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## CONTENTS



## EDITOR'S NOTE

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## BACK ISSUES

Back issues of this newsletter are available from **CRL** in hard copy as well as soft copy form. Papers featured in previous issues include the following:

*The Cognitive Perspective*
**Ronald W. Langacker**
Department of Linguistics, UCSD
vol. 1, no. 3, February 1987

*Toward Connectionist Semantics*
**Garrison Cottrell**
Institute for Cognitive Science, UCSD
vol. 1, no. 4, May 1987

*Dimensions of Ambiguity*
**Peter Norvig**
Computer Science, UC Berkeley
vol. 1, no. 6, July 1987

*Where is Chomsky's Bottleneck?*
**S.-Y. Kuroda**
Department of Linguistics, UCSD
vol. 1, no. 7, September 1987

*Transitivity and the Lexicon*
**Sally Rice**
Department of Linguistics, UCSD
vol. 2, no. 2, December 1987

*Formal Semantics, Pragmatics, and Situated Meaning*
**Aaron Cicourel**
Department of Sociology, UCSD
vol. 2, no. 3, January 1988

*Rules and Regularities in the Acquisition of the English Past Tense*
**Virginia Marchman**
Department of Psychology, UC Berkeley
vol. 2, no. 4, April 1988

*A Geometric Conception of Grammar*
**S.-Y. Kuroda**
Department of Linguistics, UCSD
vol. 2, no. 5, June 1988

*Harris and the Reality of Language*
**S.-Y. Kuroda**
Department of Linguistics, UCSD
vol. 3, no. 1, September 1988

*A Connectionist Perspective on Prosodic Structure*
**Mary Hare**, Dept. of Linguistics, UCSD
**David Corina**, Dept. of Psychology, UCSD
**G.W. Cottrell**, Dept. of Computer Science, UCSD
vol. 3, no. 2, November, 1988

*Competent Scientist Meets the Empiricist Mind*
**Valerie Walker**
Department of Philosophy, UCSD
vol. 3, no. 4, April, 1988

*Foreign Policy By Metaphor*
**Paul Chilton,** University of Warwick, U.K.
**George Lakoff,** UC Berkeley
vol. 3, no. 5, June, 1989

*Guarani Possessive Constructions*
**Maura Velazquez**
Department of Linguistics, UCSD
vol. 4, no. 1, July, 1989

H A P P Y   H O L I D A Y S

# Anticipatory Coarticulation and Aphasia: Implications for Connectionist Models of Speech Production

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## Introduction

Much of human behavior may be described as involving serially ordered processes. This is true for both motor behavior as well as perception and comprehension. What makes serially ordered aspects of behavior difficult to model is that although discrete stages of activity may be psychologically perceptible, actual behavior is rarely context-free. That is, we have the ability to perform the "same" types of motor movements in vastly differing real world situations, as well as to decode "single" units of meaning out of highly parallel information streams.

Nowhere has this phenomenon been more apparent than in speech production and perception. Even within the component of language traditionally thought to involve the most "bottom-up" information, i.e., phonology, one is confronted with information present in a highly context-dependent form. Speech has remained one of the more problematic aspects of human communication to study because it has been extremely difficult to identify the units corresponding to components of phonological analysis in either articulatory gestures or in the acoustic waveform. At the core of this problem is a phenomenon known as "coarticulation" (or "co-production", Fowler, 1980). This refers to the fact that speakers do not string together discrete sound segments as beads on a string, but rather overlap speech sounds in a graded, time-compressed manner.

Coarticulation may be generally classified as perseveratory ("backwards", "left-to-right") or anticipatory ("forwards, "right- to-left"). Anticipatory coarticulation is of special interest to speech researchers because it is considered to be a measure of the planning of upcoming speech segments. By examining speakers' ability to anticipate articulatory configurations it has been possible to gain insight into the nature of the speech sequencing process.

