SPEECH MOTOR EQUIVALENCE: THE NEED FOR A MULTI-LEVEL CONTROL MODEL

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In the last ten years it has become increasingly difficult to view the neuromotor execution of speech as a series of descending motor commands, reflecting, in some direct manner, an underlying matrix of phonetic features. Rather, it appears that patterns of speech muscle activity may depend upon moment-to-moment peripheral conditions and adaptive modification of descending commands at several nervous system levels. In the present paper I would like to outline some current thoughts with regard to these speech motor processes, including some data from our laboratory and a preliminary model to account for recent observations.

If one considers speech motor control teleologically, the adaptive modification and adjustment of descending speech motor commands, based upon peripheral feedback, is quite appealing. For example, the orofacial system obviously serves the multiple functions of chewing, swallowing, and breathing, in addition to speech. Other less natural intrusions include cigarettes between the lips, chewing tobacco, a pipe between the teeth, etc. Because many of these activities can be performed simultaneously, without major interference or conscious compensation, a nervous system capability for on-line adaptive adjustment appears almost necessary. Such semi-automatic adaptation also seems likely in laryngeal and respiratory control as well. Recent physiological investigations of the laryngeal and respiratory systems, as well as consideration of their anatomy, indicate the profound influence that torso, head, and arm movements have upon the specific muscle contractions required for speech. Trained singers are quite aware of these influences. However, for many speaking situations, we have little difficulty sustaining continuous and intelligible speech concurrently with vigorous body movements. Observing a physical fitness teacher perform calisthenics and at the same time continuously cohort his or her pupils is an obvious example of this phenomenon. A preferable observation might be a cheerleader at a U.S. football game. In these and other similar cases, e.g., a vigorous university lecturer (an example suggested by Peter MacNeilage), one is impressed with our ability to produce continuous speech without major interference. Possibly these multiple concurrent motor programs could be generated and pre-adjusted in parallel, but such an organization seems contradictory to the obvious availability of multiple afferent monitoring channels, documented differences in their nervous system origins, the principle of economy, and current information on normal and abnormal speech motor control.

In part these observations can be explained by the provocative model offered by MacNeilage (1970). He suggested that speech motor commands are adjusted to assure that individual articulators reach semi-invariant target positions, despite a substantial degree of variability in their starting positions. This kind of compensatory capability was referred to by Hebb (1949) as motor equivalence, although Hebb's definition was not quite so restrictive. Since MacNeilage's original paper, experimental observations have extended our appreciation of the adjustment capabilities operating in the speech motor control system. These recent observations appear to require an expansion of MacNeilage's insightful model and support the operation of motor equivalence in its most encompassing terms.

Indirect Experimental Evidence

The hypothesized operation of motor equivalence adjustments to descending speech motor commands implies a repetition-to-repetition flexibility in the way that a particular speech utterance is generated. Recent investigations support the operation of such flexibility both with regard to trade-offs between individual articulators and between individual synergistic muscles acting to move the same articulator. For example, it has been shown that the upper lip, lower lip, and jaw trade off reciprocally in their cooperative contributions to oral opening, viz., when the jaw had relatively large displacements the upper and lower lips had relatively small displacements, and conversely (Abbs and Netsell, 1973; Hughes and Abbs, 1976; Watkin and Fromm, 1978). Other investigators (Hasegawa et al., 1976) have reported lip and jaw reciprocity not only in regard to displacement, but for lip and jaw velocities as well. The trade-offs reported in these studies were observed for multiple repetitions of the same utterance where the net contributions of the individual movements (i.e., total oral opening or net velocity of closing) was relatively consistent. Comparable analyses of speech lung volume control illustrate a similar pattern of reciprocal trade-off between movements of the abdomen and thorax in producing subglottal air pressures (Hixon et al., 1973). In our laboratory we have found other patterns of articulatory trade-off, including reciprocal interactions between the tongue and jaw (Chuang and Abbs, In Progress).[1]

Not only do individual articulators appear to vary in their repetition-to-repetition contributions to a particular vocal tract objective, individual muscles appear to vary reciprocally in their combined contributions to an individual articulatory movement as well. In a recent experiment (Abbs and Kennedy, In Preparation), we found a reciprocal trade-off between the mentalis (MTL) and orbicularis oris inferior (OOI) muscles during repeated speech-related movements of the lower lip. This is in repetitions where the magnitude of MTL-EMG was relatively small, the magnitude of OOI-EMG was relatively large, and conversely. The flexibility of these adaptive speech motor command adjustments can be illustrated by considering this finding in relation to an earlier report by Sussman et al. (1973) of a parallel reciprocal trade-off between MTL-EMG magnitude and jaw lowering.

