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The extent of vowel-to-vowel coarticulation in English

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This acoustic study investigated the extent and nature of vowel-to-vowel coarticulation in English trisyllabic utterances (/bV1bəbV3b/) where both V1 and V3 were either /ɑ/ or /i/. Primary stress was assigned to either the first or third syllable, and secondary stress was assigned to the other syllable. The study revealed considerable variability among the four speakers in the systematic effects of non-adjacent vowels on one another. The most important result is that coarticulatory effects can, in some instances, extend beyond the bounds that previous research had assumed; both carry-over and anticipatory effects extend from one full vowel, through the medial schwa, and into the midpoint of the other full vowel. In fact, for one speaker, effects of V3 can be seen as early as V1 onset of /ɑ/. This result indicates that the foot does not define the domain over which coarticulatory effects operate. Finally, this study found no evidence of greater carry-over than anticipatory effects.

1. Introduction

A central goal of research in speech production has been the description and prediction of coarticulatory effects, defined as the articulatory or acoustic influence of one segment or phoneme on another, and resulting in the absence of a one-to-one mapping between phonemes and their output in production. One important type of evidence for this absence of one-to-one mapping is that coarticulatory effects extend from one vowel to another across one or more intervening consonants, a phenomenon referred to as vowel-to-vowel coarticulation.

Acoustic data on vowel-to-vowel lingual coarticulation in VCV utterances have shown that the transitions into and out of the consonant are influenced by the quality of the transconsonantal vowel (Öhman, 1966), presumably indicating tongue movement for the second vowel beginning before consonant closure and tongue movement for the first vowel continuing after consonant release. Palatographic data (Butcher & Weiher, 1976) and physiological data (Perkell, 1969; Kent, 1972; Kent & Moll, 1972) have also shown this effect. More recently, studies on various languages have shown lingual vowel-to-vowel coarticulatory effects not only in transitions but

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extending into the steady-state period of the transconsonantal vowel both in palatographic data (German: Butcher & Weiher, 1976; Catalan: Recasens, 1984, 1987; Spanish: Recasens, 1987) and in acoustic data (Bantu Languages: Manuel, 1990; Japanese: Magen, 1984; English: Fowler, 1981*a*; Magen, 1985; Whalen, 1990).

While there is ample evidence of the existence of vowel-to-vowel coarticulatory effects, factors have been cited which affect the extent of these effects. For instance, these effects may be constrained by intervocalic palatals and velars, whose production requires use of the tongue body in conflict with the production of vowels, thereby restricting vowel-to-vowel coarticulation (Russian: Öhman, 1966; Purcell, 1979; German: Butcher & Weiher, 1976; Catalan: Recasens, 1984). Effects may also be limited by the phonological system of the language; less coarticulation is allowed when more, rather than fewer, vowels are fitted into a vowel space (Manuel & Krakow, 1984; Manuel, 1990).

The research presented in this paper aims to address further the extent of coarticulatory effects, specifically, the degree to which coarticulation is affected by linguistic units, as reflected in the patterns of cohesion that are found in the production of speech. Although speech is considered to be a fluent motor behavior in which segmental boundaries are blurred, it has frequently been suggested that there are units of production, such as phonemes or syllables, which define the domain of coarticulatory effects (see Kent & Minifie, 1977, for a discussion). While the concept of cohesion may be taken to mean a relative affinity among units, not necessarily implying a boundary between these groupings and others (Kent & Minifie, 1977), it may, however, imply that there are limits and bounds to speech plans and to coarticulatory effects. A particularly restricted instantiation of this concept holds that coarticulatory effects cannot extend from vowel to vowel or from consonant to consonant (Gay, 1981). It has also been suggested that the unit of cohesion is at a higher level and that the syllable or a syllable-like unit is the primary unit of production in speech (Kozhevnikov & Chistovich, 1965). The data on lingual vowel-to-vowel coarticulation cited above, as well as studies involving other articulators such as the lips and the velum (e.g., Bell-Berti & Harris, 1979, 1981) and perceptual studies of coarticulatory effects extending beyond the syllable (Treon, 1970; Clark & Sharf, 1973; Whalen, 1990), however, suggest that speech is neither produced nor understood in separate syllable-link units, but that effects extend from one syllable to another.

If coarticulatory effects can extend beyond the boundaries of the syllable, further extensions are possible. One possibility, as demonstrated previously in English (Fowler, 1981*b*) and in Italian (Vayra, Fowler & Avesani, 1987), is that vowel-to-vowel coarticulatory effects may extend beyond adjacent syllables. Coarticulatory effects into adjacent syllables are handled in current models of speech production (e.g., Browman & Goldstein, 1986; Keating, 1990), but effects beyond adjacent syllables, while not ruled out, are not explicitly accounted for. In fact, the Italian data show variability in the extent of coarticulatory effects into non-adjacent syllables, suggesting that production models should allow, but not require, such effects.

A second possibility is that while vowel-to-vowel coarticulatory effects may extend into a non-adjacent unstressed syllable when a stressed syllable is followed by two unstressed syllables, effects are nevertheless foot-bound, where the foot is defined as beginning with a stressed syllable and containing everything following it up to, but not including, the next stressed syllable. (Stress is taken to be the concept common and essential to various definitions of the foot (e.g., Abercrombie, 1964; Prince, 1983; Selkirk, 1984; Goldsmith, 1990); our investigation will not attempt to distinguish further among these definitions.) Thus, coarticulatory effects would not extend from one stressed syllable into the steady state of another. In one view of coarticulation, vowels are coproduced with their neighboring consonants, and the production of a consonant is seen as a gesture superimposed on a continuous diphthongal vowel gesture (Öhman, 1966; Perkell, 1969; Fowler, 1981*a*). Moreover, stressed vowels are taken to have primacy in speech planning, while unstressed vowels do not interrupt the trajectory from one stressed vowel to another; this predicts that coarticulatory effects will end when the set of muscles used to produce one stressed vowel is crucial for the production of another stressed vowel (Fowler, 1981*a*).

A related issue is whether different degrees of stress produce differential patterns of coarticulation. In Öhman's (1966) data, both vowels of the VCV were equally stressed, so these data do not take secondary stressed vowels into account. Data have indicated that unstressed vowels offer less resistance to coarticulatory effects than stressed vowels do (Fowler, 1981*b*) and show more gestural overlap (Edwards *et al.*, 1991), but there is little research on the amount of influence exerted by primary as opposed to secondary stressed vowels.

