

A Kinematic Analysis of Anticipatory Coarticulation in the Speech of Anterior Aphasic Subjects Using Electromagnetic Articulography

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An investigation was made into the extent and time course of anticipatory coarticulation in the speech of two normal and two anterior aphasic, German-speaking subjects. Both labial and velar coarticulation gestures were investigated. Subjects produced sentences containing target words contrasting in postconsonantal vowel rounding (e.g., [gəli:gə]/[gəly:gə]) and in nasality (e.g., [ti:də]/[ti:nə]). Speech kinematics were monitored by means of electromagnetic articulography. The data revealed that for correct productions, aphasic speakers' coarticulatory patterns were more highly variable than those of control subjects. These differences, however, were found chiefly for spatial displacement characteristics, while the temporal aspects of articulator movement necessary for anticipatory coarticulation appeared largely intact. Articulator mistiming did not appear to explain a small corpus of stop/nasal substitution errors produced by one of the aphasic speakers. © 1990 Academic Press, Inc.

The authors thank John Bobela and Erich von Berger for their assistance in data analysis. This research was sponsored by Grant NS 08176-01A1 to William Katz, University of Goettingen/DFG grant to Jochen Machetanz, and BMFT Grant 0706839A to Paul-Walter Schönle. Send reprint requests to William F. Katz, The University of Texas at Dallas, Callier Center for Communication Disorders, 1966 Inwood Rd., Dallas, TX 75235.

BACKGROUND

An important goal of neurolinguistic research has been to provide an accurate account of the speech production capabilities of aphasic subjects. For this reason, a number of studies have been conducted investigating articulator timing and coordination in aphasic speech. This research has generally analyzed speech output at the level of individual sounds or "phonemes." The data have been used to develop theories concerning probable levels of speech-processing impairment in aphasia.

One theory which has been highly influential considers the errors in speech produced by posterior aphasics to originate at the "phoneme planning level" whereas "phonetic" or articulatory errors are thought to be more typical of anterior, nonfluent aphasia. This notion, first described explicitly by Alajouanine, Ombredane, and Durand (1939), has been supported by a number of recent acoustic and perceptual studies, including investigations of the voice onset time (VOT) of consonants (Blumstein, Cooper, Zurif, & Caramazza, 1977; Blumstein, Cooper, Goodglass, Statlender, & Gottlieb, 1980; Shewan, Leeper, & Booth, 1984; Gandour & Dardarananda, 1984) and the duration (Tikofsky, 1965; Peterson & Lehiste, 1960; Ryalls, 1981, 1986), formant frequencies, and fundamental frequencies (Ryalls, 1986) of vowels.

The general picture which has emerged is now thought to be more complicated than originally conceived, yet still indicates that for anterior aphasic subjects there are impairments in the timing and integration of movements of the articulatory system. Interestingly, anterior aphasic difficulties do not seem to involve "across-the-board" speech motor impairment, but instead affect particular speech gestures while leaving other gestures relatively intact. For example, anterior aphasics seem to have particular difficulty in gestures requiring precise laryngeal control and the concurrent movement of independent articulators, as is required in producing voice onset time (VOT) distinctions. On the other hand, the work of Shinn and Blumstein (1983), Katz (1987, 1988a), and others have shown that anterior aphasics are capable of reaching the spatial endpoints of articulatory positions, e.g., in positioning the vocal tract to the appropriate place of articulation for stop consonants. These data suggest that spatial aspects of articulatory movement are relatively preserved in the speech of anterior aphasic patients. In contrast to anterior aphasics, posterior aphasics appear to produce fewer errors of articulator timing and coordination, but instead make errors which are generally "selectional" or "phonemic" in nature.

It is interesting to note that the majority of studies in this area have been concerned with analyzing discrete consonant or vowel segments. In recent years, however, investigators have also begun to examine "sound-transitional" or coarticulatory phenomena in aphasic speech. Coarticulation refers to the fact that speech sounds are not strung to-

gether like beads on a string, but rather are overlapped in a time-compressed manner. The study of anticipatory (or right-to-left) coarticulation is of special interest because it is considered to be a measure of the preplanning of upcoming speech segments. By examining speakers' ability to anticipate articulatory configurations, it is possible to gain insight into the size and nature of motor sequencing units, as well as their control.

Studies of coarticulation in aphasic speech have investigated whether damage to specific areas of the brain results in delays or deficits in the execution of local anticipatory speech gestures. The existence of this type of speech timing difficulty is potentially important, because coarticulatory-type difficulties could constitute an underlying cause of the phonological speech errors observed in anterior aphasic speech. Claims have been made, for example, that speech errors produced by anterior aphasic subjects which may on the surface appear to be substitution errors could, in fact, be due to discrete interarticulatory timing difficulties (e.g., Ziegler & von Cramon, 1985).