Speech production has traditionally been divided into planning and execution processes. These processes have been commonly given names borrowed from linguistic theory, i.e., "phonemic" (or selectional), and "phonetic" (motor output). Because coarticulation involves the translation of linguistic targets into speech articulator movements, the process entails both phonemic and phonetic information. It has therefore remained controversial whether these regularities should be captured in a linguistic grammar (cf. Browman & Goldstein, 1986; Keating, in press; Fowler, in press). Importantly, the phonemic/phonetic nature of coarticulation has also made it necessary to study cognitive and linguistic representations, as well as a broad range of physical data (e.g., the kinematic properties of the speech articulators) in order to best capture the facts.

A recent breakthrough in modeling cognitive aspects of coarticulation has been made by Jordan (1986), who simulated anticipatory rounding and nasalization in a small corpus of French and English words and phrases. Jordan proposed a connectionist model which receives as input a "plan" (in the form of featural specifications for individual phonemes) and yields as output a list of coarticulatory constraints presented occurring serially across time. Jordan's model is based upon previous PDP frameworks, incorporating a recurrent network of processing units, "hidden units" to capture nonlinear response patterns (Hinton & Sejnowski, 1983), and a back propagation learning algorithm to provide training (Rumelhart, Hinton, & Williams, 1986). This model, however, has provided two key innovations: First of all, input was separated into state and plan units. This permitted nominally serial properties to be modelled without recall to explicit temporal order or action sequences. Secondly, plan units (representing phoneme strings) were designed to include "don't care" conditions. This permitted anticipated features (e.g., rounding) to spread over certain phonemic segments and not others.

Jordan was careful to point out that the model was not intended to be a "realistic model of speech production", due to the fact that complex lower-level (motoric) processes are also involved in actual speech. Moreover, it was noted that the same regularities captured in the connectionist approach could also be explained by means of "traditional" models (e.g., feature spreading, Henke, 1966). Nevertheless, Jordan's model was able to predict the degree of featural spread (i.e., the "boundary conditions" for articulators) in a manner consistent with the empirical data, and was therefore claimed to provide a more parsimonious account of coarticulation. The success of this initial attempt suggests that more elaborated connectionist models might be greatly useful in coarticulation research.

Numerous empirical studies have been conducted analyzing the acoustic, perceptual, and kinematic details of anticipatory coarticulation in the speech of normal adults (see Sharf and Ohde, 1981; Lubker and Gay, 1982, for reviews). These studies have addressed important claims about language-dependent features of speech planning, and have yielded important information about the properties of individual speech articulators. In addition, researchers have recently begun to examine the development of coarticulation in normal children (Repp, 1986; Sereno et al., 1987; Nittrouer, 1989a; 1989b; Katz, Kripke, Tallal et al, 1989, and Nittrouer and Whalen 1989), as well as in children presenting with language impairment (Hewlett, 1988; Katz, Kripke, and Tallal, 1989b).

This article will focus primarily upon studies of adult aphasic subjects (i.e., subjects presenting with specific damage to brain regions known to subserve speech and language function). This research has sought to make use of "experiments in nature" to analyze a number of important questions about speech behavior. First of all, the data address whether the sound sequencing capabilities necessary for naturally coarticulated speech are linked to the integrity of particular neural structures in the brain. It is possible to investigate, for example, hypotheses stating that anterior brain regions (esp. "Broca's Area") are preferentially involved in speech motor planning (Mlcoch & Noll, 1980, Kimura and Watson, 1989). In addition, the coarticulatory patterns of aphasic speech have been viewed as a possible means of determining the extent of normal speech motor planning processes. That is, by observing the constraints governing aphasic speech breakdown, it may be possible to infer specific planning processes at work in the normal brain. Finally, it has also been of interest to determine whether coarticulatory data comport with known patterns of "phonemic" and "phonetic" disintegration in aphasic speech.

