6 The Cortical Representation of Motor Processes of Speech

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ABSTRACT

This chapter proposes, first, a synthesis of the contemporary premises of speech motor control, and second, an analysis of the neurological disturbances of this function. It is proposed that during language acquisition, the motor system stores contractile and temporal relations that define the articulatory actions of speech. These relations are thought to be the basis of local synergies between muscle groups in various portions of the vocal tract (mediated by the primary motor cortex), and of global synergies that coordinate the actions of the entire vocal tract (mediated by the secondary motor cortex). In the post-acquisitional phase, these synergies are thought to constitute some of the basic building blocks of the articulatory utterance chain.

The relational aspect of these synergies suggests a number of verifiable hypotheses for neurological impairments of language. For instance, it predicts that certain neurological lesions may disrupt the relational aspect of the programming of articulatory events; as a result, speech would become dysfluent and dyscoordinated. These predictions are supported by research on Broca's aphasia, which is characterized by excessive dysfluency and by disruptions of interarticulatory coordination. Further, the hypothesized differentiation of local and global synergies predicts known differences between certain types of aphasia and dysarthria. Specifically, the global phonemic disturbances of conduction aphasia are found to contrast with the typically more local phonetic disturbances of spastic dysarthria.

Throughout the history of psycholinguistics, the study of neurological disorders of adult speech has held out the promise of contributing to the understanding of the relationship between linguistic performance and the neural structures mediating this performance. However, a number of factors have retarded progress in establishing direct relationships between language performance and its neurophysiological substrate. Chief among these are the great variation between apparent localization of functions in various speakers, the difficulty of inferring normal speech function from disordered function, the impossibility of conducting crucial neurophysiological experiments with human subjects, and a long history of terminological confusions.

To remedy these problems, arguments have been made for abandoning the localizationist frame of reference as primary conceptual map in favor of a psycholinguistic process frame of reference. This is because all speakers of a given language must engage in fairly similar performance processes, such as discourse structuring, lexical selection, syntactic and morphological structuring, phonological and articulatory phonetic processing. For speakers of a given language, one may assume similar interrelations between processing events, despite differences in the number of available lexical or syntactic elements. Within this framework, neurogenic language production disorders are seen as selective impairments of one or several psycholinguistic processes, regardless of site and size of the underlying lesion. This approach, which ensures greater comparability of disorders from one patient to another, facilitates the construction of measuring instruments for aphasia and dysarthria, and shows promise of reducing terminological confusions.

Despite its usefulness, this approach does not replace or abviate research on the relationship between language and its physiological substrate. Indeed, there are circumstances and research purposes where it is promising to link functional hypotheses to pertinent neuroanatomical and neurophysiological information. This is the case with motor processes of speech, where subject-to-subject variation in localization of language production processes appears to decrease with proximity to the final output. Further, the neurophysiology underlying motor control is better understood than that which mediates cognitive systems, and can thus provide some indications of how speech motor control might be organized. Finally, there is a growing body of research that ties observations on neurogenic speech disturbances to neurophysiological principles of motor control.

Thus two distinct theoretical approaches to neurogenic language impairments have emerged, on one hand, computationally oriented hypotheses arising from formal linguistics, cognitive psychology, or artificial intelligence; and on the other, neurophysiologically oriented hypotheses originating in articulatory phonetics, physiological psychology, and neurophysiology. The research purposes served by these two approaches are fundamentally different. The purpose of computationally oriented hypotheses is to state formally and explicitly how linguistic units interact in speech production without

reference to neurophysiological events. Neurophysiologically oriented hypotheses, by contrast, state general principles of operation and explain a number of observations by means of a single, coherent set of assumptions. They attempt to show the general form of the interaction of linguistic units, as much as possible with reference to it neurophysiological matrix. Although of no immediate interest to formal linguistics, computational cognitive psychology, or artificial intelligence, such hypotheses are indispensable for orienting future physiologically oriented research on speech motor control in neurophysiology, physiological psychology and articulatory phonetics, as well as to the clinical understanding of neurogenic speech disturbances.

This chapter is an attempt to formulate a neurophysiologically oriented hypothesis. It proposes that one of the fundamental cortical functions in speech motor control is to learn to execute articulatory movements by abstracting and storing relations (or "synergies") between commands for individual articulatory muscle groups[1]. It further argues that toward the end of the speech motor acquisition period, the major function of the cortex in speech motor control shifts to the selection of such synergies, and to their adjustment to environmental conditions. This view is contrary to that of some other authors (e.g., Abbs & Cole, 1982), who maintain that, rather than producing speech segments from a large number of stored movement patterns, movement patterns are generated afresh each time they are required[2].

In the first part of this chapter contemporary functional and neurophysiological perspectives of speech motor control are synthesized. In the second part, the hypothesis is outlined, and some predictions for neurogenic speech disorders are examined. Most of the findings and principles leading up to the hypothesis are well established, although they are presented here in the condensed form of a personal synthesis of the field. The hypothesis itself is more explicit and in some respects more comprehensive than previous, similar accounts (Abbs & Cole, 1982; Keller, 1984; Kelso & Tuller, 1981), and the examination of its predictions for neurogenic disorders is original[3]. To render this contribution accessible to as wide and diverse an audience as possible, little specialized knowledge concerning motor control, neurophysiol-

[1] In this chapter, the term *muscle command* refers to an internally regulated neurological impulse train, related to and preceding a peripheral contraction in a coherent muscle group. It is assumed that such a command represents the coordinated output of a large number of motoric neuronal cells.

[2] In all fairness to authors such as Abbs and MacNeilage who have in the past defended the "generating afresh" hypothesis, they have generally done so with a fair bit of caution. Far less careful of this issue have been a number of authors in the clinical domain (cited by Goehl & Kaufman, 1984); assuming not only fresh generation but also total dependence on feedback for each articulation, these authors appear to have uniformly (and erroneously) predicted severe deterioration of speech production subsequent to impairments of a feedback channel, as through adventitious deafness.

[3] This chapter incorporates and clarifies concepts previously sketched out in Keller (1975, 1978, 1979, 1984).

ogy, and neurogenic language disorders has been assumed, and the use of technical terms has been restricted to a minimum.

A. BASIC ASSUMPTIONS I: THE FUNCTIONAL ORGANIZATION OF SPEECH

1. The Variable of Time, The Planning/motor Processes Distinction and the Automaticity of Motor Actions

All consideration of language performance is ultimately tied to the parameter of time. Production processes do not only occur in "real time," but they are constrained and shaped by time limits—limits that are partly due to social and communicative needs and conventions, and are partly the result of physical inertial and oscillatory aspects of articulatory movements.