These studies have largely used acoustic or perceptual methodologies. In *acoustic* studies of coarticulation, research has focused upon labialization and nasalization. In the labialization studies, anticipatory lip-rounding has been assessed by measuring the amount of formant shift in prevocalic consonants as a function of the rounding feature of the following vowel. For American English-speaking aphasics, there have been two acoustic studies of coarticulation completed to date, which have yielded somewhat mixed results. These mixed findings are likely due to slightly differing methodologies. Katz (1987, 1988a) examined two regions of the consonantal portion of CV stimuli produced by normal and anterior aphasic subjects. The degree of vowel-anticipatory spectral information present in these consonantal regions was measured using linear predictive coding (LPC) analysis. The results demonstrated that both normal and anterior aphasic subjects produced robust acoustic correlates of anticipatory labialization, with no discernable differences as a function of Group.

Tuller and Story (1987) conducted a similar investigation of normal and aphasic subjects' fricative-vowel productions, focussing upon slightly different regions of the fricative waveform. For acoustic regions analogous to those examined by Katz, the results showed coarticulatory patterns with few differences as a function of Group (similar to the findings of Katz). However, at a slightly earlier region of the fricative waveform (i.e., fricative midpoint), acoustic correlates of anticipatory coarticulation were noted for only one out of five nonfluent speakers studied. These findings were interpreted as indicating possible Group differences in anticipatory coarticulation, at a relatively early point in fricative production.

The finding of significant coarticulatory differences between anterior aphasic and normal control subjects has also been reported in an acoustic study of German. Ziegler and von Cramon (1986b), using a discriminant analysis of LPC reflection coefficients, found less acoustic information signalling labial anticipatory coarticulation present in the speech of apraxia of speech¹ subjects than in the speech of normal, control subjects.

In sum, although current acoustical techniques have promise for analyzing coarticulatory patterns, it is difficult to arrive at a uniform picture of the anticipatory labialization capabilities of aphasic subjects from the data currently available.

The *perceptual* studies of anticipatory labialization conducted to date have shown somewhat better concordance in their results, yet still do not completely agree. In these studies, gated speech segments containing coarticulatory information relating to the following vowel are presented to listeners for a vowel-identification task. Data for both American English (Katz, 1987, 1988a) and German (Ziegler & von Cramon, 1985) have suggested that the speech of anterior aphasics contains a diminished amount of perceptual information for anticipatory coarticulation. From their results, Ziegler and von Cramon (1985) have concluded that apraxia of speech patients show a "consistent delay in the initiation of vowel gestures." On the other hand, the data of Katz (1987, 1988a) showed differences between listeners' correct identification of aphasic speakers' fricative and stop-consonant stimuli, with listeners having a far more difficult time detecting coarticulatory information in [ti/tu] stimuli as compared with [si/su] stimuli. This suggests that instead of a "uniform delay" in coarticulatory gestures, a more complicated interaction of deficits (based upon the level of complexity of each speech gesture) may be involved.

With respect to velar movement and nasality in aphasic speech, relatively little acoustic or perceptual work has been undertaken. Ziegler and von Cramon (1986b) measured the sound pressure level (SPL) of words containing nasals, spoken by apraxia of speech patients and normal control subjects. It was reasoned that the SPL would reflect the "smoothness in the diversion of the airstream from nasal to oral." Specifically, it was argued that an adequate synchronization between nasal and oral gestures would not cause a marked change in SPL levels, whereas there would be detectable damping of the SPL when premature velar elevation

¹ "Apraxia of speech" is a syndrome involving erroneous sound productions consisting of mainly distortions, substitutions, and additions. Whether apraxia of speech is a uniquely specified syndrome separate from aphasia, or whether it is a subset of Broca's aphasia remains a matter of debate (see Blumstein, 1981). For the present discussion, it will be sufficient to note that speech errors made by subjects presenting with apraxia of speech symptoms are relevant to investigations into anticipatory coarticulation breakdown.

occurred while the oral passage was still occluded by the tongue.² It was found that certain apraxia of speech patients showed "marked damping" in the transition towards the final vowel of [anə] and [inə] utterances. In addition, the apraxia of speech subjects (as a group) showed a broader distribution of SPL changes than did the normal control subjects. From these data, it was inferred that the speech of apraxia of speech patients may show premature occlusion of the velar port.

One way to address these issues more directly is to conduct kinematic studies of articulator movement. Sussman, Marquardt, MacNeilage, and Hutchison (1988) have recently reported some important kinematic findings concerning labial coarticulation. The authors used EMG and strain-gauge monitoring systems to analyze the anticipatory labialization patterns of a group of Broca's aphasic subjects. It was found that for correct productions of CV, CCV, and VC CCV stimuli, Broca's aphasic subjects exhibited lip and jaw coarticulatory behavior similar to normal subjects. This finding replicated the acoustic data of Katz (1987, 1988a). In addition, a number of error-prone productions were observed, e.g., stuttered initial consonant segments, unusually slow and prolonged progression of the lip rounding gesture, and epenthetic vowels inserted into consonant clusters. The authors stressed that study of these error-prone productions are difficult, but that such analyses are necessary in order to fully understand how brain lesions interrupt normal motor speech processing.

