in the magnitudes of locus equation slopes for each consonant. We will also attempt, in a preliminary way, to estimate the linearity of the relation of tongue body position during the vowel and position at consonant release for a set of utterances in which the consonant is fixed and the vowel varies. Then we will relate our measures of linearity to corresponding measures of the linearity of locus equation plots.

Methods

Participants. Our speakers were one female (CB) and one male (EM) native speaker of American English who were not aware of the purposes of the research.

Stimulus Materials. Our speakers produced 30 tokens each of 21 disyllables of the form schwa +CV in which C was each of the seven consonants /b/, /v/, /ð/, /d/, /z/, /ʒ/, /g/ (the set used by Fowler, 1994), and V was /i/, /a/ or /ʌ/. Fifteen tokens were produced at a self-selected normal rate and 15 at a faster rate. We varied rate, because coarticulatory overlap is found to increase at faster speaking rates (e.g., Engstrand, 1988); this should eventuate in higher slopes of locus equation plots as Brancazio and Fowler (1998) found.

Procedure. Articulatory data were obtained using an electromagnetic midsagittal articulometer (EMMA), which was designed at MIT (Perkell et al., 1992). EMMA charts a time history of the path taken by receivers attached to various articulators in the midsagittal plane of the device. It employs a measurement method based on the principle of induction. Three transmitter coils are located equidistant from one another, each of which generates a radially symmetrical alternating electromagnetic field at a different frequency. With the aid of a frequency discriminator, the three voltages induced in small receiver coils located in the area circumscribed by the transmitter coils can be isolated and used as measures of

the distances of the receivers from the transmitters. Because these distances are not large in relation to the dimensions of the receiver coils, the magnitudes of the induced voltages are not exactly proportional to the inverse cubes of the respective distances, but are given by a closely related expression that more accurately describes near-field conditions (Perkell et al., 1992). This expression allows the Cartesian coordinates of the receiver coils and their tilt relative to the transmitter axes to be calculated. For each receiver, the three voltages are low pass filtered at 200 Hz by a hardware filter and subsequently sampled at 625 Hz by a computer (12 bit resolution). Software is used to convert from voltages to Cartesian coordinates for each receiver.

In our experiment, receiver coils were placed on the vermillion borders of the upper and lower lips, on four evenly spaced points along the tongue midline, with the coils' long axis perpendicular to the sagittal plane, on the bridge of the nose, the maxillary gum line, and the mandibular gum line. On the tongue, one coil was placed at the tongue tip and one as far back on the tongue as the subject could tolerate. The remaining coils were placed at even intervals between these two extremes. (The second coil, located on the tongue blade, fell off during EM's recording session.) In any case, our analyses here are based exclusively on the third tongue coil, located on the tongue body, because it provides the most direct information about constriction location for vowels.

Speakers read key disyllables from sheets of paper held by an experimenter. Stimuli were presented so that one block of 21 disyllables was represented on each sheet of paper. To avoid final lowering of fundamental frequency and final lengthening on the last critical disyllable, each page ended in an extra disyllable, which was not measured. Stimuli were differently randomized in each block of trials. Speakers were instructed to read through each block twice, once at a normal rate of speech and once at a fast rate. The order of the two rates of speech alternated between blocks. Speaker CB produced the disyllables in isolation. EM produced the disyllables in the carrier phrase "Enough əCV, bub." (We chose this carrier phrase after collecting data from CB. The purpose was to prevent coarticulation across disyllables that we thought might have occurred in CB's speech. We chose the carrier to minimize coarticulatory effects of the carrier on the target disyllable. In the carrier, the consonants flanking the target were nonlingual and the nearest vowels on either side were central.)

Measurements. Measurements of tongue body fronting and height were obtained at the nine points during each disyllable illustrated in Figure 2. These points were selected by first locating the acoustically defined onset and offset of the initial schwa (T1 and T4, respectively) and of the final vowel (T6 and T9); these were visually determined from displays of the waveform and a wide-band spectrogram. T2 and T3 were marked at one-third and two-thirds, respectively, of the distance between T1 and T4; T7 and T8 similarly trisected the T6–T9 segment. Finally, T5 was located exactly halfway between the offset of the schwa (T4) and the onset of the final vowel (T6). Additionally, acoustic measures of F1, F2, and F3 were taken at points T2 and T3 during the schwa, and T6, T7, and T8 during the final vowel. Acoustic analyses were accomplished using HADES (Rubin, 1995). Linear predictive coding (LPC) analysis (using 29 coefficients) was used for acoustic measurements of EM's productions. For speaker CB, LPC analysis did not provide reliable measures; therefore, formant measurements were derived by calculating centroid frequencies of prominent spectral peaks from a DFT (with 256 samples, producing 12.5 ms windows) analysis.
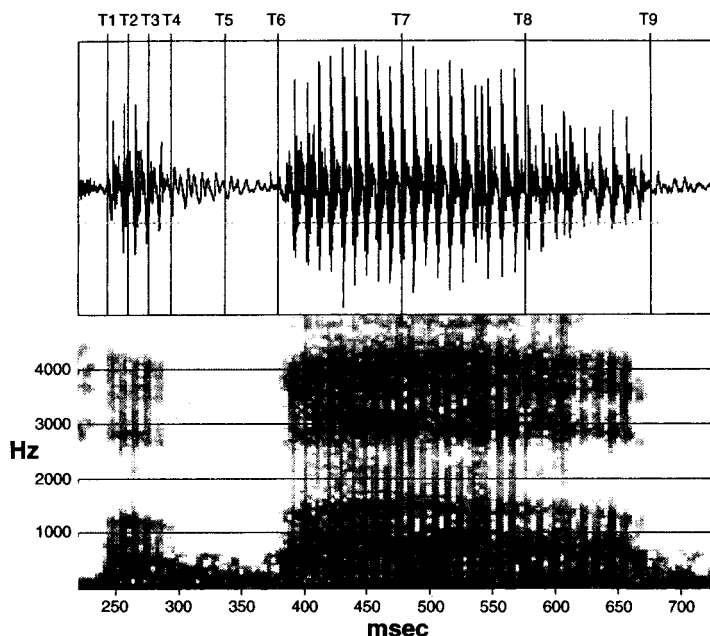
Figure 2

Articulatory and acoustic measurement points in the disyllables of the experiment.

In analyses below, we will report findings on measures of tongue body height and fronting and on acoustic F1 and F2 measures only. Except in the locus-equation-related analyses, we focus on disyllables ending in /i/ and /ʌ/. Results with the vowels /a/ and /ʌ/ were closely parallel in the speech of CB; we focus on /ʌ/ in the speech of EM, because, for most əCa tokens, he produced a vowel that we identified as /æ/.

Results and Discussion

Because our research addresses three distinct issues relating to coarticulation resistance, and because analyses are complex, we organize this section into a series of *Results* sections followed by *Summary* sections. The collection of findings will be addressed in the *General Discussion*. We begin with some preliminary analyses.

Preliminary overview of the data

Untransformed articulatory and acoustic measures. Figure 3 and Tables 1 and 2 show some of the data that we used to compute the difference scores (/i/ minus /ʌ/) on which later analyses focus. Figure 3 shows averaged tongue body measures (fronting (x) and height (y)) at eight articulatory measurement points (T1–T8 in Figure 2) in CB's normal rate productions of /əvi/ and /əvʌ/ (left panels) and of /əzi/ and /əzʌ/ (right panels). More front values are lower numbers in the top panels. Height increases bottom to top in the bottom panels. We expect /v/ to be a low resistant consonant and /z/ to be high resistant. In the front-back dimension, the tongue body measures for utterances with different final vowels are separated even at the beginning of the schwa (T1), but follow parallel trajectories during /əvi/ and /əvʌ/ through measurement point T4 (the end of the schwa) after which the tongue body moves forward for /i/, but moves hardly at all for /ʌ/. In the disyllables /əzi/ and /əzʌ/, tongue body fronting is not different at T1. Subsequently the
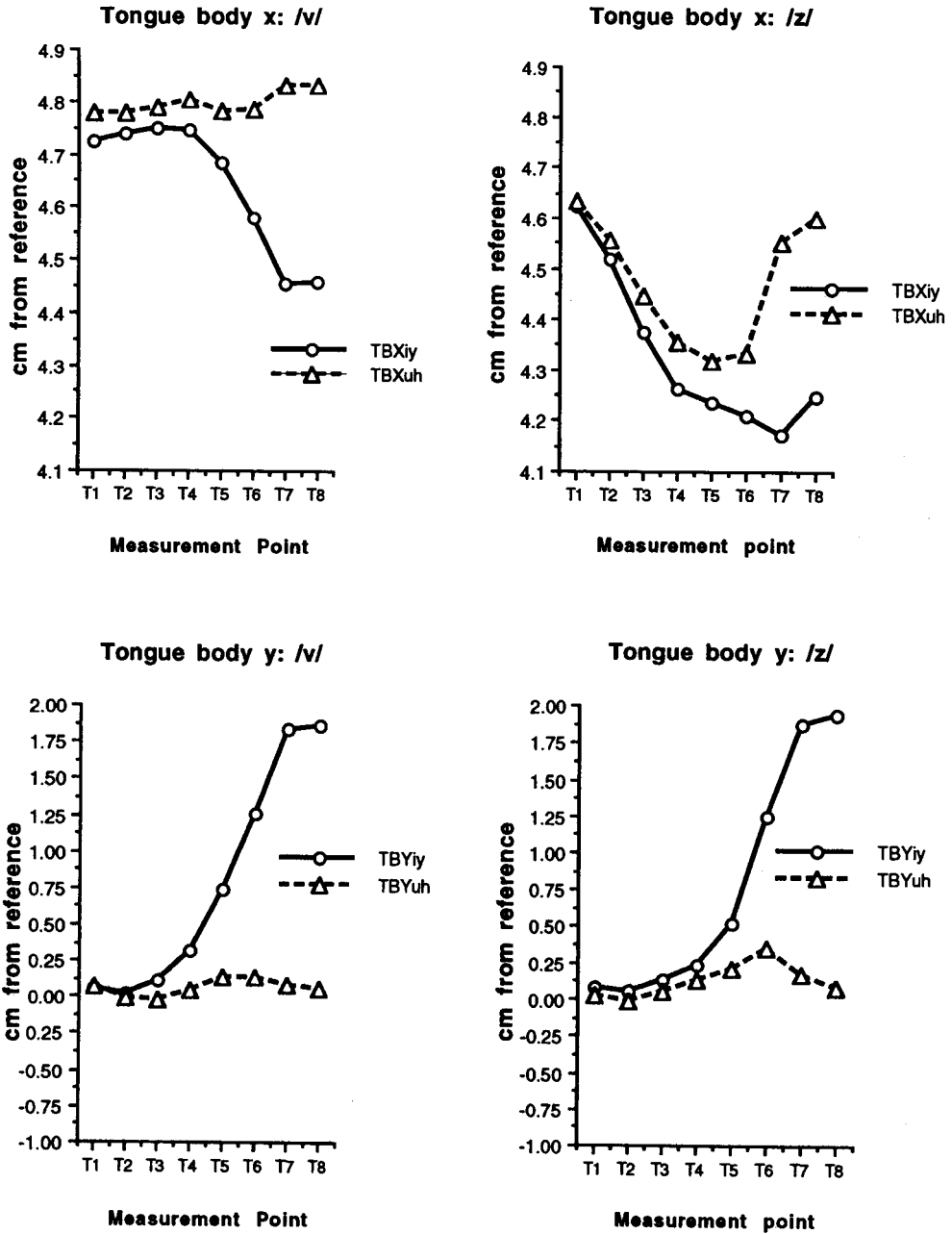
Tongue body x: /v/

Tongue body x: /z/

Tongue body y: /v/

Tongue body y: /z/

Figure 3

Tongue body measures during / əvi / and / əvʌ/ (left panels) and / əzi / and / əzʌ / (right panels).

