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## 28 Central and Peripheral Components in the Control of Speech Movements

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In the late 1950s and 1960s much of the work at Haskins Laboratories focused on issues related to the representation of the phoneme—the presumed unit of speech. Attempts to find evidence for invariant signal properties in the acoustic stream representing the phoneme had been generally unsuccessful because of contextual variation, that is, coarticulation. As suggested by MacNeilage (1970) this led to two related positions regarding the nature of phonemic invariance. One position, posited by Lindblom (1963), Ladefoged (1967), and Stevens and House (1963), was that invariance is in the vocal tract targets rather than in the peripheral manifestations at any observable level. The Haskins position was “that the EMG [electromyographic] correlates of the phoneme will prove to be invariant in some significant sense” (Liberman, Cooper, Harris, MacNeilage, & Studdert-Kennedy, 1967, p. 84). The motivation for this search was that if there were phonemic units of speech, and the evidence from speech perception studies suggested that there were, they should be invariantly present in the muscular activity output. They reasoned that the acoustic signal was too far removed from the source of the invariance, since the invariance was a reflection of characteristics internal to the organism, in the central motor commands. Therefore, the best place to search for invariance was in the peripheral manifestation of the central motor commands, which can be examined in the

activity of the muscles of the vocal tract using electromyography. The earliest studies of this kind were conducted by Katherine Harris and her colleagues at Haskins and resulted in a number of interesting and important findings that have had both theoretical and technical impact on the field of speech science (Harris, Lysaught, & Schvey, 1965; Harris, Schvey, & Lysaught, 1962; Lysaught, Rosov, & Harris, 1961; MacNeilage, 1963). However, even at this level of observation, numerous attempts by various investigators failed to find an acceptable degree of invariance in the peripheral manifestation of the central motor commands, and the search was abandoned. One of the limiting factors in the earlier research into invariance in speech production resulted from the limited consideration of the sensorimotor nature of the behavior. As will be suggested below, speech, as all behavior, is built from and maintained by an integration of sensory and motor signals operating at different functional levels and on different time scales. Attempting to identify the underlying processes and components of speech production without explicit consideration of the sensorimotor character of the behavior can only result in incomplete models of limited relevance to understanding speech motor behavior.

### Some History

Perhaps the longest-standing issue in motor control has been the role of sensory feedback in the control of behavior. This issue has generated considerable controversy and dichotomous theoretical positions among students of both speech production and general motor control. Perhaps the most prevalent position is one in which voluntary movement is viewed as being built from explicit sensory-mediated consequences, but that once the movement pattern is acquired, sensory information is no longer necessary. In the field of speech, such a position seems to have originated from the apparent resistance of various methods of sensory reduction to have a significantly degrading effect on speech motor performance in adults (cf. Borden, 1979; Lane & Tranel, 1971). For example, following experimentally induced reduction in oral kinesthesia, global measures of speech production have been found to be minimally disrupted (Gammon, Smith, Daniloff, & Kim, 1971; Ringel & Steer, 1963; Scott & Ringel, 1971). Additionally, reduced or distorted auditory information has resulted in only mildly distorted or essentially normal speech motor output (Kelso & Tuller, 1983; Lane & Tranel, 1971). Other considerations, like neural transport delays involving afferent-to-efferent loops (Kent & Moll, 1975) and the apparent ballistic nature and short duration of many speech movements, have led to the position that speech movements are exclusively preprogrammed with sensory information that is used only in long-term adaptation or speech skill acquisition (Borden, 1979). From this perspective speech movements would be generated from preset motor patterns and executed independently of any afferent-dependent actions. Similar theoretical positions have been postulated based, in

part, on limb studies showing that functionally deafferented animals (Fentress, 1973; Polit & Bizzi, 1979; Taub & Berman, 1968) and humans (Rothwell et al., 1982) are capable of executing learned and novel motor tasks (Kelso & Stelmach, 1976 for review). These results indicate that motor tasks can be carried out with reduced or absent afferent input, apparently relying on some stored motor commands. However, it is also true that motor acts executed in the absence of afferent information are often only grossly normal; that is, they often lack their normal precision (Sanes & Evarts, 1983).