In this paper, I shall first provide a brief summary of the facts known about coarticulation in normal adult speech. This will be followed by a short description of aphasic speech characteristics, including facts known about coarticulation. The body of this report will be concerned with new research addressing labial, lingual, and velar anticipatory coarticulation in normal and aphasic German-speaking subjects. The results of these investigations indicate that anterior aphasic subjects show essentially intact anticipatory coarticulation. These data will be discussed in light of current models of speech production.

## Coarticulation in normal, adult speech

The most widely studied forms of anticipatory coarticulation involve the motion of the lips, tongue, and velum. Anticipatory labial coarticulation typically involves initiation of a rounding gesture during consonant production preceding a rounded vowel. For example, a speaker producing the English syllable [su] will round his lips at the start of the [s] in anticipation of the rounded vowel [u]. In contrast, no rounding occurs when he is producing the syllable [si].

Studies of anticipatory lingual coarticulation typically focus on the front/back positioning of the tongue in velar stop closure as a function of the feature specification of the following vowel. For instance, the English phoneme /k/ has a front allophone with a relatively anterior vocal tract constriction, and a back allophone with a relatively posterior constriction.

Anticipatory velar coarticulation describes effects upon velar height as a function of the nasality features of upcoming phones. For example, the presence of the nasalized consonant [n] in the English word "pent" may begin shortly after the initial [p], effectively nasalizing the vowel [E].

Coarticulation has been studied by means of acoustic, perceptual and kinematic analyses. These studies have indicated that the timing and extent of anticipatory coarticulation is language-particular. Thus, one finds that lip rounding is anticipated earlier and with greater precision in Swedish (a language having an elaborate set of rounded vowels) than in English (which has relatively little vowel rounding). It has also been shown that within a given language there may be substantial individual variation, with some subjects showing more "feature-based" anticipatory patterns, and others showing evidence of anticipation over a "phase-locked", single window of time (see Lubker and Gay, 1982, for details).

## Speech production in aphasia

The major subdivision between aphasic syndromes is based upon the character of speech output (Goodglass and Kaplan, 1982). Aphasic subjects with lesions in the anterior portion of the brain generally present speech marked with difficulties in the initiation and sequencing of articulatory movements. These symptoms are generally considered to be an integral part of a nonfluent aphasia, referred to as "Broca's aphasia." There may also be agrammatism, which is a reduction and simplification of grammatical forms, including the loss of small function words. These factors add up to a speech pattern which is halting and effortful, generally termed "dysfluent."

In contrast, aphasics with posterior lesions generally present with speech which is fluent and well-articulated, though semantically impoverished. These deficits are generally considered to be an integral part of two posterior aphasia syndromes ("Wernicke's aphasia", "Conduction aphasia"). Wernicke's aphasia involves a severe impairment of auditory and written comprehension, and speech which is semantically "empty" and difficult to understand. There is an abundance of high-frequency, low-content words (e.g., "thing", "it"), and a reduction of substantive nouns and verbs to convey meaning. The speech of these patients typically shows verbal and phonemic paraphasias. There may be a phenomenon known as "press for speech" (or "logorrhea") in which the patient, even in a conversational setting, produces copious amounts of speech without stopping. The syndrome of Conduction aphasia is qualitatively similar to Wernicke's aphasia in a number of respects, however, the chief difference is that repetition is greatly impaired in relation to the level of fluency in spontaneous speech.

Traditional clinical descriptions of aphasia consider the errors in speech produced by anterior aphasics to reflect phonetic or articulatory errors, whereas the errors of posterior aphasics are thought to originate at the phoneme planning level. In recent years, fine-grained acoustic analyses have uncovered additional data which generally support this dichotomy. With respect to anterior aphasic subjects, the data all suggest impairment in the timing or integration of movements of the articulatory system. These anterior aphasic impairments do not seem to reflect a global weakness or discoordination of the articulators. Rather, articulatory disabilities appear to be best characterized as affecting two "independent" articulators, e.g., coordinating vocal fold vibration with the tongue tip release of stop consonants.