TABLE 1

F1 and F2 values at measurement points T2, T3, T6, T7, T8 for speaker CB's productions collapsed over rate

| | F1 (Hz) | | | | | F2 (Hz) | | | | | |
	T2	T3	T6	T7	T8	T2	T3	T6	T7	T8	Dur.
əbi	598	542	310	327	323	1279	1290	1980	2285	2341	412
əbʌ	597	542	411	615	640	1230	1176	1094	1221	1245	411
əvi	570	462	302	326	312	1298	1276	1988	2217	2300	424
əvʌ	597	517	376	642	672	1220	1150	1125	1228	1259	447
əgi	577	488	291	327	318	1422	1644	2268	2352	2398	426
əgʌ	584	508	370	637	660	1257	1340	1892	1301	1299	414
əði	586	521	344	344	330	1395	1514	1906	2239	2312	425
əðʌ	590	516	368	633	665	1289	1334	1574	1295	1286	416
ədi	576	518	293	330	329	1526	1709	2048	2288	2322	447
ədʌ	588	531	352	633	652	1401	1532	1876	1296	1304	439
əzi	549	410	306	329	325	1533	1633	1890	2252	2302	458
əzʌ	563	457	377	652	667	1403	1501	1598	1314	1342	439
əʒi	528	388	314	345	360	1605	1781	1963	2148	2235	457
əʒʌ	539	422	347	638	678	1391	1614	1774	1364	1290	458

TABLE 2

F1 and F2 values at measurement points T2, T3, T6, T7, T8 for speaker EM's productions collapsed over rate

| | F1 (Hz) | | | | | F2 (Hz) | | | | | |
	T2	T3	T6	T7	T8	T2	T3	T6	T7	T8	Dur.
əbi	409	359	281	254	258	1126	1131	1985	2306	2345	383
əbʌ	434	406	441	556	556	1061	1056	1108	1220	1196	372
əvi	406	349	271	255	259	1149	1189	1980	2301	2334	389
əvʌ	430	371	411	568	581	1080	1090	1109	1223	1203	383
əgi	391	309	244	246	250	1558	1880	2448	2448	2398	380
əgʌ	446	379	359	533	572	1291	1617	1956	1527	1274	392
əði	416	350	269	254	260	1310	1326	1899	2368	2368	385
əðʌ	458	422	393	560	566	1165	1201	1257	1255	1227	371
ədi	421	395	322	256	326	1458	1581	2074	2297	2348	383
ədʌ	451	430	352	548	576	1299	1396	1583	1384	1245	368
əzi	392	344	280	260	329	1323	1350	1802	2277	2350	392
əzʌ	412	367	365	551	563	1208	1243	1235	1273	1196	394
əʒi	361	314	273	273	337	1546	1669	1949	2158	2266	403
əʒʌ	386	340	354	554	584	1378	1513	1594	1340	1235	394

trajectories diverge, but they are roughly parallel until T6. Clearly a reason for the parallelizm in the trajectories is the constriction location for /z/, which is more forward than that for /ʌ/. Another way to see the difference in coarticulation resistance in the tongue body x measures is to note that, in /əvʌ/, but not /əzʌ/, the tongue body is roughly in position for /ʌ/ throughout the disyllable. This is true in the y (height) dimension as well. In addition, along this dimension the trajectories in the /i/ and /ʌ/ disyllables diverge at about T3 (two thirds of the distance into schwa) in the /v/ disyllables, but they follow roughly parallel trajectories through T5 in the /z/ disyllables.

Tables 1 and 2 show our acoustic measures of F1 and F2 across the five acoustic measurement points for all 14 disyllables. Table 1 presents the data from CB's productions collapsed over rate and Table 2, EM's corresponding measures. The mean duration of the disyllables in ms and collapsed over rate is provided in the final column. We caution the reader that we are not confident of measures of F1 during schwa, particularly for disyllables spoken at the fast rate. The F1 values at T3 were uniformly lower than at T2 due to the onset of the consonant constriction. However, aside from this, because the durations of the schwas were very short (particularly in the fast productions), the second acoustic measurement point (T3) was in very close temporal proximity to the following consonant constriction. This appeared to introduce contamination in the analysis window for T3 from voicing following the consonants' constrictions (in particular, during the fricatives).

Vowel-to-vowel coarticulation is evident in F1 if F1 is lower in frequency during schwa (measures T2 & T3) before /i/ than /ʌ/. It is evident in F2 if F2 is higher during schwa before /i/ than /ʌ/. Evidence for vowel-to-vowel coarticulation is more striking in F2 than in F1 in Tables 1 and 2. Coarticulation resistance would be expected to reduce any such effects before high as compared to low resistant consonants. Our acoustic analyses reported below test for any effects of vowel-to-vowel coarticulation and of coarticulation resistance.

Acoustic durations. Because we will ask whether coarticulation resistance is lower for consonants produced at a fast as compared to a normal rate, we must test the efficacy of our rate manipulation. Both speakers showed highly significant effects of the rate manipulation on total disyllable duration (CTB: $F(1, 387)=247.8, p<.0001$; EM: $F(1, 379)$ $=901.08, p<.0001$). The average duration difference between disyllables produced at the normal and fast rates was 56 ms for CB and 80 ms for EM. This difference is substantial; normal rate disyllables averaged about 460 ms for CB and 425 ms for EM. Significant rate effects were also present when tests were done separately on acoustic schwa duration (CTB: 12 ms difference; $F(1, 387)=71.90, p<.0001$; EM: 14 ms difference $F(1, 379)=170.541$, $p<.0001$), consonant closure duration (CTB: 16 ms difference; $F(1, 387)=118.45, p<.0001$; EM: 20 ms difference $F(1, 379)=203.31, p<.0001$) and V2 duration (CTB: 27 ms difference; $F(1, 387)=138.82, p<.0001$; EM: 46 ms difference $F(1, 379)=491.91, p<.0001$).

A different issue regarding duration is whether disyllables having consonants that differ in expected coarticulation resistance also differ in the durations of their closure intervals and schwa vowels. This is relevant, because we will be asking whether vowel-to-consonant and vowel-to-vowel coarticulation is less in magnitude and extent in disyllables having expected-high than expected-low resistant consonants. If closure durations are longer for high than low resistant consonants then our midclosure measurement point is farther from the coarticulating vowel for high than low resistant consonants, and comparisons of

differences due to resistance differences on coarticulation magnitudes are inappropriate. Likewise, if schwa + closure intervals are longer in disyllables with high than low resistance consonants, then our comparison of vowel-to-vowel coarticulation in the context of high and low resistance consonants may be inappropriate.

For talker CB, closure durations ranged from 87 ms to 129 ms for high resistant consonants and from 86 ms to 108 ms for low resistant consonants. However, only the closure duration of expected-high resistant /d/ fell well outside the range of durations of the low resistant consonants (129ms). For EM, findings are complementary. The closure duration of /d/ (84 ms falls inside the range of closure durations for expected low resistant consonants (82 ms to 94ms); the other expected high resistant consonants fall outside the range by up to 15 ms (102 ms to 109ms)). When we look at effects of coarticulation resistance on vowel-to-consonant coarticulation, we will look separately at the high resistant consonants with longer and shorter closure intervals to see whether findings may be affected by these differences.

As for vowel-to-vowel coarticulation, the relevant duration is the summed duration of schwa plus the closure interval. Again, the question is whether that interval is longer for high resistant consonants so that, for example, when we look at a point one third of the way into the schwa, is that point, in fact, farther from the acoustically measured onset of V2 for high than low resistant consonants. For CB, that tends to be the case. For every expected high resistant consonant excepting /ð/, the duration of schwa plus closure is longer for expected high than low resistant consonants. For EM, consonants /d/ and /ð/ fell inside the range of durations for the expected low resistant consonants. /z/ and /ʒ/ did not. There is, therefore, a trend for expected high resistant consonants to have longer schwa plus closure durations than low resistant consonants; this, in itself, may be a reflection of resistance to coarticulation as we will speculate in the *General Discussion*. However, the differences are not large. (The difference between the longest schwa + closure duration for high and low resistant consonants is 20 ms for both CB and EM.) In addition, in each comparison we made, some high resistant consonants fell within the durational range of the low resistant consonants and some did not. This will allow us to assess whether these duration differences underlie any differences we find in temporal extent and magnitude of coarticulation by high and low resistant consonants. Accordingly, we are confident that our measures taken at fixed ordinal positions in our disyllables (e.g., 1/3 and 2/3 of the way from the acoustic onset of schwa, mid consonant closure, etc.) can provide interpretable evidence of effects of differences in coarticulation resistance.

Coarticulation resistance differences among consonants

Our subsequent analyses focus on differences in articulatory and acoustic measures at the different measurement points depending on whether the vowel is /i/ or /ʌ/.

Articulatory measures — Talker CB.   We first looked for evidence of differences in coarticulation resistance among the seven consonants on which we collected data. As we predicted earlier, we expected the nonlingual consonants, /b/ and /v/, and the lingual consonant /g/ to show larger anticipatory coarticulatory effects of the vowel in the consonant than the remaining lingual consonants.

To test for the expected patterning of coarticulation resistance among the consonants,

we looked at tongue body (TB) x (fronting) and y (height) measures during consonantal closure (articulatory measurement point T5 in Figure 2) and at release (measurement point T6). Our dependent measure was a difference score in which we subtracted from values for utterances ending in /i/ those ending in /ʌ/ (at measurement points T5 & T6). We used a difference score because it focuses attention on the findings of greatest relevance to this study, namely the time of earliest onset and the magnitudes of vowel-to-consonant and vowel-to-vowel coarticulation. We subtracted tokens that had been produced in the same experimental block and that matched in rate of production.

For ease of display and communication, we plot differences in the expected direction (i.e., utterances ending in /i/ having higher or more front tongue body positions than those ending in /ʌ/) as positive difference scores in our figures. The two panels of Figure 4 provide the /i/ minus /ʌ/ findings for talker CB. For both fronting and height measures and both during closure and at release, CB consistently shows more fronting and height of the tongue body when the stressed vowel is /i/ than when it is /ʌ/. Not surprisingly, differences tend to be greater at the later measurement point.

Of major interest to us, however, were differences in the magnitude of the difference scores as a function of the coarticulation resistance of the consonant. We predicted larger /i/-/ʌ/ differences when the consonant was /b/, /v/, or /g/ than when it was any of the other consonants. On the fronting measure, this expectation was borne out by every comparison; on the height measure, /g/ grouped more with the other lingual consonants than with the nonlingual consonants. This appears to represent /g/'s somewhat special status. Producing /g/ entails making a complete constriction with the tongue body on the palate. Accordingly, the height dimension of the tongue body is highly constrained. However, /g/ is well-known to be associated with variation in the point of constriction along the palate, and so is less constrained in the x dimension.

We performed analyses of variance with factors consonant, rate, and measurement point (T5, consonant closure, vs. T6, consonant release). Separate analyses were performed on TB x and y. Subsequently, we performed planned comparisons in which we contrasted difference scores in utterances with /b/, /v/ and /g/ with those in the other utterances. In both analyses, the effect of consonant was significant, TB x: $F(6, 190) = 10.55, p < .0001$; TB y: $F(6, 190) = 32.05, p < .0001$. The effect of measurement point was significant as well, TB x: $F(1, 190) = 576.79, p < .0001$; TB y: $F(1, 190) = 1481.49, p < .0001$, with greater difference scores at T6 than at T5 in both fronting and height. Consonant interacted significantly with measurement point, TB x: $F(6, 190) = 23.04, p < .0001$; TB y: $F(6, 190) = 29.25, p < .0001$, but in both cases the main effect of consonant was significant for T5 and T6. Planned comparisons (conducted separately for T5 & T6) contrasting difference scores between utterances with consonants expected to be high and low in coarticulation resistance yielded highly significant outcomes (smallest $F(1, 190) = 22.91, p < .0001$), even though /g/ tended to group with the lingual consonants in the TB y measures. For this talker, the effects of rate and the interactions were uniformly nonsignificant. That is, contrary to our expectations, on these measures, the talker did not show an overall increase in magnitude of coarticulation, and, by inference, a decrease in overall coarticulation resistance with rate.

We determined whether the differences in magnitude of coarticulation resistance for the expected low and high resistant consonants were due to the fact that high resistant consonants had longer closure intervals than low resistant consonants. We have two
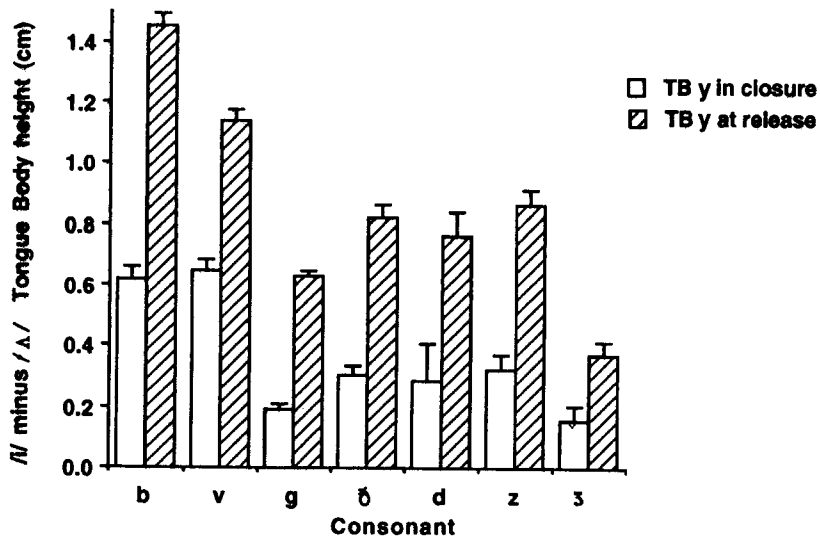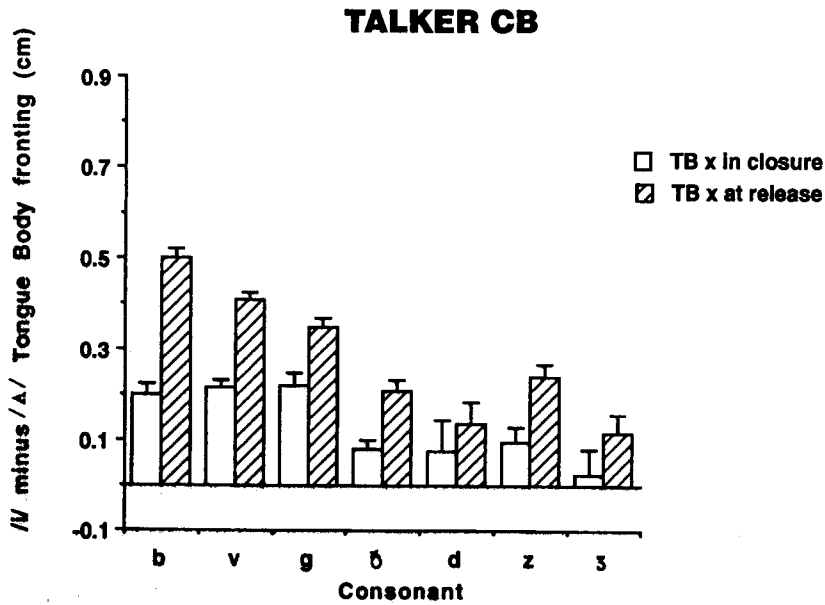
TALKER CB

Figure 4

Vowel differences (/i/ minus /ʌ/) in tongue body fronting and height during consonantal closure and at release in the disyllables of talker CB.

indications that they were not. First, effects of coarticulation resistance were significant at T6, that is at consonant release where the differences in the duration of the closure interval are irrelevant. Second, we can compare the coarticulation resistance of /v/ versus /ð/, which had almost identical closure intervals (86 ms, 87 ms respectively), and we can compare the resistance of /b/ (108 ms closure) versus /ʒ/ (109 ms closure). In three of four comparisons (tongue body fronting, height for the two consonant pairs), the expected low resistant consonant was associated with a larger /i/-/ʌ/ difference than its expected high resistant counterpart.

