

## Chapter 4

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# Multilevel Control Model for Speech Motor Activity

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It has been suggested that a current limitation in our understanding of the mechanisms of motor control is the limited knowledge regarding the structure of the central nervous system as a multivariable controller (Ito, 1982). In attempting to understand the control of speech movements and the aberrations associated with speech movement disorders, the problem is compounded because the multiple movements of this motor act are subordinate to an overall communication goal. This is illustrated by the presence of motor equivalence in which speech motor actions are implemented in a complex, but systematically variable manner (cf. Abbs, 1986; Gracco & Abbs, in press, b; Hughes & Abbs, 1976; MacNeilage, 1970). In response to the apparent variability in the movements and muscle activities associated with speech production, experimental effort has been directed toward the identification of invariant relations in the speech production process. The search for invariance is based on the assumption that stereotypic or invariant motor actions reduce the control complexity of a motor task. While the search for movement invariance has provided some general insight into motor control considerations, many issues remain unresolved (cf. Perkell, 1986; Stein, 1982 for reviews).

A major factor often overlooked in the search for and identification of invariant or simplifying relations is the mechanisms by which such relations are mediated. For example, one hypothesized invariant relation for limb and speech movements involves the scaling of a base velocity profile which accounts for the kinematic changes associated with movements of different amplitudes and durations (Atkeson & Hollerbach, 1985; Munhall, Ostry & Parush, 1985; Ostry & Cooke, in press). One consequence of focused

attempts to uncover underlying control principles reflected in invariant relations has been in the limited consideration of sensory information in the motor control process. It is often overlooked that scalar adjustments could not be accomplished without sensory information regarding the relative position of the structures prior to movement as well as an estimation of the distance to be moved.

In this chapter, it will be suggested that sensory information is used in multiple ways during the planning, programming, and execution of speech movements. Without considering the influence of sensory information and the underlying dynamic process, invariance may be relegated to an interesting observation. Variance, on the other hand, provides information on the underlying task-specific goals as well as insight into the mechanism underlying hypothesized invariant relations. Perhaps more can be gained in our understanding of the speech motor process if we attempt to account for the sources of variability as well as continue the search for invariant articulatory relations. In the next section, a perspective will be presented which briefly considers the importance of sensory information in the control of speech movements. More detailed considerations have been presented elsewhere (Borden, 1979; Gracco, 1984; Gracco & Abbs, *in press*, a).

#### THE IMPORTANCE OF SENSORS

The ability of an organism to carry out certain motor tasks with reduced or absent sensory information has been used to argue against the role of sensors in the guidance of movement (Fentress, 1973; Polit & Bizzi, 1979; Taub & Berman, 1968). However, as has been shown repeatedly, movements carried out in such states are often only grossly normal and require rather simple or stereotypic tasks (Bossom, 1974; Polit & Bizzi, 1979; Rothwell, Traub, Day, Obeso, Thomas & Marsden, 1982; Sanes & Evarts, 1983).

For the control of speech movements, it has been shown that sensorimotor mechanisms have the requisite characteristics to be used in the control and coordination of speech (Abbs & Gracco, 1984; Folkins & Abbs, 1975; Gracco & Abbs, 1985; Kelso, Tuller, Bateson, & Fowler, 1984; Shaiman, Abbs & Gracco, 1985). These studies have demonstrated that the motor control processes underlying speech production are afferent-dependent, task specific, functionally organized, and can operate at short latencies. Further, given the multiple paths through which different sensory modalities may access motor centers, it is doubtful that all sensory information is ever really eliminated. Even for highly patterned and automatic behaviors such as locomotion, sensory information has been shown to interact with neural pattern generators providing the necessary adjustments in motor output to accommodate moment-to-moment environmental (terrain) changes (cf. Grillner, 1981; Grillner & Wallen, 1985). The important finding from sensory reduction or deafferentation studies is that motor tasks can, and probably do, rely on some internal (stored) motor relations; however, normal motor actions are never carried out in the absence of continuous sensory information.

