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Determining the extent of coarticulation: Effects of experimental design[a)]

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The purpose of this letter is to explore some reasons for what appear to be conflicting reports regarding the nature and extent of anticipatory coarticulation, in general, and anticipatory lip rounding, in particular. Analyses of labial electromyographic and kinematic data using a minimal-pair paradigm allowed for the differentiation of consonantal and vocalic effects, supporting a frame versus a feature-spreading model of coarticulation. It is believed that the apparent conflicts of previous studies of anticipatory coarticulation might be resolved if experimental design made more use of contrastive minimal pairs and relied less on assumptions about feature specifications of phones.

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The purpose of this letter is to explore some reasons for what appear to be conflicting reports of the nature and extent of anticipatory coarticulation (Kozhevnikov and Chistovich, 1966; Lubker and Gay, 1982; Bell-Berti and Harris, 1982; Engstrand, 1981; Perkell, 1986; Sussman and Westbury, 1981). Generally, these results have been claimed to support one of two conflicting positions: One view, which we will refer to as the look-ahead model (e.g., Henke, 1967), is that articulatory features of a target phone migrate to preceding phones to an extent that depends on the feature composition of the latter. Another view, which we will refer to as frame theory (Bell-Berti and Harris, 1982), presumes that anticipatory coarticulation is due to the coproduction of neighboring segments (Fowler, 1980) in a relatively fixed temporal frame. It is our position that (1) the apparent conflicts depend in substantial part on assumptions made about the feature specification of phones, and (2) experimental design can obviate the need for such assumptions. In particular, we will refer to anticipatory lip rounding, although we believe that we are addressing the general phenomena of anticipatory coarticulation (Bladon and Al-Bamerni, 1982).

Previous studies of lip rounding (e.g., Bell-Berti and Harris, 1979, 1982; Benguerel and Cowan, 1974; Daniloff and Moll, 1968; Engstrand, 1981; Lubker and Gay, 1982) have employed alveolar consonant strings before rounded vowels on the assumption that these consonants are unspecified with regard to lip configuration. Thus the presence of electromyographic (EMG) activity or protrusive lip movement during these consonants has been presumed to indicate the onset of vowel-conditioned lip activity. However, if this activity is inherent to the production of the consonants themselves, then the onset of anticipatory vowel-related lip rounding cannot be determined unless the experimental de-

[a)] Portions of this letter were presented at the 103rd Meeting of the Acoustical Society of America [Gelfer *et al.*, J. Acoust. Soc. Am. Suppl. 1 **71**, S104–S105 (1982)].

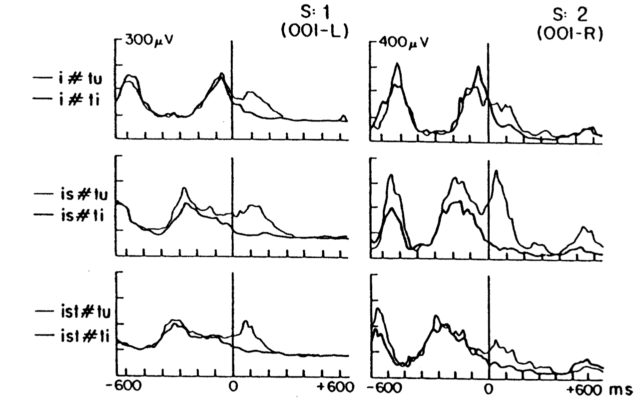

FIG. 1. Ensemble-average OOI EMG activity for 15–20 tokens of each of six utterances (three minimal pairs) for two subjects. Time 0 represents the release of the consonant occlusion, determined from the acoustic waveform.