Our analyses show clear and consistent effects of coarticulation resistance differences between lingual and nonlingual consonants. /g/, a low resistant, lingual consonant showed resistance to fronting that was similar in magnitude to that of the nonlingual consonants and to height that was similar to that of the lingual consonants.

Articulatory measures — Talker EM. Findings were similar for talker EM. The two panels of Figure 5 display the descriptive statistics.

Like CB, EM showed uniformly positive differences in tongue body height and fronting both during closure and at release on the measure /i/ minus /ʌ/. Also like CB, difference scores were large for consonants /b/ and /v/ as compared to lingual consonants other than /g/. EM did show two differences in patterning from CB. Whereas for CB, /g/ grouped with /b/ and /v/ on the fronting measure but with the other lingual consonants on the height measure, for EM, /g/ uniformly grouped with the high resistant consonants. Second, /ð/ showed /i/-/ʌ/ differences in height that were nearly as large as those shown by /b/ and /v/.

In analyses of variance with factors consonant, rate, and measurement point (T5, consonant closure, vs. T6, consonant release), and dependent measures TB x and y, EM showed significant effects of consonant, TB x: $F(6, 183) = 75.88$, $p < .0001$; TB y: $F(6, 183) = 186.63$, $p < .0001$, and measurement point, TB x: $F(1, 183) = 1551.99$, $p < .0001$; TB y: $F(1, 183) = 2488.28$, $p < .0001$, with greater difference scores at T6 than at T5. Consonant also had a significant interaction with measurement point, TB x: $F(6, 183) = 98.42$, $p < .0001$; TB y: $F(6, 183) = 76.48$, $p < .0001$, but in both cases the main effect of consonant was significant for both T5 and T6. Unlike CB, EM showed a significant effect of rate on TB x, $F(1, 183) = 8.52$, $p < .005$, with difference scores, as expected, larger at the faster rate of production. Rate was not significant for TB y ($p = .10$). The interactions of consonant and rate did not approach significance; however, rate did significantly interact with measurement point, TB x: $F(1, 183) = 19.24$, $p < .0001$; TB y: $F(1, 183) = 6.16$, $p = .015$. Further analyses revealed that the rate effect was significant on TB x at T5, $F(1, 183) = 14. 05$, $p < .0005$, and marginal ($p > .01$) for TB x at T6 and TB y at T5, but was not significant on TB y at T6.

Planned comparisons on the effects of consonant (conducted separately for T5 & T6) contrasted difference scores (/i/-/ʌ/) when consonants were /b/, /v/ and /g/ versus when they were the other lingual consonants. All comparisons were highly significant (smallest $F(1, 183) = 46.90$, $p < .0001$). However, /g/ patterned more like a high than a low resistant consonant on both fronting and height measures. Moreover, /ð/ appeared to pattern somewhat more like a low resistant consonant in the height measure.

As noted earlier, of the four high resistant consonants, only /d/ had a closure duration as short as those of the expected low resistant consonants. To ascertain whether our findings
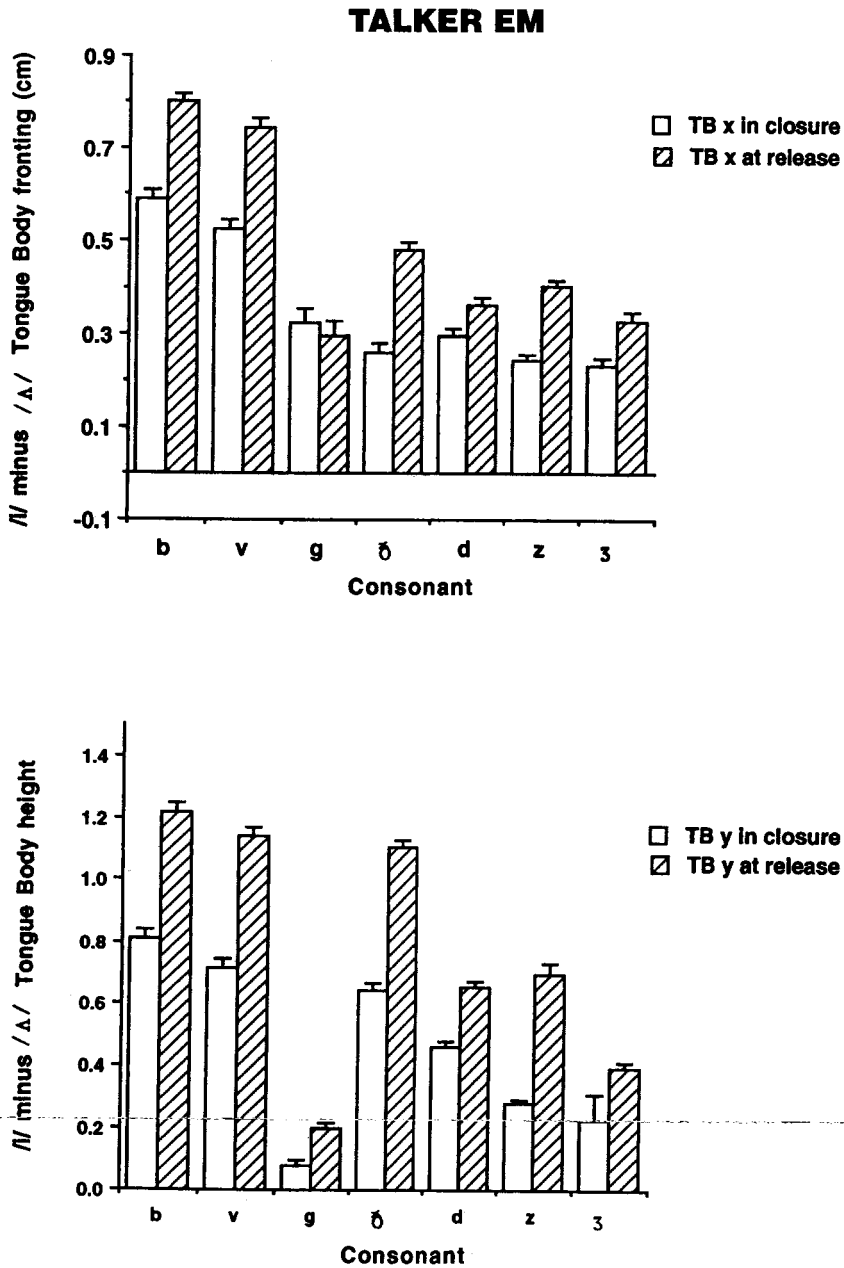
TALKER EM

Figure 5

Vowel differences (/i/ minus /ʌ/) in tongue body fronting and height during consonantal closure and at release in the disyllables of talker EM.

of less vowel-to-consonant coarticulation in closures of high than low resistant consonants (excepting /g/) were due to the longer closures of the high resistant consonants (so that our assessment point at mid closure was farther from the vowel), we compared /i/-/ʌ/ differences during mid closure of /b/ and /d/, which had comparable closure durations (85 ms and 84 ms respectively). Low resistant /b/ showed larger difference scores than higher resistant /d/ on both tongue body measures.

Acoustic consequences — Talker CB. We focus our attention here on measures of F2, because effects are larger there. For completeness, however, we also report analyses of F1.

Figure 6 shows / i / minus / ʌ / differences in F2 values for talker CB at the measurement points, T6, T7, and T8. Predicted low resistant consonants are shown on the left side of the figure. Data are collapsed over rate, because in the ANOVAs to be reported, rate never interacted with consonant.

We ran an analysis of variance with factors consonant, rate, and measurement point on the difference score /i/ minus /ʌ/ on F2. The purpose was to ask whether effects of coarticulation resistance of the consonant can be seen in F2 at consonant release and thereafter. The effect of consonant was highly significant, $F(6, 191)=146.9, p<.0001$, as was the effect of measurement point, $F(2, 382)=2727.0, p<.0001$. The effect of measurement point reflected a marked increase in the difference scores over measurement points. These two factors interacted significantly, $F(12, 382)=92.5, p<.0001$, respectively. Figure 6 illustrates the interaction. There are large effects of coarticulation resistance in the difference scores at the earliest measurement point (T6, release), with /b/ and /v/ especially being associated with larger difference scores than the lingual consonants. (These difference scores correspond closely to locus equation slopes; large differences in F2 at vowel onset for different vowels will produce a steep locus equation slope.) The differences in the difference scores across consonants are much weaker at the later measurement points (i.e., during the vowel). However, despite the highly significant interaction, in separate analyses on the three measurement points, the effect of consonant was highly significant for both difference scores at all three measurement points. Planned contrasts between difference scores for /b/, /v/, and /g/ versus the other lingual consonants revealed significant differences in all three tests (two difference scores by three measurement points; smallest $F(1,189)=36.3, p<.0001$). The analyses show that, at consonant release, the acoustic signal provides considerably more information about the stressed vowel in the context especially of /b/ and /v/ and to a lesser extent /g/ than in the context of the other lingual consonants.[1]

In the analysis, the effect of rate and its interaction with measurement point also reached significance, $F(1,191)=3.99, p=.05; F(2,382)=9.27, p<.0001$, respectively. The effect of rate reflected the larger difference score at the faster rate of speaking; the interaction was significant, because that difference was present only at T6. Note that our articulatory measure (/i/ minus /ʌ/) during consonant closure did not show an effect of rate.

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[1] /g/'s difference score was numerically greater than that of any of the other lingual consonants; however, its score was much closer to that of the nearest lingual consonant (/ð/) than to those of /b/ and /v/.
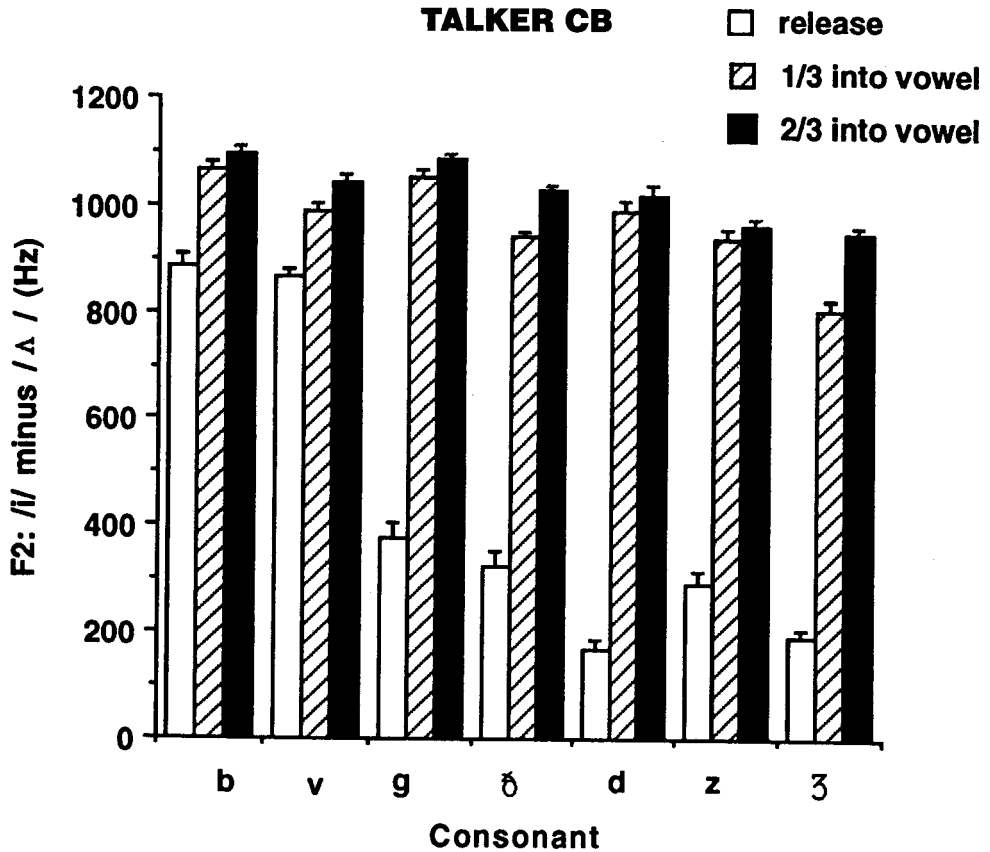
Figure 6

Vowel differences in F2(/i/ minus /ʌ/) at consonantal release and at two points in the stressed vowels in the disyllables of talker CB.