In addition to the experimental results summarized above, the importance of sensory information in the control of speech movements is suggested by anatomic considerations related to orofacial sensory receptor density and expanded thalamic and cortical orofacial representations. For example, Munger and Halata (1983) and Halata and Munger (1983) examined the sensory innervation of primate facial skin finding dense sensory innervation in the perioral and intraoral regions. These authors reported multiple innervation of cutaneous receptor sites suggesting that stimulation of any site is capable of activating multiple ascending pathways. Numerous investigations have demonstrated multiple ascending pathways from peripheral orofacial structures to the thalamus, multiple sensory and motor cortical areas, the basal ganglia, and cerebellum (cf. Gracco & Abbs, in press, a (for review). For example, there are at least four orofacial representations within the parietal lobe (Leinonen & Nyman, 1979; McKenna, Whitsel & Dreyer, 1982; Sur, Nelson & Kaas, 1982) and at least five orofacial representations within the primary and nonprimary motor areas in the frontal lobe (Muakkassa & Strick, 1979; Rizzolatti, Scandolara, Gentilucci & Camarda, 1981; Schell & Strick, 1984; Sessle & Wiesendanger, 1982). In addition, there are orofacial representations in the "motor" portion of the basal ganglia (Crutcher & DeLong, 1984; DeLong & Georgopoulos, 1981), the deep cerebellar nuclei (Schell & Strick, 1984; Stanton, 1980), and multiple nuclear regions of the thalamus (Carpenter, Nakano & Kim, 1976; Kaas, Nelson, Sur, Dykes & Merzenich, 1984; Smith, 1975). Furthermore, somatic sensory information is known to project, directly or indirectly, from peripheral orofacial sensory nuclei to all of these cortical and subcortical areas. It appears, as with other motor systems, that multiple afferent innervation and parallel sensorimotor processing is a characteristic of the orofacial system (cf. Merzenich & Kaas, 1980; Mountcastle, 1979). The presence of multiple pathways providing sensory information directly and indirectly to the multiple cortical and subcortical orofacial areas underscores the potential sensorimotor processing and reflects on the importance of the orofacial sensorimotor system.

In addition to the multiple afferent channels and extensive cortical and subcortical representation, other indirect evidence underscores the potential importance of sensory information in the control of orofacial actions. It has been observed in numerous experiments that the orofacial region, consisting of both perioral and intraoral regions, is one of the most sensitive of the human body (Schmidt, 1978). Psychophysical studies of tactile discrimination have shown that the lips and the tongue tip are extremely sensitive skin regions, second only to the finger tips. While psychophysical studies do not reflect motor control capabilities, they nevertheless indicate that the dense somatic sensory information is finely-tuned and utilized in "higher level" sensorimotor processes. When considering the classic motor and sensory homunculus found in any neurological text, one is struck by the massive amounts of cortical tissue representing the orofacial structures. It has been suggested that the expansive cortical *motor* representation of the speech structures reflects the importance of speech and verbal communication in the phylogenetic development of the species (Phillips & Porter, 1977; Young, 1950). Similarly, what is the

importance of the expansive orofacial representation within the somatic sensory cortex? It seems illogical that the extensive, multiple sensory representation is used solely for the psychophysical identification of objects placed on and around the lips, jaw, or tongue. It also seems inconceivable that the sensory representation of orofacial structures reflects swallowing or mastication processes exclusively since lesions to the orofacial areas of the parietal cortices do not produce significant dysphagia or related problems. Considering the orofacial sensory receptor density, sensitivity, and the extensive cortical orofacial representation, it is suggested that peripheral orofacial sensors and the somatic sensory information transduced are an integral component in the modification of speech motor output.

In the following sections, this conceptualization will be elaborated by considering speech physiology investigations which support a speech motor control hierarchy involving goal-level planning, temporal specification of individual movements, predictive sensorimotor parameterization, and on-line coordination within and among the articulators. These stages are similar in many respects to the traditional motor behavior concepts of motor planning, motor programming, and motor execution. However, the present model will be defined with specific emphasis on the role of sensory information during each stage to ultimately produce the observable motor output. It is suggested that sensory information is an essential component of each of the levels in the motor control hierarchy, although the sensory information extracted may be used in different ways throughout the unfolding motor act.

### GOAL-DIRECTED MOTOR PLANNING

Attempting to understand the nervous system actions involved in the coordination of movement, Bernstein (1967) suggested it was important to determine what was represented within the central nervous system. Bernstein hypothesized that it was not the individual movements themselves, but the actual goal of the individual movements represented as an abstract entity, later becoming realized through the motor execution process. For a certain class of speech movements (bilabial closing), we have recently suggested that it is the *combined* actions of the articulators which may be represented as the motor plan for oral closure (Gracco & Abbs, in press, b; see also Saltzman, 1979; Saltzman, in press). That is, at an early stage in the speech production process, the movement plan reflects an abstract representation of the subsequent movement goal (e.g., oral closure).