An alternative perspective can be generated from consideration of the numerous studies demonstrating movement changes following dynamic mechanical perturbation applied to a moving articulator. It has been observed that loads applied to the lips or jaw result in changes in articulatory movement. Perturbation of a moving articulator results in patterns of compensation: disruptions to the lips result in compensatory changes in the lips and jaw (Abbs & Gracco, 1984; Gracco & Abbs, 1985, 1988) and the larynx (Löfqvist & Gracco, 1991; Munhall, Löfqvist, & Kelso, 1994); jaw loads result in compensatory changes in the tongue (Kelso, Tuller, Vatikotis-Bateson, & Fowler, 1984), lips (Folkins & Abbs, 1975; Shaiman, 1989), and velum (Kollia, Gracco, & Harris, 1992). Task-specific responses are observed when an articulator is actively involved in the sound segment being produced, but not when an articulator is inactive (Kelso et al., 1984; Shaiman, 1989). These studies suggest that speech is always produced with at least some consideration of ongoing sensory information. Experimental interference with hearing one's own speech (using distorted auditory feedback or masking) results in changes in a number of speech output variables including fundamental frequency, vocal intensity and to a lesser extent, speech movements (Siegel & Pick, 1974; Lane & Tranel, 1971; Forrest, Abbas, & Zimmermann, 1986). Delayed auditory feedback results in a slowing of speaking rate that can result in a breakdown in fluency (Fairbanks, 1955; Howell, El Yaniv, & Powell, 1987; Lee, 1950), whereas low pass filtering results in changes in nasal resonance (Garber & Moller, 1979) and both increases and decreases in lip, jaw, and tongue movement (Forrest et al., 1986). Recently, a number of investigations have used perturbations of the frequency content of the auditory feedback signal to examine changes in fundamental frequency and intonation (Elman, 1981; Kawahara, 1994).

The apparent inconsistency in speech production theories regarding the sensory contribution to speech motor control is one of interpretation. The results of all studies support a general intuitive position that all behaviors involve, to some extent, the integration of sensory information. A simple reflex, of any origin and in any organism, requires sensory stimulation. Human thought, often assumed to represent the highest level of ontogenetic advancement and to set humans apart from the nonhumans, is stimulated by the organisms' environment. However, although thoughts and actions may be conceptualized as emergent

properties, they emerge in relation to some antecedent event or series of events. The registration of events can only come through sensory channels. Given both the density of sensory receptors found within the vocal tract and the sensory discrimination possible with articulators like the tongue and lips (see Kent, Martin, & Sufit, 1990 for review), a more reasonable position is that taken by Weiss more than 50 years ago, when he suggested:

Nobody in his senses would think of questioning the importance of sensory control of movement. But just what is the precise scope of that control?  
Weiss (p. 23, 1941)

That is, it is obvious that behavior is always sensorimotor in nature, and it is illogical to suggest that speech might be a special case in which sensory-mediated information is unimportant or simply ignored.

### Control Processes

A related issue convolved with the role of sensory information in speech production has to do with the characteristics of the control process. Theoreticians focusing on the sensory-dependent vs. sensory-independent issue have also focused, simultaneously, on whether speech motor action is produced by a closed-loop or an open-loop system. In this context, "closed-loop" is often used synonymously with "feedback" and the term "open-loop" is often used synonymously with "no feedback." This simplistic dichotomy has had a long and unproductive history; furthermore, it is based on the inaccurate assumption that open-loop implies the lack of sensory influence (see discussion by Abbs & Cole, 1982).

Control systems are classified into two general categories: open-loop and closed-loop. The distinction is determined by the control action, which is the quantity responsible for activating the system to produce the output. For example, an open-loop control system is one in which the control action (the input) is independent of the output: a closed-loop control system is one in which the control action is somehow dependent on the output. In this regard, maintaining a limb in a specific position in the face of perturbing stimuli would be an example of the operation of closed-loop control: the control action is being adjusted by the deviations in the output of the system. A classic example of an open-loop control system is an automatic toaster in which the control action is controlled by a timer and once initiated, the action is completed without changes resulting from errors in the toasting quality. This simple and relatively straightforward example, however, assumes that the user, who can adjust the timer at anytime, is not part of the control system. More precisely, the user can only influence the control action in the future, not in the present, through changes in the timer. As such, a system can be open-loop but still be sensory

dependent. One of the requirements of an open-loop system is accurate calibration, so that a precise input-output relation is established that allows the system to operate without direct feedback of any desired quantity.

Early motor control research emphasized the use of closed-loop control to regulate some physical variable (e.g., limb position, muscle length, muscle force, etc.). Servomechanistic models have been proposed in which the control of muscle length or limb position is regulated (Hammond, 1960; Merton, 1953) by comparing actual length or position with a model or reference, using the difference between the actual and model values as an error signal to generate a corrective movement. Similarly, speech theorists (Fairbanks, 1955; MacNeilage, 1970; Sussman, 1972) posited models of speech production employing closed-loop control of muscle length or spatial targets. Within the context of postural maintenance or slow tracking, sensory information from muscles or movement can provide the input necessary for the fine adjustments and error-correction capabilities characteristic of a closed-loop system. In the case of rapid coordinated movements, however, the inherent pathway delays and comparator-processing time, coupled with high loop gain, result in serious limitations for servocontrol (Rack, 1981).