As an example of a socially imposed time limit, asking a question usually sets up a time constraint for the answer; if the answer is not produced within that time, it may be ignored or discounted. As an example of an inertial and oscillatory time constraint, one may think of the articulatory rhythm imposed by the weight and the contractile characteristics of the speech musculature on a continuous, rapid (diadochokinetic) repetition of "dadada . . ." (see also Kelso & Tuller, this volume). Due to such constraints, audible spontaneous speech is typically (a) restricted to certain time slots and (b) produced at a fairly rapid and rhythmic rate.

In order to be able to produce such well-paced utterances, speakers plan out portions of their utterances beforehand. Evidence for this is that the search for a difficult-to-remember word may take more time than is indicated by its prompt appearance in the appropriate spot in the utterance; in fact, normal anticipation errors such as ". . . *T*anadian from *T*oronto . . ." (Fromkin, 1973) indicate that planning events may precede execution events by a considerable margin, and may thus involve processes that are functionally separate from execution processes. In this view, planning and motor processes in continuous discourse operate concurrently (in parallel), while operating on linguistic information sequentially.

This by now well-established psycholinguistic notion (e.g., Foss & Hakes, 1978; Keller, 1979; MacKay, 1970) corresponds to our introspective awareness, and accounts satisfactorily for a number of normal speech phenomena (e.g., anticipatory speech errors, hesitations). In the present context, the notion of differential time constraint further permits us to delimit speech motor processes from speech planning processes by the criterion of automaticity. Due to the rigid time constraints imposed on motor processes by the processing mechanics, motor processes must deal primarily with highly repetitive, not-too-varied and predictable relationships which can be automatized through learning. Examples are: processes for translating the chain into executable and coordinated articulatory movements, for adjusting the output to actual speaking conditions, and for muscular execution. These processes involve fewer and more frequent elements than do planning processes, and can thus be highly automatized.

By contrast, the planning stage appears to involve above all those processes that cannot easily be automatized, because they involve the manipulation of unpredictable or infrequent processing variables. Decisions for the implementation of various aspects of the speaker's discourse, the selection of lexical items, and many syntactic and morphological decisions are complex and involve a great variety of infrequent elements that are not easily automatized.

It merits pointing out that the present distinction between planning and motor processes is not synonymous with the difference between supraphonological and phonological levels, characteristic of most linguistic descriptions. Phonological anticipation errors indicate that planning must be concerned with phonological information, whereas motor processing can be shown to be concerned with selected morphological events.

For example, evidence from spontaneous speech errors indicates that the morphophonological choice between the indefinite articles "a" and "an", preceding words beginning with consonants and vowels, is usually made during motor processing (see Fromkin, 1973, pp. 229 & 259). If it can be assumed from the model of the anticipatory errors that most speech errors occur at the interface between planning and motor processes, an adjustment in the "a/an" choice subsequent to the speech error implies that the "a/an" choice is a motoric process. Fromkin's data show, for example, that "an ice cream cone" became "a kice ream cone," and "a history of an ideology" became "an istory of a hideology." In those cases, the spontaneous speech errors apparently created inputs to the motor processes to which the *a/an* selection process adapted instantaneously, evidently during the process of motoric outputting.

Similarly, by the automaticity criterion, the selection of the most common closed-class (function) words could be performed during motor processing, whereas the selection of most open class (lexemic) words could be performed during planning. This is because the selection of closed class words is highly predictable and makes use of frequently used manipulanda, while the selection of open class (lexical) words involves a large inventory of words of generally lesser frequency of occurrence. Consequently, the selection of closed-class words can be more easily automatized than the selection of open class items, and can be integrated more readily into time-critical speech production processes.

The overall speech production framework to emerge from these considerations is somewhat different from traditional conceptions of speech production. Early linguistic models were constructed around the separability of semantic, morpho-syntactic and phonological levels, yet all but ignored time constraints and related concepts of processing complexity and automaticity. Within an online processing model, considerations of time constraints became primordial, since the possibilities of buffering information decrease with proximity to final output. The more peripheral motoric processes are thus seen to be more time-critical than the more central cognitive processes. As a consequence, the demarcations between semantic, morpho-syntactic and phonological types of processing become obscured, and the distinctions between more or less predictable (and thus more or less automatizable) processes of any type become more pronounced.

Although the notions of time constraints and automaticity have not yet been extensively investigated, there are some indications that this conceptualization makes the right predictions for both normal and neurogenically impaired speech. In normal speech, for instance, the degree of vowel reduction appears to be determined in part by the degree of automaticity of the syllable in question; unstressed syllables are shorter in duration and involve lesser articulatory movements than stressed syllables (Delattre, 1969; Ostry, Keller, & Parush, 1983). The vowels of unstressed syllables are thus said to be "reduced" in comparison to those of stressed syllables. But similar reductions in syllable duration and articulatory gestures have also been observed for closed-class words, as compared to their open-class homonyms. In pilot data from our laboratory, the French closed-class items "la" [la] (the) and "vers" [vɛR] (toward) have been found to be produced in a shorter time than their homonymous lexemes "las" [la] (weary) and "vers" [vɛr] *"worm"* in the sentence *"le vers las rampe vers la cabane" (the weary worm crawls toward the hut" ("vers": paired* $t = 5.8$, $p < .025$, one-tailed, $n = 5$; "las/la": paired $t = 3.2$, $p < .05$, one-tailed, $n = 4$).

Predictions for neurogenically impaired speech are similarly encouraging. If closed-class items can indeed be inserted into the speech chain during the motor processing stage, it would follow that lesions affecting motoric output processing should in some proportion of cases also affect closed-class processing, while leaving essentially intact open-class processing. Syndromically, this prediction corresponds to clinical experience: although only a subset of patients with motoric types of aphasia show agrammatism (i.e., impairments in the processing of predictable, easily automatized closed-class items), those that do show agrammatism without fail also experience motoric speech impairments. Further, the recent documentation of two aphasic patients who showed agrammatism without comprehension deficit of closed-class items (Miceli, Mazzucchi, Menn, & Goodglass, 1983; Nespoulous & Dordain, 1985), further supports the notion that this type of disorder may take its origin in motoric processing.

We conclude from these arguments that motor processes are differentiated from cognitive processes primarily by their responsiveness to time constraints, and are by implication limited to automatizeable processes operating on predictable and high frequency items.

2. Perceptual Goals

Traditionally, the motor processes of speech have been seen as performing a simple translation between a planned utterance and its muscular and acoustic equivalent. Partly because of our robotic preconceptions, this has seemed to be nothing more than a mechanical task, consisting of "looking up" and executing typical motor equivalents or stereotyped muscle actions in response to given demands.

However, the research of the last 15 years on articulatory motion in speech (the so-called "kinematics of speech") has shown that the likely course of events is quite different. Most importantly, it has been found that a given perceptual goal can be achieved by different muscle actions, depending on momentary and local requirements. As far back as 1955, Stevens and House calculated formant frequencies for a vocal tract simulation and showed that a given vowel does not require a unique vocal tract configuration (Fig. 6.1). They found that a vowel formant pattern typical of a given phoneme could be obtained with a whole range of vocal tract configurations by manipulating the degree of mouth opening, the radius of minimal constriction, and the distance between the glottis and the point of maximal linguo-palatal constriction ("point of constriction").