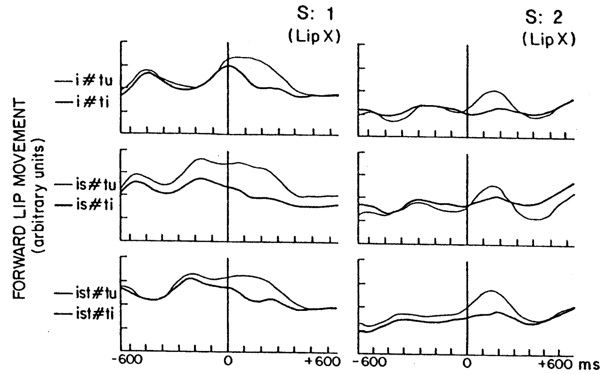

FIG. 2. Ensemble-average horizontal lip movement for 15–20 tokens of each of six utterances (three minimal pairs) for two subjects. Time 0 represents the release of the consonant occlusion, determined from the acoustic waveform.

sign allows for the differentiation of consonantal and vocalic effects.

A technique that would allow for such differentiation involves the comparison of utterance pairs that are minimally contrastive for rounded and unrounded vowels. While a few studies have used the minimal contrast technique, some to rule out the occurrence of labial gestures unrelated to the target vowel articulation (e.g., Bell-Berti and Harris, 1982; Benguerel and Cowan, 1974), others to examine differential effects of preceding vowel segments on the anticipation of vowel rounding (e.g., Sussman and Westbury, 1981), none has really used it in a way that would truly allow for the differentiation of consonantal and vocalic effects.

We used surface electromyography (Allen *et al.*, 1972) and opticoelectrical tracking to record EMG activity in the vicinity of orbicularis oris inferior (OOI) and lower lip movements of two native speakers of American English. The EMG electrodes were placed just below the vermilion border lateral to the midline. We will label this electrode placement as OOI; however, it is not expected that the EMG activity is related directly to the activity of a single muscle (Blair and Smith, 1986). Speech and nonspeech verification gestures (lip protrusion and retraction, and productions of sustained [u] and [i]) suggested that the recorded EMG activity was associated with lip rounding and protrusion. The subjects produced 20 repetitions of minimally contrastive /iC_nV/ utterances within the carrier phrase, "It's a __ again." In these utterances, V was either /i/ or /u/, and C_n was /s/, /t/, or some combination of the two. Thus the consonant sequences varied both in number (from one to four consonants) and duration (from 65 to 385 ms). The techniques used in processing these signals have been described elsewhere (Baer *et al.*, 1979; Bell-Berti and Harris, 1982; Kewley-Port, 1977) and conform to commonly used signal-averaging methods (see, for example, Gracco and Abbs, 1985, 1988).

In comparing OOI EMG activity and horizontal lower lip movement data (Figs. 1 and 2), we determined that the EMG activity was reflected in the lip movement and have, thus, used this EMG activity as an index of lip protrusion. Examining the EMG activity (Fig. 1), we note that, in both the /iC_ni/ and /iC_nu/ utterances, the onset of EMG activity occurs earlier as consonant string duration increases. If we had examined only the /iC_nu/ utterances, we would have concluded that there had been a migration of lip rounding back to the beginning of the consonant string, supporting the look-ahead model. However, since the same pattern is observed for the /iC_ni/ utterances, this EMG activity cannot reflect the onset of vowel-related lip rounding (i.e., the migration of the vowel feature). Since the relationship between consonant string duration and the onset of OOI activity is observed in both rounded and unrounded vowel environments, this pattern is not necessarily associated with lip rounding. Indeed, for both of the subjects, correlation coefficients between EMG onset time and consonant string duration are comparable for the /iC_ni/ utterances and their rounded counterparts (Fig. 3).