## Coarticulation in aphasia

Ziegler and von Cramon (1985, 1986, 1986b), based upon acoustic and perceptual studies of German-speaking anterior aphasic subjects, argue that anterior aphasia may involve a "delayed onset of anticipatory vowel gestures relative to the labial occlusion." A similar conclusion was tentatively reached by Tuller and Story (1986), who conducted an acoustic analysis of coarticulatory information present in the speech of English-speaking anterior aphasic subjects.

In contrast, Katz (1987, 1988) conducted an acoustic and perceptual study of English-speaking aphasics which showed a "mixed" pattern of results for anterior aphasic subjects. The acoustic data showed no differences between the coarticulation present in normal and anterior aphasic speech, while the perceptual data indicated somewhat degraded coarticulatory information in the speech of anterior aphasic subjects. Moreover, group differences in the perceptual data varied as a function of stimulus type. It was concluded that a "uniform delay" in coarticulation does not adequately characterize anterior aphasic speech. Rather, coarticulatory "planning" was considered to be intact, while the degree of actual coarticulatory behavior was considered to vary as a function of the complexity of the motor gestures involved.

Little direct kinematic exists concerning this issue. Sussman, Marquardt, MacNeilage, & Hutchison (1988) have reported kinematic findings concerning labial coarticulation in aphasia. It was found found that for correct productions of CV, CCV, and VC#CCV stimuli, anterior aphasic subjects exhibited lip and jaw coarticulatory behavior similar to normal subjects.

With respect to velar coarticulation, a series of kinematic experiments have been conducted by Itoh and colleagues in Japan. Using both fibroscopic (Itoh, Sasanuma, and Ushijima, 1979) and X- ray microbeam (Itoh, Sasanuma, Hirose, Yoshioka, and Ushijima, 1980) techniques, these authors analyzed the speech of a Japanese- speaking, anterior aphasic subject. The results showed a great deal of variability in the apraxic patient's speech kinematics, particularly with respect to the successional patterns of velar movement. However, despite occasional deviations, it was concluded that anticipatory coarticulation was intact.

As the preceding, somewhat equivocal pattern of results indicates, it is difficult to obtain a coherent picture of coarticulation in aphasic speech based solely upon acoustic or perceptual data. Rather, it is essential to combine acoustic and perceptual investigations with direct kinematic measurement. Moreover, studies which provide information about the simultaneous motion of several articulators offer a greater advantage for understanding coarticulatory impairment than do analyses of individual articulator movement. For these reasons, Katz, Machetanz, Orth, and Schoenle (1989c, 1989d) conducted kinematic and acoustic analyses of the speech of German-speaking anterior aphasic subjects. This work made use of the recent technology of electromagnetic articulography, which affords real-time, simultaneous tracking of several articulators in the vocal tract. Also, by using German-speaking subjects, it was possible to study lip-rounding contrasts which did not involve changes in tongue position (as found in English).

## Experiment

### Method

#### Subjects

Subjects included two anterior aphasic and two normal, control speakers. All subjects were adult, right-handed native speakers of German, from similar dialect regions. Aphasic subjects presented with single, clearly defined anterior lesions (see Katz et al., 1989c for details), and were classified based upon clinical exam and speech pathology assessment. Control subjects had no history of neurological disease, and no speech or language difficulties.

#### Procedure

Speech kinematics were measured using the electromagnetic articulography system developed at the University of Goettingen Department of Clinical Neurophysiology (Schoenle, Grabe, Wenig, Hohne, Schrader, & Conrad, 1987). This device allows for the simultaneous recording of multiple points in and outside of the vocal tract. Subjects were seated in a quiet testing room and were fitted with a helmet containing three magnetic transmitter coils. Minute receiver coils were attached to the upper lip (UL) and lower lip (LL) (for the labial study) and to the tongue tip and velum (for the nasal study). A computer was used to sample positional data for two receiver coils, and to record acoustic data.