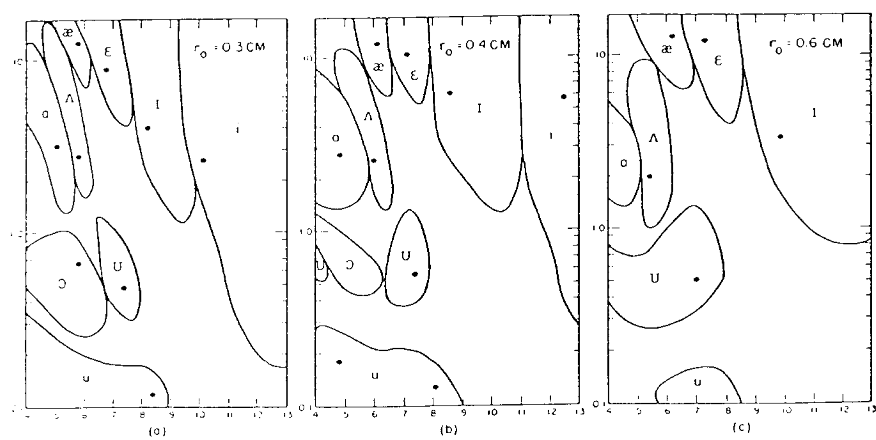

FIG. 6.1. Different configurations of the vocal tract capable of producing the complex acoustic waveforms of certain English vowels (Stevens & House, 1955). These results derived from calculations for a simulated vocal tract, indicate that the full set of English vowels can be produced by various combinations of maximal intra-oral constriction (panels a to c), the distance between the larynx and the point of maximal contribution (x axis) and the degree of mouth opening (y axis). (From Stevens & House, 1955.)

Subsequently, observational and experimental data gave further credence to the notion that two tokens of the same perceived acoustic category can be produced with widely differing gestures. A number of authors demonstrated covariance between two participating articulatory structures, such as when the lips show a small movement in performing an oral closure at times when the lower jaw performs a large movement, and a large movement when the lips show a small movement (Hughes & Abbs, 1976; cited in Abbs, 1982). Also, it was found with various articulatory gestures that the placing of an unexpected interference on an articulator produces short-latency compensatory movements in an unaffected coarticulator. In an experiment that has become a classic in this domain, Folkins and Abbs (1975, 1976) put an unexpected load on the jaw during the jaw closure for *p* in [h*æpæp*] and observed compensatory behavior in the two lips, implemented so rapidly that there was a satisfactory oral closure despite the arrested jaw movement (Fig. 6.2). Oral closures resulting in the same perceived phoneme were always performed in these experiments, no matter whether they involved varied movements of the lips, or compensation by one structure for another.

This suggests that the ultimate criterion (the "goal") of articulatory performance is not articulatory, but perceptual. Under this hypothesis, a typical speaker would consider his motor performance to be satisfactory as long as his output conforms largely to the perceptual categories he has internalized for the given language. His ultimate criterion would be perceptual, even though his internal and automatic self-correction processes may depend upon criteria that integrate auditory with correlated proprioceptive information. At

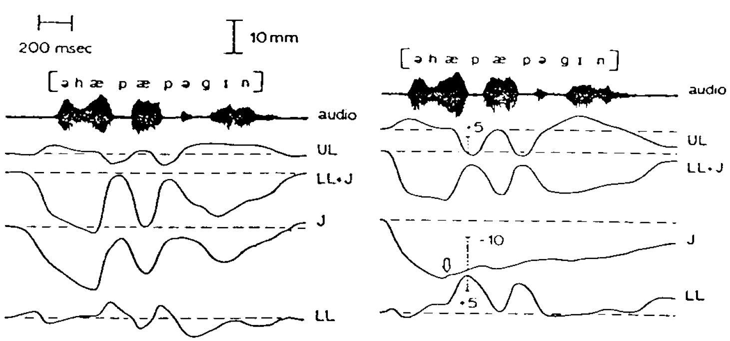

FIG. 6.2. Compensatory lip movements with perturbation of the jaw trajectory during the articulation of the stimulus phrase "Say a [hæpæp] again." On the left panel, the upper lip (UL) descended during the transition from [hæ] to [p], while the jaw (J) and the lower lip (LL) rose. On the right panel, the jaw action was impeded at the moment indicated by the arrow. The two lips compensated this perturbation by performing relatively greater movements (additional displacement for each lip: 5 mm). The audio trace indicates that despite this maneuver, the lip occlusion was sufficient to block all speech sounds. (Folkins & Abbs, 1975.)

the segmental level, the perceptual category boundaries presumably correspond to phonemic category boundaries, whereas at supersegmental levels, they may correspond to category boundaries established according to the particularities of the language in question (viz., syllabic structure, stress, and/or intonational contour patterns). We thus expect a speaker to correct himself primarily when the perceptual category boundaries are violated and only rarely when they are not. Although systematic examinations remain to be performed, this prediction receives some support from the predominance of phonemic over sub-phonemic exchange errors in normal speech (Shattuck-Hufnagel, 1983).

The perceptual goal thus occupies a key position in the present theoretical framework. At the same time, acoustic or perceptual category boundaries should not be considered to be inviolable; some speakers of English can be observed to habitually neutralize even stressed vowels, while others systematically transgress phoneme boundaries due to an articulatory handicap. I have observed a patient with congenital cerebral palsy who lacked facial nerve (cranial nerve VII) muscle control but who had intact glossopharyngeal (c.n. IX) and hypoglossal nerve (c.n. XII) control. He was incapable of controlling his lips, but could produce effective alveolar and oral stops and nasals. While speaking, he regularly substituted alveolar for labial consonants. Although his speech was clearly affected by these phonemic substitutions, it was surprisingly understandable, especially after some auditory training. Evidently, listeners will tend to auditorily compensate the breach of perceptual categories as long as the redundancy in the message permits. Yet it remains that generally, speakers will tend to respect such perceptual boundaries, particularly when it is important that they be well understood.

3. The Notion Of Motor Equivalence

These observations on speech motor control can be summarized by the concept of motor equivalence (Hebb, 1949). In its original formulation, motor equivalence captured the principle underlying the finding that rats, trained to run a certain maze, will subsequently show superior performance in swimming a similarly laid-out water maze. More recently, the term has been applied to motor function in the sense that a given motor objective can be implemented by a number of different muscle contractions, or different muscle groups, on condition that contractions combine to achieve a given goal.