An alternative proposal has been offered by Greene (1972), who proposed a style of control for purposeful movements that incorporates open-loop, or feedforward, control based on anticipatory or predictive adjustments that allow greater speech and flexibility required to regulate a complex dynamic system. Essentially, the input from one or several sensory systems is used to predict the requirements of an upcoming movement and produces a control signal that incorporates the predicted requirement. Before turning to a consideration of how best to describe the sensorimotor control system, some developmental considerations may be helpful in identifying the processes and objects that sensory mechanisms might influence.

### Developmental Considerations

As in the acquisition of any other motor skill, the early stages of speech motor development involve practice and feedback. Of interest here are what role sensory influences have to play in that development. The period from perhaps one to six months of age, the period in which the infant engages in cooing, laughter, produces vowel sounds and reduplicated babbling, is the time when the most fundamental sensorimotor links and basic neuromotor patterns for speech are being established. Even at birth, however, the neonate exhibits coordinated activity of the physiological systems that underlie the speech production process. The earliest communicative behavior, crying, reflects the coordinated activity of the respiratory, laryngeal, and supralaryngeal systems exhibiting the same fundamental principles seen in the older child and adult. That is, vocalization involves manipulating discrete portions of the vocal tract, in the presence of a

constant pressure source, to produce sound that is interpreted by the listener. What is elaborated during development is the ability to make finer and finer distinctions with the vocal apparatus. More precisely, speech motor development is a process in which the child learns how to make fractionated movements of the vocal tract to produce sounds corresponding to the adult phonological system.

Two conditions are required for these elaborations to occur: the child must possess the physiological capability to make configurational changes of the vocal tract and the ability to discriminate the acoustic properties of the sounds of the language. When these conditions are met, one generally finds that the acquisition of sounds progresses from rather gross movements of lips and jaw and tongue to more refined and fractionated action of the same articulators (Kent, 1992). For example, bilabial consonants are acquired earliest; labiodentals are acquired later. The production of labiodental sounds requires the ability to contract only a portion of orbicularis oris inferior and to use a different portion of mentalis to generate the correct movement vector for /f/ than that for /p/. Similarly, one can account for the development of other articulatorily complex sounds—for example, /ɜ-/ is the last sound to be acquired, presumably because of its motor requirements (Shriberg & Kent, 1982). One of the hallmarks of the developing child is the ability to learn to contract a portion or a unique combination of muscles or groups of synergistic muscles and to produce a novel configuration. Motorically, the developing child is constantly modifying and refining its sensorimotor map to establish a degree of activation that can serve the needs of adult speech production—that is, the shaping and refining of vocal tract actions to the minimal functional structure necessary to produce the sounds of the language. This developmental process has a significant consequence: coarticulation, which can be viewed as the ultimate adaptation. By learning and refining motor patterns to their minimal functional structure, articulatory regions that are not necessary for a specific sound essentially become available for producing overlapping or contiguous sounds, and in so doing, maximize the speed at which sounds can be produced and information transferred.

From this perspective, speech development involves refining motor patterns and perceptual abilities associated with discriminating the phonetic segments of the language. During the early stages of development, the infant is developing an internal model of the vocal tract and establishing relations between movements of the vocal tract and their perceptual, auditory, and somatic sensory consequences. This learning phase is highly dependent on sensory stimulation from all possible sources: visual, auditory, and somesthetic. The different modalities provide different, but related, information to the child, establishing mappings between multimodal sensory information and the various neuromotor processes underlying adult speech production. Presumably, once development is

complete, sensorimotor transformations that allow rapid and direct mappings between sensory modalities and levels of the motor output have been acquired.