Overall these observations suggest that there may be several levels of programming and adjustment in the motor generation of speech. At some level, possibly corresponding to the phonetic feature input to the speech control system, overall vocal tract goals must be specified. However, due to the contrast between (1) the relative consistency with which these overall vocal tract goals are achieved, and (2) the variability of individual articulatory movements and muscle activity patterns, it would appear that these different output parameters are not programmed at the same levels of the nervous system.

Some Direct Evidence

The major issues with regard to this hypothesized motor control process concern the levels of the nervous system at which the adjustments might occur and the extent to which afferent feedback plays an important role. In attempts to more directly address these issues, several investigators have introduced unanticipated disturbances to the lips and jaw during ongoing speech (Bauer, 1974; Folkins and Abbs, 1975; 1976; Kennedy, 1977; Murphy and Abbs, In Progress). In these studies it was reasoned that if the nervous system sites where adaptive adjustments occurred were at "lower levels", semi-automatic, short-latency compensations would prevent unanticipated disturbances from interfering with ongoing speech. In the 15 subjects run with this particular paradigm, there have been no cases of disruption to ongoing articulation. In those studies where the latency of the compensations was discernible, it ranged from 25-50 msec. Compensatory responses have been observed in the muscles of the articulator to which the load was applied as well as in other articulators contributing to the same vocal tract goal, i.e., loads applied to the jaw yielded compensations in both the upper lip and lower lip musculature. The diffuse yet functional nature of these multiple compensatory responses corroborates the earlier suggestion that individual articulators and individual muscles can be adjusted flexibly to achieve desired overall vocal tract objectives. Based upon these findings, it appears that lower levels of the nervous system may be plausible sites for the adaptive modification of descending motor commands. Lower level sites for these adjustments are supported also by the observation that while the subjects in these studies perceived the articulator loading, they were unaware of generating the compensatory adjustments.[2]

A recent finding that might point to the possible origin of these compensatory adjustments is the observation that individuals with cerebellar disease and ataxic dysarthria are unable, without practice and conscious intervention, to adjust their lip movements to overcome experimental stabilization of the jaw (Netsell et al., In Preparation). Indeed, these patients report that many of their speech movements must be "consciously controlled". Certainly, if one accepts Eccles' (1973) suggestion, the cerebellum, with its multiple afferent and efferent connections, would be a primary candidate for yielding the semi-automatic, unconscious adjustments apparently required for normal speech. Other yet lower level sites

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(1) These patterns are most apparent in phonetically naive speakers. "Trained phoneticians" appear to produce speech, especially with regard to these reciprocal articulatory movements, quite different from that of normal speakers (cf. Gay, 1976).

(2) In our experience, the major difficulty in these unanticipated disturbance studies is discerning the peripheral manifestations of the disturbance. That is, while ongoing speech is seldom disrupted, the compensatory degrees of freedom are so great that one cannot always ascertain which muscles or movements were involved. This problem has apparently impeded some investigations using aerodynamic disturbances (Perkell, 1976).

might include areas in the brain stem where single point electrical stimulation yields very complex and semi-coordinated gestures of the laryngeal, masticatory, lingual, and facial musculature (Luschei, Personal Communication).

A Preliminary Model

Figure 1 is a schematic attempt to represent the motor control processes warranted from the data cited above.