In this view, the motor system does not mechanically translate a conceptual goal into a set of muscular contractions. Rather, its responsibilities is to learn command structures defining combinations of muscular contraction which can implement a perceptual goal, to select structures appropriate to the present circumstances from the family of structures that have previously been successful, and to adjust or bias, the selected commands in terms of the prevailing circumstances. The crucial concept inherent in this formulation is that there are whole families of commands to be learned, selected, and adjusted, whereby each family is united by a single goal. Motor equivalence is a general principle of motor action, and can be documented for actions as divergent as speaking, playing golf, or shooting rifles, each being characterized by achievement goals that are remote from the anatomical structure involved in its implementation.

The motor system thus has no direct link with the achievement goal. Because the system can only control muscle contractions, its task is to learn—perhaps through perceptually guided, successive approximations—the combinations of contractions which can achieve the given perceptual goal. Under these circumstances, the nervous system will discover a set of systematic relations between commands to various muscle groups, and between the muscle commands and the achievement of the remote goal. In doing so, the system learns to set its contractions of muscle groups in such a way that the combined effect falls within the boundaries set for the achievement of the goal; in the process, the system abstracts relations, or "synergies", between the various "successful" muscle contractions, and by implication, between the commands that implemented them.

The central concept is that movement commands are fundamentally defined as learned relations between specifications for the contraction of individual muscles. Informally, this knowledge can be envisaged to be relationships of the type "if degree of contraction in muscle group A is relatively small, then there must be a greater degree of contraction in muscle group B, in order to implement the goal correctly and with maximal efficiency," or "contraction in muscle group A must be initiated when contraction in muscle group B has attained degree x." These relations are seen as hierarchically organized, whereby the two levels of greatest importance to speech motor control are that of the movement aggregate, associated with the motor programming stage and responsible for an entire speech gesture, and that of the grouping of individual muscle commands for a given speech tract valve, characteristic of the execution stage and responsible for aspects of the speech gesture, such as nasality, voicing or labial closure.

4. The Reduction Of The Degrees Of Freedom

In order to implement the multitude of relations between muscle commands in a real-time speech event, the system must set the degree of muscle contraction for each muscle group, taking into account the named local and general conditions. Since there are around 60 identifiable muscle groups in the human vocal tract, each capable of a range of contractions, and cooperating to produce around 10 to 15 phonemes a second, the system encounters considerable computational complexity. This problem is known as the "degree of freedom" problem.

To briefly summarize arguments presented in great detail by Kelso and colleagues (e.g., Kelso & Tuller, 1981; Kelso et al., 1983), physiological systems faced with this problem will attempt to reduce computational complexity by establishing "coordinate structures", which are links, or predictable relations, between the freely varying variables. This is comparable to a "program" for movement synergies, phrased in terms of sequential, overlapping and parallel relationships between muscle commands. These programs permit the system to simplify its task by letting learned links between muscle commands take care of predictable relations for a given condition.

Two important consequences of reducing the system's degrees of freedom are first, that movements become more stereotyped (through the loss of degrees of freedom of movement), and second, that the gain in simplicity translates into greater speed of operation (unless the system is specifically "set" for slowness). We may speculate that the speed obtained by applying this type of knowledge results from eliminating repeated complex calculations of sequential organization and degree of muscle contractions.

5. Are Movement Parameters Produced From Storage Or Calculated Anew In Speech Production?

The present proposal emphasizes that movement information is learned, which in turn implies that normal, skilled articulation involves selecting aggregates of muscle commands from a store of commands, rather than generating afresh all the movement information each time a speech articulation is to be produced[4]. This position is somewhat controversial. Some authors would maintain that the number of movement aggregates to be stored is necessarily excessive, because there are several hundreds of thousands of possible phoneme-to-phoneme movement transitions to be stored away, just counting possible CVC combinations. In their view, this is an unlikely and inefficient account of normal speech production.

However, this argument loses some of its punch if one takes into account the unequal distribution of phoneme transitions in the language. Roberts' (1965) frequency tables for phoneme-to-phoneme transitional frequencies indicate, for instance, that out of 512 possible phoneme-to-phoneme transitions involving at least one vowel, just 37 transitions (or 7%) capture 51.4% of all transitional events. Other types of transitions are similarly unequally distributed. It therefore does not seem impossible for a neurological system to learn of the order of several hundred or several thousand of the most fre-

[4] In line with theories that view memory storage as occuring in close conjunction with neuron pools involved in a given process, the store for articulatory movement aggregates is assumed to be a facilitation process for previously used neuron interactions. "Selection from store" can thus be understood as "the activation of those neuron interactions that have been potentiated through previous use".

quent phoneme sequences, leaving the least frequent transitions to be calculated as the need arises.

The second argument brought against the "learning and storing" view of muscle commands is the demonstrated presence of fast compensations to unexpected perturbations in the vocal tract (see section on Perceptual Goals). It is argued that this is evidence that the system calculates movements in an ongoing fashion, taking into account all current, past and future conditions in the vocal tract, including unexpected perturbations.

However, it can be argued that the presence of compensations does not negate the learning and storing away of articulatory movement information. It is equally possible that generally, the system produces skilled speech from storage, but retains the option to bias it just before outputting, in order to compensate potential perturbations and to learn new movement patterns as the need arises. This view is concordant with relatively recent views on feedback in speech and with some pertinent findings on neurogenic disorders (see below). It also has the non-negligible advantage of embracing the concept of motor learning inherent to all language learning, be it the learning of a specific language, or learning to compensate for a regular encumbrance in the speech tract.

6. The Variability Of Feedback

Feedback processes assume the responsibility of informing the system about preceding local conditions in the vocal tract, and of initiating corrective action if necessary. Their organization is still in some dispute, because there is seemingly contradictory evidence on the importance of feedback information to the motor processes of speech. On the one hand, the efficient, short-latency compensations to perturbations obtained by Abbs and his coworkers indicate that in the normal speaker, the system has continuous and rapid access to sensory feedback on conditions in the vocal tract.

On the other hand, experimental or pathological interference with various types of feedback from the vocal tract has relatively little effect on the quality of speech, even when auditory and proprioceptive channels are impaired simultaneously. Borden (1979), for instance, reviews experiments in which auditory, tactile and proprioceptive feedback was distorted or interrupted by a variety of means, such as providing delayed auditory feedback, testing with noise conditions, or blocking sensory feedback through nerve anesthesia. The overwhelming impression conveyed by these experiments is that spontaneous speech in normal adults under predictable conditions does not crucially depend on feedback, despite some loss of precision when feedback is impaired (Gracco & Abbs, this volume). Convergent results derive from studies of the adventitiously deaf; adults who undergo sudden loss of hearing do not lose their ability to speak. Other than minor difficulties with fricatives

and with judging voice amplitude, such persons show essentially intact speech; in blind listening conditions, their speech cannot be reliably distinguished from normal speech (Goehl & Kaufman, 1984).