The individual articulators are considered as a single entity and the goal of the subsequent motor act is established. The movement plan essentially links the goal with the physical reality of establishing and subsequently executing the appropriate motor patterns to accomplish the task. This hierarchical structure involving the goal and subsequent specification of the individual components is a general characteristic of the communication process. That is, speech involves the conveyance of a message to a listener. The individual

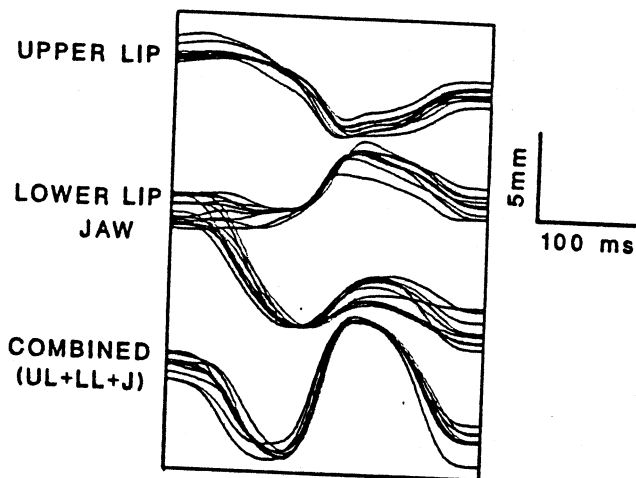


Figure 1. Nine superimposed closing movements of the upper lip, lower lip, and jaw for the first /p/ in sapapple. The bottom trace is a derived signal obtained by adding the separate displacements.

muscle contractions and resulting movements producing the acoustic cues are subordinate to the goal of communication. In the present chapter, goal-directed speech motor planning is only evaluated within the context of the movement goal, although such movements are always subordinate to the acoustic consequences they produce and ultimately to the listeners' perception.

As mentioned previously and illustrated in Figure 1, it appears that the motor plan for speech, at least during oral closure, is formulated in terms of the combined action of the articulators. Presented in Figure 1 are superimposed closing movements of the upper lip (UL), lower lip (LL), and jaw (J) during multiple repetition of the utterance "sapapple". The bottom trace is a derived displacement signal representing the instantaneous sum of the individual lip and jaw movements over the same time interval. As can be seen, while the action of individual articulators is variable with regard to their final displacements, the combined action, illustrated at the bottom of Figure 1, remains relatively invariant. This can be seen qualitatively in this figure and has been shown quantitatively (Gracco & Abbs, in press, b). The apparent goal of oral closure may reflect a tendency to produce an invariant vowel formant trajectory or may simply reflect a movement goal of closing the acoustic tube in preparation for the upcoming implosion of air for the /p/ these two possibilities are not mutually exclusive. However, it does appear that the invariant movement characteristic for this speech gesture is the combined oppositional action of the articulators. As such, speech movement invariance reflects an abstraction not obvious from the actions of the individual articulators.

The role of sensory information at this stage of the motor control process is not obvious. However, if one considers the oral closing movements within a broader time frame, a hypothetical

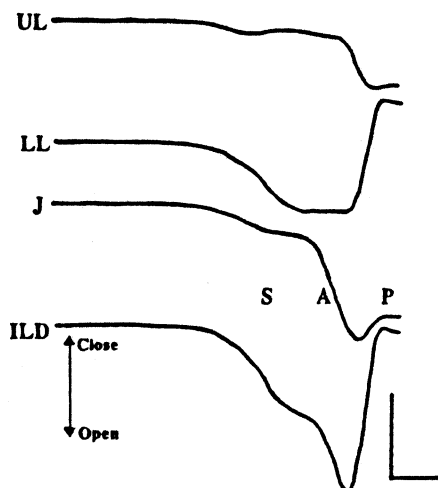


Figure 2. Subject's production of "sapapple" starting with lips closed at rest. The four traces from top to bottom are movements of the upper lip (UL), lower lip (LL), jaw (J), and interlip distance (ILD) obtained by calculating the distance between the lips during the utterance. Calibrations are 5 mm (vertical) and 50 ms (horizontal).