With respect to velar coarticulation, a series of kinematic experiments have been completed by Itoh and colleagues. Itoh, Sasanuma, and Ushijima (1979) conducted a fibroscopic investigation of velar movements during speech by a Japanese-speaking apraxia of speech patient. The main findings were that this subject's general successional pattern of velar gestures was similar to those of normal subjects, although the apraxic subject showed much more variability. Anticipatory coarticulation was considered to be essentially intact, although some deviations from normal patterns were observed. Specifically, there were cases in which the verbal apraxic subject began coarticulatory velar lowering earlier than did normal subjects.

These findings were replicated in a subsequent study using an X-ray microbeam technique, which allowed simultaneous observation of several articulators (Itoh, Sasanuma, Hirose, Yoshioka, & Ushijima, 1980). It was found that temporal organization between the lip and velum of the apraxia of speech patient was generally intact, but was occasionally disturbed. The authors concluded that "motor programming for the temporal organization of different articulators becomes difficult in apraxia

² Note, however, that without actual airflow measurements of the oral and nasal cavities, it may be problematic to impute velar synchronization difficulties based upon acoustic amplitude shifts.

of speech under certain conditions resulting in inconsistent articulatory errors" (p. 73).

In the present experiment, we have sought to provide additional data regarding labial and nasal anticipatory coarticulation in the speech of anterior aphasic subjects. Using the recent technology of electromagnetic articulography, both labialization and nasalization were investigated, using stimuli produced in three places of articulation. High quality, synchronized acoustic data were also obtained in order to track the acoustic and perceptual correlates of anticipatory coarticulation. These acoustic data are described in a separate article (Katz, Machetanz, Orth, & Schönle, in press).

METHOD

There has been some recent controversy concerning methodology used to study anticipatory coarticulation in aphasia (Katz, 1988b; Sussman et al., 1988; Ziegler, 1989). Sussman et al. (1988) have discussed the fact that analyzing coarticulatory movement patterns of anterior aphasic speech may be problematic because these subjects' deviant output makes coarticulatory patterns difficult to determine. For example, the authors, describing their aphasic speaker database, state:

There were different kinds and degrees of articulatory behavior encountered that could be classified as deviant. Some caused only slight problems in the measurements, others required adjustments to the normal measurement procedures, and others precluded any measurements from being taken. (p. 375)

Having initially encountered problems similar to those described by Sussman et al. (1988), we would like to emphasize a number of methodological steps taken in the present research which assisted in the measurement of coarticulation, and provided greater generalizability across subjects. First of all, the use of a magnetometer system permitted precise, relatively noninvasive examination of articulator movement. Second, kinematic waveform-averaging techniques were employed in order to elucidate regularities across speakers' individual utterances. Third, RMS distance-averaging techniques allowed precise quantification of spatial variation within the speech of individual speakers. Finally, by defining coarticulation as the first point in time at which context-dependent, horizontal-, or vertical-direction differences arise for a given articulator, it was possible to obtain a definition of "gestural anticipation" useful for aphasia research.

Subjects

Subjects included two anterior aphasic and two normal, control speakers. All subjects were right-handed native speakers of German, from similar dialect regions. Aphasic subject classifications were based upon clinical exam and speech pathology assessment, including the Aachen Aphasia Exam (Huber, Weniger, Poeck, & Willmes, 1980).

Anterior aphasic subject EG was a 51-year-old female librarian, who had a stroke in 1982. CT scans showed a large lesion in the region of the left middle cerebral artery (Fig. 1). The lesion extended deep into white matter, but spared the angular gyrus and supra-marginal gyrus. The patient was initially classified as Global aphasic, but was subsequently classified as a Broca's aphasic.

Anterior aphasic subject AW was a 62-year-old engineer, who had a stroke in 1987. CT scans revealed a large ischemic insult of the left middle cerebral artery, extending deep

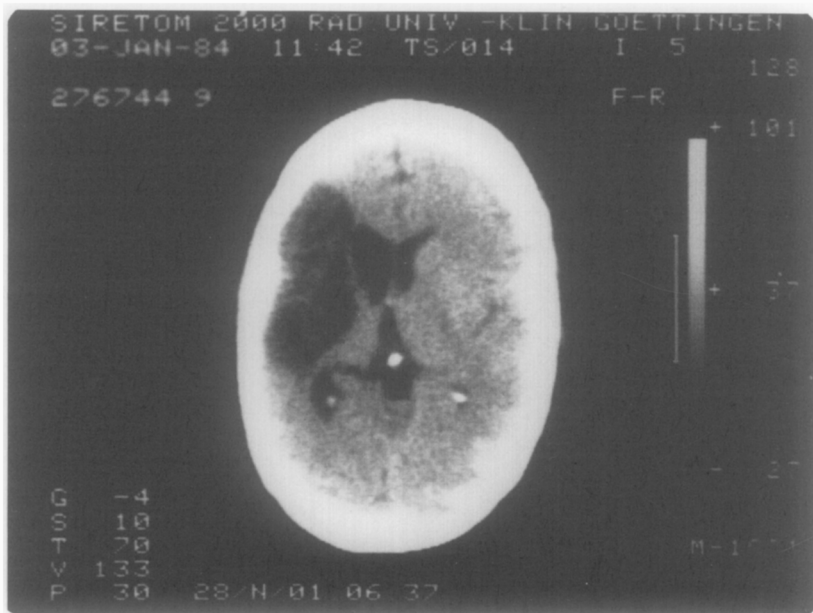


FIG. 1. CT scan of patient EG demonstrating an extensive lesion in the region of the left middle cerebral artery.

into the insula, but sparing subcortical structures (Fig. 2). Patient AW was classified as a Broca's aphasic.