Borden resolves this paradox by postulating that interference with feedback has only minor effects when speech is produced in predictable conditions (i.e., head upright and vocal tract unimpeded in an experienced speaker), but seriously hampers the compensation of unpredictable conditions and the calculation of less habitual movements (i.e., the presence of unpredictable vocal tract conditions in an experienced speaker, or a speaker inexperienced with a given language or set of vocal tract conditions). In this view, feedback recedes for the most part to a surveillance position in the motorically proficient adult, while it contributes directly to the calculation of articulatory movements during a motor learning phase, be it in childhood or in adult life. In support of this position, Borden summarizes studies showing that young children learning their first language and adults learning a second language are more severely affected by disruptions of auditory feedback than are adults speaking their native language (see MacNeilage, Rootes, & Chase, 1967). This notion is also supported by Oller and MacNeilage's (1983) reports that children are less capable than adults at compensating the presence of bite blocks between their teeth.

We note that this hypothesis does not address the question of feedback in the traditional either–or terms of "closed loop" or "open loop" operation (operating with or without feedback control), but it suggests that the exact degree of involvement of feedback information depends on the present state of the speaker's motor competence. In addition to being compatible with the notion that skilled movements in predictable conditions are produced from storage, this flexible view of feedback incorporates the speed advantage of movements selected from storage with reduced calculation load. At the same time, it accounts for results obtained with the perturbation paradigm by permitting a selected movement to be biased to compensate for unexpected perturbations and inhabitual steady-state conditions in the speech tract.

B. BASIC ASSUMPTIONS II: THE PHYSIOLOGICAL ORGANIZATION OF SPEECH

1. The Relation Between Limb And Speech Motor Control

Because much previous work in motor neurophysiology has concentrated on limb control, it is important to open this section by discussing the appropriateness of using neurophysiological findings on limb control in an exploration of speech motor control.

In terms of anatomy and neurophysiology, there are important differences between limb and speech articulations. The limb control system is fundamentally concerned with relatively gross bone movement, whereas the speech control system involves principally fine movement of muscular tissue; further, limb movement typically involves rotation around a pivot, accomplished by a group of lateralized muscles operating in a dominant agonist/antagonist muscle mode, whereas speech articulation involves a large number of bilaterally attached minor muscle groups serving to shape several muscular masses (e.g., tongue, lips, velum) by means of complex agonist/antagonist formations. These differences bear on the lateral versus bilateral nature of final cortical motor control, and they may be expected to have consequences upon the degree of complexity in coordination, accomplished by the respective neurological control structures.

Another difference concerns the locus of control for the two systems. At least with respect to subhuman hind limb control, contemporary thinking distributes the main loci of control between the cortex and the spinal cord. Because decerebrate cats (spinal cord sectioned off from the brain) can be induced to walk on a treadmill while they are unable to walk on their own, it is argued that the so-called "spinal mechanism" of neural control must contain most of the "program" for the walking sequence (Carew, 1981), while the higher brain centers coordinate reflex activity with voluntary motor action and mediate spinal cord mechanisms by switching back and forth between different phases of the walking program (between the "swing phase", when the foot is off the ground and the "stance" phase, when the foot touches ground.

By contrast, there is little evidence for homologues to spinal mechanisms in speech motor control. For one thing, brainstem-based reflexes bear no obvious functional similarity to articulatory movement, since they have primarily vegetative and protective functions (e.g., to keep the teeth from biting the tongue or to keep water out of the lungs) (Abbs & Cole, 1982). Secondly, relatively short delay times (15 to 20 ms) are possible between the cortex and the articulatory musculature, enabling the cortex to adjust the articulatory program to perturbations within the constrained time frames of speech execution (Abbs & Cole, 1982; Cole & Abbs, 1983).

In view of such evidence, and taking into account the probable difference in evolutionary origins for limb and speech motor control, we assume that (a) the final output control over speech articulators tends toward bilaterality, although it is probably more unilateral in the case of the limbs, (b) the cortical component of neural control is more important for speech than it is for hind limb motor control, and (c) feedback for speech motor control is mediated primarily by the cortex, whereas it is handled more extensively at the spinal level in the case of certain forms of limb control. Evidence from neurophysiological experiments on limb control must therefore be interpreted with care and cannot automatically be presumed to be a standard model for speech control.

These differences in motor control design are not taken to be at odds with the similarities between limb and speech articulator movement that have been documented for aspects of displacement and velocity in speech and limb movement (Ostry & Cooke, this volume; Ostry, Keller, & Parush, 1983). If the two types of movements show kinematic similarities at the same time that neurophysiological evidence indicates differences at the level of the control structures, we must assume that the measured kinematic parameters do not address differences in locus or nature of the control structure, but that they are indicative of another level of motor functioning, or the effect of physical laws or physiological regularities governing any movement mediated by muscular tissue.

2. Somatotopic Organization, Direct Neural Innervation, And The Fractionation Of Movement

It is well known that the neural tissue making up the cortex is somatotopically organized. In the case of the motor system, this generally means that the surface stimulation of adjacent neural cells in certain areas of the cortex tends to produce simple, observable motor responses in closely situated muscular groups. With respect to sensory processing, this means, in the case of experiments with humans, that the stimulation of closely situated portions of certain areas of the cortex gives rise to perceived sensations in adjacent parts of the body; in the case of experiments with animals, however, it means that tactile stimulation of adjacent parts of the body tends to produce increased neural responses in neighboring parts of the cortex. The immediate motor and sensory responsibilities can be mapped out on the cortical area in question, or can be summarized by homunculi drawn on the cortical surface, with body parts proportional to the area of associated motor or sensory cortex.

The somatotopic organization of the human cortex differs from that of other mammals in ways that may bear on speech motor processing and its disturbances. First, there is much greater separation between motor and sensory representations in the human cortex than in that of other mammals. Ghez (1981) reports that there is complete overlap of motor and sensory representations in the hedgehog, a mammal whose anatomy seems to have remained unchanged for millions of years. With phylogenetic development, separate areas emerge in which either motor or sensory functions are dominant; in the cortex of higher primates including man, the frontal lobe is the site of primarily motoric functions, while the parietal and superior temporal lobes are dominant for sensory functions.

Parallel to the appearance of dominant (but not exclusive) areas for motor and sensory functions in the cortex, there is a development of increased direct cortical innervation of the peripheral musculature, with an associated increase of fine motor control over separate body parts (Ghez, 1981). This development is known as the "fractionation of movement." Lower mammals, including cats, present corticospinal motor innervations that terminate exclusively in the dorsal portions of the spinal cord where they do not make any direct connection with the motoneurons originating in the spinal cord. Progressively, as one examines prosimians, monkeys, apes and humans, there appear corticospinal tracts making monosynaptic contact with motoneurons of the distal limb musculature, and later, of the proximal musculature.

Similarly, there is indirect evidence to suggest that vocal tract control is more elaborate in humans than in lower mammals; the portion of motor cortex devoted to the vocal tract is found to be proportionally greater in humans than in apes, with about 30% of the human primary motor cortex devoted to direct innervation of the vocal tract, while the comparable figure for the simian primary motor cortex is about 18% (calculation based on homunculi shown in illustrations in Eyzaguirre & Fidone, 1975).