function of sensory information may be formulated. The superimposed movements displayed in Figure 1 represent the closing actions of the UL, LL, and J from maximum opening for the vowel to peak closing displacement. The behavior of the articulators, considered prior to the onset of movement, reveals another aspect of the goal-level motor plan. Figure 2 illustrates a single kinematic profile from a subject repeating 'sapapple'; the subject began this trial with lips together at rest. As with the previous figure, the bottom trace is a representation of the interlip distance during the entire utterance. As can be seen, the lips and jaw displacements prior to closure reflect not just the vowel opening, but the total oral opening with reference to the lips at rest. That is, the total closing movement must incorporate the immediate goal of closing the oral cavity based on the opening for the vowel /ae/ as well as the distance previously opened for the /s/. Therefore, the total movement goal can be thought of as moving the lips and jaw back to their original position (closure) following maximal oral opening. However, as we have recently shown, the positions of the articulators at opening and closing and their moment-to-moment trajectories are not invariant, but vary substantially (Gracco & Abbs, in press, b). Rather than each articulator returning to some prespecified spatial target, the overall goal-level movement plan may be to generate the appropriate amount of total sensory input resulting in a condition similar to that attained at rest. That is, the referent for oral closure in terms of the lips and jaw movement may be a somatic-sensory based pattern reflecting a combined level of sensory input. This conceptualization suggests that many combinations of UL, LL, and J final positions will result in the same total sensory "experience". This speculation is consistent with the systematic

spatial variability observed experimentally. Thus, speech motor planning may reflect an abstract relational state among all articulators involving a predetermined sensory-based referent. The ongoing sensory information most likely involves immediate somatic sensory as well as later occurring auditory information extracted from the kinematic and acoustic signals, respectively.

Once the plan is specified, the remaining processes involve the programming of the appropriate motor actions, including coordinating the multiple articulators, and subsequently, motor execution. Prior to considering the programming and execution processes, it will first be helpful to review some results from speech physiology studies which provide some insight into these hypothesized sensorimotor processes.

### SPEECH MOTOR PROGRAMMING

Folkins and Abbs (1975) were the first to demonstrate that the speech system had the capability to respond at short latencies to sensory input resulting from unanticipated mechanical disruptions. Subsequent reinterpretation of those data by Abbs and Cole (1982) led to another important characteristic of the speech system. When a speech structure is perturbed or impeded during its goal-directed movement, adjustments are made in the perturbed and unperturbed articulators. Such functional autogenic and nonautogenic adjustments have been observed for many of the speech articulators, apparently reflecting a general characteristic of all speech movements (cf. Abbs & Gracco, 1984; Folkins & Zimmermann, 1982; Kelso et al., 1984; Riordan, 1977; Shaiman, Abbs & Gracco, 1985). Similar observations have been made for postural adjustments (Marsden, Merton & Morton, 1981; Nashner & Cordo, 1981; Nashner, Woollacott & Tuma, 1979), compensatory eye-head movements (Bizzi, Kalil & Tagliasco, 1971; Morasso, Bizzi & Dichgans, 1973), wrist-thumb interactions (Traub, Rothwell & Marsden, 1980), and thumb-finger actions (Cole, Gracco & Abbs, 1984). The implication from these findings is that sensory information is an integral component in the control of movement. More importantly, the presence of sensorimotor interactions reflects the existence of specific anatomical pathways within as well as across motor structures. These connections provide convergence and divergence of sensory information onto various, synergistically-related motor structures. However, these pathways are not obligatory or "hard-wired" as in a stereotypic reflex pathway. Rather, these connections can be flexibly and specifically activated or inactivated depending on task requirements (cf. Abbs et al., 1984; Kelso et al., 1984). It appears that a distinction can be made between the anatomical connections for voluntary motor behaviors and a more functional process used to activate and route the relevant sensory signals.

One way of conceptualizing such processes is through the construct of a motor program. It is reasonable to suggest that motor programs may reflect the specific anatomical connections and synaptic interactions between various and related body regions, and the (internal) activation of the relevant pathways prior to move-

ment. The programming process would consist of the subsequent (external) sensory parameterization or scaling of these connections in a functionally task-specific manner. The distinction between an internal program and an external parameterization process synthesizes the concepts of movements as stored motor programs and movements generated afresh through ongoing sensory information. Without doubt, there must be some type of stored motor patterns or synergistic relations which then rely on updated sensory information to specify movement characteristics. The cortical activity preceding voluntary movement recorded through the intact human scalp (e.g., Bereitschaftspotential or BP potential) and the subsequent premotion positivity (cf. Deecke, Becker, Grozinger, Schied & Kornhuber, 1973) may be a direct reflection of the internal activation of a motor program or sequence of motor programs. Without extensive anatomical investigations, the extent and details of the anatomical connections or interconnections underlying motor programs within the orofacial system can only be implied. However, recent physiological studies provide some insight into the characteristics of the motor programming process.