The two control subjects were matched for the sex and the approximate age of each aphasic subject. 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 Göttingen Department of Clinical Neurophysiology (Schönle et al., 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). The UL and LL coils were placed on the midsagittal, exterior surface of each lip, at the most anterior point of the red margin. Velar coils were placed on the midsagittal, uvular surface of the velum, at a position equidistant between the uvular apex and base. Tongue coils were placed on the midsagittal, dorsal surface, approximately 1/3 the length of the tongue body from the tip. 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 (Table 1). There was a total of 10 stimulus items (4 labial, 6 nasal). The

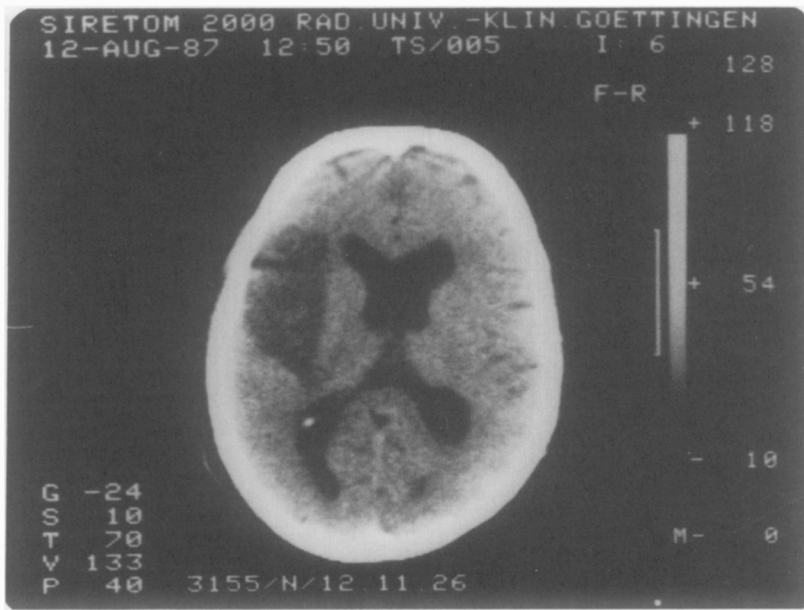


FIG. 2. CT scan of patient AW demonstrating a large lesion in the region of the left middle cerebral artery.

labial stimuli ([gəli:gə]/[gəly:gə]; [gəle:zə]/[gələ:zə]) consist of word pairs contrasting minimally in the rounding feature of the vowel following the consonant [l]. The nasal stimuli ([ti:gə]/[tingl]; [ti:də]/[ti:nə]; [ti:bə]/[ti:mə]) 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").

Each stimulus was repeated 15 times (in succession), with brief pauses between sentences. Intertrial intervals were cued by one of the researchers, and were approximately 3 sec in duration. Labial and nasal productions were obtained in two separate testing sessions, each of which lasted approximately 45 min. The order in which labial and nasal stimulus sets were presented was counterbalanced between the four subjects. Stimulus production within each testing session was fixed according to a uniform schedule.

Analysis

Subjects' productions were perceptually screened by the researchers, and speech errors were identified. 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 10 correct repetitions were selected for analysis.

Kinematic data were analyzed from graphic representations of articulator position and tangential velocity. A time-synchronized display showing two channels of articulatory movement and the acoustic waveform were displayed on a CRT. The direction of articulator movement could be determined from separate plots showing anteroposterior (x-axis) and

TABLE 1
STIMULI

Labial	Nasal
“Geliege” [gəli:gə] (gerund/lying down)	“Tiger” [ti:gə] (tiger)
“Gelüge” [gəly:gə] (ger./prevarication)	“Tingel” [tingl] (performance on a country stage)
“Gelese” [gələ:zə] (ger./reading)	“Tide” [ti:də] (tide)
“Gelöse” [gələ:zə] (ger./solving)	“Tine” [ti:nə] (woman’s name)
	“Tiber” [ti:bə] (Tiber river)
	“Thieme” [ti:mə] (company name)

vertical (y-axis) motion. By comparing the extent and direction of articulator movement during the production of speech segments contrasting in labialization (e.g., [gəli:gə]/[gəly:gə]) or in nasality (e.g., [ti:də]/[ti:nə]), it was possible to directly view anticipatory coarticulation effects.

In addition, quantitative records of speech timing were obtained using interactive software designed for speech movement analysis. This software allowed researchers to place cursors at specific points in the CRT display of speech kinematics, and automatically write time and displacement values at these positions to files for statistical analysis.