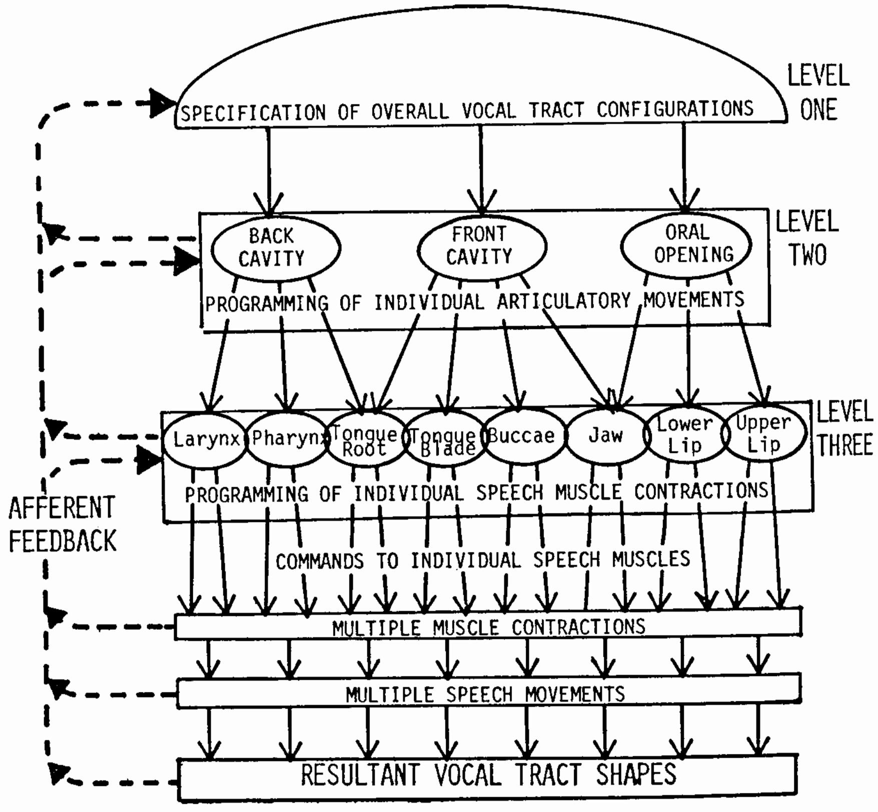

Figure 1

A multi-level model of the speech motor programming process. Solid lines represent descending control signals and dashed lines afferent feedback information. Dashed lines between levels of programming represent the ascending components of internal feedback pathways.

This model posits three levels of speech motor programming. At the highest level, overall vocal tract goals are specified, perhaps corresponding to some matrix of phonetic features. At the least, these goals represent the temporal-spatial configurations necessary for appropriate modulation of aerodynamic and acoustic signals. The second level of programming is involved in determining the particular set of individual movements that are to be employed in achieving the desired vocal tract goals. The third and final level of programming is concerned with specifying the individual muscle contraction patterns necessary to the generation of individual articulatory movements. These two lower levels of programming are based upon the observations (cited earlier) that (1) individual articulatory movements are not invariant with regard to particular vocal tract goals, i.e., repetitions of the same speech element, even if acoustically and perceptually similar, are produced often by different combinations of articulatory movements, and (2) individual muscle contractions are not invariant with regard to particular articulatory movements, i.e., repetitions of an articulatory movement are produced by different combinations of individual muscle contractions. As shown in Figure 1, it is posited also that the programming/adjustment of descending motor commands is accomplished with the aid of afferent feedback. This feature of the model is based upon the observations of compensatory responses to unanticipated articulator loading. That is, while it is plausible to consider parallel pre-adjustment of multiple motor commands (through some sort of efferent copy), in response to steady-state, anticipated disturbances (Lindblom et al., In Press), rapid adjustments to dynamic, unanticipated loads appear to require an afferent feedback control capability.

It is apparent from this representation that the model previously offered by MacNeilage does not account for all the motor command adjustments that apparently are accomplished by the speech motor execution system. That is, the adjustments to descending motor commands, at least as evidenced by the data cited above, obviously involve more than compensations for variations in individual articulator starting positions. Indeed, it appears that the primary controlled output parameters of the speech production system are not individual articulatory movements, but a series of overall vocal tract configurations. This model has other implications as well. For example, analyses of individual articulatory movements or muscle contractions in relation to underlying phonetic features appear to be based upon the assumption that there is but a single level of speech motor programming. However, with multiple levels of adjustment, there is some question as to whether individual muscle contractions or articulatory movements are related, except in a probabilistic manner, to overall vocal tract phonetic features. If such a direct relationship exists, it may be necessary to hypothesize different features or to reallocate the current features, at least in part, to lower levels of the nervous system.

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