We also ran an analysis of variance with factors consonant, rate and measurement point, performed on the difference score /i/ minus /ʌ/ on the measure of F1 (see Table 1 for mean F1 measures that underlie the difference scores). The effect of consonant on the difference score was significant, $F(6,192)=6.43$, $p<.0001$. Although the largest difference score (collapsed across measurement point, thus combining consonant release and the vowel) was found for /v/ (250 Hz), the other low resistant consonants, /g/ (243 Hz) and /b/ (235 Hz) were not second and third, but rather third and fourth, trailing /z/. The effect of measurement point was highly significant, $F(2,384)=2092.92$, $p<.001$, with difference scores increasing monotonically over the three measurement points (63 Hz, 303 Hz, 334 Hz).

The interaction between these variables also reached significance, $F(12, 384)=3.71$, $p<.0001$. We asked whether the interaction occurred because high resistant consonants reduced the /i/-/ʌ/ difference especially at consonant release. This was the case. On average, the low resistant consonants were associated with a larger difference score at release (84 Hz vs. 47 Hz for higher resistant consonants; /b/, /g/, and /v/ had the three largest

difference scores at T6), but not within the vowel (differences between low and high resistant consonants were 3 Hz and 11 Hz at the two measurement points in the vowel).

In the analysis of F1, no other main effect or interaction reached significance.

Acoustic Consequences — Talker EM. Figure 7 shows /i/-/ʌ/ differences in F2 values for talker EM at the same three measurement points. Values in the figure are collapsed over speaking rate. Consistent with the articulatory measures on these utterances, two of the predicted low resistant consonants, /b/ and /v/, are associated with larger difference scores especially at the earliest measurement points than are the remaining consonants. As the articulatory measures had shown, here, too, /g/ groups with the high resistant consonants.

In analyses of variance on F2 difference scores with factors consonant, rate, and measurement point, the effect of consonant was highly significant, $F(6, 186) = 88.59$, $p < .001$, as was the effect of measurement point, $F(2, 372) = 2130.0, p < .0001$, and their interaction, $F(12, 372) = 37.94, p < .0001$. Figure 7 shows that the interaction is significant because the differences in the /i/-/ʌ/ difference score comparing /b/ and /v/ against the other consonants, were large at the earliest measurement point and small at the later two points. However, as for CB, separate analyses of variance at the three measurement points found significant effects of consonant in all analyses (smallest $F(6, 186) = 7.74$, $p < .0001$), and planned comparisons of the predicted low (/b/, /v/, /g/) versus predicted high resistant consonants yielded significant outcomes in all three analyses, albeit with markedly decreasing F values at the later measurement points (smallest $F(1, 186) = 7.61$, $p = .006$).

In the analysis, there was no effect of rate ($F < 1$); however, there was an interaction of rate and measurement point, $F(2, 372) = 4.63, p = .01$. Despite the significance of the interaction, the effect of measurement point was strikingly similar at the normal and faster rates. In both cases, F2 difference scores increased across the three measurement points.

In analyses of variance on the measure of F1 difference scores (see Table 2 for mean F1 measures that underlie the difference scores) with factors consonant, rate, and measurement point, the main effect of consonant and of measurement point were significant, $F(6,186) = 3.01, p = .0078; F(2,372) = 122.86, p < .0001$. The main effect of rate did not reach significance; nor were any of the interactions significant. As for the effect of consonant, the largest difference scores (collapsed across measurement point) were associated with /b/ (253 Hz) and /v/ (258 Hz); /g/'s difference score (240 Hz) was fourth largest, trailing that of /ð/. The smallest difference score occurred in disyllables with consonant /d/ (191 Hz). The effect of measurement point was significant, because difference scores were smaller at release (averaging 104 Hz) than at the later two measurement points (296 Hz and 292 Hz). These two factors did not interact ($F < 1$); accordingly, there is no tendency for low and high resistant consonants to differ more in their F1 difference scores at release than thereafter.

Summary of vowel-consonant coarticulatory effects

The most important finding so far is confirmation, in the main, of the expected differences in coarticulation resistance of our seven consonants. Variation in coarticulation resistance revealed itself in our first set of analyses as variation in anticipatory effects of the vowel on the positioning of the tongue body during closure and at consonant release. Effects of
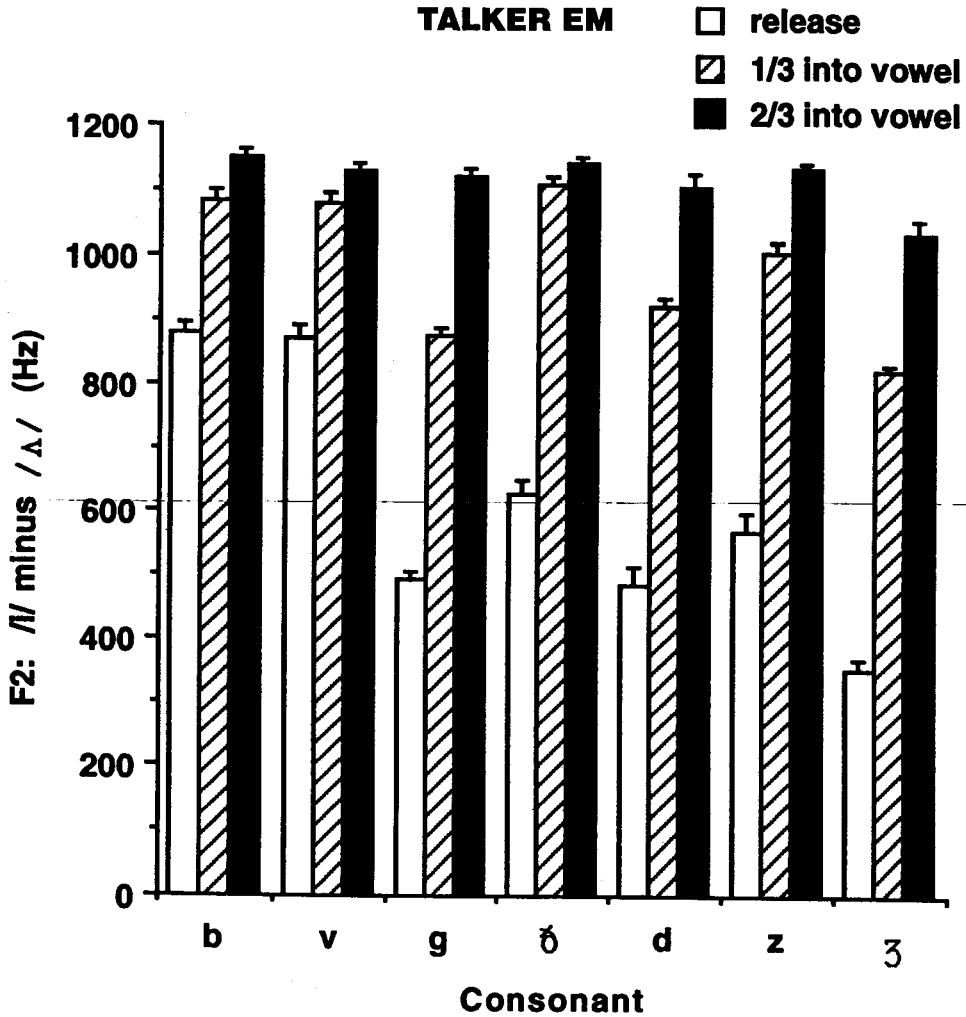
Figure 7

Vowel differences in F2(/i/ minus /ʌ/) at consonantal release and at two points in the stressed vowels in the disyllables of talker EM.

the vowel were more substantial during closure and at release of /b/ and /v/ than during /d/, /ð/, /z/, and /ʒ/. For speaker CB, /g/ grouped with the low resistant consonants, /b/ and /v/, in the fronting dimension of the tongue body, but with the high resistant consonants in height. For speaker EM, /g/ was uniformly a high resistant consonant.

Acoustic measures of F2 taken at consonant release and at two later points in the vowel showed parallel and closely consistent effects of consonantal coarticulation resistance to the articulatory measures. That is, /i/-/ʌ/ differences in F2 at those three measurement points all were smaller in the context of /d/, /ð/, /z/, and /ʒ/ than in the context of /b/ and /v/. For CB, although /g/ had the third highest /i/-/ʌ/ difference in F2, consistent with

its being a low resistant consonant, visibly, in Figure 6, it groups with the high resistant consonants, as it did also for EM compatibly in this case with its articulatory grouping.

Acoustic measures of F1 taken at consonant release and at two later points in the stressed vowel patterned roughly as expected. That is, low resistant consonants were generally, though not wholly consistently, associated with larger /i/-/ʌ/ differences than high resistant consonants.

As for rate effects, we expected to see larger coarticulatory effects with faster rates of speaking. Other investigators have reported such findings (e.g., Brancazio & Fowler, 1998; Browman & Goldstein, 1986; Engstrand, 1988). We interpret such effects as reductions of coarticulation resistance at faster rates of speaking. In the speech of CB, we found the expected rate effects only in the acoustic domain and only for the F2, not the F1, difference scores. We saw no rate effect in our articulatory measures of vowel differences in tongue body fronting and height during consonant closure and at release.

Findings in the speech of EM were almost complementary. In three of four analyses of the articulatory data, EM showed the expected effect of rate — that is, larger vowel difference scores at the faster rate. However, acoustic difference scores in neither F1 nor F2 were reliably different at the two rates of speech. Possibly our rate differences were not sufficiently large to show large or reliable effects on coarticulation.

Effects of coarticulation resistance differences among consonants on vowel-vowel coarticulation

We next examine the effects, if any, of differences in coarticulation resistance of consonants on vowel-to-vowel coarticulation.

Articulatory measures — Talker CB. A first question is whether we see differences during schwa in the fronting and height of the tongue body depending on whether the forthcoming vowel is /i/ or whether it is /ʌ/. That is, do we see anticipatory vowel-to-vowel coarticulation at all? A second question is whether any such differences increase early to late in the schwa, and a third question is whether differences are overall smaller or delayed in the context of high than of low coarticulation resistant consonants.

To address the first question, we need to determine whether /i/-/ʌ/ differences in tongue body fronting and height are consistently positive during the schwa. To determine that, we averaged TB x difference scores (and separately, TB y difference scores) across the four articulatory measurement points during schwa, and we conducted t-tests of the difference scores against 0. If the difference scores are consistently positive, these t-values should be positive and significant. Both t-tests were highly significant, TB x: $t(203) = 6.05$, $p < .0001$; TB y: $t(203) = 9.65$, $p < .0001$.

To address the second and third questions, we performed ANOVAs with factors consonant, rate, and measurement point (articulatory points T1-T4) on dependent measures TB x and TB y /i/-/ʌ/ difference scores.

In the analysis of the /i/-/ʌ/ difference in tongue fronting, there was a main effect of measurement point and an interaction of that factor with consonant, $F(3, 570) = 3.13$, $p = .025$; $F(18, 570) = 2.12$, $p = .005$. The interaction (shown in Figure 8, top) occurred in part because, whereas in the context of the majority of the consonants, the /i/-/ʌ/ difference

increased from the first to the fourth measurement point (although not always mono-tonically), the difference was reversed in the context of /ʒ/. In addition, disyllables with /ð/, which showed very large vowel differences from the beginning of the schwa, showed a decrease in the difference score from measurement point three to four.

The /i/-/ʌ/ difference scores show at best weak evidence that the magnitude of coarticulation is affected by the coarticulation resistance of the consonant. Schwas in disyllables including the low resistant consonants neither begin with larger coarticulatory effects nor show the largest effects at the fourth measurement point. However, at the fourth measurement point, the three predicted low resistant consonants do show larger difference scores than all but one of the predicted high resistant consonants (/ð/). Moreover, the three predicted low resistant consonants are the only consonants showing a monotonic increase during schwa. Consistent with these observations and the nonsignificance of the main effect of consonant, a planned comparison testing the low against the high resistant consonants was nonsignificant.

As for tongue body height, analysis of the /i/-/ʌ/ difference (see Figure 8, bottom panel) showed a main effect of measurement point, $F(3, 570) = 18.39$, $p < .0001$, with difference scores increasing over time and an interaction with consonant, $F(18, 570) = 2.22$, $p = .003$. The interaction may reflect the larger increase in the /i/-/ʌ/ difference in the context of /v/ than of other consonants and the lack of monotonicity in the change over measurement points for disyllables with /g/ and /ʒ/. In both of these latter cases, the difference score reduces from measurement point 3 to 4. Again, the magnitudes of antici-patory vowel effects do not appear to differ systematically for disyllables including low and high resistant consonants, and results of a planned comparison contrasting difference scores of the low and high resistant consonants was nonsignificant.