**Speech material**

Speakers were asked to produce real word stimuli designed to probe the timing of anticipatory labialization during consonant production and anticipatory nasalization during vowel production. There was a total of 10 stimulus items (4 labial, 6 nasal). The labial stimuli ([g*li:g*]/[g*ly:g*]; [g*lez*]/[g*lo:z*]) consist of word pairs contrasting minimally in the rounding feature of the vowel following the consonant [l]. The nasal stimuli ([ti:g*]/[tingl]; [ti:d*]/[ti:n*]; [ti:b*]/[ti:m*]) consist of word pairs differing in the nasality features of each word's initial vowel and middle consonant. The nasal stimuli were also selected to represent velar, alveolar, and labial place of articulation for middle (word-internal) consonants. All stimuli were embedded in the carrier phrase: "Ich sagte _______ zweimal" ("I said ________ twice").

Subjects' productions were perceptually screened by the researchers, and speech errors were identified. Detailed classification of speech errors are listed in Katz et al. (1989c). For the normal control subjects, no speech errors were noted. For the aphasic subjects, a total of 22 speech errors were detected (= 7.3% of the 300 total repetitions by aphasic subjects). Errors were separately classified for further analysis. From a total of 15 repetitions recorded for each stimulus type (per speaker), the first ten correct repetitions were used for kinematic and acoustic analyses.

**Analysis**

Kinematic data were analyzed from graphic representations of articulator position and tangential velocity. In addition, quantitative records of speech timing were obtained using interactive software designed for speech movement analysis.

Speech acoustics were analyzed using the a speech processing program for microcomputer. Speech samples were low-pass filtered and digitized. Speech segment regions were identified in the waveform from an oscillographic display, and segment durations were recorded. Due to the known difficulty of analyzing cues for vowel nasalization present in prevocalic consonantal spectra only labial stimuli were analyzed. For the labial [g*lVg*] stimuli, 5 segments ([g], schwa, [l], vowel, final [g*]) were delineated (see Katz et al., 1989c for details).

For each stimulus, an analysis window was placed over specific areas of each segment. Spectra were then obtained using Fourier analysis and linear predictive coding (LPC). Analysis of anticipatory lip-rounding focussed upon spectral peaks in the liquid portion of the waveform anticipating the second formant of the vowel. Additional details are provided in Katz et al., 1989c.

**Kinematic Results**

**I. Correct productions**

**A. Labial stimuli**

**i. Articulator displacement**

Lip rounding may be characterized in terms of both extension and vertical movement (raising or lowering, depending upon the region of the lip examined, and upon individual subject characteristics). The two control speakers produced robust UL protrusion (extension and lowering) for rounded (as compared with unrounded) stimuli. These lip protrusion gestures were rapid, concise, and were clearly related to production of the rounded vowel in the utterance. In addition, speaker PS showed substantial extension and lowering of LL (and jaw) for both stimuli series, while speaker EO demonstrated only slight LL (and jaw) protrusion for [g*ly:g*] as compared with [geli:ge].

Considering next the anterior aphasic data, UL protrusion was also found for rounded (as compared with unrounded) stimuli. The overall time course of these gestures differed somewhat between the two aphasic subjects. Speaker AW showed rapid UL movements corresponding with production of rounded vowel segments (i.e., resembling the data of the control subjects). In contrast, speaker EG showed more gradual UL movements, with a much lesser amount of net displacement. In terms of LL (and jaw) movement, both aphasic speakers showed articulator protrusion (extension and raising) for rounded (as compared with unrounded) stimuli.

In order to determine the extent to which speakers differed in the regularity of articulator movement, a measure of item-to- item displacement variation was computed (see Katz et al., 1989c). The aphasic speakers showed greater overall variation than the control speakers, with particularly high variation for LL (and jaw) displacement. The results of two-way (Group x Articulator) analyses of variance (ANOVA) confirmed that these patterns were statistically significant.