Considering the dynamically changing peripheral conditions (e.g., time-varying articulator positions and highly specific articulator interactions), the underlying control process must be extremely flexible. The flexibility and concomitant complexity of the speech motor control process is reflected in results of perturbation studies demonstrating multiple time dependent sensorimotor mechanisms operating during ongoing speech production (Gracco, 1984; Gracco & Abbs, 1982; Gracco & Abbs, 1985). The compensatory movement and EMG response patterns and variable compensatory response latencies demonstrated in these studies appear to reflect systematically variable sensorimotor actions. For example, lower lip perturbations introduced prior to the onset of muscle contraction result in long latency compensatory responses in all the synergistic muscles of the labial complex (Gracco & Abbs, 1982). These displacement perturbations result in proportional increases in the EMG activity and subsequent movements to almost totally readjust to the altered peripheral conditions (Gracco, 1984; Gracco & Abbs, 1985). These results suggest that prior to *motor activation* (EMG onset) for a particular movement, sensory signals can rapidly access and significantly modify motor output. Further, these sensory signals can be used to reparameterize or reprogram the previously programmed response. The latency and functionality of these compensatory responses suggest that for normal unperturbed speech movements, sensory information related to articulatory position could be used to compute the necessary forces required to generally specify or program the articulators. From this perspective, speech motor programming reflects the general physiological "tuning" of the hard-wired neural circuitry with later execution adjustments providing the details (cf. Abbs et al., 1984; Gracco & Abbs, 1985 for further elaboration).

However, the exact mechanism to accomplish such a task has not been specified and leads to a major consideration for the utilizing of sensory information during the ongoing control of speech movements. For speech motor programming, the time required for such processing becomes a limiting factor. For example, consider



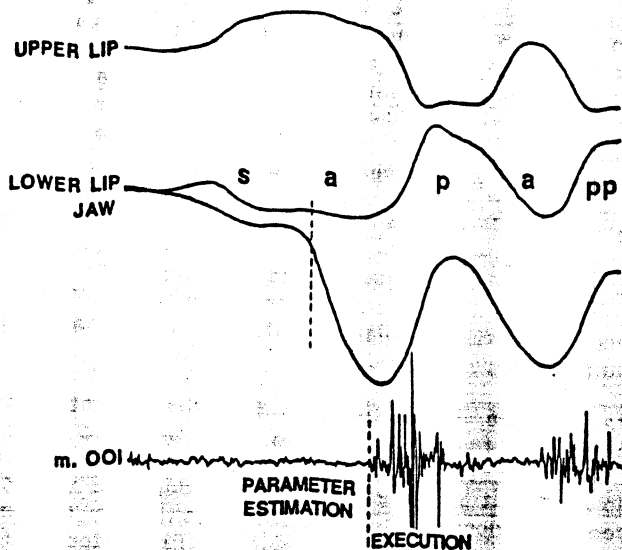


Figure 3. The upper lip, lower lip, and jaw movements for sapapple and the corresponding muscle activity from Orbicularis oris inferior (OOI). Also illustrated is the time interval for the hypothesized parameter estimation (parameterization) and subsequent motor execution processes.

the simple speech gesture shown in Figure 3. From the previous conceptualization, the parameterization of the first 'p' in "sapapple" requires that the nervous system know or estimate the amount of oral opening for the /ae/ in order to issue the appropriate commands to achieve oral closure. As can be seen, however, the jaw is the major structure in determining interlip distance and is never really in a static state. The problem of parameterization becomes one of available time. For bilabial sounds, for example, the dynamics of oral closure are based on the amount of oral opening. If sensory information is to be used in the programming process, based on the position of the articulators at peak oral opening, there does not appear to be enough time available between maximum oral opening and the onset of EMG activity for oral closure. That is, at the time of maximum oral opening, the EMG signals associated with lip closing are initiated within approximately 10 to 15 msec. This is probably not sufficient time to scale and certainly not to compute the necessary labial and mandibular forces and subsequently generate the appropriate neural signals to the synergistic muscles.