RESULTS AND CONCLUSIONS

I. Correct Productions

A. Labial Stimuli

i. Articulator displacement. Figure 3 shows, for each speaker, plots of lip movement for stimuli contrasting in labial rounding (i.e., [gələ:zə]/[gələ:zə] and [gəli:gə]/[gəly:gə]). Each panel shows articulator movement during the portion of the utterances beginning at the midpoint of the vowel [a:] in the word “sagte” and ending at the beginning of the diphthong [aⁱ] in the word “zweimal.” This portion was selected because it could be precisely located in the kinematic and acoustic displays, and because it contains the speech segments critical for analyzing anticipatory coarticulation. The kinematic plots shown in these figures are averaged over 10 correctly-produced stimuli. The uppermost graphs show move-

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 [gəly:gə] as compared with [gəli:gə].

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. This involved determining the average displacement for 10 repetitions, calculating the Euclidean (root mean square) distance between each individual repetition and the average, then dividing this sum by the number of points. This may be represented by the formula:

Root mean square

$$(\text{RMS}) \text{ displacement deviation} = \sqrt{1/n * \sum_{i=1}^n (a_i - b)^2}$$

where n = number of points

a_i = individual trial displacement values

b = average displacement values

A graph of these data is shown in Fig. 4, which displays item-to-item deviation for labialization gestures by the four speakers. Data for the x- and y-axes are displayed separately. The aphasic speakers showed greater overall variation than the control speakers, with particularly high variation for LL (and jaw) displacement. In order to quantify these data, two-way (Group \times Articulator [UL, LL]) analyses of variance (ANOVA) were conducted. The results showed a significant main effect for Group [$F(1, 748) = 187.4, p < .001$], and Articulator [$F(1, 748) = 6.67, p < .01$]. These data indicate that aphasic speakers are more variable than control speakers, and that LL (and jaw) shows greater displacement variability than UL.

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. Fig. 5 displays these data for labialized (left) and nasalized (right) stimuli.

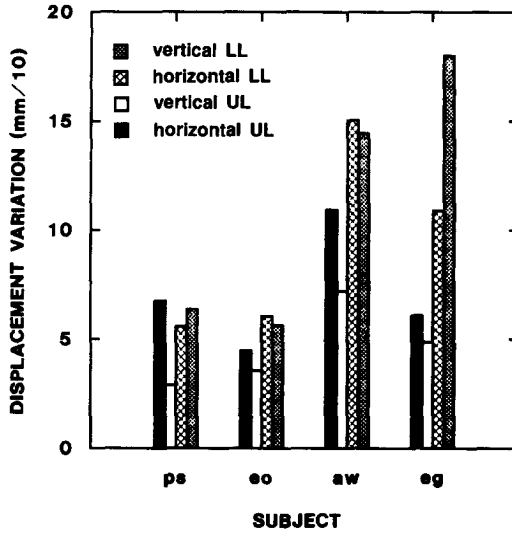


FIG. 4. Root mean square displacement variation for labial stimuli produced by normal (PS, EO) and aphasic (AW, EG) speakers.

Each panel shows the median and quartile distribution of durations for the portion of each utterance beginning with the midpoint of the [a:] in the word "sagte" and ending with the midpoint of the diphthong [a:] in the word "zweimal." Outlier data points (i.e., exceeding the interquartile range) are plotted with asterisks. These graphs show that the aphasic speakers produced slower speech, with greater variation in segment tim-

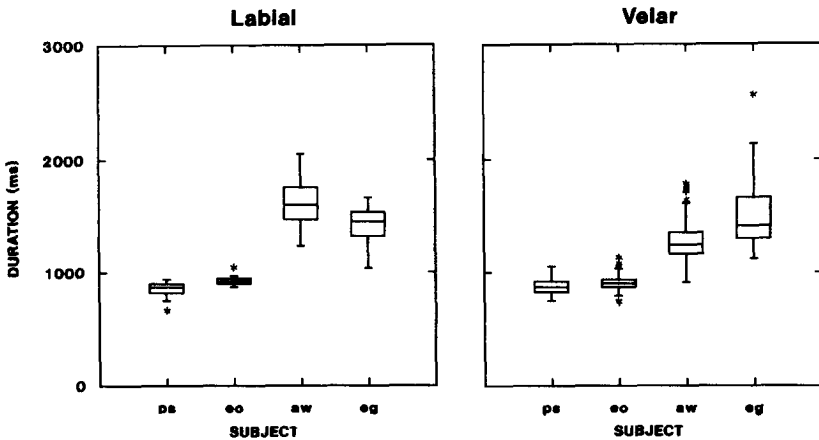


FIG. 5. Duration of normal (PS, EO) and aphasic (AW, EG) speakers' productions. Each plot shows the median and quartile distribution for utterance durations beginning with the [a:] of "sagte" and ending with the [a:] of "zweimal." Values exceeding the interquartile range are represented with asterisks.

ing, than is found in the speech of normal, control subjects. In addition to these overall durational characteristics, 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). These findings are in accord with previous descriptions of verbal apraxic speech (Kent & Rosenbek, 1982, 1983; Rosenbek, Kent, & LaPointe, 1984; Ziegler & von Cramon, 1986a).