A third possible factor affecting the extent of coarticulatory effects concerns their direction, whether from left to right (carry-over coarticulation) or from right to left (anticipatory coarticulation). Related to this is the question of whether anticipatory and carry-over effects are different from one another; anticipatory effects are held to involve articulatory preprogramming, while carry-over effects are considered mechanical and attributable to the mass and inertia of articulators (Henke, 1966; MacNeilage & DeClerk, 1969; Gay, 1977; Recasens, 1984, 1987; Huffman, 1986; cf. Whalen, 1990).

The issue of directionality has been explored extensively in physiological, acoustic, and perceptual studies on several languages, in which data from a variety of phonetic contexts involving several different articulators have been examined. Just as the experimental conditions vary, so do the results, with some studies showing carry-over exceeding anticipatory effects, some showing anticipatory exceeding carry-over, and some showing no difference (for a thorough review of the issue, see Sharf & Ohde, 1981). Further evidence that a simple directional pattern may be hard to identify comes from a study on Italian which reveals, under identical experimental conditions, greater carry-over effects for one speaker but greater anticipatory effects for another (Vayra, Fowler & Avesani, 1987).

Focusing specifically on the literature which addresses vowel-to-vowel coarticulation in English, research in perception shows the influence of anticipatory effects (Clark & Sharf, 1973; Fowler & Smith, 1986), and studies examining acoustic (Öhman, 1966) and physiological (Kent, 1972; Kent & Moll, 1972) data also show evidence of anticipatory coarticulation. However, production data which allow comparisons of the direction of vowel-to-vowel effects in English indicate that carry-over effects generally exceed anticipatory effects in physiological (Gay, 1974;

Parush, Ostry & Munhall, 1983) and acoustic (Bell-Berti & Harris, 1976; Fowler, 1981*a,b*; Huffman, 1986) studies.

In this study, we will look at trisyllabic utterances having primary or secondary stressed vowels in the first and third syllables and a schwa in the medial syllable as a means of investigating three issues: first, the distance over which coarticulatory effects extend, specifically, whether vowel-to-vowel coarticulatory effects can extend beyond adjacent syllables and beyond the foot; second, the role of primary vs. secondary lexical stress in determining the extent of these effects; third, the direction of these effects, examining anticipatory *vs.* carry-over coarticulation as factors mediating the extent of coarticulation. Throughout our investigation, we will address the range of speaker variability in production.

2. Methods

2.1. *Speakers*

The speakers were four male native speakers of American English, two from Detroit (SK and AH), one from Philadelphia (DR), and one from western Massachusetts (GB), aged 27 to 37 years.

2.2. *Stimuli*

The stimulus list comprised 72 stimuli, embedded in nine carrier sentences of English, each containing an item from a set of eight target words. (See Appendix 1.) The target words were of the form /bV1bəbV3b/, where V1 and V3, henceforth to be referred to as full vowels, were either /i/ or /ɑ/ and primary stress on the first or third syllable was marked by an accent mark on V1 or V3, respectively. (The full vowels that did not get primary stress, V́, received secondary stress, V̀.) Nonsense items were used, instead of real words, to control the phonetic environment of the vowels to be analyzed; the labial /b/ was chosen to minimize the effects of consonant articulation on lingual articulations (cf. Öhman, 1966; Butcher & Weiher, 1976; Purcell, 1979; Recasens, 1984). In every case, the target item, although a nonsense word, could be understood only as a noun.

Of the nine sentences, three contained the target item in sentence initial context (or preceded by the), three in sentence medial context, and three in sentence final context. (See Appendix 1). To prevent speakers from reading the material in a sing-song manner, for each of three sentential contexts (initial, medial, final) there were sentences with three metrical patterns: one iambic (◡'); one trochaic ('◡); and one dactylic ('◡◡). Where metrical and other phonetic considerations were in conflict or where the target did not fit the metrical pattern, it was the metrical pattern that was not strictly followed. To avoid the temporal reduction in longer as opposed to shorter sentences (Gaitenby, 1965; Lindblom & Rapp, 1973), the sentences were all approximately the same length, 11 or 12 syllables. All target words that were preceded or followed by phonetic material were preceded by the reduced vowel /ə/ and followed by the reduced syllable /tə/. In initial and medial contexts, the target was followed by the same phrase, to the extent possible.

2.3. *Procedure*

The productions of the speakers were recorded in a sound-attenuated booth at the Haskins Laboratories. Before actual recordings were made, speakers practiced by reading the target items in randomized lists until they were proficient at producing the indicated stress patterns and reading the symbols i̱, ɑ, and ə̱ as the vowel qualities intended (/i/, /ɑ/, /ə/, respectively). Next, they read the test sentences with real words in place of nonsense words to ensure that in natural oral reading they could produce both stress patterns in all three sentential contexts. (See Appendix 2.) The speakers were instructed to read at a normal speaking rate.

The total number of sentences in the stimulus set for each speaker was: SK, 8 target words ×3 sentential contexts ×3 sentence types (differentiated by metrical pattern) ×5 repetitions = 360; DR, 8 items ×3 sentential contexts ×2 sentence types ×5 repetitions = 240; GB and AH, 8 items ×3 sentential contexts ×2 sentence types ×4 repetitions = 192.[1] In addition, each subject produced two randomized blocks of the complete set of utterances which were used if an item needed to be replaced, as discussed below.[2]

The test sentences were digitized at a sampling rate of 10 kHz and filtered at 5 kHz. Any sentence containing a pause large enough to be recognized auditorily, a disfluency, or a target item incorrect either in vowel quality or stress pattern was replaced by the appropriate item from one of the additional randomized blocks. Additionally, for each speaker the experimenter listened to randomized lists of the targets both as produced within their carrier phrases and when excised from their carriers to avoid rhythm-induced expectations of stress (Bolinger, 1965; Martin, 1970); if the utterance did not correspond to the one intended, it was replaced.