### ii. Articulator timing

Because it was considered important to examine the extent to which anticipatory coarticulation varied with speaking rate, the overall duration of speakers' utterances were analyzed. It was found that the aphasic speakers produced slower speech, with greater variation in segment timing, than is found in the speech of normal, control subjects. Further analysis of aphasic speakers' temporal patterns indicated that these subjects showed a prevalence of intersyllabic pauses, as well as occasional segment prolongations (particularly for vowels) in their speech. These findings are in accord with previous descriptions of verbal apraxic speech.

In order to analyze the point of anticipatory coarticulation onset, individual repetitions were inspected with attention paid to the exact point in the acoustic waveform at which kinematic, coarticulatory effects could be noted. The results demonstrated that lip protrusion was, for all subjects, confined to a region proximate to the rounded vowel. The beginning of labial protrusion generally began either shortly before, or during production of the syllable [g*], i.e., the syllable preceding that containing the rounded vowel.

Although speakers were quite consistent across repetitions (with control subjects showing greater consistency than aphasics), there were notable Speaker- and Group-dependent differences in coarticulation onset. These individual patterns are discussed at length in Katz et al. (1989c). In general, the data may be summarized as showing that anterior aphasic subjects show more variation in their onset positions, although this does not fit the pattern of a uniform delay. Rather, aphasic speakers' variation generally involved unusually early lip protrusion in comparison to that found for control subjects.

## B. Nasal stimuli

### i. Articulator displacement

The two control speakers showed little movement of the velum during production of the non-nasalized stimuli, whereas robust velar port opening (i.e., velar extension and lowering) was observed for productions of the nasalized stimuli. In comparison with the normal speakers, the aphasic speakers showed highly impaired patterns of velar movement (detailed in Katz et al., 1989c). These impairments were more marked for aphasic subject EG than for subject AW. However, despite these imprecise movement patterns, aphasic subjects showed clear evidence of correct, anticipatory velar port opening before nasalized consonants.

As with the labialization stimuli, variation in velum displacement was quantified by calculating the RMS distance between individual utterances and averaged displacement waveforms. Statistical analysis revealed that aphasic speakers produced greater overall variation in velum and tongue displacement than the control speakers. This was particularly true for the velar movement of aphasic subject EG, who showed the opposite pattern (i.e., greater velar than lingual variation). Taken together, these data indicate that the two aphasic speakers, considered as a "group", were more variable than controls, and that aphasic subject EG showed a particularly high degree of velar movement variation.

### ii. Articulator timing

The time course of correct velar stimuli productions was investigated by conducting comparisons of the acoustic and kinetic data. As with the labialization results, subjects were found to be quite consistent from utterance to utterance, though aphasics showed greater variability in onset position. Both control speakers showed context-dependent differences at a region of the speech waveform located between the end of the aspiration following the [t] segment, and the first 40 ms of vowel pulsing. Similarly, the first noticeable context-dependent difference in the movement traces of the aphasic subjects (i.e., visible changes in the rates of velar lowering) was noted to be within this same temporal region. In other words, even though the displacement of velar position was noted to be qualitatively different and more variable for aphasic speakers, the aphasic subjects appeared to initiate nasalization gestures at approximately the same point in time during speech as normal controls. These data suggest that, although the overall ability to control spatial positioning of the velum was clearly compromised for aphasic speakers, temporal aspects of velar, coarticulatory movement appeared relatively preserved.

### II. Error-prone productions

An investigation was made into the claim that speech production errors perceptually resembling phone substitutions might in fact be the result of discrete, interarticulatory phasing difficulties (e.g., Mlcoch & Noll, 1980; Ziegler and von Cramon, 1985). There were, however, very few speech errors in the database containing the target structures of interest. These consisted of instances in which aphasic subject EG produced substitutions of "[tid*]" for [tin*] targets. For these cases, there were found to be [d] stop consonant bursts in the acoustic waveforms. Kinematic analyses showed that in two of the cases, velar movement more closely resembled correctly-produced [d] than [n] gestures, while in the third case the displacement patterns fell midway between those typical of nasal and non-nasal consonants. In sum, these data do not suggest that a slightly mistimed [n] production resulted in a [d] percept, but rather indicate that these errors likely resulted from phone selectional ("phonemic") difficulties.