This analysis also revealed a rate by consonant interaction, $F(6, 190) = 3.50$, $p = .003$. The interaction revealed an unexpected pattern of results. At the normal rate of speaking, the high resistant consonant /d/ and the low resistant /g/ were associated with the largest difference scores; at the faster rate, consonants associated with the largest difference score were the high resistant /ʒ/ and the low resistant /v/.

Because these analyses showed weak effects of coarticulation resistance, we did not address the question whether any such effects were artifacts of the duration differences between expected high and low resistant consonants such that high resistant consonants typically were associated with longer schwa + closure intervals than low resistant consonants.

A comparison of Figures 4 and 8 allows the magnitude of difference scores to be traced from schwa onset through consonant release. For both the fronting and the height measures, two patterns are evident. Either difference scores are roughly monotonically increasing in the set of measures or they increase through measurement point 3 (within schwa) then are lower at measurement points 4 and 5 (schwa offset/closure onset and mid closure), increasing again thereafter. The latter pattern, characteristic of /ð/ and /ʒ/ in the fronting measure and /g/ and /ʒ/ in the height measure, suggests a transient clamping of stressed vowel production by a consonant. A question of interest to us was whether the amount of vowel-consonant coarticulation predicts the amount of vowel-to-vowel coartic-ulation or whether the magnitudes are independent, as suggested by the occasional findings by Recasens described earlier. Our comparison of the figures does not provide a clear answer.
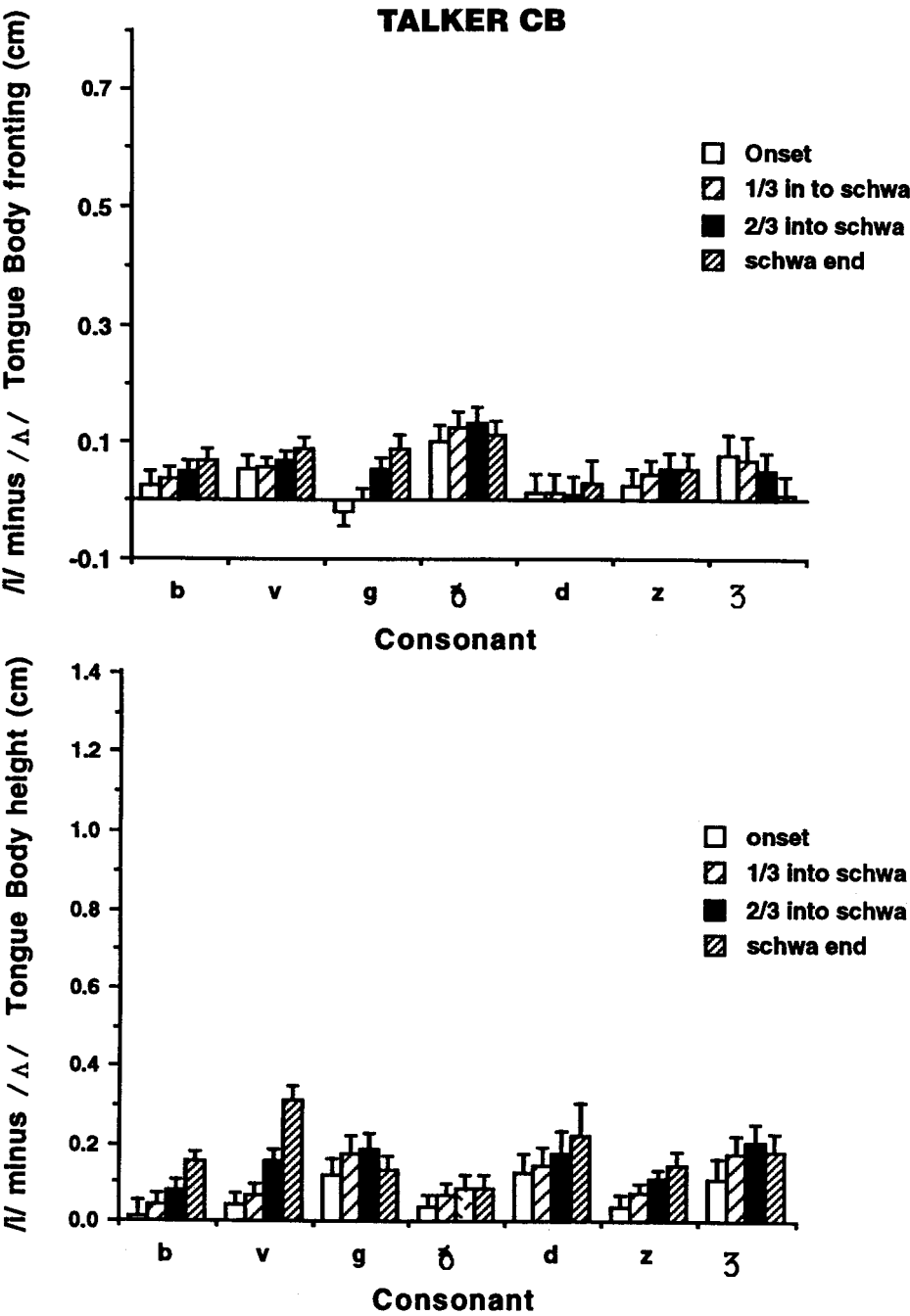
Figure 8

Vowel-to-vowel coarticulatory effects in the speech of talker CB: vowel differences (/i/ minus /ʌ/) in tongue fronting and height at four measurement points in schwa.

TABLE 3

Correlations between /i/-/ʌ/ differences in TB *x* and *y* during consonant closure with corresponding differences at four measurement points (1,2,3,4) during schwa

	1	2	3	4
Talker CB				
TBx	.03	.09	.35	.35
TBy	.04	.13	.44	.50
Talker EM				
TBx	.46	.55	.67	.79
TBy	.20	.38	.62	.83

For this talker, /b/ and /v/ are associated with low resistance to coarticulation everywhere and /g/ is everywhere low resistant in the fronting dimension. This is consistent with there being a relation between coarticulation magnitude in the two domains. However, in the fronting measure, /ð/ and /ʒ/, and on the height measure, /g/ and /ʒ/, provide outcomes that we might expect if coarticulation magnitudes are not wholly dependent in the two domains. That is, there is more coarticulation earlier in schwa than there is at its end and the reduction endures until consonant release.

Another way to relate coarticulation resistance of the consonant to vowel-to-vowel coarticulation magnitude is to correlate the /i/-/ʌ/ difference in tongue body fronting and height during consonant closure (our measure of coarticulation resistance) with the corresponding differences during schwa at the four different measurement points. Table 3 (top) provides the data for talker CB's /i/-/ʌ/ difference measures (required for significance, approximately .135; correlations based on 204 observations). On both TB *x* and TB *y*, correlations increase over measurement points. Across the two tongue body measures, by the third and fourth measurement points both correlations are significant. The significant correlations mean that the larger and smaller /i/-/ʌ/ articulatory differences during consonantal closure that are associated with lower and higher degrees of coarticulation resistance are being manifested during the schwa as well, albeit weakly.

Articulatory Measures—Talker EM. As for CB, for talker EM, we averaged TB *x* (and separately, TB *y*) /i/-/ʌ/ difference scores across the four measurement points in schwa. We conducted *t*-tests to determine whether these difference scores differed significantly from zero, signifying significant anticipatory vowel-to-vowel coarticulation during schwa. In both analyses, results were highly significant, TB *x*: $t(196)=18.72, p<.0001$; TB *y*: $t(196)=21.60, p<.0001$.

We next asked whether the difference scores increased early to late in the schwa and whether the magnitude of vowel-to-vowel effects was modulated by coarticulation resistance of the consonant. We ran ANOVAs with factors consonant, rate, and measurement point on measures TB *x* and TB *y*. In the analysis of TB *x*, the /i/-/ʌ/ difference did increase early to late in schwa, $F(3, 549)=314.0, p<.0001$. There was also a main effect of consonant, $F(6, 183)=10.20, p<.0001$, which interacted with measurement point, $F(18, 549)=14.08$, $p<.0001$. The interaction, shown in Figure 9, reflected variation in the magnitude of the

change in the /i/-/ʌ/ difference score over measurement point depending on the consonant. The effects are those expected if coarticulation resistance is modulating vowel-to-vowel coarticulation. A planned comparison contrasting the difference scores for low and high resistant consonants was highly significant, $F(1, 183) = 49.57, p<.0001$. Unlike CB's data on /i/-/ʌ/ had shown, by the third and fourth measurement points, schwas preceding /b/, /v/, and /g/ show the largest /i/-/ʌ/ differences in tongue fronting. Second, subtracting the difference score at the latest measurement point from that at the earliest for each consonant yields larger differences for consonants /b/ (.194 cm), /v/ (.187 cm), and /g/ (.141 cm) than for any of the predicted high resistant consonants (largest change: .104). That is, although schwa begins with a positive /i/-/ʌ/ difference at the earliest measurement point regardless of the following consonant, by the fourth measurement point, differences are larger preceding low than high resistant consonants.

In addition to the major effects of interest in the three-way ANOVA, there was a main effect of rate, $F(1, 183) = 16.84, p<.0001$, with difference scores greater at the faster rate of speaking.

A difference in findings of CB and EM, perhaps underlying the lesser evidence for effects of coarticulation resistance on vowel-to-vowel coarticulation in CB's data, are differences in the magnitude of the /i/-/ʌ/ differences. EM shows larger magnitude differences both in fronting and in height than does CB. This may be a consequence of EM speaking overall faster than CB. (Recall that EM's disyllables averaged 425 ms in duration whereas CB's averaged 460 ms.)

The analysis of TB y also yielded a main effect of measurement point, $F(3, 549) = 196.37, p<.0001$, with difference scores increasing over time. The main effect of consonant was also significant, $F(6, 183) = 2.59, p=.002$, and consonant interacted with measurement point, $F(18, 549) = 34.23, p<.0001$. However, on this measure, the consonants did not group by predicted coarticulation resistance consonants as Figure 9 reveals. The planned comparison contrasting difference scores of low and high resistant consonants was nonsignificant. Whereas /b/ and /v/ showed the greatest increase in the difference score from the earliest to the latest measurement point and the largest difference scores at measurement point 4, /g/ showed essentially no change and a smaller difference score at measurement point 4 than any of the predicted high resistant consonants.

To ascertain whether the differences in magnitude of coarticulation we saw that conformed to predictions based on coarticulation resistance were artifacts of differences in schwa+closure durations between disyllables with high and low resistant consonants, we selected two high-low resistant pairs with comparable schwa+closure durations. They were /v/ and /ð/ (152 ms, 150 ms respectively) and /b/ and /d/ (135 ms, 125 ms). On the measure tongue body fronting, the low resistant consonants showed larger /i/-/ʌ/ differences than their high resistant counterparts in every comparison (measurement points T1-T4). However, on the measure of tongue body height, which had not shown as consistent evidence for an effect of coarticulation resistance, exactly half of the comparisons were as predicted. We can be confident that reported effects of coarticulation resistance on coarticulation of tongue fronting are not artifacts of duration differences between low and high resistant consonants. We cannot be as confident about coarticulation of tongue height.