2.4. *Acoustic analysis*

The acoustic measurements on which this study is based were the first and second formant frequency values at the midpoint of V1 and V3 (/i/ and /ɑ/) of the /bV1bəbV3b/ utterance. Using a waveform editor, labels were placed at the releases of the first, second, and third /b/, considered the onsets of V1, schwa, and V3, and at the moments of closure of the second, third, and fourth /b/, considered the offsets of V1, schwa, and V3. Release and closure were taken to be the point on the waveform at which there was a marked change in the form of the periodicity, a substantial increase in amplitude for the release and a substantial decrease in amplitude for the closure. Despite the variation in the duration and intensity of the release bursts, for the sake of consistency, labels were placed at the onset of the burst for every vowel. The point halfway between labeled onset and offset was labeled the midpoint of each vowel.

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[1] Only SK, the first speaker to be recorded, produced all nine sentences listed in Appendix 1. The other three speakers recorded only the iambic and trochaic patterns, since preliminary analysis on SK's data showed that metrical pattern had no effect on formant frequencies.

[2] Although each subject produced two additional blocks of the utterances, there were several missing data points. For DR, there were 16 missing data points; for SK, 3; for AH, 2, and for GB, none.

The formant frequencies of labeled points were obtained by root-solving the 14-coefficient autoregression analysis, with a 20 ms analysis window with 10 ms overlap, using LPC analysis in a Haskins-modified ILS package. When the root-solving analysis could not pick up formant values for either F_1 or F_2, an LPC spectral section (smoothed) of the point in question was examined on two separate occasions and formant values for the peak located by eye, if possible.

F_1 and F_2 values for the frame closest to the midpoint label and for one frame on each side of that frame were examined. If the LPC technique did not pick up F_1 or F_2 values at the labeled midpoint, as happened, for example, if the bandwidth of /ɑ/ was too wide, the values of the adjacent frame closer (in ms) to the labeled midpoint were used. In almost all cases, the LPC technique did pick up F_1 and F_2; therefore, values used in subsequent analyses as the midpoint values were those of the frame actually closest to the midpoint label marked on the waveform.

3. Results

The English vowel /i/ has a low F_1 and a high F_2, while /ɑ/ has a high F_1 and a low F_2. In interpreting the values of target vowels, therefore, we assume that the effect of a flanking vowel /i/ on the target vowel /ɑ/ will be manifest as a lower F_1 and a higher F_2, and the effect of /ɑ/ on /i/ will be manifest as a higher F_1 and lower F_2.

Fig. 1 shows the averaged formant values ($F_1 \times F_2$) for each of the four speakers at the midpoint of V1 for the four major categories of tokens examined in this study, collapsed over stress pattern: /bɑbəbib/ and /bɑbəbɑb/, where V1 is /ɑ/, shown in Fig. 1(a); /bibəbɑb/ and /bibəbib/, where V1 is /i/, shown in Fig. 1(b). Filled symbols represent a flanking vowel (V3) /ɑ/, while unfilled symbols represent a flanking vowel (V3) /i/.

Analogous to Fig. 1(a and b), the averaged formant values ($F_1 \times F_2$) for

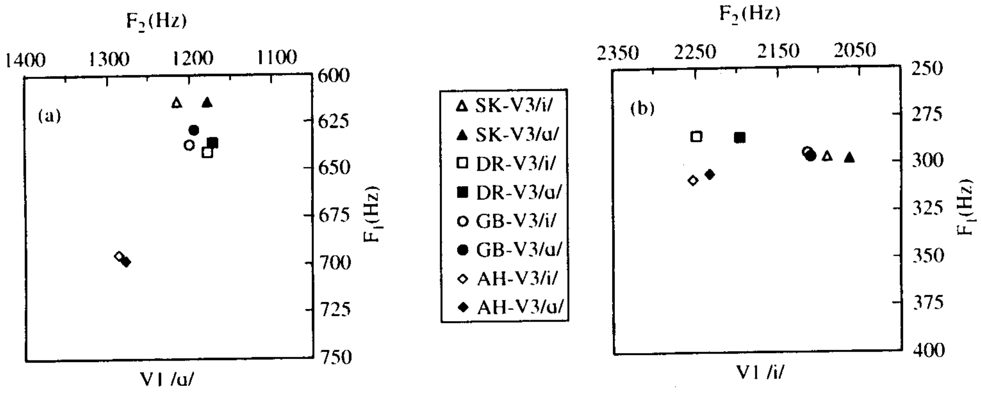

Figure 1. Anticipatory effects for speakers SK, DR, GB, and AH. Acoustic effects on V1 midpoint when flanking vowel (V3) is /i/ (unfilled symbols) and /ɑ/ (filled symbols): (a) when V1 is /ɑ/, and (b) when V1 is /i/.

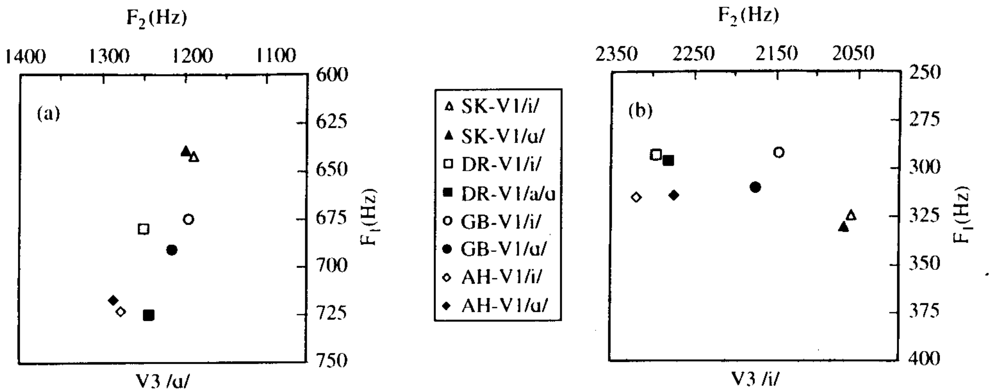

Figure 2. Carry-over effects for speakers SK, DR, GB, and AH. Acoustic effects on V3 midpoint when flanking vowel (V1) is /i/ (unfilled symbols) and /ɑ/ (filled symbols): (a) when V3 is /ɑ/, and (b) when V3 is /i/.

/bibəbɑb/ and /bɑbəbɑb/, where V3 is /ɑ/, are shown in Fig. 2(a), and /bɑbəbib/ and /bibəbib/, where V3 is /i/, are shown in Fig. 2(b) for the four speakers at the midpoint of V3. Filled symbols represent a flanking vowel (V1) /ɑ/, and unfilled symbols, a flanking vowel (V1) /i/.