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. That is, it was asked at which point in the speech waveform could anticipatory movement adjustments pertaining to labialization first be determined. Examples of these kinematic/acoustic correspondences may be observed in Fig. 6, which plots sample lip movement, speech

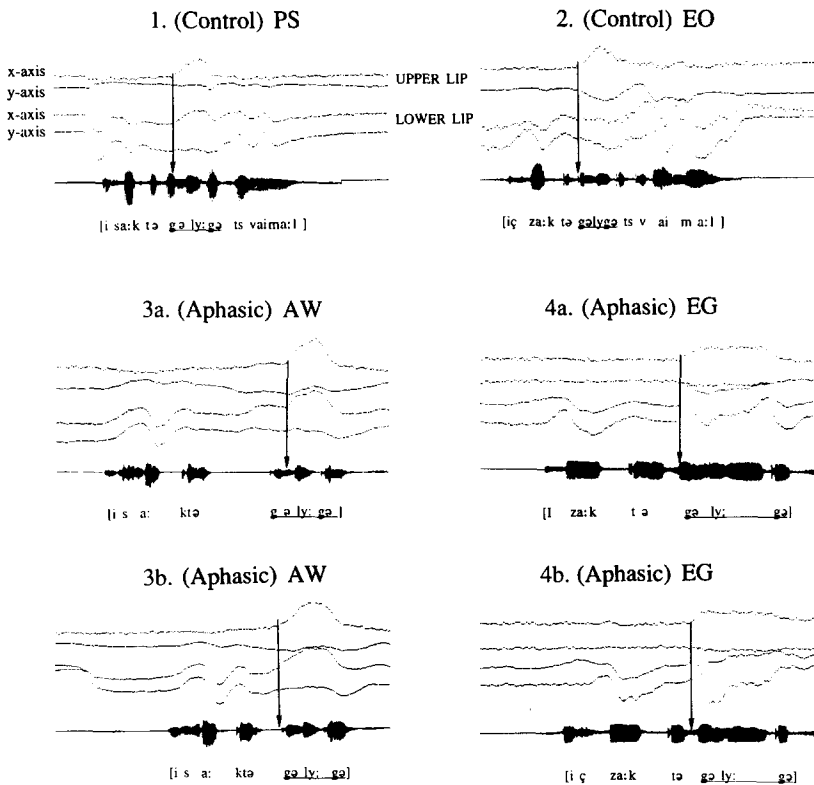


FIG. 6. Examples of kinematic and acoustic data for speakers' labial stimuli productions. Shown are horizontal (x-axis) and vertical (y-axis) movement plots for UL and LL during production of sentences containing the target word [gəly:gə] (underlined). Each panel plots 2.56 sec of speech.

waveforms, and phonetic transcriptions for sentence portions containing [gəly:gə] produced by the four speakers.

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 [gə], 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. Examples of these differences may be seen in Fig. 6. Control speaker PS consistently began protrusion at a point in time corresponding with the end of the burst of [g], and the beginning of voicing for [ə]. Control speaker EO began slightly earlier, at a point approximately 10 msec before the beginning of the burst for [g]. Aphasic speaker AW showed more variable patterns. In five repetitions, this subject began anticipatory labialization at approximately the same point in the speech waveform as the control subjects, i.e., within the first third of the segment corresponding to the vowel [ə] of [gə]. An example of this pattern is shown in panel 3a. However, in the other five repetitions analyzed, rounding was begun slightly earlier than in the speech of the control subjects. In these repetitions, an example of which is shown in panel 3b, AW began rounding anywhere from 40 msec preceding the burst up until the exact onset of the burst. Aphasic subject EG produced speech with an UL movement onset point resembling that of control subject EO, i.e., at the very beginning of the burst (panel 4a). Yet, in one repetition rounding was initiated approximately 40 msec before the burst for [g] (panel 4b). As with the data for control subjects, the timing of coarticulatory onset for the LL coil showed local patterns closely associated in time with the onset positions of the UL coil.

In summary, these data suggest that anterior aphasic subjects initiated coarticulatory labialization at approximately the same point in time as normal, control subjects. Aphasic subjects showed more variation in their onset positions, although this did 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. Examples of velar movement patterns, averaged across 10 repetitions, are given in Fig. 7. In this figure, the alveolar consonant stimulus pairs [ti:də]/[ti:nə] are shown. The patterns noted for these stimuli were found to be similar to stimuli differing in consonant place-of-articulation (i.e., [ti:bə]/[ti:mə] and [ti:gə]/[tingl]).