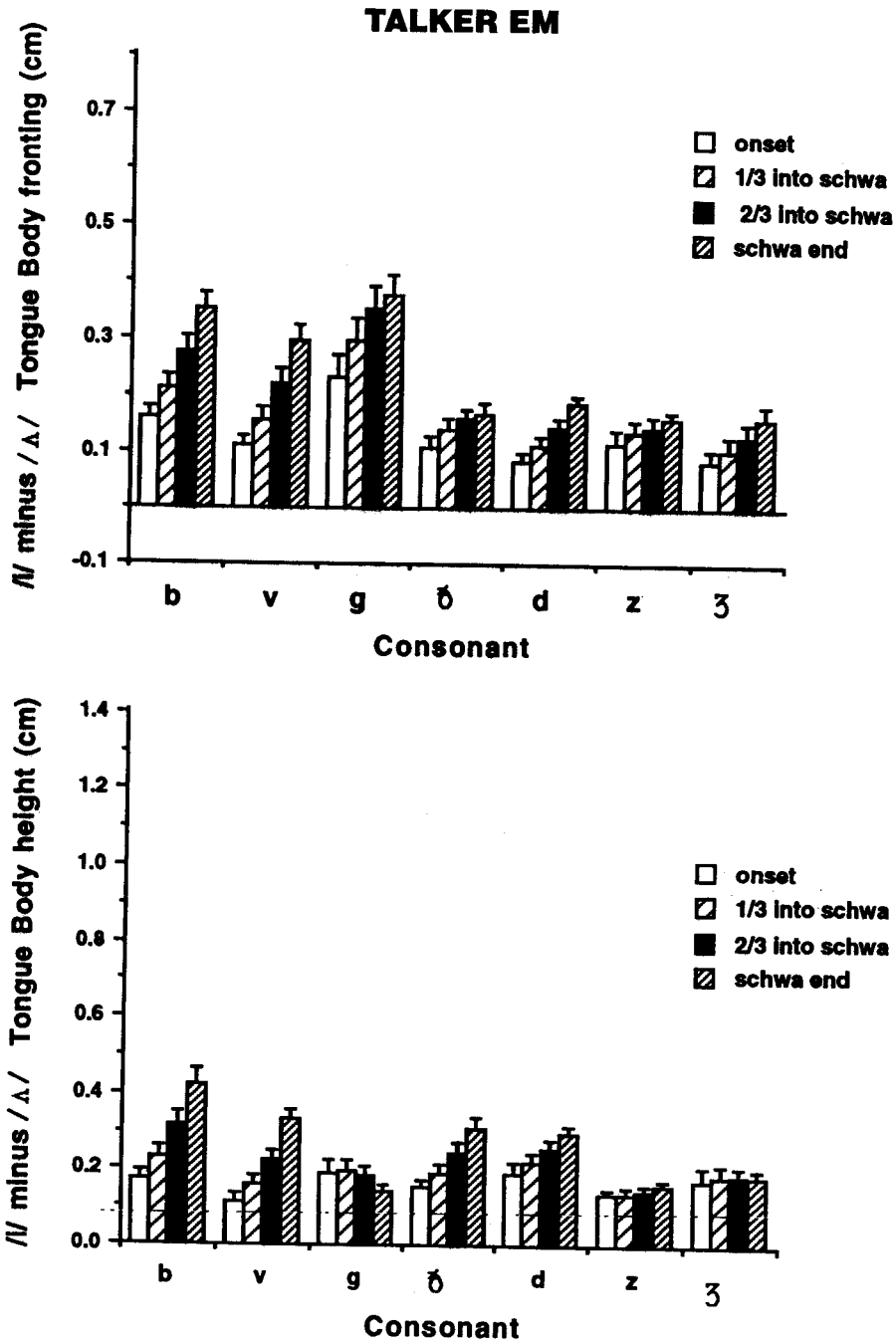Comparison of Figures 5 and 9 allow the course of /i/-/ʌ/ differences to be traced

TALKER EM

Figure 9

Vowel-to-vowel coarticulatory effects in the speech of talker EM: vowel differences (/i/ minus /ʌ/) in tongue fronting and height at four measurement points in schwa.

from schwa onset to consonant release. On the fronting measure, EM shows a monotonic increase in the difference score throughout the six measurement points for the low resistant consonants /b/ and /v/, but not for /g/. /g/ and the predicted high resistant consonants show increases in the difference score at least through the end of the schwa but a clamping either at closure (/z/, /ʒ/) or at release (/g/, /d/, /ð/). As we had observed before, for this talker, /g/ belongs with the high resistant consonants even on this measure of fronting. On the height measure, three consonants, /b/, /v/ and, unexpectedly, /z/, show monotonic increases through the six measurement points. Three (/d/, /ð/, and /ʒ/) show increases through measurement point 4, a clamping at 5 and a further increase at 6. /g/ appears to be the highest resistant consonant of all on this measure. In this case, the difference score is lower at measurement points 3–5 than at 1–2 and 6. As we found for CB, this comparison does not yield an entirely clear picture of the relation between magnitudes of vowel-to-vowel and vowel-to-consonant coarticulation. However, EM shows more cases than CB in which difference scores are larger during schwa than during closure or release of the consonant. On the fronting measure, all consonants except /b/ and /v/ exhibit some clamping of vowel production during their domain that is not evident during schwa. The consonants (except /z/) show the same pattern on the height measure. This is consistent with an interpretation that stressed vowel production begins at schwa onset regardless of the coarticulation resistance of a following consonant. (Note, however, that, on the fronting measure, the overall magnitude of vowel-to-vowel coarticulation is less during schwas followed by the predicted high than low resistant consonants; see the correlations below.)

As we had for CB, for EM, we looked at the relationship between vowel-to-vowel and vowel-to-consonant coarticulation in another way by correlating difference scores during consonant closure (as a measure of consonantal coarticulation resistance) with those during each measurement point in schwa. That is, we asked whether consonants that permitted little anticipatory vowel production in their own domains also were associated with smaller magnitudes of transconsonantal vowel-to-vowel coarticulation. Table 3 (bottom) shows that there was indeed such a relationship. Correlations were uniformly positive and significant (Required for significance, approximately .135; correlations based on 197 observations for the /i/-/ʌ/ difference measures). The magnitudes of the correlations between the TB x and TB y difference scores at measurement point T5 and the difference scores at points 1, 2, 3, and 4. EM's correlations are markedly higher than CB's; all reach significance at $p<.0001$. This shows that despite evidence of some independence between vowel-to-vowel and vowel-to-consonant coarticulation (in the sense that the magnitude of coarticulation in schwa can be greater than that in the consonant, which is closer to the coarticulating vowel), nonetheless the coarticulation resistance of a consonant has an impact on the magnitude of vowel-to-vowel coarticulation.

Acoustic consequences — Talker CB. The articulatory measures on talker CB provided weak evidence of different patterns of vowel-to-vowel coarticulation across consonants with different degrees of coarticulation resistance. Here we ask whether differences are manifested acoustically.

We looked at /i/-/ʌ/ differences in F2 at the first two acoustic measurement points (T2 and T3 in Figure 2; see Figure 10, top panel). Not surprisingly, the differences are much smaller than in Figure 6 where differences within the stressed vowel itself were displayed. However, average differences were uniformly positive as in Figure 6. These
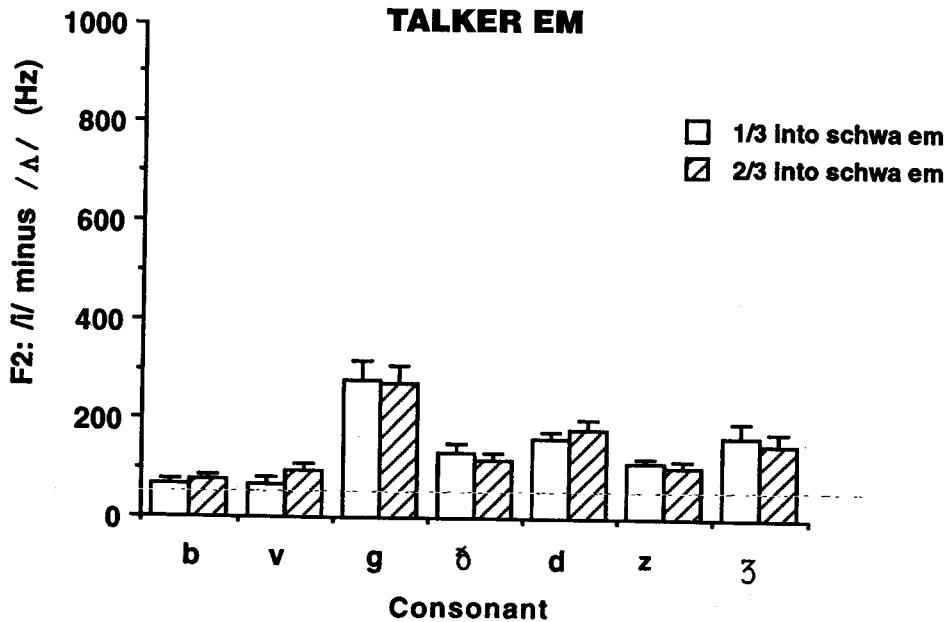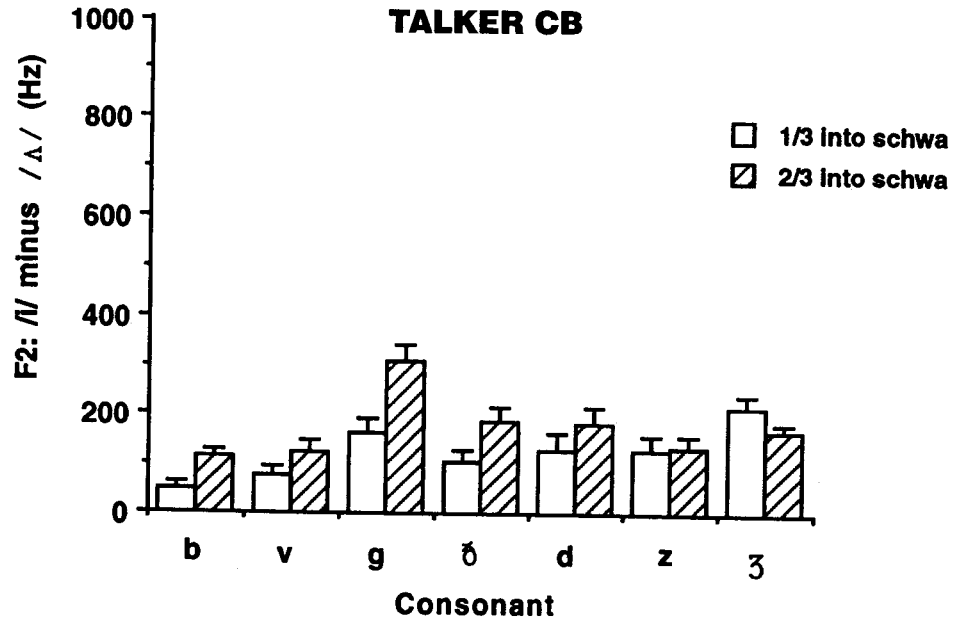
Figure 10

Acoustic evidence of vowel-to-vowel coarticulatory effects in the speech of talkers CB and EM: measures are differences in F2(/i/ minus /ʌ/) taken at two points during schwa.

findings of anticipatory coarticulatory effects of a stressed vowel on a transconsonantal schwa are consistent with many earlier observations (e.g., Fowler, 1981; Magen, 1991). We conducted a *t*-test on the difference scores to ensure that the differences were significantly different from zero, and were in the expected direction (positive differences, meaning that F2 was higher preceding /i/ than /ʌ/). The *t*-test on difference scores averaged across the two measurement points confirmed these expectations, $t(204)=17.02, p<.0001$. Second, we conducted an analysis of variance with factors consonant, rate, and measurement point. The main effect of measurement point was significant, $F(1, 191)=23.24, p<.0001$, as was the main effect of consonant, $F(6, 191)=6.65, p<.0001$, and their interaction, $F(6,191)=5.11, p<.0001$. The effect of measurement point reflected the finding that differences were larger at the later measurement point. The interaction with consonant occurred because that direction of difference held for all consonants except /ʒ/. The magnitude of the /i/-/ʌ/ difference in F2 during schwa was not associated with the coarticulation resistance of the consonant. Again, /g/ was associated with the largest overall difference; however, /b/ and /v/ were associated with the smallest and the second smallest differences respectively.

There was, finally, a significant interaction of consonant with rate, $F(6, 191)=4.51$, $p=.0003$, which reflected the finding that, for six of the seven consonants, /i/-/ʌ/ differences were larger at the faster rate of speech; for /d/ the direction of difference was reversed.

We also looked at /i/-/ʌ/ differences in F1 at the first two acoustic measurement points. A *t*-test on the difference scores averaged across the measurement points revealed that the /i/-/ʌ/ difference was significantly less than zero, $t(204)=-5.16, p<.0001$, meaning that F1 values were lower preceding /i/ than /ʌ/, as expected (see Table 1). In an analysis of variance with factors consonant, rate, and measurement point (T2 and T3), the main effect of consonant was significant, $F(6,191)=3.37, p=.004$. The largest /i/-/ʌ/ differences in F1 occurred in disyllables with /v/; however, otherwise the patterning of difference scores did not conform with expectations based on coarticulation resistance. The effect of measurement point also reached significance, $F(1, 191)=10.32, p=.0015$, with difference scores larger, as expected at the later measurement point. The effect of rate was not significant; nor were any interactions.

Acoustic Consequences—Talker EM. As was the case with CB, a *t*-test on the F2 /i/-/ʌ/ difference scores averaged across T2 and T3 revealed that the difference was significantly greater than zero, $t(198)=17.51. p<.0001$. Figure 10 (bottom panel) shows the results of the F2 analysis of EM's disyllables ending in /i/ and /ʌ/. For comparability with findings of CB, we have presented the interaction of consonant by measurement point. However, in the analysis of EM's data, with factors, consonant, rate, and measurement point, the only significant effect was the main effect of consonant, $F(6, 185)=14.94, p<.0001$. The figure reveals that, in contrast to CB's schwa vowels, EM's do not exhibit a consistent increase in the /i/-/ʌ/ difference with measurement point. Nor is there any tendency for schwas preceding the three low resistant consonants to show larger /i/-/ʌ/ differences than those preceding the four high resistant consonants, although schwas preceding /g/ do show the largest differences of all at both measurement points.