In determining the statistical reliability of the patterns which appear in Figs. 1 and 2, for each speaker, F_1 and F_2 values at the midpoint of V1 and V3 were used in analysis of variance with these factors: position in the word [first syllable (V1), third syllable (V3)]; target vowel quality, (/ɑ/, /i/); primary stress (V́1, V́3); flanking vowel quality (/ɑ/, /i/). Non-coarticulatory results, that is, those not involving the flanking vowel quality factor, are discussed in detail in Magen (1989).

In interpreting results, a significant effect of flanking vowel quality on the formant values of the target vowel is considered evidence of coarticulation. Interactions involving position in the word (V1, V3) and flanking vowel quality provide evidence of either greater anticipatory or carry-over coarticulation, respectively. Also relevant is the interaction of flanking vowel quality and stress, that is, whether it is primary stressed vowels that exert greater influence on secondary stressed vowels or vice versa. In all cases in which there was an interaction of factors, an additional (simple main effects) analysis was performed to determine whether effects of one factor were significant across the levels of the other factor. Eight ANOVAs were performed, examining F_1 and F_2 values for each of the four subjects. Table I presents a summary of the results, which are discussed in more detail in the text.

3.1. F_1

Comparison of the relation of the filled symbols to the unfilled symbols on the $F_1 \times F_2$ plots in Fig. 1(a and b) shows that there are no substantial F_1 anticipatory effects in the mid-point of V1 for any of the speakers.[3]

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[3] For SK, however, there is a significant effect of stress, mitigated by a three-way interaction of stress by position in the word by flanking vowel quality [$F(1, 698) = 6.29$, $p < 0.05$]. The effect holds only for V1 in the anticipatory direction. This is discussed below in relation to effects over time for this speaker (Section 3.3.1.), and illustrated in Fig. 3.

TABLE I. Summary of ANOVA significant main effects and interactions involving flanking vowel quality. Factors are POSITION in the WORD, STRESS, FLANKING VOWEL QUALITY, and TARGET VOWEL QUALITY. Results of analyses performed to determine the significance of one factor across levels of the other factor (simple main effects) are printed in lower case and indented; ! indicates an effect opposite of the predicted effect

	F_1
SK	POSITION in the WORD × STRESS × FLANKING VOWEL QUALITY
	flanking vowel quality × stress at V1 (anticipatory)
DR	POSITION in the WORD × FLANKING VOWEL QUALITY POSITION in the WORD × TARGET VOWEL QUALITY × FLANKING VOWEL QUALITY
	position in the word × flanking vowel quality at /ɑ/ flanking vowel quality × target vowel quality at V3 (carry-over)
GB	FLANKING VOWEL QUALITY
	POSITION in the WORD × FLANKING VOWEL QUALITY
	flanking vowel quality at V3 (carry-over)
AH	—
	F_2
SK	POSITION in WORD × FLANKING VOWEL QUALITY
	POSITION in WORD × STRESS × FLANKING VOWEL QUALITY
	flanking vowel quality × stress at V1 (anticipatory)
DR	FLANKING VOWEL QUALITY
GB	POSITION in WORD × FLANKING VOWEL QUALITY
	! flanking vowel quality at V3 (carry-over)
AH	TARGET VOWEL QUALITY × FLANKING VOWEL QUALITY
	flanking vowel quality at /i/

Turning to F_1 carry-over effects, as the difference between the filled and unfilled squares of Fig. 2(a) shows, there are straightforward carry-over results for F_1 of DR. These are particularly strong for this speaker when V3 is /ɑ/, a difference of 45 Hz, but are negligible when V3 is /i/, as shown in Fig. 2(b). The absence of anticipatory effects and the presence of carry-over effects for DR results in a significant interaction of position in the word and flanking vowel quality $[F(1, 432) = 8.2, p < 0.01)]$; additionally, there is a three-way interaction of position in the word by target vowel quality by flanking vowel quality $[F(1, 432) = 6.67, p < 0.01]$. There is a significant effect of flanking vowel quality by position in the word when V3 is /ɑ/ $[F(1, 432) = 14.72, p < 0.0001]$, but not /i/. Additionally, there is an effect of target vowel quality by flanking vowel quality for V3 $[F(1, 432) = 7.64, p < 0.01]$ but not V1. There are no interactions involving stress.

For speaker GB, there is also a clear carry-over effect for F_1 of both vowels, a difference of 16 Hz for /ɑ/ and 18 Hz for /i/. There is a main effect of flanking vowel quality $[F(1, 368) = 5.06, p < 0.05]$ and for this speaker, as for DR, the asymmetry between anticipatory and carry-over results appears as a significant interaction of position in the word and flanking vowel quality $[F(1, 368) < 9.53, p < 0.01]$. Flanking vowel quality is significant for target vowel V3 $[F(1, 368) = 14.42, p < 0.001]$, but not for V1. There are no stress interactions. For speakers AH and SK there are neither significant F_1 effects, nor interactions.

Summary of F_1 effects: With the exception of SK, whose effects depend on stress (see Section 3.3.1.), there are no anticipatory F_1 effects. There are straightforward F_1 carry-over results DR and GB, and no real effects for SK and AH.

3.2. F_2

Referring back to Fig. 1 we can see from the relation of the filled to unfilled symbols that, for F_2, there is some amount of anticipatory coarticulation in the predicted direction for all speakers, regardless of whether V1 is /ɑ/ or /i/. On the other hand, as shown in Fig. 2, F_2 carry-over coarticulatory effects have a very surprising pattern in these data. F_2 values for V3 would be predicted to be higher when V1 is /i/ than when V1 is /ɑ/. In fact, while this pattern is obtained weakly in some cases, the opposite of this pattern is found for three of the four speakers for at least one of the two vowel qualities, although effects are not strong in most cases.

For GB, while the unpredicted pattern is found for anticipatory effects, the difference is negligible, as the circles in Fig. 1 show. It is with respect to the carry-over effects that results for this speaker deviate decidedly from the predicted direction. As the circles in Fig. 2 show, the average F_2 value of V3 is higher when V1 is /ɑ/; there is a difference of 20 Hz when V3 is /ɑ/ and 28 Hz when V3 is /i/. Analysis of variance shows a main effect of position in the word [$F(1, 368) = 29.43, p < 0.0001$] and a significant interaction between the position in the word and flanking vowel quality [$F(1, 368) = 9.28,\ p < 0.01$]. Flanking vowel quality is significant when the target vowel is V3 [$F(1, 368) = 9.86,\ p < 0.01$], but not V1.