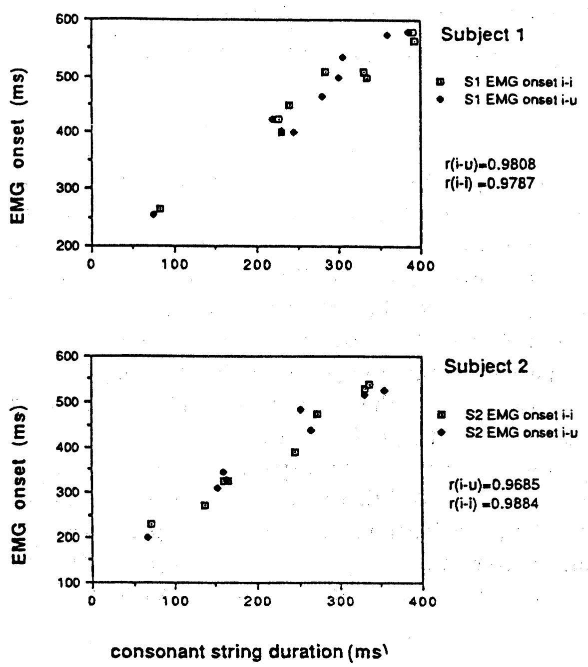

FIG. 3. Onsets of ensemble average EMG activity before V_2 for 18 utterances (nine minimal pairs) for subject 1, and 16 utterances (eight minimal pairs) for subject 2.

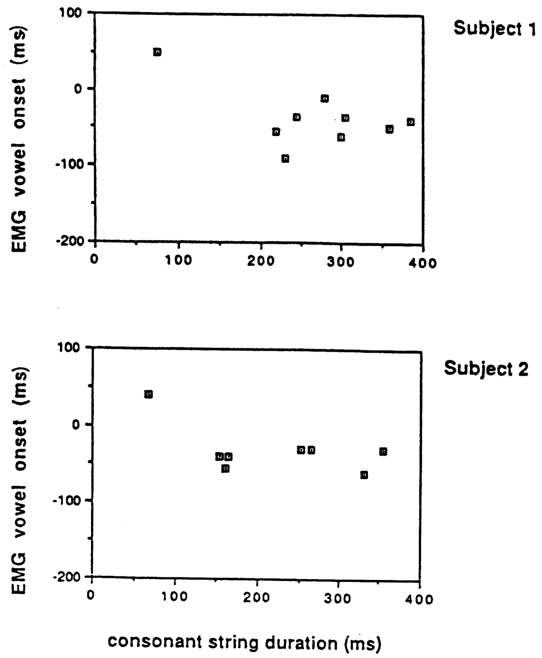

FIG. 4. Statistically determined onsets of vowel-related EMG activity for nine minimal contrasts for subject 1 and eight minimal contrasts for subject 2.

It seems obvious that the progressively earlier EMG activity does not reflect vowel events, but reflects consonant-related events instead. That is, the two signals diverge only in the vicinity of the acoustic onset of V_2, with a second peak of activity evidence when V_2 is /u/, and suppression of activity when V_2 is /i/ (Fig. 1). However, because the EMG signal never returns to a baseline level before V_2, the onset of the [u]-related EMG activity was determined statistically (using t tests) as the earliest time at which the mean amplitude difference betwen the two signals reached significance ($p < 0.05$). Of course, this approach can be taken with kinematic data as well.

The statistically determined onsets of rounded vowel activity are plotted as a function of consonant string duration (in ms) for the minimal pairs for each subject in Fig. 4. In contrast to the onsets of consonant-related EMG activity (Fig. 3), these onsets bear no obvious relation to the durations of the consonant strings. Rather, with the exception of [i#tu], they occur within a temporally restricted range (between 0 and 90 ms before the release of the consonant occlusion), thus bearing a stronger relationship to the onset of the rounded vowel than to the onset of the consonant string.

This paper advocates the need to use a minimal-pair paradigm to resolve the conflicting results of previously reported studies of anticipatory lip rounding. We suggest that at least some of the apparent discrepancy arises from problems in experimental design. Furthermore, the data suggest that one cannot assume, for alveolar consonants at least, that lip configuration is unspecified. Indeed, it is clear that some speakers produce alveolar consonants with significant orbicularis oris activity in both rounded and unrounded vowel environments. Using minimal contrasts, we showed that those gestures which were variable in onset at the EMG level were clearly tied to something that was acoustically variable as well—namely, the beginning of consonant strings of differing durations. Our statistically determined EMG vowel onsets have also shown the onset of EMG activity for [u] to be related to the acoustic onset of that vowel, and not to the migration of the vowel-rounding gesture to preceding consonants. We suggest that future studies of coarticulation in any articulator would do well to employ the technique of minimal contrasts.

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