The two control speakers showed no movement of the velum during

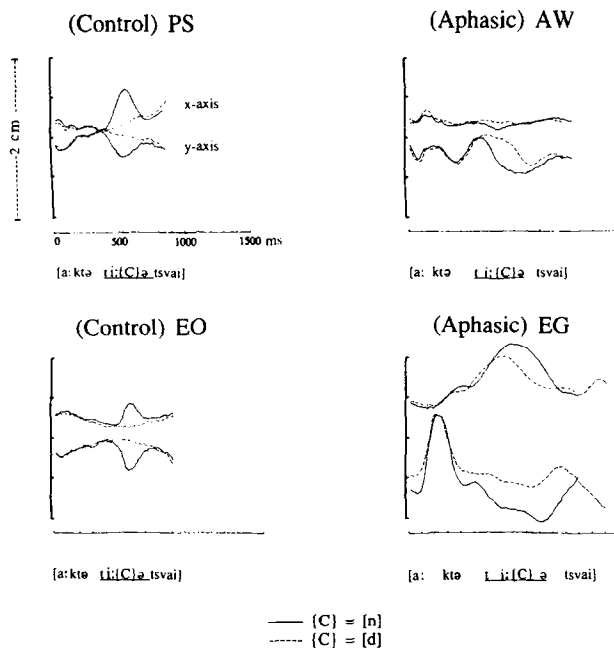


FIG. 7. Averaged articulator displacement for velar stimuli produced by normal and aphasic speakers. Each panel plots horizontal (x-axis) and vertical (y-axis) movement for 10 repetitions of stimuli containing the stimulus words [ti:nə] and [ti:də].

production of the non-nasalized stimulus [ti:də], whereas robust velar port opening (i.e., velar extension and lowering) was observed for productions of the nasalized stimulus [ti:nə]. In contrast, the aphasic speakers showed quite different movement patterns. Examination of whole sentence data for speaker AW showed that this subject tended to lower his velum towards the end of words, then abruptly raise the velum to achieve a closed velar port just prior to the beginning of a new word or syllable. In his production of the non-nasalized stimulus [ti:də], there was no velar lowering during the syllable [ti:], indicating a correct closure of the velar port for non-nasalized, stop consonants (as found for control subjects). There was, however, an unusual drop in velar height with the production of the second syllable [də]. Superimposed upon this general movement pattern, AW nevertheless appeared to produce appropriate velar opening gestures for the nasalized stimulus [ti:nə]. During nasalized productions, there was a rapid lowering of the velum occurring at approximately the burst for [t], followed by a gradual rise in velar height for the production of the subsequent word ("zweimal"). This velar lowering had a more rapid trajectory than its non-nasalized counterpart. Little anteroposterior motion was recorded for the velum of this subject.

Aphasic subject EG showed a similar overall movement pattern as subject AW, however EG showed even greater degrees of impairment. Examination of whole sentence patterns revealed a tendency for inappropriate velar lowering. Whereas in the data of AW this was noticeable toward the end of words and syllables, in the speech of EG velar lowering began shortly after the beginning of each new segment. Similar to AW, EG produced rapid, abrupt velar closing gestures before new words and syllables. For example, during production of the non-nasalized stimulus [ti:də], there was inappropriate velar fronting, and slight velar lowering. Nevertheless, EG's velar movement for the nasalized stimulus [ti:nə] were in a direction appropriate for nasalization. As with the data of AW, the velum began a more rapid descent for [ti:nə] than for [ti:də], and showed greater anterior displacement. This context-dependent difference appeared at approximately the start of the burst for [t].

As with the labialization stimuli, variation in velum displacement was quantified by calculating the RMS distance between individual and averaged displacement waveforms. The results are shown in Fig. 8, which plots, for each speaker, tongue and velum displacement variation. It was found that the 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. In order to quantify these data, two-way, Group \times Articulator (tongue, velum) analyses of variance (ANOVA) were conducted. The results showed a significant main effect for Group [$F(1, 1368) = 480.7, p < .001$], and

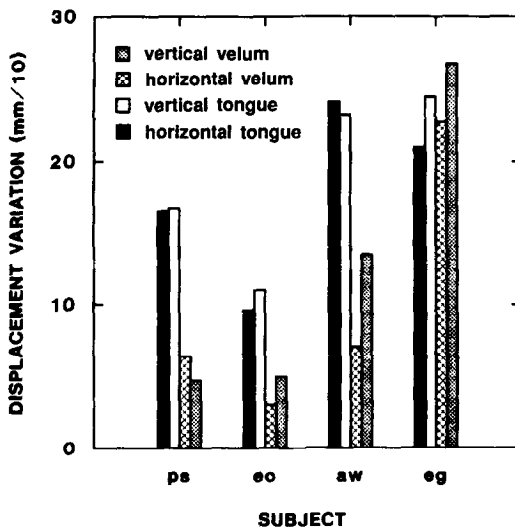


FIG. 8. Root mean square displacement variation for velar stimuli produced by normal (PS, EO) and aphasic (AW, EG) speakers.

Articulator [$F(1, 1368) = 137.2, p < .001$]. There was also a significant Group \times Articulator interaction [$F(1, 1362) = 10.1, p < .002$], reflecting the fact that control speakers produced significantly more lingual than velar variation, whereas this was not the case for the aphasic speakers. In particular, aphasic subject EG 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. Examples of speakers' kinematic and acoustic data for sentence portions containing the word [ti:nə] are given in Fig. 9. Each panel displays data for a subject's single production, showing tongue and velum displacement, the acoustic waveform, and a phonetic transcription. 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 msec 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.