A *t*-test on the F1 /i/-/ʌ/ difference scores averaged across T2 and T3 revealed that

the difference was significantly less than zero, $t(199) = -10.56, p < .0001$. In an analysis of F1 measures with factors consonant, rate, and measurement point, the main effects of consonant, $F(6,186) = 3.44, p = .003$, rate, $F(1, 186) = 6.17, p = .01$, and measurement point, $F(1, 186) = 19.11, p < .0001$, reached significance. As for the effect of consonant, /g/ was associated with the largest difference score among the consonants; however, generally the patterning of difference scores were not as expected if coarticulation resistance affects vowel-to-vowel coarticulation along the height dimension. The effect of rate reflected the finding that difference scores were overall higher at the faster rate. The effect of measurement point was significant, because, as expected, difference scores were larger at the later measurement point, as indicated in the presentation of the mean F1 measurements in Table 2.

The three way interaction of the independent variables also reached significance, $F(6, 186) = 3.24, p = .0047$. This was because, whereas for some consonants (in particular, /b/ and /ð/) the difference score was larger at T3 than at T2 and larger at the fast than at the slow rate, aspects of this pattern did not hold for every consonant.

Summary of vowel-vowel coarticulatory effects

Both speakers showed clear vowel-to-vowel coarticulatory effects in both articulatory and acoustic measures beginning at schwa onset. The tongue body was more forward and higher in disyllables with final /i/ than in disyllables with final /ʌ/. F2 during schwa was higher in the context of /i/ than of /ʌ/.

There was weak evidence in articulatory measures for an effect of coarticulation resistance on vowel-to-vowel coarticulation. CB showed a greater degree of final vowel-dependent effects on fronting by the final measurement point in schwa for schwas preceding low than high resistant consonants. This difference was not wholly consistent; /ð/ showed the largest vowel difference of all by the final two measurement points. EM showed highly consistent effects of coarticulation resistance in measures of tongue fronting. As for tongue height, the only consistent index of coarticulation resistance was the correlation of vowel difference scores in schwa with difference scores at consonant closure. For both talkers and for both TB x and TB y, correlations reached significance by measurement points three and four (and earlier for EM) during the schwa vowel.

Despite these findings, neither talker showed consistent effects of coarticulation resistance in our measures of F1 or F2.

The relation of coarticulation resistance to locus equation slopes and to linearity of locus equation plots

Talker CB. As we suggested in the introduction, the acoustic consequences of differences in coarticulation resistance that we have seen at the onset of the stressed vowel of our disyllables should have an impact on locus equation slopes. These slopes (e.g., Lindblom, 1963; Sussman, e.g., 1989; Sussman, McCaffrey, & Matthews, 1991) are obtained by plotting F2 at transition onset after consonant release against F2 in the vowel for CVs in which the consonant is held constant as the vowel varies. Plots of these x (F2 in the vowel), y (F2 at transition onset) coordinates reveal linear relations between the variables and slope relations between them that vary with the consonant.

Because our high resistant consonants were found to be associated with smaller /i/-/ʌ/ differences in F2 at consonant release and because we found this acoustic effect of coarticulation resistance to weaken in the vowel (at measurement points 4 and 5), we should expect our articulatory measures of coarticulation resistance of the consonants to correlate well with variation in locus equation slope, supporting the view (Fowler, 1994; Sussman, 1994) that coarticulation resistance underlies the slope differences.

Because we only have three vowels[2], and studies of locus equations typically have considerably more, we compared the slope, intercept, and R^2 values in our present data with those in the data of Fowler (1994), who examined the same seven consonants produced in the context of eight different vowels by 10 speakers. We used our acoustic measurement points T6 and T8 as measures of F2 at transition onset and in mid vowel.

Plots of slope by intercept are presented in Figure 11. The top panel shows data from Fowler (1994) and the middle panel shows CB's data. In the middle panel, each consonant is represented by two points, one each for the two speaking rates. (Contrary to our expectations, there was no consistent tendency for the faster rate condition to be associated with the higher slope.) Except for the slope for /g/ in the present data, findings are similar to those of Fowler (1994). For speaker CB, R^2s ranged from .52 to .96 across the seven consonants (computed separately by consonant and rate).

To relate the slopes to our measures of coarticulation resistance, we performed correlations between locus-equation slope and /i/- /ʌ/ differences in TB x and y during consonant closure (articulatory measurement point T5) for talker CB. Correlations were performed on 14 pairs of data points (7 consonants and 2 rates). The correlation of slope with TB y was especially high at .91; the correlation was statistically significant. The correlation of slope with TB x was lower, at .68, although it was also significant (p=.0058).

We also attempted to relate the linearity of locus equation plots to the corresponding relation of tongue position during mid vowel and at consonant release. However, we should note that our ability to do this is limited in two ways. First, we have only three vowels from which to determine linearity. Second, we are required to partition tongue body position into its x (front-to-back) and y (low-to-high) coordinates, and so our estimates of linearity are made separately on these dimensions. However, these are not orthogonally controlled dimensions of movement of the tongue; accordingly our estimates of linearity may not be accurate.

We asked whether, in CVs with the consonant fixed, changes over vowels in TB x and y at mid vowel accurately predicted changes at consonant release and whether the predictive relation was linear. Finally, we asked whether slopes of regression equations for different consonants produced at different rates with dependent measures TB x and y predicted locus equation slopes. The regression coefficients are presented in Table 4, along with locus equation coefficients computed on the same utterances.

For CB, the R^2s for regressions relating TB x at mid vowel (measurement point 8) to TB x at consonant release (measurement point T6), using individual utterances as data, ranged from .06 to .96; those for TB y ranged from .48 to .98. These are generally lower

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2   Although we did not use /a/ utterances in our earlier analyses, we will use them here to compute locus equations for CB.
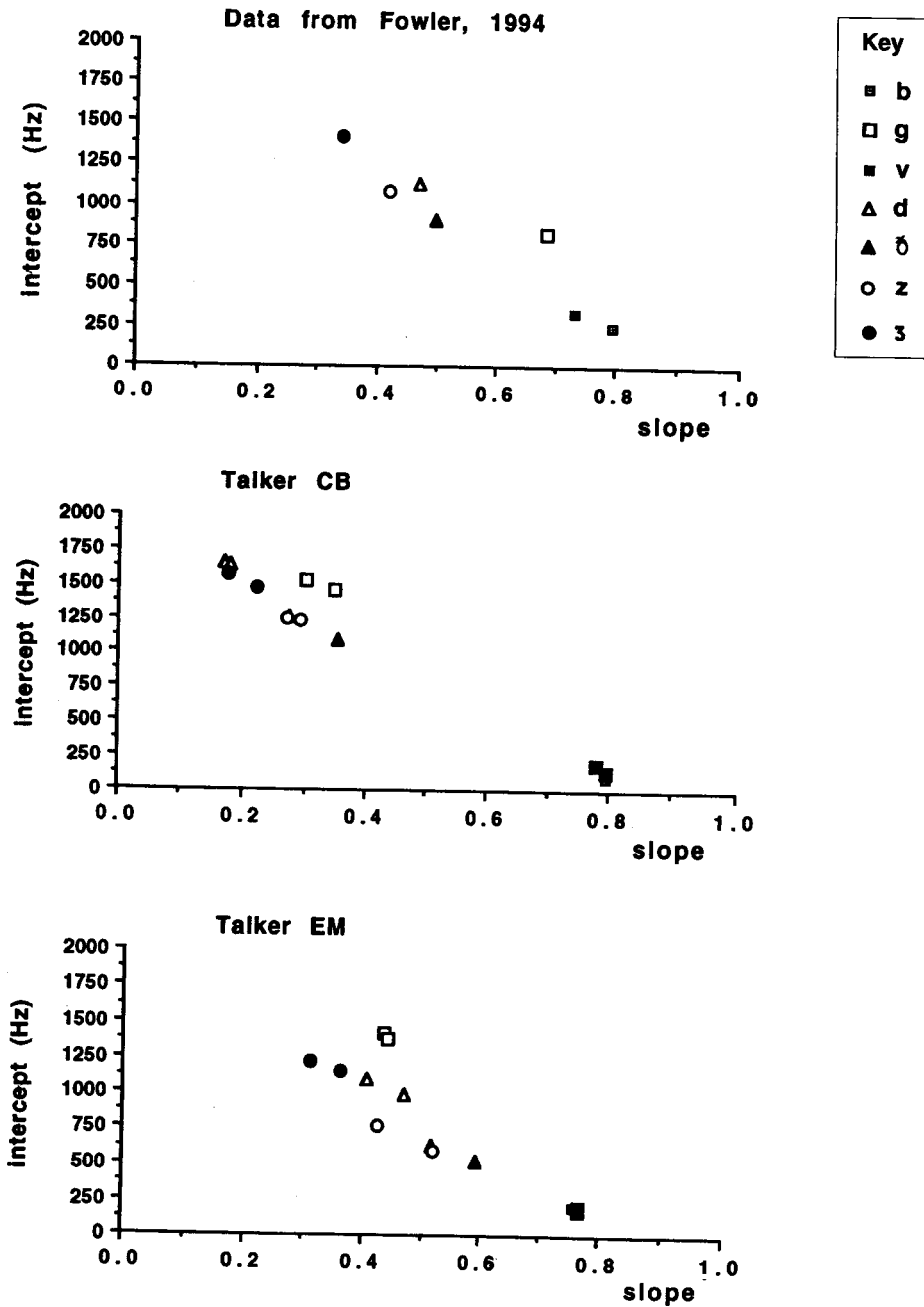
Figure 11

Locus equation slopes and intercepts. (Top panel: data from Fowler (1994); middle panel: data of CB; lower panel: data from EM.)

TABLE 4

Slopes, intercepts and R^2 for regressions relating articulatory measures of CB's productions at T6 and T8 for TB x and TB y, along with locus equation coefficients, computed by consonant and speaking rate (normal, 'N', vs. fast, 'F')

Cons.	Rate	TB x			TB y			F2		
		slope	int.	R^2	slope	int.	R^2	slope	int.	R^2
/b/	N	.730	1.21	.89	.717	−.15	.98	.797	115.5	.96
	F	.755	1.09	.93	.695	−.13	.97	.797	101.2	.96
/v/	N	.607	1.87	.79	.612	.12	.98	.797	134.1	.96
	F	.719	1.35	.83	.595	.09	.95	.782	196.8	.96
/g/	N	.509	2.10	.72	.303	1.39	.96	.301	1526.1	.75
	F	.532	2.01	.69	.328	1.31	.95	.348	1453.6	.74
/ð/	N	.355	2.61	.44	.441	.18	.93	.275	1260.3	.67
	F	.320	2.73	.47	.426	.22	.90	.355	1093.2	.66
/d/	N	.229	3.38	.14	.372	.46	.63	.169	1647.9	.52
	F	.216	3.46	.06	.390	.59	.66	.179	1635.8	.57
/z/	N	.292	2.97	.39	.452	.37	.85	.291	1237.4	.62
	F	.266	3.09	.13	.407	.32	.88	.270	1245.6	.52
/ʒ/	N	.462	2.65	.13	.214	1.01	.48	.175	1565.1	.55
	F	.435	2.76	.19	.229	.98	.53	.220	1467.2	.71

than R^2s for measures of F2 in other studies. However, the R^2s associated with TB y are comparable to those on our measures of F2. These are low because of our small vowel set.

Slopes of regression lines for both TB x and TB y correlated highly with locus equation slopes ($r = .86$ and $r = .89$, respectively, $p < .0001$). Their correlation with each other was less strong ($r = .61, p = .02$). Accordingly, we ran a multiple regression analysis using slopes of both TB x and TB y vowel midpoint-to-consonant release relations as predictors of locus equation slope. The result was highly significant ($R^2 = .98, p < .0001$) with both TB x, $t(11) = 6.69, p < .0001$, and TB y, $t(11) = 7.69, p < .0001$, contributing significantly to the R^2 value. This tells us that the slope of the linear relation between TB x at vowel midpoint and at consonant release and the corresponding slope of the linear relation involving TB y explain almost all (98%) of the variance in locus equation slope. This leaves very little variance to be explained by any parameter of an equation expressing a nonlinear relation between the articulatory variables.

Talker EM. Figure 11 (bottom panel) shows the slopes and intercepts of regression equations for Talker EM; these equations are based only on productions of disyllables with vowels /i/ and /ʌ/. As for CB, each consonant is represented by two symbols, one each for disyllables produced at the normal and faster rate. (For this talker as for CB, there was no consistent relation between rate and locus equation slope.)

To relate the slopes to our measures of coarticulation resistance, we correlated slopes with /i/-/ʌ/ differences in TB x and y during consonant closure. The correlations both were positive and highly significant, TB x: $r(12) = .89, p < .0001$; TB y: $r(12) = .85, p < .0001$.