## Acoustic Results

### I. Correct productions (labial stimuli)

### Vowel-anticipatory peaks in [l] spectra

Data for the vowel pairs [i:]/[y:] and [e:]/[o:] were grouped for comparison of coarticulatory effects. For both sets of stimuli, the distribution of peaks for productions by aphasic subjects was more variable than for those of normal subjects. This was particularly true for the higher frequency regions (above 2 kHz). Aphasia-related generalizations about coarticulatory shift were difficult to make for [i:]/[y:], because the effect did not seem clearly established for the two normal subjects in the F2 range, and because data from the aphasic speakers showed substantial variation in the F3 frequency range. For [e:]/[o:], spectral peaks in the F2 frequency range showed evidence of coarticulatory effects for both aphasic and control subjects. Considering both stimulus sets together, aphasic speakers' productions appear to provide evidence for vowel context-dependent spectral shift in a manner similar to (or exceeding that of) productions by normal subjects.

## Discussion

Although the present data must be considered preliminary because of the small number of subjects investigated, the findings address a number of important issues concerning the neurological bases of speech production. To briefly summarize the results, the kinematic data showed that for both labial and nasal (correct) productions, aphasic speakers' coarticulatory patterns were more highly variable than those of control subjects. These differences, however, were noted chiefly for spatial displacement characteristics, while the temporal aspects of articulator movement involved in anticipatory coarticulation appeared largely intact. It was also found that velum mistiming did not appear to explain a small corpus of stop/nasal substitution errors produced by one of the aphasic speakers.

The acoustic data largely agree with the kinematic findings. To the extent that vowel formant frequency energy could be traced back into the portion of the waveform corresponding to the prevocalic consonant, [l], the correct productions of the anterior aphasic subjects showed patterns of labial anticipation similar to (or exceeding that of) normal speakers.

A major empirical issue which these data address concerns whether anterior aphasic subjects show systematic delays in the production of anticipatory coarticulation information during speech. With respect to labial anticipation, uniform coarticulatory delays on the order of 20-30 ms have been proposed as a possible speech characteristic of German (Ziegler and von Cramon, 1985; Ziegler, 1989) and English-speaking (Tuller and Story, 1987) anterior aphasic subjects. In contrast, Katz (1987, 1988) and Sussman et al. (1988) have provided evidence suggesting that temporal control of anticipatory labial coarticulation is largely intact in anterior aphasic speakers' correct productions. The data from the present experiment replicate the findings of Sussman et al. (1988), and support the acoustic data of Katz (1987, 1988), in that anterior aphasic subjects were found to produce coarticulatory gestures as early as (or earlier than) matched control speakers. These data suggest that if listeners show uniform delays in picking up coarticulatory information present in anterior aphasic speech, this may be due to complicating factors other than actual coarticulatory cues (see Katz et al., 1989c for discussion).

With respect to anticipatory velar movement, the present study addresses the question of whether discoordinations in velar movement might correspond to coarticulatory impairments (e.g., Mlcoch and Noll, 1980) and whether such discoordinations might also account for perceptually apparent "substitution" errors in the speech of anterior aphasic subjects (Itoh et al., 1979, 1980; Ziegler and von Cramon, 1986b). The present data replicate the findings of Itoh et al. (1979, 1980), in that they demonstrate essentially intact anticipatory coarticulation in the correct speech of anterior aphasic subjects.