One possibility which we are exploring is that certain sensory receptors can provide predictive information on the extent of the oral opening prior to completion of oral opening. As mentioned, the jaw is the primary articulator specifying the extent of oral opening. The jaw closing muscles are heavily endowed with muscle spindles which have been shown to have a velocity sensitive component and discharge in relation to muscle stretch (Cody, Harrison & Taylor, 1975; Goodwin & Luschei, 1975; Larson, Smith & Luschei, 1981).

During opening, the jaw closing muscles (specifically masseter) would be stretching and the muscle spindles would be discharging with a signal proportional to jaw velocity. Given the consistent velocity/amplitude relationship characteristic of all movements, the jaw velocity information could be used to estimate jaw opening magnitude. From the jaw opening signal, along with the sensory information from the static lip positions prior to closing, the nervous system would have enough information to generally determine the task dynamics (i.e., how much force will be required to achieve oral closure). In support of this speculation are data illustrating the relationship between the magnitude of jaw opening velocity and total closing displacement of the upper lip, lower lip, and jaw for the first "p" in sapapple (Figure 4). As can be seen, the total closing displacement is highly related to the jaw opening velocity indicating that as the jaw opens farther, its velocity is higher and the amount of total displacement required of the combined articulators increases. Similar results are obtained when the individual articulators are plotted as a function of jaw opening velocity.

These data provide some support for the hypothesis that sensory signals arising from jaw opening may be used in a predictive manner to parameterize the motor program for subsequent oral closure. However, it is necessary to consider the time course of the jaw opening velocity and its relationship to the muscle actions generating the lip and jaw movements. Presented in Figure 5 is a single trial example illustrating the temporal relationship between jaw opening velocity and the EMG activity of OOI.

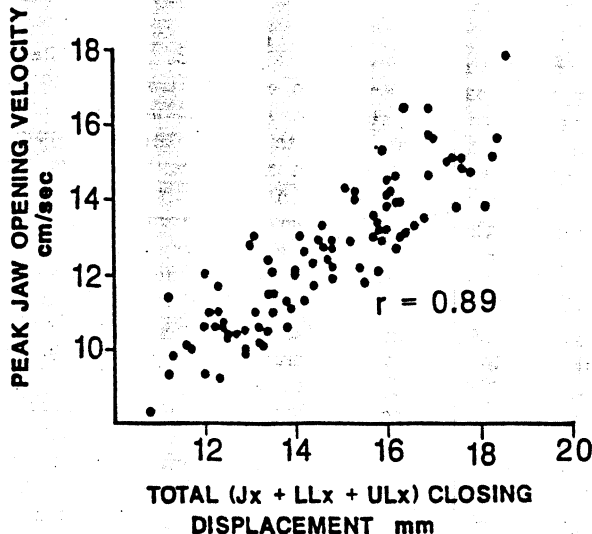


Figure 4. Peak jaw opening velocity (Jx) plotted as a function of the total combined oral closing displacements obtained by summing the peak displacement of the upper lip, lower lip, and jaw (ULx, LLx, Jx). Also shown is the correlation coefficient obtained for the multiple trials.

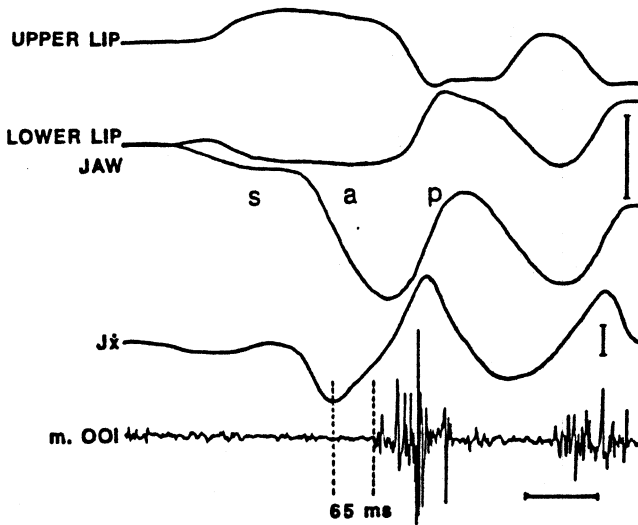


Figure 5. Illustration of the time course of jaw opening velocity ( $Jx$ ) and the relationship between peak opening velocity and the onset of OOI activity for the first closing movement. Calibration is 100 ms.