For speaker AH, both carry-over and anticipatory effects depend on the quality of the target vowel. As the pattern of the diamonds in Figs. 1 and 2 shows, the effects of the flanking vowel on F_2 are minimal when the target vowel is /ɑ/ [Figs. 1(a) and 2(a)], but are more pronounced and in the predicted direction when the target vowel is /i/ [20 Hz in Fig. 1(b) and 45 Hz in Fig. 2(b)]. ANOVA shows an effect of flanking vowel quality [$F(1, 364) = 5.94,\ p < 0.05$] and an interaction of target vowel quality by flanking vowel quality [$F(1, 364) = 6.46,\ p < 0.05$]. The effects of flanking vowel quality for the target vowel /i/ are significant [$F(1, 364) = 12.28,\ p < 0.001$], while those for /ɑ/ are not. There are no stress interactions for this speaker.

For speaker DR, there are both anticipatory and carry-over differences in F_2. As Fig. 1 shows, when V1 is /ɑ/, anticipatory effects are quite small (only 6 Hz) while the /i/ differences are sizable (53 Hz). As Fig. 2 shows, DR is the only speaker for whom the predicted carry-over coarticulatory pattern is found consistently. Regardless of whether V3 is /ɑ/ or /i/, F_2 of V3 is slightly higher when V1 is /i/. ANOVA shows the effect of flanking vowel quality to be significant [$F(1, 432) = 8.05,\ p < 0.01$], and despite the differences between /ɑ/ and /i/, there are no interactions.

As the triangles of Fig. 1 illustrate, for speaker SK, there is a substantial amount of anticipatory coarticulation for both /ɑ/ and /i/ V1 (37 and 30 Hz, respectively). The carry-over results for speaker SK (Fig. 2) are in the unpredicted direction but less pronounced than those of GB, with a difference of only 10 Hz for /ɑ/ and 11 Hz for /i/. There is a significant interaction of flanking vowel quality and position in the word for SK [$F(1, 698) = 18.21,\ p < 0.0001$]. Additionally, as shown in

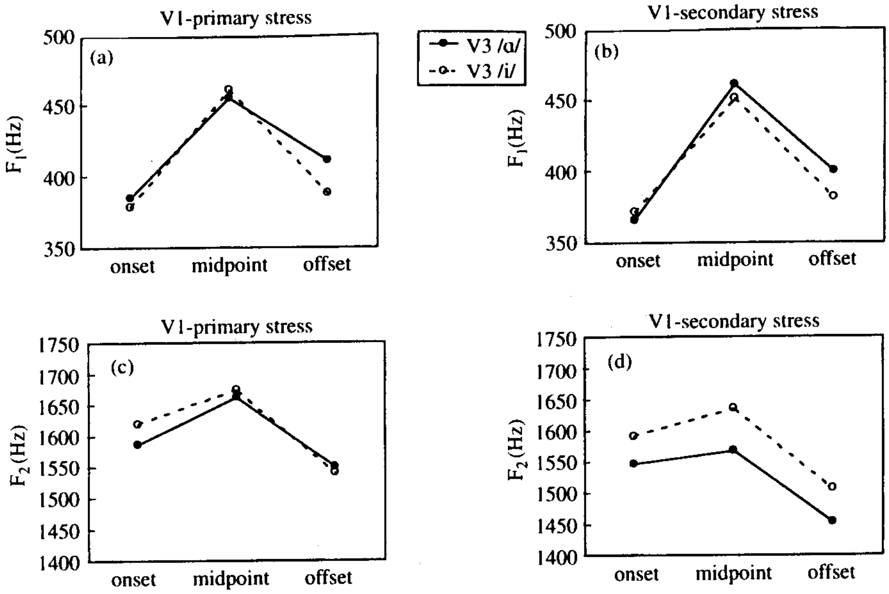

Figure 3. Effects of stress on anticipatory coarticulation over time, speaker SK. Acoustic effects on V1 onset, midpoint, and offset when flanking vowel (V3) is /i/ (unfilled circles) and /ɑ/ (filled circles): (a) F_1 for V́1, (b) F_1 for V́1 (c) F_2 for V̀1 (d) F_2 for V̀1.

Fig. 3, anticipatory effects for F_2 obtain for V̀1 but not V́1. Analysis of variance shows a significant three-way interaction of stress by flanking vowel quality by position in the work [$F(1, 698) = 14.79$, $p < 0.0001$]. Effects are significant for V̀1 [$F(1, 698) = 32.56$ $p < 0.0001$], but not V́1.

Summary of F_2 effects: All speakers show an anticipatory effect in the predicted direction; this effect is statistically significant for DR and SK, although for SK, effects are significant for V̀1 but not V́1. F_2 carry-over results show great variability. Effects are in the predicted direction for DR and for AH, when the vowel is /i/, but are in the opposite direction for SK and GB, reaching statistical significance for GB.

3.3. *Effects over time*

The coarticulatory effects found at the midpoint suggest that such effects might be present and traceable throughout the vowel. To explore this, additional analyses were performed, examining the first and second formant frequency values at the onset and offset of V1 and V3 for a single speaker, using the procedures for acoustic analysis outlined above in the Methods section. After preliminary acoustic analysis of the four speakers, SK's data were chosen for this stage of the study for practical reasons: the LPC analysis missed many fewer points in the onsets and offsets than were missed in the data of the other speakers;[4] his data set was the largest; and,

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[4] Since the analysis program was designed such that the last frame reported often contained information beyond the point labeled on the waveform, the frame next to the offset was almost always used. However, when this frame was missed, the frame which was two frames away from the offset was used instead.

both V1 and V3 were long enough to allow three distinct measurements for the three locations—onset, midpoint and offset. For both F_1 and F_2 of both V1 and V3, separate analyses of variance were performed with a repeated measures factor of location (onset, midpoint, offset), and the factors stress, V1 quality (/ɑ/, /i/) and V3 quality (/ɑ/, /i/), a total of four analyses of variance. (Rather than perform three separate analyses of variance on related values, repeated measures analyses were performed, allowing the comparison of effects at the three points within the same vowel.) Note that analyses presented in this section examine effects on V1 and V3 separately; therefore, the analogues to the factor flanking vowel quality in the analyses discussed in Sections 3.1. and 3.2. are the factor V3 quality and V1 quality, respectively, whereas the analogues to target vowel quality for V1 and V3 are V1 quality and V3 quality, respectively.