As we had for CB, we also attempted to assess the linearity of the articulatory tongue

TABLE 5

Slopes, intercepts and R^2 for regressions relating articulatory measures of EM's productions at T6 and T8 for TB x and TB y, along with locus equation coefficients, computed by consonant and speaking rate (normal, 'N', vs. fast, 'F')

Cons.	Rate	TB x slope	TB x int.	TB x R^2	TB y slope	TB y int.	TB y R^2	F2 slope	F2 int.	F2 R^2
/b/	N	.906	−.08	.99	.800	−.26	.98	.762	199.4	.98
	F	.901	−.11	.99	.795	−.24	.98	.760	197.3	.97
/v/	N	.826	−.17	.99	.804	−.23	.98	.769	174.4	.97
	F	.843	−.18	.98	.823	−.19	.98	.768	197.3	.98
/g/	N	.311	−.99	.75	.168	−.23	.74	.442	1376.5	.97
	F	.327	−.95	.73	.172	−.24	.87	.435	1418.5	.97
/ð/	N	.472	−.79	.95	.749	−.30	.96	.519	634.3	.92
	F	.496	−.76	.97	.809	−.12	.99	.593	524.9	.95
/d/	N	.493	−.52	.95	.438	−.20	.95	.406	1096.8	.94
	F	.513	−.50	.96	.486	−.17	.98	.469	988.3	.77
/z/	N	.397	−.40	.96	.492	−.66	.81	.426	74.1	.68
	F	.447	−.45	.99	.549	−.56	.94	.520	589.0	.92
/ʒ/	N	.725	−.73	.89	.306	−.12	.99	.312	1222.2	.87
	F	.737	−.74	.89	.300	−.12	.88	.361	1141.6	.96

body relations underlying acoustic linearity in locus equation plots. We performed regression analyses predicting tongue body position in the front-back and height dimensions during the vowel (measurement point T8) to that at consonant release (measurement point T6). The coefficients of these regressions are presented in Table 5. R^2s were very high for six of the seven consonants, ranging from .89 to .99 for TB x and .81 to .98 for TB y; for /g/, fits were slightly more modest ranging from .73 to .87.

Simple correlations between locus equation slope and slopes of regressions using TB x and y were significant, TB x: $r(12) = .64$, $p = .013$; TB y: $r(12) = .84$, $p < .0001$. As it had been for CB, the simple correlation between slopes of regressions using TB x and y was lower, $r(12) = .58$; $p = .03$. Accordingly, we looked to see whether they jointly predicted locus equation slope more successfully than either did alone. In this case, the answer was no. TB y slopes entered the regression; TB x slopes did not.

Summary of the relation of locus equation slopes and linearity to coarticulation resistance

Our analyses were successful in relating variations in locus equation slopes to variation in coarticulation resistance. That is, disyllables with consonants showing small /i/-/ʌ/ artic-ulatory differences during consonant closure were associated with shallower locus equation slopes than disyllables with consonants showing large vowel differences in closure. With our very small vowel set, we were not well equipped to address the question whether the linearity of locus equation plots have underlying them linearity of the relevant articulatory variables. In addition, we are handicapped by not having a unidimensional measure of our

articulatory variable, tongue body position. In any case, our analyses did show a close relation between locus equation slopes and slopes of regression equations relating TB x and y values at consonant release and mid vowel.

GENERAL DISCUSSION

One aim of our research was to provide descriptive measures of coarticulation resistance differences among consonants of English using electromagnetometry. Our results largely confirm those of Recasens (1984a), on a speaker of Catalan, and using electropalatography, in showing differences in anticipatory vowel-to-consonant coarticulation depending on the identity of the consonant. In particular, during their constriction intervals and at release, labial consonants /b/ and /v/ were associated with large differences in fronting and height of the tongue body if the following vowel was /i/ rather than /ʌ/. CB also showed large differences in fronting if the consonant was /g/. Other lingual consonants showed smaller differences due to the vowel. For our speaker CB, anticipatory vowel effects were not greater for disyllables spoken at a faster rate; for EM, they tended to be.

Differences in coarticulation resistance of the consonant had acoustic consequences not only at release of the consonant, but also in the stressed vowel itself. Differences, particularly in F2 at consonant release, depending on whether the stressed vowel was /i/ or whether it was /ʌ/, were modulated in magnitude by the coarticulation resistance of the consonant. Following /b/, /v/, and to a lesser degree for CB, /g/, F2 difference scores were greater at consonant release than following the other consonants. The magnitude of these differences shrank considerably well into the vowel, but nonetheless were still statistically reliable. This indicates that the coarticulation resistance of the consonant exerts an impact on vowel articulation, not only in the domain of the consonant itself, but well afterwards as well.

A possible effect of coarticulation resistance that we did not expect to see occurred in our measures of acoustic duration of the disyllables and their component parts. Both talkers showed a tendency for closure durations in which the consonant was high in coarticulation resistance to be longer acoustically than those with lower resistance consonants. This leads us to speculate that it is another consequence of coarticulation resistance. That is, higher resistance consonants may exert a more powerful clamping effect on the articulators that implement them than lower resistance consonants. If we think of vowels that coarticulate with consonants as competing for some of the same articulators, then we can think of vowels "losing" the competition longer in the context of high than low resistance consonants. These ideas are preliminary, but they foster looking further at durational consequences of coarticulation resistance.

A second aim of our research was to examine the effect of differences in coarticulation resistance among consonants on vowel-to-vowel coarticulation that occurs across the consonant. We found clear evidence of anticipatory vowel-to-vowel coarticulation, and some indications of modulation of its magnitude, but not temporal extent, by coarticulation resistance. The clearest indication of that modulation was provided by our correlations of vowel differences in tongue body height and fronting during schwa with the same differences during consonantal closure. The latter provides our measure of the different resistances of the consonants to anticipatory coarticulation by the following vowel. We found that this

measure was increasingly highly correlated with tongue body and fronting differences due to the stressed vowel in the schwa. That is, with a single exception, the magnitude of the correlations increased monotonically from the earliest to the latest of the four articulatory measurement points during schwa. Correlations were significant throughout schwa for speaker EM and by measurement point three or four for CB. The significant correlations mean that disyllables with low resistant consonants, as assessed by our measurements during consonant closure, were associated with larger vowel-to-vowel coarticulatory effects during schwa than disyllables with high resistant consonants. These findings, too, are largely compatible with those reported by Recasens (1984b) on a single speaker of Catalan.

Despite this finding, we found no differences in the temporal onset of vowel-to-vowel effects as a function of coarticulation resistance and no clear acoustic reflections in schwa of coarticulation resistance differences among consonants.

A reason why we were interested in looking at vowel-to-vowel coarticulation across variation in coarticulation resistances of intervening consonants was a sporadic finding by Recasens. The finding was that vowel-to-vowel anticipatory and carryover effects were sometimes found at points in a vowel that were distant from the consonant but not at points closer to the consonant. This is an intriguing finding, because of what it may imply about how coarticulation resistance differences are implemented in speech production. It implies that resistance can be exerted by a clamping of the tongue dorsum by the consonant. Phasing of vowels one to the other may occur approximately invariantly regardless of the identity of the consonant. Variation due to the consonant then occurs as the vowels are coproduced with the consonant. The consonant begins to clamp the tongue dorsum to an extent that is greater for higher than for lower resistant consonants. The clamping reduces or prevents effects of vowel production on fronting and height of the tongue body in its domain. Following earlier ideas of Fowler and Smith (1986; who termed the concept "prominence") and Löfqvist (1990; who called it "dominance"), one can think of the gestures of a consonant or vowel first strengthening then weakening over time. The strength of the consonant's clamping of the tongue dorsum then would be strongest in the time interval identified as the temporal domain of the consonant (perhaps strongest of all during consonant closure) and weaker earlier than that and later than that time. This is consistent with two of our findings. One was the growth of correlations between vowel differences in tongue body fronting and height during consonantal closure and vowel differences progressively into schwa. Strong correlations mean that the coarticulation resistance of the consonant is exerting a progressively stronger effect as measurement points approach the consonant itself. The second consistent finding was the presence in F2 measures in the stressed vowels of progressively weak effects of coarticulation resistance. Coarticulation resistance effects were quite marked at consonant release, but were progressively more subtle (though still statistically significant) at measurement points one third and two thirds of the way into the stressed vowel.

Related to this idea that coarticulation resistance is implemented as a clamping of the tongue dorsum by the consonant, we might ask whether it is ever the case that there is greater anticipatory vowel-to-vowel coarticulation in the schwa than in the consonantal closure. The prominence or dominance idea implies that production of the final vowel of our disyllables should strengthen progressively until some time following consonant release and then weaken progressively. However, coproduction with a high resistant consonant may
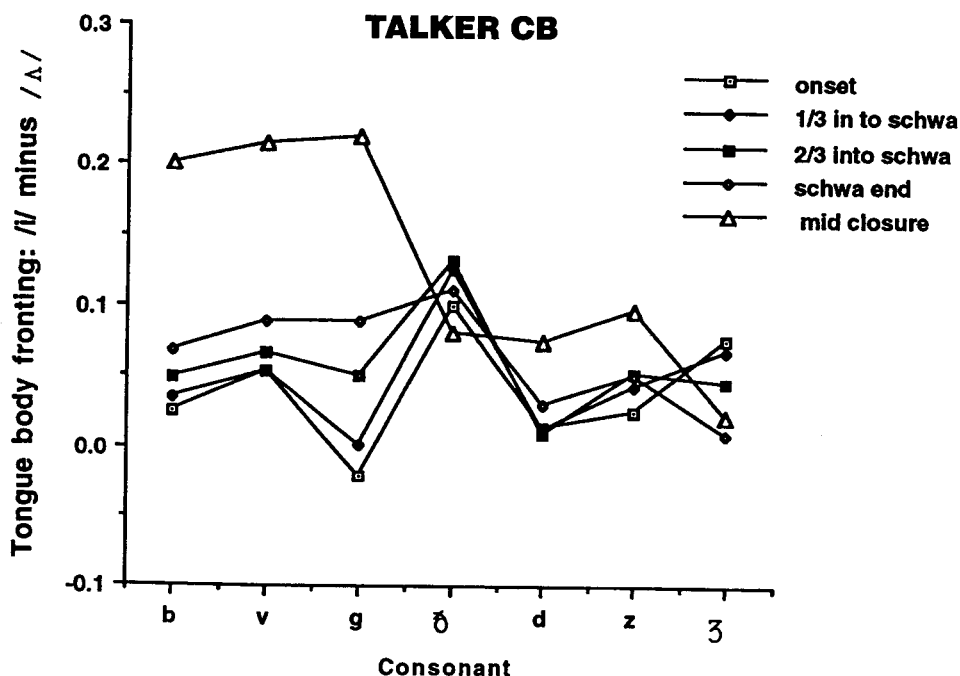
Figure 12

Vowel differences (/i/ minus /ʌ/) in tongue body fronting in the disyllables of speaker CB taken at the first five measurement points (schwa onset to consonant closure)

modulate that pattern. Figure 12 shows /i/-/ʌ/ differences in tongue body fronting for talker CB, who does show evidence of modulation of the stressed vowel's prominence pattern by high resistant consonants. The figure shows the tongue body difference score at the first five articulatory measurement points, that is, four points in schwa and during consonant closure. Disyllables with the low resistant consonants, /b/, /v/, and /g/, all show a monotonic increase in the difference score over measurement points consistent with a gradual increase of the stressed vowel's prominence over time. High resistance consonants all show some modulation of that pattern. /d/ and /z/ show no change in the difference score over time until measurement point T5. /ð/ shows a monotonic increase during schwa through T3, but then a decrease in the vowel difference at T4 and during consonantal closure. The temporal window of the clamping appears to be quite narrow in the anticipatory direction for these consonants. It appears wide for the high resistant consonant /ʒ/. Here, the vowel difference measure actually decreases monotonically over time through consonant closure.

Overall our findings on coarticulation resistance are highly compatible with those of Recasens despite the difference in the instrumentation used in the two sets of studies and despite the fact that most of Recasens' data largely are on speakers of languages other than English. In particular, we conclude that Recasens' occasional finding of vowel-to-vowel coarticulatory effects that disappear near a high resistant consonant is not unique to speakers of Catalan. Nor are the effects artifactual consequences of using an electropalatograph, which can only track changes in contact of the palate by the tongue.

A third aim of our research was to attempt to link two findings in the literature, namely those relating to coarticulation resistance and those relating to locus equations. We asked whether variation in coarticulation resistance of consonants predicted variation in locus equation slope. In the *Introduction*, we showed that locus equation slopes reported by Sussman (Sussman et al., 1991; Sussman,1994) were highly correlated with an acoustic measure of coarticulation resistance reported by Recasens (1985). In our research likewise, we found, particularly for tongue fronting measures of coarticulation resistance, strong and highly significant correlations between coarticulation resistance and locus equation slope.

We had limited success addressing the question of whether the linearity of locus equation plots have underlying them a uniformity of the coarticulation resistance of each consonant to the set of vowels. We encountered several difficulties in our efforts to compare the linearity of the acoustic and articulatory variables. One difficulty is that we had only three stressed vowels (only two for one of our speakers), rather than the eight to ten that are more common in locus equation studies. A second difficulty, however, is one of determining the right analysis to make the test. We have x and y coordinate values for tongue body position. It is difficult to decide exactly what analysis of these two dimensional measures is most commensurate with the one dimensional acoustic measures that enter locus equation analyses. Despite these difficulties, we did show a close correspondence of indices of acoustic and articulatory linearity—namely slopes of regression equations. In the case of CB, slopes of tongue position relations almost perfectly predicted locus equation slopes. We consider it unlikely that an orderly output constraint, in addition to coarticulation resistance, will be required to explain the linearity of locus equation plots. Future research can address questions about the articulatory underpinnings of acoustic linearity more directly by using a more extensive set of vowels.

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