It appears that there is approximately 65 msec between the peak jaw opening velocity and the onset of the labial EMG (this does not take into account the actual burst duration which is on the order of 100 msec). Previous studies have shown that compensatory responses to perturbations occur at latencies between 25 - 75 msec (Abbs & Gracco, 1984; Gracco & Abbs, 1982; Kelso et al., 1984), making 65 msec sufficient time to parameterize the articulators. It appears that the time is available for sensory information from the preceding speech movement to be used in the programming of the following speech movement. Experiments are currently under way to address the hypothesis that sensory signals arising from the stretching of jaw closing muscles are critical in the programming of orofacial closing movements.

In the preceding discussion, it has been suggested that speech movements are constructed, prior to execution, through the interaction of two processes, each relying on different amounts of stored and incoming sensory information. The motor program may be considered the more hard-wired process, relying on both synaptic connections and stored internal activation patterns for the appropriate muscles. The programming process, in contrast, is the more dynamic process relying heavily on sensory information to adjust the timing and magnitude of the motor program patterns underlying movements. This distinction between the program and the programming process is currently a heuristic one; however, it is worth considering in that it is a recognition that motor behavior relies on the anatomical connections that must exist as well as the internal (CNS) and external (sensory receptors) interactions necessary to activate and adjust these connections in a functionally task-specific manner.

## SPEECH MOTOR EXECUTION

Motor execution, the final stage of the motor control process, can perhaps be considered an extension of the programming process. Motor execution is the actual implementation of the programmed motor plan consisting of the EMG output and any motor adjustments which occur during the initial phases of the resulting movement. Speech motor adjustments have been observed up to approximately 40 msec following EMG onset associated with bilabial closure (Gracco & Abbs, 1985). After this time, the system gain drops to almost nothing indicating a phasing out of sensory influences on the programmed speech motor output. It is interesting to note that the movement acceleration peaks at about this same time suggesting that only the very early sensory input from the actual movement may affect the final execution process. It is possible, however, that the sensory input generated during the movement may be used to modify the antagonist muscle (for closure, depressor labii inferior) to adjust the terminal movement characteristics. Overall, it appears that the early stages of speech motor programming may be sufficiently precise to require only minimal adjustments of the synergistic actions. While the characteristics of speech motor execution are limited, it appears that these adjustments apparently travel by way of short latency neural pathways in which the metrics of the transfer function between afferent input and motor output have been preset (cf. Gracco & Abbs, in press, a, for further elaboration). Furthermore, sensorimotor characteristics during speech motor execution possibly suggest different neural centers mediating these responses than those underlying speech motor programming (Gracco & Abbs, 1985). While somewhat speculative, the suggestion that speech production reflects a time-dependent modulation of multiple cortical and subcortical areas is consistent with numerous behaving animal investigations (Brinkman & Porter, 1979; Crutcher & DeLong, 1984; DeLong, Crutcher & Georgopoulos, 1981; Evarts & Tanji, 1976; Godschalk, Lemon, Nijs & Kuypers, 1981; Halsband & Passingham, 1982; Horak & Anderson, 1984a, 1984b; Lemon & van der Burg, 1979; Thach, 1975, 1978; Wise & Tanji, 1981). Collectively, such studies have demonstrated a dynamic and differential involvement of cerebellar, basal ganglia, supplementary motor area, premotor area, and sensorimotor cortical regions during different phases of the motor implementation process.

Another sensorimotor mechanism which appears to have significant influence on speech motor execution is the gating or modulation of sensory input during the initial phases of movement. That is, the reduced gain evidenced by the limited compensatory capability of the perioral system immediately preceding EMG onset (Gracco & Abbs, 1985) appears to reflect a modulation or reduction in the influence of sensory information immediately prior to and during the actual movement. It has been shown that the sensory transmission via most ascending pathways is reduced prior to movement onset (Coulter, 1974; Dubner & Sessle, 1971; Ghez & Pisa, 1972; Kuypers & Tuerk, 1964). This modulation results in a reduction in the amount of sensory information reaching thalamic and cortical centers

(Chapin & Woodward, 1982a, 1982b; Starr & Cohen, 1985). Such modulation has been shown to originate, in part, from projections of sensorimotor cortical neurons onto brainstem or spinal nuclei resulting in primary afferent depolarization. Such modulation would minimize (not eliminate) the influence of sensory input generated during the later phases of the movement. It is interesting that at the time when sensory influences on motor output would be greatest, much of the effect is minimized by the sensory gating. One possible explanation is that given the finely-tuned predictive capability of the nervous system, only minor adjustments need to be accomplished as the actual movement unfolds. Additionally, the sensory gating of afferent influences may be used to diminish or eliminate the interaction of reflexes with the voluntary motor commands. Whatever the explanation, it appears that speech motor execution involves multiple sensorimotor adjustments to coordinate the multiple degrees of movement freedom and achieve the multiarticulate movement goal.