3.3.1. *Anticipatory effects of V3 on V1 at onset, midpoint, and offset for speaker SK*

Fig. 4(a–d) shows anticipatory coarticulatory effects at onset, midpoint, and offset for speaker SK. As shown in Fig. 4(a and b), effects of F_1 emerge across the vowel, although they are very small. The repeated measures ANOVA shows a main effect of V3 quality [$F(1, 333) = 7.72$, $p < 0.01$]; although effects are not equally strong across the vowel, the interaction for location is not significant. As can be seen in Fig. 3(a and b), the stress by V3 quality interaction, present in the midpoint (see footnote 3), is mitigated by a three-way interaction of location by stress by V3 quality [$F(1, 333) = 4.07$; $p = 0.05$]. The difference between the F_1 values of V1, depending on flanking vowel, do not show a consistent pattern across locations.

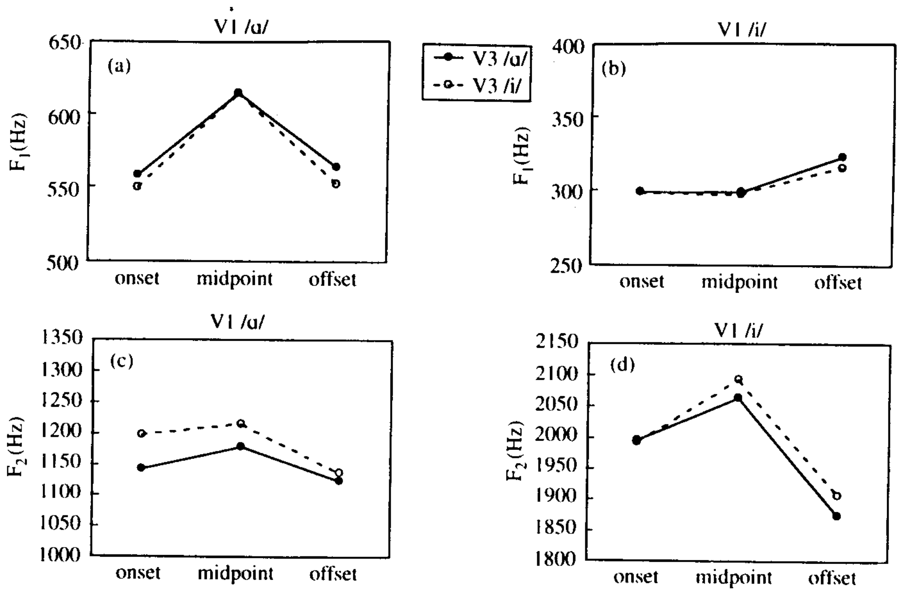

Figure 4. Anticipatory effects over time, speaker SK. Acoustic effects on V1 onset, midpoint, and offset when flanking vowel (V3) is /i/ (unfilled circles) and /ɑ/ (filled circles): (a) F_1 when V1 is /ɑ/, (b) F_1 when V1 is /i/, (c) F_2 when V1 is /ɑ/, (d) F_2 when V1 is /i/.

Returning to Fig. 4(c and d), which shows coarticulatory patterns for F_2, effects of quality of V3 can be observed at vowel onset when V1 is /ɑ/ [Fig. 4(c)], but not /i/ [Fig. 4(d)]. At the vowel midpoint, coarticulation continues for /ɑ/ [Fig. 4(c)] and becomes evident for /i/ [Fig. 4(d)]. The ANOVA shows the effects of V3 quality to be significant [$F(1,322) = 29.29$, $p < 0.0001$]. Despite the unexpected decrease in extent of effects of V3 on V1 from onset to offset observed in Fig. 4c, interactions of V3 quality with location are not significant. There is, however, a three-way interaction of V3 quality by V1 quality by location; the interaction is significant only at the onset [$F(1,322) = p < 0.01$], consistent with the differences between Fig. 4(c) and Fig. 4(d).

For F_2, as Fig 4(c and d) shows, at each location investigated in V1 of SK, onset, midpoint, offset, V́3 consistently influences V̀1 more than V̀3 influences V́1. Accordingly, the repeated measures analysis shows the stress by V3 quality interaction to be significant [$F(1,322) = 16.61$, $p < 0.0001$], as at the midpoint. Also in keeping with midpoint results, V3 quality is not significant for V́1, but is significant for V̀1 [$F(1,322) = 46.70$, $p < 0.0001$]. The difference between the F_2 values for V́1, depending on flanking vowel, are: onset, 32 Hz; midpoint, 12 Hz; offset, −10 Hz. For V̀1, the corresponding differences are 46, 68, and 54.Hz.

3.3.2. *Carry-over effects of V1 on V3 at onset, midpoint, and off-set for speaker SK*

Plotted in Fig. 5(a–d) to illustrate carry-over effects, analogous to Fig. 4(a–d), are the average formant frequencies for the four categories of tokens for SK at the onset, midpoint, and offset of V3. Effects of V1 on F_1 and F_2 of V3 are minimal at all temporal locations. Repeated measures analysis of variance for F_1 shows that the