These indicators further support the notion that the human motor cortex is particularly well equipped to serve the speech functions described above. The frontal lobe has undergone the greatest phylogenetic development in man, it is motorically dominant and suited to fine motor control, and it is the site of a disproportionally large area concerned with vocal tract control. This area thus appears to be specialized for the mediation of fine motor control in the vocal tract, available above all for speech motor processing.

3. Primary And Secondary Motor Cortex

Another well established concept of importance to speech disorders is the difference between primary and secondary motor cortex. The primary motor cortex (Brodmann area 4) is situated bilaterally, immediately anterior to the central sulcus (Rolandic fissure). Electrical surface stimulation of this type of cortex elicits controlateral, discrete movements in a freely suspended anesthesized animal (Thompson, 1967). The secondary motor cortex is less clearly circumscribed. In animals, stimulation of parietal lobe areas dominant for sensory function will also tend to evoke muscle contractions, even when cortico-cortical connections to the primary motor cortex are ablated. However, contractions are evoked only at stimulation levels much superior to those used in the primary motor cortex (Thompson, 1967). Lesion studies in a variety of animals further suggest more complex motor programming by anterior frontal lobe cortex than is performed by the primary motor cortex (Denny-Brown, 1951), and more recent single-cell experiments have identified neuronal units in the parietal cortex related to specific classes of movements (Stein, 1978).

Penfield and Roberts' (1959) reports on the effects of stimulation of the exposed human brain during open-brain surgery indicate that with respect to speech as well, the primary and the secondary motor cortex may fulfill largely different functions. They report that stimulation of the primary motor cortex on either hemisphere resulted in uncontrollable vocalization and slurring of speech (although the right-hemisphere data are less convincing than those of the left hemisphere; see also Bhatnagar and Andy, 1983). By contrast, stimulation of the nonprimary speech areas, exclusively on the language-dominant hemisphere (perisylvian precentral, parietal, and temporal cortex), produced hesitations and perseverations on naming. Further stimulation effects dominantly but not exclusively related to the secondary motor cortex, were the repetition of syllables and serious distortions of speech (plus interference with a number of speech planning processes).

Although Penfield and Roberts used fairly powerful levels of stimulation by modern standards, an inspection of their figures indicates that these effects are fairly exclusive to either the primary or the secondary motor cortex. Further, this type of data is complementary with anatomical evidence concerning the origin of the cortico-bulbar pathway fibres, as well as with more recent localization indicators of ongoing brain activity (e.g., magnetography, see Beatty, Richer and Barth, in press; or blood flow studies, see various articles in vol. 9, no. 1 of *Brain and Language,* 1980).

These differences between stimulation effects in the primary and secondary cortex are quite revealing if interpreted in terms of relations between muscle commands during speech processing (cf. Fig. 6.1). Both vocalization and slurring, occurring with primary motor cortex stimulation, can be interpreted to involve primarily muscle commands affecting a single speech valve (speech valves are functionally-defined synergistic muscular units, such as those controlling the laryngeal, velo-pharyngeal, linguo-palatal and labial ports). In vocalization, articulators assume a relatively fixed position for the period of stimulation, devoid of the dynamic characteristics of normal speech motor action, while the laryngeal valve alone is active (in conjunction with the thoracic musculature, of course). Similarly, at least one manner of provoking slurring is to pose a steady impediment to the air stream by means of the linguo-palatal valve, possibly through a relaxation of the valve's entire musculature.

By contrast, perseverations and repetitions, provoked by secondary motor cortex stimulation, must involve entire movement aggregates (producing phonemes or syllables). This means that stimulation in the secondary motor cortex can mobilize motor units regulating the entire speech musculature. Penfield and Roberts' results may thus be interpreted to say that the primary cortex appears to be more directly concerned with synergistic contractions of functionally related muscular structures (valves), giving rise to friction, nasality, vocalization, etc., whereas the remaining perisylvian speech motor areas, particularly in the frontal lobe, are more directly concerned with the organization of larger aggregates of movements involving the whole speech musculature, that is, units at the phonemic and higher levels of phonological organization. These data are thus in support of the distinction between programming and execution stages in motor processing, introduced previously (section 6.A1).

The present interpretation of the responsibilities of the primary and secondary motor areas is also supported by more recent open brain stimulation experiments conducted by Ojemann and colleagues (e.g., Ojemann, 1980; Ojemann & Mateer, 1979). The stimulation of motor cortex in both hemispheres led to speech arrest and to impairments in mimicking single as well as multiple orofacial movements. In the dominant hemisphere, global mimicking impairments extended to the immediate premotor cortex. However, stimulation outside of this region in a wider area of peri-Sylvian cortex in the dominant hemisphere affected only the mimicking of sequences of orofacial movements, and left intact the mimicking of single movements. Areas where stimulation led to speech arrest and to impairment of all mimicking thus correspond to primary motor areas, whereas areas where only sequential mimicking was impaired correspond to secondary motor areas. Finally, results reported by Ojemann (1980) indicate that the extent of the primary motor cortex shows less inter-subject variation that of the secondary motor cortex.

4. Movement Versus Muscle Control: Intracortical Stimulation Experiments In Monkeys

The hypothesized concept of speech valve control in the primary motor cortex is also supported by neurophysiological investigations on cortically induced wrist movements in the monkey. Such movements are under direct cortical fine motor control and are thus probably more comparable to articulatory movements than motions partly mediated by spinal mechanisms (such as walking movements in the cat).

Meticulous studies by such researchers as Asanuma and Evarts (e.g., Asanuma, 1973; Evarts, 1974) have shown that certain neurons of the primary motor cortex relate directly to specific muscle groups at the periphery. By means of microelectrode investigations applying minimal stimulation currents inside the top four millimeters of cortical tissue, these authors were able to stimulate muscles groups independently of other groups to perform movements like thumb flexion, extension, adduction, and abduction (Asanuma, 1973). Such neurons are arranged in columnar arrays, called *cortical efferent zones,* which contain thousands of neurons and typically project to separate muscles around a single joint (Henneman, 1974).

Efferent zones with excitatory muscular effect are often situated close to zones with inhibitory effect on antagonist muscles, but neuron pairs with reciprocal excitatory and inhibitory effect are seldom situated within the same efferent zone. Each of these zones also receives proprioceptive and tactile sensory information from a large number of adjoining muscular areas, situated again primarily around a specific joint. Results obtained from the motor cortex of cats and monkeys were similar, except that monkeys showed a greater incidence of overlap between efferent zones for antagonist muscles, a finding probably related to their ability to fix a joint by simultaneously contracting antagonist muscles, such as when holding an object (Asanuma, 1973).