#### SUMMARY

The preceding chapter has attempted to speculate on the nervous system control of speech with explicit consideration of sensory information and the underlying sensorimotor processes. Shown in Figure 6 is a schematic representation of the hypothesized levels of the speech motor control process. The movement plan involves the establishment of the movement goal incorporating the necessary acoustic consequences of the combined articulator actions.

#### MULTILEVEL SENSORIMOTOR CONTROL OF SPEECH

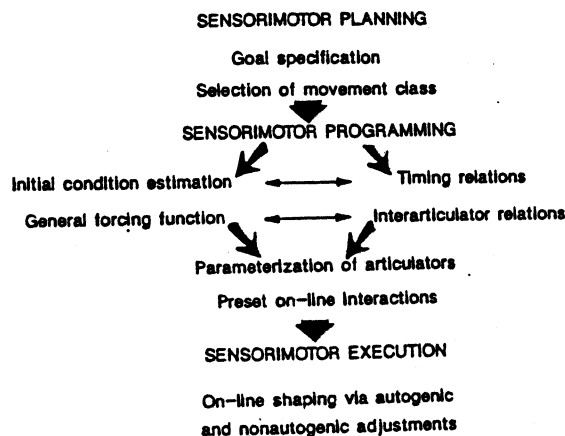


Figure 6. Schematic representation of the multilevel sensorimotor control processes hypothesized to underlie speech production.

As a way to generalize this conceptualization of speech movement planning to different speech sounds, it is suggested that within the planning process there is a general specification of a movement class. That is, the speech movement plan would involve specification of a general action (closing the acoustic tube) and the selection of the appropriate muscles. This general movement action could apply to all closing movements whether they involve the lips, jaw, or tongue and need only be adjusted for different preceding vowels. The acoustic-encoded movement goal of bilabial, lingual alveolar, and lingual velar stops would be to produce a terminal vowel formant trajectory appropriate to the specific vowel and ultimately close the acoustic tube through the combined articulator actions.

During the programming process, the first consideration is articulator timing. In the present representation, the temporal specification of movement timing is included within the programming process; however, it could easily be considered part of the movement plan and may reflect a separate nervous system process. One important aspect of the timing specification is that the underlying mechanism takes into account the different biomechanical characteristics of the lips, jaw, tongue, etc. to produce the orderly and consistent invariant timing patterns observed within (Gracco & Abbs, in press, b) and across (Tuller, Kelso & Harris, 1982) speech movements.

Within the invariant temporal framework, the relevant articulators are parameterized based on incoming sensory information. The parameterization involves the estimation of initial conditions (e.g., magnitude of oral opening) via predictive mechanisms, resulting in the establishment of general forcing functions and the resultant scaling of the individual articulator actions. The final stage in the motor control process is the actual implementation of the motor plan based on the previously programmed articulator adjustments, executed through flexible sensorimotor mechanisms.

The conceptualization of the speech motor control process presented above reflects a number of considerations that are crucial in developing a complete understanding of normal and disordered speech motor behavior. First, sensory information is an integral part of movement control and coordination and is potentially available throughout the movement planning/execution process. It appears that ongoing sensory information can influence both the spatial and temporal adjustments within and across articulatory subsystems. This suggests that observations of a single system (e.g., larynx, tongue, etc.) or a single variable may not provide a clear picture of the complex sensorimotor adjustments underlying speech production. Second, it is important that we consider the underlying neurophysiological substrate in any hypothetical process. The constructs of planning, programming, coordinative structures, synergies, etc. are only simplifying analogies to help understand the actions of the central nervous system. Attempts must continue to uncover the detailed characteristics of these constructs as well as to synthesize human behavioral studies with relevant nonhuman research which can deal directly with the potential functions of certain neural centers. While not elaborated in the present chapter, the potential neural processes underlying the planning, programming, and execution of speech and movement in general have been

presented elsewhere (cf. Abbs, 1986; Brooks, 1979; Gracco & Abbs, in press, b). Finally, the hierarchical control process provides a structured task level of analysis that may be helpful in characterizing normal speech motor behavior and, subsequently, understanding speech movement disorders.

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