MOTOR UNIT DISCHARGE PATTERNS DURING SPEECH: TEMPORAL REORGANIZATION DUE TO COARTICULATORY AND PROSODIC EVENTS

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The functional unit of muscle contraction, and hence movement control, is the motor unit. A motor unit consists of an alpha motoneuron, located, in the case of speech muscles, within a motoneuron pool in the brainstem, and the single muscle fibers innervated by the axonal branches of that motoneuron. For the past few years my colleagues and I have been interested in describing how motor unit discharge properties change to meet the demands of rapid tension development characteristic of speech production. Observation of motor unit discharge activity represents the closest look at the encoding operations of the central nervous system as the peripherally recorded muscle action potentials (MAPs) of motor units (MUs) stand in a 1:1 relationship to discharges of centrally located alpha motoneurons.

Data will be restricted to MU events within the anterior belly of digastric (ABD), a muscle involved in lowering the jaw during speech. Specially constructed intramuscular wire electrodes, designed to facilitate recording at high force levels, were used in all studies. All measurements were performed on a digitized oscilloscopic display (maximum resolution = 0.1 msec) utilizing computer software routines written for temporal and statistical analyses of motor unit/articulator events during ongoing speech (complete details of recording and measurement procedures can be obtained from Sussman et al, 1977).

Recruitment Order

A current view explaining activation of individual MUs is the Size Principle (Henneman et al, 1965). Briefly stated, the

Size Principle holds that MUs are activated according to motoneuron size, with the smallest neurons (having the lowest excitability thresholds) discharging first, followed by successively larger motoneurons. Evidence supporting this view has been extensively gathered, but primarily from animal experimentation. Recruitment order of MUs active during human isotonic movements, such as speech, have not received much attention to date. Our data overwhelmingly supports the Size Principle. Recruitment order of ABD MUs was observed to be fixed and based on size (as determined by peak-to-peak amplitudes of MAPs). The consistency of MU activation for jaw lowering represents an invariant aspect of the encoding program for speech.

Data on recruitment order can also be related to various aspects of articulatory dynamics. Both jaw displacement and velocity were found to be positively related to the number of MUs active (Sussman et al, 1977). In addition, the initial interspike interval (ISI) of the third recruited MU has consistently been shown to be linearly related to both jaw displacement and velocity. During jaw lowering for the initial vowel in /aepae/ tokens, it was found that jaw displacement and velocity increased as the initial ISI decreased. Correlation coefficients ranged from -.44 to -.67 and were significant beyond the $p < .05$ level for all utterances examined. The relationship between discharge rate of a MU and some aspect of articulatory dynamics was only found for the larger and later recruited MUs (specifically the third MU recruited). The smaller first and second MUs recruited did not exhibit a straightforward relationship between its initial firing rate and jaw movement. Since the larger and later recruited MUs add a proportionately larger contribution to overall tension development (i.e. larger MUs have higher twitch tension levels) compared to initially active, smaller MUs, it is not surprising to notice movement variables being influenced by discharge characteristics of the larger MUs only.

Temporal Reorganization: Coarticulatory Influences

The temporal interval separating activation of the first recruited MU and the initiation of jaw lowering for an open vowel such as /ae/ can be a valuable dependent variable in providing a glimpse at the time program applied to the events of speech motor control. Such an analysis was made for 64 utterances of /aepae/ with separate measurements taken for initial vowel lowering and final vowel lowering. The results are schematically illustrated in Figure 1. For all utterances the first discharge of the first recruited MU occurred approximately 40 msec after the jaw began to lower for V1, and approximately 28 msec prior to jaw lowering for V2 opening gestures. These consistent differences (across three subjects) can be related to the differences in peripheral biomechanics existing at the moment of jaw lowering for the initial preconsonantal vowel versus the final postconsonantal vowel. It is well known that the jaw exhibits anticipatory coarticulation for an open vowel in final position of VCV tokens (Sussman et al, 1973) Thus, the jaw is lowering for the postconsonantal vowel from a position that is considerably lower than the jaw position preceding the initial preconsonantal vowel. Abbs and Eilenberg (1976) have shown that the mechanical advantage of ABD in exerting a lowering force on the mandible decreases the more the jaw is lowered. This reduction of mechanical advantage represents a diminution of the effective muscle force of ADB to bring about additional lowering for the postconsonantal vowel /ae/. The earlier activation of the initially recruited MU for the final postconsonantal vowel as compared to the initial preconsonantal vowel may reflect a temporal adjustment of the motor time program needed to partially offset the less favorable mechanical advantage of the jaw during this time. It is consistent with this hypothesis that there was a highly significant positive correlation ($r = .74$, $p < .01$) between jaw position during the medial consonant and temporal onset of MU I. Thus, the lower the jaw immediately prior to subsequent lowering for the postconsonantal vowel, the earlier did MU I activity begin for jaw lowering for V2. This example provides the first illustration of temporal reorganization, on the cellular level, to a behavioral and biomechanical aspect of the encoding program for speech.