As for theories concerning aphasics' error-prone productions, the present findings do not rule out the possibility that interarticulatory phasing difficulties may account for occasional substitution errors. In the present database, however, there was very little evidence for this. Of the three stop/nasal substitution errors examined, all contained clearly identifiable stop consonant bursts, suggesting selectional ("phonemic") rather than interarticulatory discoordination in motor output. Only one of the three substitution errors showed kinematic patterns allowing for the possibility of interarticulatory discoordination (i.e., velar displacement patterns midway between those typical of nasal and non-nasal consonants).

A key theoretical aim of this research is to explore how patterns of coarticulation in aphasic speech can inform models of normal speech production. With respect to localization of function issues, the present data suggest that anticipatory coarticulation capabilities of the adult brain do not critically rely upon anterior structures (e.g., Broca's area). Rather, it appears that anterior regions are involved in coordinating the timing of the articulators for producing individual phones (e.g., VOT values for stop consonants) and possibly single syllables (see Kimura and Watson, 1989), but not for effecting anticipatory transitions between phones. If future experimentation confirms the finding that highly automatized behavior such as anticipatory coarticulation does not require the integrity of anterior structures in adult subjects, then models implicating specific anterior regions (e.g., Broca's area) as general "speech programming" centers will certainly require revision. It may instead be the case that anticipatory coarticulation is a property more globally represented throughout the language "zone" of the brain (i.e, dominant peri- Sylvian cortex and subcortical structures). This type of diffuse neural representation has been proposed for other properties of language, such as the representation of individual lexical items (Ojemann, 1983).

The present findings agree with the traditional view that anterior aphasics demonstrate problems chiefly at the "phonetic" level, while posterior aphasic evidence mainly "phonemic" (selectional) deficits. That is, anterior aphasics appear to have difficulty in interarticulatory coordination, which impinges on their ability to initiate and produce a variety of speech sounds. The problem is not in phoneme selection, it is in outputting selected sounds. In a similar fashion, it may be assumed that anterior aphasics retain representations containing information about the coarticulatory spread of featural information. Such representations would be qualitatively similar to the "boundary conditions" yielded as the output of the Jordan (1986) model. In keeping with this view, one could reason that where the system fails for anterior aphasics is in the mapping of coarticulated representations into motor output.

Future investigations might examine these issues by "lesioning" models of coarticulation in speech production, and observing the manner in which feature spreading is affected. Results from "lesioned" connectionist models have recently been used by investigators to simulate cognitive breakdown in adult aphasia (Gigely, 1988) and acquired dyslexia (Hinton & Shallice, in press). The present data, however, suggest that "lesion" experiments using models similar to Jordan (1986) would be most relevant to deficits in posterior aphasic speech, i.e., deficits involving "phonemic" (selectional) errors. In order to best model anterior aphasic speech, it is essential to first develop connectionist models which incorporate information about the kinematic properties of the articulators. Models designed to capture the "lower-level" inertial properties of the articulators are currently under development by a number of researchers (e.g., Browman and Goldstein, 1985; Kelso, Saltzman, and Tuller, 1989).[1]

Additional information about the role of brain structures in speech motor programming might be obtained by comparing the present results with data concerning the development of coarticulatory patterns in children. Recent findings have suggested that the ability to sequence intersyllabic anticipatory coarticulation information is present from an early age, and may be more extensive in young children than in older children (Nittrouer et al, 1989; Nittrouer and Whalen 1989; Katz et al., 1989a). These data suggest that intrasyllabic coarticulation patterns might develop during early stages of brain development, at which point they are relatively susceptible to disruption. However, once mature coarticulatory capabilities are established, they may be far less susceptible to disruption, even in the face of massive damage to anterior brain structures.

[1] These models assume that the articulators may be viewed as a series of mass-spring oscillators, whose "dynamic" patterns may be described mathematically in terms of system constraints upon oscillatory properties. Because "dynamic" models offers a high degree of mathematical rigor, they have been viewed favorably by a number of connectionist researchers. However, these models remain controversial within the speech research community. For example, see Keller (in press) for an alternative view.

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