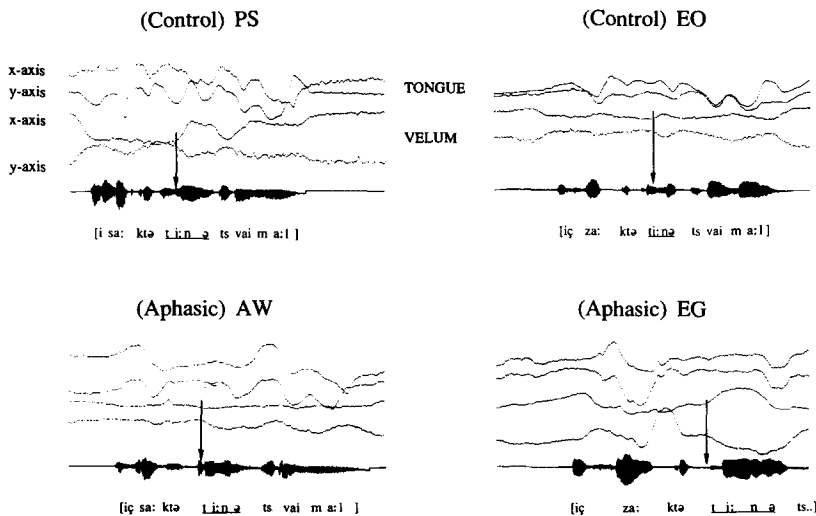


FIG. 9. Examples of kinematic and acoustic data for speakers' single labial stimuli productions. Shown are horizontal (x-axis) and vertical (y-axis) movement plots for the tongue tip and velum during production of sentences containing the target word [ti:nə] (underlined). Each panel plots 2.56 sec of speech.

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 to be relatively preserved.

II. Error-Prone Productions

An investigation was made of 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 & von Cramon, 1985). There were, however, very few speech errors in the database containing the target structures of interest.

Speaker AW (who exhibited a lesser degree of speech difficulty than EG) produced 3 errors, while EG produced 19 errors. Of the 22 total errors recorded, the majority involved intraword or intrasyllable hesitations, along with occasional consonant or vowel distortion errors (e.g., excessive consonant aspiration, inappropriate vowel nasalization). There were six cases involving perceptually apparent substitutions. Of these, three involved segments of interest. These consisted of instances in which subject EG produced substitutions of "[ti:də]" for [ti:nə] targets. For these cases, there were found to be [d] stop consonant bursts in the acoustic waveforms. The kinematic data 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. Taken together, 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.

DISCUSSION

In this study, an investigation was made of the extent and time course of local speech events produced by normal and anterior aphasic subjects. Although the data must be considered preliminary because there were only two aphasic and two control subjects investigated, the findings nevertheless address a number of important issues concerning the neurological bases of speech production.

To briefly summarize the results, it was found 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 found chiefly for spatial displacement characteristics, while the temporal aspects of articulator movement necessary for

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 chief question 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 msec have been proposed as a possible speech characteristic of German (Ziegler & von Cramon, 1985) and English-speaking (Tuller & Story, 1987) anterior aphasic subjects. In contrast, Katz (1987, 1988a) 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 findings of Katz (1987, 1988a), in that anterior aphasic subjects were found to produce coarticulatory gestures as early as (or earlier than) matched control speakers.

A possible explanation for previous findings of *perceptually* apparent delays in coarticulation might concern the fact that anterior aphasic speech has been shown to be impoverished in a number of ways (e.g., marked by excessive aspiration of consonants, mistimed VOT, and highly variable vowel formant frequencies). It is possible that speech having such deficiencies could tax the perceptual systems of listeners to the point where rounding information is obscured. In other words, there may be a threshold effect, where the same amount of rounding cues present in the speech of a normal speaker would not be recognizable in the speech of an anterior aphasic speaker. Such an explanation would also be compatible with the data of Katz (1987, 1988a), who showed that American English-speaking, anterior aphasic subjects' *acoustic* cues pertaining to rounding were indistinguishable from those of normal controls, whereas normal listeners showed significantly poorer *perception* of coarticulatory information when presented with the speech of the aphasic (as compared to control) speakers. With respect to anticipatory velar movement, the present study addresses the question of whether discoordination in velar movement might correspond to coarticulatory impairments (e.g., Mlcoch & Noll, 1980) and whether such discoordination might also account for perceptually apparent "substitution" errors in the speech of anterior aphasic subjects (Itoh et al., 1979, 1980; Ziegler & von Cramon, 1986b). Concerning anticipatory impairments, 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 data 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).

To the extent that the present data indicate little coarticulatory deficit in adult patients having substantial damage to anterior brain structures, the data suggest that speech sound transition capabilities are either not subserved by these adult brain structures, or that these capabilities somehow remain intact in the face of this damage. 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 these regions (e.g., Broca's region) as general "speech programming" centers may require substantial revision.

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