### Sensory Considerations

There are three sensory modalities that can influence the production of speech: the visual, auditory, and somatic modalities, each of which provides unique and somewhat redundant information to the speech motor control system. One of the characteristics that distinguishes the three modalities from one another is the information that can be extracted from the input modality. For example, visual input cannot provide direct information on the speaker's own production mechanism but can and does provide important environmental information. Visual information provides the speaker with cues regarding the successful transfer of information to the listener as well as information on the environment that may be relevant to successful information transfer. The visual modality may act to tune the output to the environment rather than have any specific effects on the output characteristics. The auditory system, in contrast, can provide more direct information on the state of the speaker's speech production mechanism including both the phonetic and prosodic properties of the signal (Svirsky, Lane, Perkell, & Wozniak, 1992). Inaccurate or distorted articulations, speech errors, and intonational information are carried very well and with a high degree of precision by the auditory modality. The predominant result of most of the studies using auditory distortions to evaluate the potential role of hearing in speech has been that changes are related, directly or indirectly, to loudness or intonation. Intuitively, this seems reasonable, since auditory information is only indirectly related to articulation and requires a complex mapping between acoustic characteristics and changes in the articulatory source. It is often the case that this mapping is not unique, and the ability of the nervous system to extract speech movement consequences directly can often be limited. The experiments by Kawahara (1993), mentioned above, also offer some evidence that the time scale for normal monitoring of the auditory stream for speaking may be longer than that required for discrete speech movement changes. Kawahara's experiments contain some of the best controlled auditory perturbation manipulations and have the most consistent experimental findings to date. One relevant finding is that the average latency of the response to the transformed auditory manipulation is 150 ms. Previous work by a number of investigators attempting to elicit audio-laryngeal reflexes with unnatural stimuli have found much shorter latencies.

The most direct source of sensory information for the control of movement is from the somatic sensory receptors located throughout the human body. The kind and density of receptors within various regions of the body is generally consistent with the kind of information coded by the receptor and the sensitivity of the region. The human vocal tract contains regions that are as tactilely

sensitive as the fingers and face. The tongue, face, and fingers have a denser distribution of cutaneous sensory receptors than the upper arm or upper leg. As a consequence the finger tip, tongue, and face have very localized discrimination. Sensory receptors from the vocal tract that have the potential to contribute to the control of movement belong to a class of receptors called exteroceptors, whose information may principally serve either conscious sensation or regulation (Eyzaguirre & Fidone, 1975). This class includes a variety of receptors, only two of which may have any direct affect on speech movement control: proprioceptors and cutaneous mechanoreceptors. Proprioceptors are found in muscles and joints and provide information on the velocity and amount of muscle stretch and muscle tension. Cutaneous mechanoreceptors are found in the smooth and the hairy skin throughout the vocal tract and discharge in response to the state and changes in the state of the vocal tract. Somatic sensory receptors are functionally designated as having either static or dynamic properties depending on their discharge characteristics: static receptors discharge as long as a stimulus is present; dynamic receptors discharge only with the application or removal of an adequate stimulus. The static and dynamic receptor classification can be further delineated by consideration of the relative adaptive nature of the response to stimulation. (Detailed consideration of the specific receptor types within the vocal tract can be found in Dubner, Sessle, & Storey, 1978, and Kent, Martin, & Sufit, 1990). Generally, within the vocal tract somatic receptors are able to provide the relevant information to code the shape of the vocal tract as well as any change in vocal tract shape. Moreover, because of the low frequency nature of speech movements, the receptors can update the relevant information in real time.

As suggested above, whatever information is used must be used in a predictive manner, since once a movement is made it is too late to make an adjustment during running speech. Based on previously reported latencies (Abbs & Gracco, 1984) and the time necessary for using predictive estimates (coded velocity and/or acceleration) of the peripheral conditions to modify speech motor commands, it has been suggested that speech motor commands can be updated automatically from somatic sensory receptor information (Gracco, 1987). Even during rapid speech, time is available to make a simple coordinate transformation between somatic sensory input and somatic motor output. For the auditory modality, the same possibility is not as plausible, because of the additional transformation required and the potential ambiguity between the auditory signal and the state of the vocal tract. It is also possible that the auditory system may not operate with a sufficiently short time-constant to make adjustments that are required for movement-to-movement parameterization. While auditory-motor reflexes can be elicited with short latencies (15 ms), they are generally not functional and require stimulation that is not normally generated during ongoing speech. As mentioned above, the Kawahara (1993) results, using more natural and finer-grained changes in fundamental frequency,



revealed average latencies on the order of 150 ms, latencies that would be too long to make adjustments on the order of individual vocal tract actions. These latencies, however, would be consistent with a suprasegmental role for the auditory system during ongoing speech. While speculative, it can be suggested that the auditory system may be contributing to the control process with a longer time constant than that of the somatic sensory system (see also Lane & Webster, 1991; Perkell, Lane, Svirsky, & Webster, 1992). Given the more direct relation between the somatic input and motor output than between the auditory input and motor output, this is a plausible position and one that is open to empirical evaluation.