The primary motor cortex concerned with limb movement therefore appears to be "hard-wired" for producing individual muscle contractions, and it seems to be "programmable" for movements; further, the primary motor cortex appears to be anatomically "predisposed" for programming musculature involved in synergistic action around a given joint. The somatotopic organization of efferent zones insures that movements can be easily programmed by intra- and inter-columnar communications, if necessary with reference to sensory information arriving from the periphery. If this structural arrangement generalizes to vocal tract control in humans, it would appear that the architecture of the primary motor cortex favors, or at least does not impede, the hypothesized learning of relations governing synergistic contractions within specific speech tract valves.

In this sense we may have an answer to a question debated by neurophysiologists for close to a century, i.e., whether the cortex is organized so as to control individual muscle contractions, or whether it is organized in terms of controlling whole movements or even aggregates of movements. In retrospect, it appears that this was an unfortunate manner of posing the question. Since the cortex evidently controls both individual contractions and whole movements, it now turns out to be more profitable to specify to which degree, and in which parts of the brain, the system is "hard-wired", "programmed", or "predisposed toward spontaneous development of programs" to handle muscle contractions, movements or aggregates of movements.

As applied to speech production, the question is whether and to which degree there is predisposition for the development of articulatory programs. As we saw, evidence extrapolated from simian finger movement appears to favor a "predisposition" conception for the development of valve-related synergistic programs at the primary motor cortex level, and a "programming" conception for the higher-level organization of speech motor movement at the secondary motor cortex level.

C. THE HYPOTHESIS

At this point, the various strands of argumentation may be coalesced into an hypothesis on the cortical functions in the motor processing of speech.

First, we retain from the neurophysiological considerations that the cortex is the kingpin of the neurophysiological system subserving speech motor control. There is an absence of evidence for a speech homologue to the spinal mechanisms found for walking in subhuman animals, and the advanced level of the fractionation of vocal tract movement in humans indicates that the cortex is well-equipped to learn motor control over complex articulatory movements. Probably available to this learning process are neuronal structures permitting direct interactions between motor and sensory types of information; also, feedback delays between the periphery and the cortex are sufficiently short, so as to permit control over ongoing articulatory movement within the cortex.

Second, we retain from the functional considerations that the motor processing system: (a) uses and abstracts relations, or links, between the actions of different muscle groups, in line with given perceptual goals, and (b) takes into account preceding, ongoing and anticipated vocal tract conditions, as well as predominating local and external conditions. Both the need to reduce the system's degrees of freedom of operation and the multiple interplays between articulators impose the development of a network of predictable relations between muscle commands. As a result, speech motor action is mediated by families of linked commands, united by common perceptual goals and by similar articulatory movement characteristics. Three central aspects of speech motor control are therefore learning which, how, and under what circumstances muscle commands are grouped, selecting appropriate muscle command groups in skilled speech, and adjusting them to environmental conditions to the degree that they diverge from commands used in predictable speech articulations.

Third, we postulate that the bilateral primary motor cortices are concerned with more elementary aspects of speech motor control than is the unilateral secondary motor cortex in the language-dominant hemisphere. It would seem that the primary motor cortices are predisposed to develop linkages between muscle groups within individual speech tract valves (the labial, linguo-palatal, velo-pharyngeal, and laryngeal ports), whereas the secondary cortex is concerned with relations within organized movement aggregates involving the entire speech musculature. We retain that the anatomical extent of the primary and secondary cortices was functionally defined in this paper, and that these areas may show considerable subject-to-subject variation, particularly in the case of areas serving secondary motor function.

Finally, we postulate that in skilled speech production, and under predictable circumstances, the cortex selects commands for the most part without having to calculate muscle contraction settings on the basis of feedback information; however, in the initial stages of speech motor control, movement information is calculated on the basis of ongoing feedback about local and general environmental conditions. We also postulate that at the skilled stage, feedback continues to be used for calculating compensation biases for unexpected perturbations, for infrequent phoneme-to-phoneme transitions, and for inhabitual steady-state conditions in the vocal tract.

D. AN EXAMINATION OF PREDICTIONS FOR CORTICAL NEUROGENIC DISORDERS

1. Definitions

For the purposes of this section, it is important to define a few terms. Descriptively speaking, neurogenic disorders of speech motor processes tend to cause two rather different, but not mutually exclusive, impairments. On the one hand, a patient may produce distorted speech, whereby the entire speech chain is affected in the same manner, and where deviations from the norm for the most part fall within categorical (phonemic) bounds set by the perceptual goal. In their pure form, such phone*t*ic disorders are seen in patients affected by various types of dysarthria.

On the other hand, a patient may produce phonologically disordered speech; that is, speech characterized among other things by a variety of errors affecting individual phonemes or groups of phonemes. These errors transgress the categorical bounds of the perceptual goal to form phoneme substitutions ("literal paraphasias"); further, there are repetitions, additions, and omissions of phonemes or groups of phonemes. In their pure form, such phone*m*ic disorders are seen in patients affected by various types of aphasia.

Syndromically, phonetic disorders are typically seen in patients showing lesions of subcortical structures (extrapyramidal system, cerebellum, brain stem, and lower motor neurons). One type of dysarthria (pseudobulbar palsy) is caused by a lesion of the cortico-bulbar pathways (upper motor neurons) (Darley, Aronson, & Brown, 1975). Because these pathways originate largely in the bilateral primary motor cortex, it is also common to observe certain cortically-lesioned patients showing similar phonetic disorders, (i.e., continuous distortion of the speech chain) in addition to other language impairments, such as phoneme substitutions. In its pure form, this type of cortical dysarthric difficulty is described as "anarthrie pure" in the French literature, a term which will be used here in its English translation of "pure anarthria" (désintégration phonétique" in Alajouanine, Ombredane, & Durand, 1939). In its less pure forms, it is known as "trouble arthrique" or "arthric difficulty".

Syndromes characterized by phonemic disorders are seen in a variety of patients, showing various cortical or, more rarely, subcortical lesions, particularly in association with two major syndromes: (a) a syndrome characterized by slowness of speech and arthric difficulty, sometimes by agrammatism (the underuse of function or "closed-class" words), and by relatively intact comprehension (a syndrome known as "Broca's aphasia"), and (b) a syndrome whose main characteristic is a phonemic disorder associated with a severe repetition deficit, but devoid of arthric difficulty ("conduction aphasia"). A third common syndrome is characterized by a lack of arthric difficulty, by comprehension deficits, by word finding difficulties, and by paragrammatic speech (short stretches of grammatically correct speech within a deficient overall grammatical and discourse structure) ("Wernicke's aphasia"). Patients of this type show fewer phonemic difficulties than do those marked by other syndromes.

Although statistical differences have been demonstrated for these different types of neurogenically disordered speech (Keller, 1984; Nespoulous, Joanette, Ska, Caplan, & Lecours, this volume; Nespoulous, Lecours, & Joanette, 1983), no overall hypothesis has been advanced which successfully predicts the observed differential phenomena. The present neurofunctional hypothesis predicts many of the hitherto unexplained differences between syndromes as a consequence of impairments of the speech production processes defined here and of their underlying relational structure.