Temporal Reorganization: Stress

Previous studies investigating articulatory reorganization due to stress have shown that higher levels of integrated EMG signals, higher rates of articulator movement, and closer approximations of intended target positions accompany high stress conditions. Until recently, there have been no descriptions of temporal change in motor unit discharge patterns due to the prosodic application of syllable stress.

A subject repeated /aepae/ twenty times with equal "moderate" stress on each syllable and twenty times with heavy stress on the second syllable. The first three recruited MUs were examined for both stress conditions. Figure 2 shows recruitment latencies separating the initial discharges of the first three recruited MUs in conjunction with the temporal onset of jaw lowering for the second syllable for both /aepae/ and /aepǽe/ tokens. A temporal starting point, $t = 0$, was taken to be the onset of MU I's initial spike. For stressed utterances there was a consistent shortening of the intervals separating successively recruited MUs and a shorter latency between MU I's initial discharge

and the moment of jaw lowering for /ae/. Table 1 gives data characterizing the temporal reorganization pattern in terms of means (in msec), standard deviations, and variability coefficients ($SD/\bar{X}$). Not only was the time program advanced for the stressed condition, but, in addition, there was a marked reduction in variability. The percent reduction in variability, calculated by comparing the unstressed and stressed variability coefficients, revealed a 60% reduction for the MU I - MU II interval, a 82% reduction for the MU I - MU III interval, and a 62% reduction for the MU I - jaw lowering interval.

Other changes in discharge characteristics accompanying stress were an increase in mean firing rate (impulses/sec) for each MU and a decrease in the mean initial interspike interval. This later parameter is indicative of a higher instantaneous discharge rate (1/initial ISI) for the stressed syllables. In addition to the higher instantaneous discharge rates for all three MUs, there was also a marked reduction in the variability of the initial ISI, with a progressively larger percent decrease in variability coefficients with recruitment order -- 21% reduction for MU I, 30% for MU II, and 42% for MU III. Thus, there was a "tighter" control over the onset times for the larger and later recruited MU.

These preliminary findings showing a sharp reduction in the variability of recruitment intervals (e.g. MU I-MU II), activation intervals (MU I-jaw lowering), and initial interspike intervals, add a new dimension to our understanding of articulatory movements underlying syllable stress. In addition to the connotations that go along with the familiar Öhman notion of "an instantaneous addition of a quantum of physiological energy" (Öhman, 1967, p. 33) for stressed productions, the encoding program for speech, as observed in our data, suggests a more precise control of the timing of cellular events, as well as a more forceful execution of the peripheral dynamics.

Motor unit events and their systematic changes during various conditions of ongoing speech can be sensitive indicants of higher level linguistic conditions. Alterations in the temporal program underlying muscle and hence articulator activation can be observed at the level of the alphamotoneuron (at least indirectly that is).

References

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Table I: Means (in msec), standard deviations, and variability coefficients (SD/$\bar{X}$) for various temporal intervals characterizing motor unit/articulatory events during unstressed and stressed tokens.

		MU I→MU II	MU I→MU III	MU I→Jaw Lowering
	$\bar{X}$	31.9	40.9	53.8
Unstressed	SD	23.2	41.3	53.3
	VC	.7273	1.0098	.9907
	$\bar{X}$	23.7	26.6	33.4
Stressed	SD	6.8	4.9	12.8
	VC	.2869	.1842	.3832

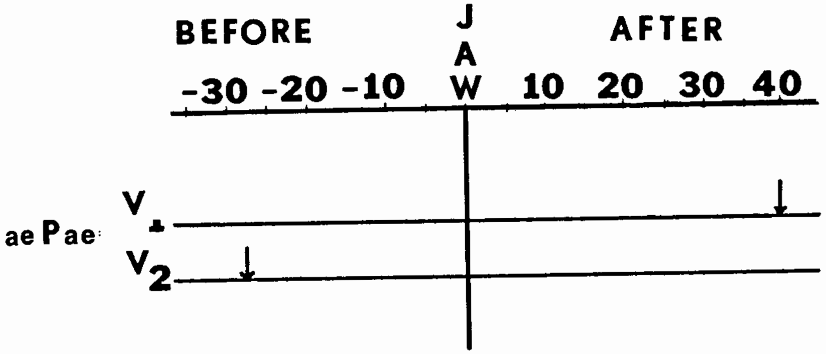

Figure 1: Temporal onset (msec) of initial discharge of the first recruited motor unit with respect to jaw lowering for initial (V1) and final (V2) vowel.

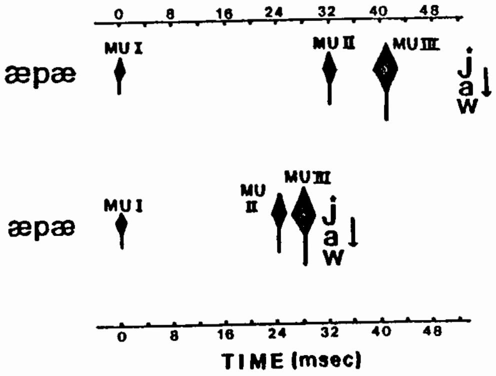

Figure 2: Recruitment latencies separating initial discharges of three recruited motor units during normal and stressed [æpæ]. Asterisks show onset of jaw lowering for open vowel of second syllable.