### The Sensorimotor Domain

In order to complete this limited overview of the potential role of sensorimotor mechanisms in speech production, it is critical to establish the context from which sensory-based adjustments are made. As suggested above, during speech motor development a child learns a set of coherent motor patterns that can be used to produce the unique sounds of the language, along with a set of coordinate transformations between the state of the vocal tract and the desired perceptual results. Once these mappings have been accomplished the child has acquired a set of characteristic motor commands that can be used as the input to the speech motor system and has also acquired a way of modifying the commands to adapt to changing peripheral conditions. These characteristic motor commands form the basis for speech production and act as the substrate upon which all modulating processes operate (Gracco, 1991; Perkell, Matthies, Svirsky, & Jordan, 1994). As such, speech movements are not generated *de novo* for each occurrence or production but rely on learned neuromotor commands that are stored in the nervous system. Based on arguments presented elsewhere it is suggested here that the learned motor patterns for speech reflect control structures or units that are organized according to the physiological (neuromuscular) components that generate the sounds of the language (see Gracco, 1990, 1991). Such a conceptualization is consistent with a model of speech production in which articulatory actions map onto the phonetic segments of the language, but this view is equally captured by the notion of gestural constellations (Browman & Goldstein, 1989, 1992), activation variables (Saltzman & Munhall, 1989), and coordinative structures (Easton, 1972; Fowler, 1980). Phoneme-based models have a long history, with many originating from Haskins Laboratories (Cooper Liberman, Harris, & Grubb, 1958; Halle, 1962; Halle, 1964; Halle & Stevens, 1964; Liberman, 1957; Liberman, Cooper, Harris, & MacNeilage, 1962; Liberman, Cooper, Harris, MacNeilage, & Studdert-Kennedy, 1967; Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Lindblom, 1963; Moll & Shriner, 1967; Öhman, 1967; Stevens & Halle, 1967; Stevens & House, 1963). However, as noted above, a major problem with all

theoretical positions positing units of any kind has been the failure to find invariant units at any peripheral level of observation such as the acoustic, kinematic or electromyographic. However, rather than reflecting a problem for models with invariant constructs, the lack of invariance should be considered the norm and a reflection of the adaptive nature of the speech motor control process. For example, the same set of motor commands issued without regard to changing peripheral conditions (phonetic context) would almost always result in errors. Contextual variations, which are ubiquitous in speech, necessitate a mechanism able to adjust to the output of a constantly changing peripheral environment. Combining the notion of a predictive control process, in which the current state of the vocal tract is used to update activated characteristic neuromotor patterns through a simple sensorimotor coordinate transformation, with invariant motor commands is one way in which flexibility is achieved for ongoing speech production. Two important aspects of speech motor control involve the notion of stored motor commands that activate vocal tract configurations and the sensorimotor updating of a future (not present) set of motor commands. It should be pointed out that characteristic motor patterns are only viewed as categorically invariant (see Gracco, 1991, for more detail) and that the motor commands and the sensory interactions are only two processes that modify the observable output. Other linguistic and cognitive influences interact to produce changes in speech motor output; that is, speech movements are an end-product reflecting a number of serial and parallel processes.

## CONCLUSION

Speech production, as most skilled motor behavior, is viewed as a sensorimotor process in which central representations interact in complex ways with peripheral sensory signals to produce the resulting dynamic movement patterns (Abbs, Gracco, & Cole, 1984; Gentner, 1987; Gracco, 1987; Gracco, 1987). The issue dealt with here is when and how the various sensory signals modify speech motor output. The thesis developed is that the role of a sense modality in the speech production process is dependent upon the functional properties transduced by that modality, and that each modality (kinesthetic, auditory, and visual) provides different kinds of information to the nervous system that in turn influence the production process in unique but related ways. From a control standpoint, the control action is a set of motor commands for each unique sound of the language. These motor commands are modulated by the constantly changing peripheral environment in such a way that the positions of various articulators for one segment act to generate changes in future motor commands for another segment. The use of invariant motor commands, specified as equilibrium positions, integrated with explicit consideration of peripheral sensorimotor modulations, has been offered successfully in a model of jaw motion (Flanagan, Ostry, & Feldman, 1990; Laboissiere, Ostry, & Feldman,

submitted). In spite of limitations of current models, it is clear that any model of speech production must have some explicit transformation of the output by afferent-dependent coding of vocal tract states, so that the control system will have the necessary adaptability. In conclusion, it appears that the concepts of variable articulations and invariant vocal tract targets can be integrated and understood once the potential contribution of sensory information is included. The empirical work done by Katherine Harris and her colleagues as well as the empirical work they motivated have facilitated this important theoretical synthesis.

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