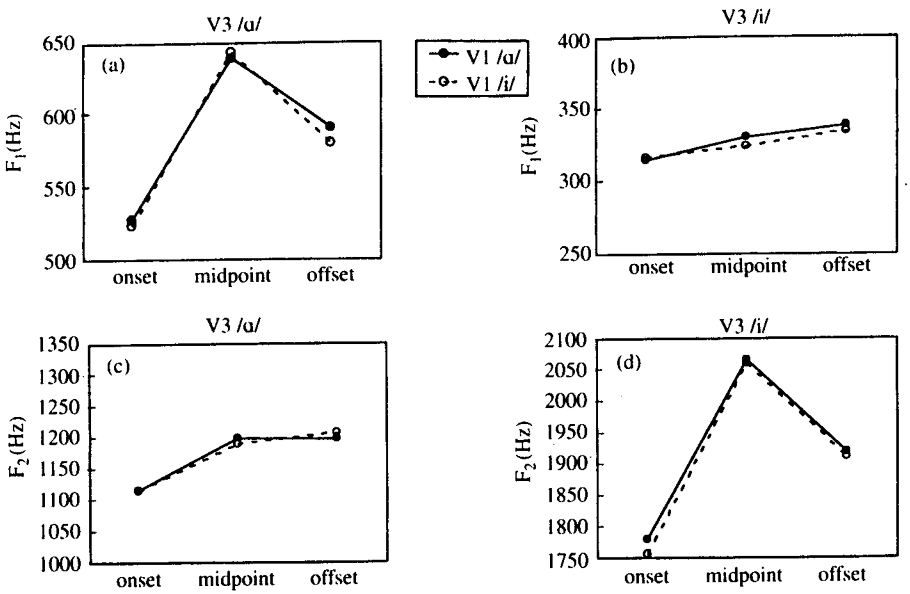

Figure 5. Carry-over effects over time, speaker SK. Acoustic effects on V3 onset, midpoint, and offset when flanking vowel (V1) is /i/ (unfilled circles) and /ɑ/ (filled circles): (a) F_1 when V3 is /ɑ/, (b) F_1 when V3 is /i/, (c) F_2 when V3 is /ɑ/, (d) F_2 when V3 is /i/.

effect of the V1 quality is not significant, nor are there any significant interactions. The F_2 ANOVA shows neither significant effects nor significant interactions.

Summary of effects over time: F_1 anticipatory effects over the course of V1 are not consistent. F_2 effects can be seen at the onset of V1 for /ɑ/, and at the midpoint for /i/, decreasing somewhat at the offset. There is an effect of stress such that V3 influences V1 more than V3 influences V1. There are no sizable carry-over effects for either F_1 or F_2.

4. Summary and Discussion

In reviewing the results of the vowels in this study, we note that the data examined show a great deal of speaker variability. This result is in accord with other evidence indicating individual differences in the production of American English vowels (e.g., Johnson, Ladefoged & Lindau, 1993), as well as results on Italian which show different patterns of coarticulation for participating talkers (Vayra, Fowler & Avesani, 1987). Our aim in this study was to explore the extent and the nature of coarticulatory effects: the distance over which coarticulatory effects extend, the possible role of stress in mediating these effects, and the strength and nature of carry-over and anticipatory effects. Before examining each of these issues, we will review the results of this study and discuss the issue of variability which they raise.

A review of the anticipatory coarticulatory results of this study shows that there are no real effects for three of the speakers for F_1, with the exception being SK, whose effects are mediated by stress. For F_2, all speakers show an anticipatory effect in the predicted direction. Moreover, for SK, the speaker for whom data were examined at onsets and offsets, F_2 anticipatory effects are quite strong and can be seen as early as V1 onset for /ɑ/. In addition, it is only for SK that stress mediates anticipatory effects; for F_2, just as for F_1 for this speaker, anticipatory effects are significant for V̀1, but not V́1.

A review of the carry-over results shows that F_1 effects of V1 on V3 are straightforward for DR and GB, while there are no substantial effects for SK and AH. It is in the carry-over results for F_2, however, where the greatest variability is manifest. Results are in the predicted direction for DR and for AH, when the vowel is /i/. Results are in the opposite direction for SK and GB, reaching statistical significance for GB.

The variability in results among subjects suggests an exploration for its possible sources, either in the subjects' linguistic background or in some other aspect of the signal itself, such as duration. Concerning the subjects' background, while we have very little data which actually address the issue of dialect, the two speakers of the same dialect, AH and SK from Detroit, show no similarity in their patterns of coarticulation, discouraging the suggestion that dialect is a determining factor.

Concerning duration, based on related studies (e.g., Fowler, 1981*b*) and on our own pilot research (Magen, 1985), we had originally expected to find greater coarticulatory effects where durations are shortest, that is, where the target vowel is closest to the flanking vowel. Word durations (V1 onset to V3 offset) as well as individual vowel durations were examined for each subject in this study. Word durations can be taken as an indication of speaking rate: for SK, 422 ms; DR, 441 ms; GB, 461 ms; and AH, 411 ms. (The data are presented in greater detail in Magen, 1989.) Since all durations were shortest for AH and longest for GB, we expected to see greater coarticulatory effects for AH and lesser effects for GB, with DR and SK falling between, an expectation not borne out by the formant data. Overall, then, there appears to be no relation between duration and coarticulation which would account for subject variability. Additionally, evidence of variability shows up in the directionality of effects and in whether sizable effects are observed for F_1, F_2, or both. Since the distance in time between V1 onset and V3 offset is necessarily constant for each token, duration does not help to explain these types of subject variability.

4.1. *The extent of coarticulatory effects*

One major goal of this investigation was to look beyond the coarticulatory boundaries suggested by previous research to examine the possibility that coarticulatory effects may extend further than from one syllable to the next or from one stressed syllable to the next. We found that coarticulatory effects can extend further than previously thought, although not for all speakers in all circumstances. Specifically, there is evidence for three of the four speakers (SK, DR, AH) that the first vowel anticipates the third vowel, for one of these speakers, SK, as early as V1 onset of /ɑ/. Moreover, effects of the first vowel carry over as far as the midpoint of the third vowel for three of the four speakers (DR, GB, AH) for either F_1 or F_2 or both in at least one of the vowels examined.

That coarticulatory effects extend from V1 to V3 and vice versa indicates that these effects can both last longer and begin sooner than has generally been believed, since the effects go well beyond the intervening schwa and beyond the transitions out of and into the full vowels. The results of this study, showing coarticulatory effects between vowels of non-adjacent syllables, indicate, therefore, that the implicit limits on coarticulation set by existing speech production models (e.g., Browman & Goldstein, 1986, 1990; Keating, 1990) require extension, an issue also raised by Whalen (1990) in relation to V-to-V anticipatory effects extending back 300 ms. The variability among speakers in this study suggests that the flexibility already built into these models will need to be exploited further in their extension. Thus, while the models need to allow coarticulatory effects between vowels of non-adjacent syllables, they need also to permit the variability with respect to articulatory timing which is manifest in the speaker specific patterns of carry-over as opposed to anticipatory effects. Furthermore, as discussed below in relation to GB's carry-over results, there is the possibility that systematic effects of neighboring vowels on one another are not solely assimilatory, but are dissimilatory in some cases.

4.2. *The role of stress*

The finding that coarticulatory effects extend from one stressed syllable to the midpoint of another speaks to the issue of the relation between prosodic and segmental levels of linguistic analysis. The data provide examples of both carry-over and anticipatory effects which cross a foot boundary, thereby indicating that the foot is not the domain over which these effects operate. These results are at variance with a coproduction account offered by Fowler (1981*b*), which predicts that coarticulatory effects will end when the set of muscles used to produce one stressed vowel is crucial for the production of another stressed vowel.

The literature provides a basis to expect that primary stressed vowels would show stronger effects on secondary stressed vowels than vice versa (e.g., Kent & Netsell, 1971).[5] In addition, in previous research, we find the suggestion that unstressed syllables are characterized by greater gestural overlap than stressed syllables are (Edwards, Beckman & Fletcher, 1991; Fowler, 1981*b*). Differences in F_0 and vowel duration (Lehiste, 1970; Klatt, 1976) and gestural stiffness (Kelso, Vatikiotis-Bateson, Saltzman & Kay, 1985) have also been noted. That primary stressed vowels showed a stronger effect on secondary stressed vowels for only one of the four speakers examined, SK, suggests that this strategy is optional and that the patterns of interarticulator coordination in the production of primary and secondary stressed vowels may vary in this respect just as coarticulatory strategies do generally.

4.3. *The strength and nature of anticipatory and carry-over effects*

These data allow us to focus on the issue of directionality, that is, whether carry-over or anticipatory coarticulation is greater, and therefore whether there are predictable patterns of cohesiveness among syllables. Previous acoustic studies of vowel-to-vowel coarticulation in English have indicated that carryover coarticulation exceeds anticipatory coarticulation (Gay, 1974; Bell-Berti & Harris, 1976; Fowler, 1981*a*, *b*; Parush *et al.*, 1983; Huffman, 1986). In this study, the speakers differ from one another with respect to the primacy of anticipatory as opposed to carry-over effects, indicating a variability in patterns of gestural timing.

A possible explanation for the lack of directional asymmetry in this study is that, because labial consonants are less restrictive of vowel articulation, the difference between anticipatory and carry-over coarticulation did not consistently emerge. This is in contrast to other studies, (Huffman, 1986; Recasens, 1989) in which intervocalic consonants requiring lingual activity were used, with results showing carry-over effects exceeding anticipatory.

Another possible explanation for the difference between previous studies and this one is that in this study both vowels examined have some degree of stress. In fact, what is striking in this regard is that the interaction between stress and vowel quality apparent in SK's data is evident only in the anticipatory direction, such that there are coarticulatory effects on V̀1 but not on V́1. A highly speculative explanation for this is that primary stress on the third syllable of a trisyllabic word may be considered marked, and therefore the speaker may be employing an unnatural articulatory strategy. However, it is worth pointing out that an investigation using the same data set examined in this study but focusing instead on effects on the medial schwa between two stressed vowels likewise found no evidence for the primacy of carry-over effects (Magen, 1989).

One pattern in these data, which can be noted tentatively, is that there is a

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[5] Because it is not directly relevant to coarticulation, the main effect of stress is not reported in this paper; however, the data for all speakers in this study show secondary stressed vowels to be more centralized versions of the intended vowel than are their analogues among primary stressed vowels; thus, for example, /í/ has a higher F_2 and lower F_1 than /ì/ (for details, see Magen, 1989).

tendency for F_2 effects to be anticipatory while F_1 are more likely to be carry-over. This is apparent if we consider that there are eight possible comparisons (2 vowels ×4 speakers) for anticipatory coarticulation (see Fig. 1) and eight for carry-over coarticulation (see Fig. 2). For F_2, eight out of eight comparisons of anticipatory coarticulation show the expected effect, whereas for carry-over coarticulation, the expected effect emerges in only three out of eight comparisons. For F_1, three out of eight comparisons of anticipatory coarticulation are (weakly) in the expected direction, while the comparisons of carry-over coarticulation show five out of eight stronger expected effects. An additional means of comparison, also exhibiting a trend only, can be made by noting that in the statistical analyses for F_1, there are two cases of carry-over effects exceeding anticipatory as opposed to one of anticipatory exceeding carry-over, while for F_2, there is one case in which anticipatory effects exceed carry-over, and none in which carry-over effects exceed anticipatory. These data are merely suggestive; however, since F_1 can be associated with jaw movement and F_2 with tongue movement, this trend in the data could be taken to suggest that the jaw, the more massive articulator, is moving more slowly than the tongue (cf. Alfonso & Baer, 1982).

The carry-over effect of F_2 for speaker GB, in which V3 is more /ɑ/-like when the first vowel is /i/, is not only the reverse of what a straightforward account of coarticulation would predict, but also the reverse of the predicted effect that appears in this speaker's F_1 data. It may be that this unpredicted effect is caused by the tongue overshooting its target as it proceeds from the very different configurations for /i/ and /ɑ/ in /bibəbɑb/ as opposed to producing the second /ɑ/ gesture of /bɑbəbɑb/. This overshoot effect may be mechanical or, given the distance over which it extends, may be considered controlled or planned (Whalen, 1990). Any theoretical account of what appears to be a contrast effect would be highly speculative based on so little data, but it is worth mentioning findings on vowel quality in Turkish (Beddor & Yavuz, 1995) and velar height in English (R. Krakow, personal communication) that might also be described as contrast or dissimilatory effects, suggesting that systematic effects of neighboring syllables on one another may not be solely coarticulatory or dependent on a pattern of cohesion obtaining across syllables. Our own data, in any case, refute a description of carry-over effects as totally dependent on the sluggishness of articulators (cf. Henke, 1966; MacNeilage & DeClerk, 1969; Huffman, 1986; Recasens, 1987).

To sum up the results of this study, we note that whether carry-over or anticipatory effects are dominant in English varies according to speaker, and that there is a clear pattern of the effect of stress in mediating coarticulatory effects for only one speaker. Interestingly, there are effects of non-adjacent vowels on one another in both anticipatory and carry-over directions. While these effects are largely the assimilatory effects usually referred to as coarticulatory, there is evidence in one case of a systematic contrast or dissimilatory effect. Most importantly, there are several instances of these effects exceeding the bounds that previous research had assumed, even extending beyond the foot boundary.

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