2. Difficulties Of Relating Neurogenic Language Disorders To Speech Production Processes

Despite this optimistic outlook, the major aphasic and dysarthric syndromes are not easily related to the speech production processes which have above been distinguished on functional, anatomical and experimental grounds. The major problem is that syndrome-process relationships are, for the most part, not one-to-one; some syndromes appear to affect several processes at a time, while others seem to interfere with processes affecting the transfer of information from one process to the next, and thus appear to argue in favor of processes not previously differentiated.

Patients with Broca's aphasia, for instance, show evidence of impairments at both the motor programming and the motor execution levels. Their frequent phonemic substitutions, their occasional productions of nonnative sounds, and their propensity towards consonant cluster simplification (Keller, 1984) indicate severe deficits at the motor programming level; at the same time, the continuous phonetic distortions (slurring, nasality, breathiness, etc), which typically affect their entire speech chain, are indicative of problems at the command execution level.

Conduction aphasia, on the other hand, appears to affect primarily the interface between planning and motor processes. One of the most characteristic impairments of these patients is that they often execute erroneous phonemes or syllables, but attempt to correct them immediately. Both correct and erroneous phonemes and syllables tend to be motorically intact (at least to the transcriber's ear), and their frequent, immediate attempts at correction indicate that their awareness of the intended utterance must be reasonably good (see also Joanette, Keller, & Lecours, 1980, for further evidence of intactness of planned phonemic targets). Analyzed in terms of the speech processes proposed above, it must be assumed that with respect to phonemic substitutions, their essential problem is neither at the planning or at the motor programming level; rather, it may very well occur at the point where the planned utterance is mapped, or "scan-copied", into the motor processes, in other words, at the interface between the two types of processes.

Essentially two analytical procedures are available to the theoretician faced with this problem. Either, processes are postulated directly on the basis of neurologically impaired language (an approach exemplified by Marshall and by Paradis in the present volume), or the attempt is made to relate externally motivated processes to the speech disorders of these patients (the approach chosen here). Both approaches have their advantages and their drawbacks. The advantage of the first approach is that all impairments and their derivative postulated processes are guaranteed to have "neurofunctional reality" in at least one patient. On the other hand, this approach can lead to an enormous proliferation of processes, with the attendant possibility that significant similarities between processes be obscured. Further, this approach may lead to the postulation of nongeneralizable processes, since there is no guarantee that all patients use exactly the same mental processes in those cases where alternative psycholinguistic strategies are possible.

The alternative approach chosen here may not be able to relate processes to disorders quite as directly, but its inherent lack of expliciteness is compensated by the pertinence assured by the multiple motivations for fewer, but better known processes (such as planning, motor programming and motor execution). This approach also appears preferable in view of a further difficulty in interpreting neurogenically impaired speech, which arises from the fact that this type of speech is not only characterized by the impairments themselves, but also by adjustments to the disorder, such as actions taken to overcome, compensate or circumvent a difficulty occasioned by the pathology. Observed pathological behaviors are often indeterminate as to whether they take their origin in the lesion itself, or in the adjustment to the lesion; an approach devoid of external motivation may thus run the risk of interpreting adjustment behaviors as lesion-impaired behaviors.

To illustrate, the fact that French and English Broca's aphasics tend to simplify their consonant clusters (Keller, 1984) was cited above in support of the notion that Broca's aphasics suffer from problems in motor programming. In this interpretation (which I believe to be correct), such patients have a lesion-induced difficulty in programming the complex and time-critical transitions between two or three consonants of a consonant cluster. Yet the same phenomenon could also be interpreted as a compensatory strategy. Since much of English and French phonological structure is characterized by the CV alternation pattern, it can be hypothesized that patients who are habitually faced with motoric difficulty, would tend to preferentially select those articulatory sequences which are in conformity with the CV alternation pattern, and thus to favor single consonants over consonant clusters. Uncertainty with respect to these alternatives is reduced if interpretation proceeds from independently-motivated speech production processes to impaired speech.

In the following sections, the adequacy of predictions from the present hypothesis will be examined with respect to (a) some typical major lesion effects, (b) effects on speech rate, and (c) effects on inter-articulatory organization (cf. Fig. 6.1). Also, we examine some of the predictions concerning the difference between primary and secondary motor cortex and concerning feedback from the vocal tract.

3. Predictions Concerning Typical Major Lesion Effects On Planning And Motor Processes In Speech

The Difference Between Planning and Motor Processes. The distinction between motor and planning processes has been attributed to two criteria, precedence and automaticity. Precedence is the notion that planning processes must feed into motor processes, while automaticity captures the idea that motor processes involve time-critical operations, while the planning stage groups those that are less time-critical. Planning processes can thus deal with non-repetitive, less-automatized operations on open-ended classes of linguistic units, while motor processes were seen to be constrained to repetitive and automatized operations on relatively small classes of linguistic units.

It can be seen that automaticity can account for the difference between anomia and agrammatism. Anomia (word-finding difficulty) is an impairment in the selection and/or representation of open-class or lexical words, and is particularly frequent in Wernicke's aphasia, while agrammatism is an impairment in the selection and/or representation of closed-class or function words and is most often found in Broca's aphasia.

This analysis is thus supportive of the traditional syndrome distinctions which characterized Wernicke's aphasia as a pre-motor impairment, and Broca's aphasia as a motor deficit. However in contrast to previous accounts associating agrammatism with a motor deficit (e.g., Goodglass, Fodor, & Schulhoff, 1967, who suggested that agrammatism was an inhibition due to motoric difficulty), the present analysis provides an explicit, time-based rationale for viewing agrammatism as one aspect of faulty motor processing, and for associating this disorder with one and not the other of the two aphasic syndromes in question. In further support of the motoric quality of agrammatism is the fact that agrammatism can be found to affect exclusively the productive modality (Miceli et al., 1983; Nespoulous & Dordain, 1985).

The criterion of precedence can account for a number of further differences between the two syndromes, particularly those relating to phonological impairments. Because planning is thought to be concerned with the preparation of the phonological representation of certain utterance segments, a disruption of these processes should in Wernicke's aphasia lead to impaired phonological representations in the planned utterance segments. This in turn should be reflected in an impaired self correcting ability, and in a distinctive pattern of phonological substitution or omission errors. By contrast, Broca's aphasics should show relatively intact self correcting ability, and a pattern of phonological disorders indicative of motor processing impairment.

These predictions appear to be supported. The results on successive approximations to a target (e.g., "*A moh-, ma-m, mail, mail box*") indicate that among Wernicke's, conduction and Broca's aphasics, Wernicke's aphasics were least able to correct their phoneme substitutions (Joanette et al., 1980). Also, these patients had particular difficulties articulating phonemes when two succeeding target words contained several similar phonemes (e.g., *caramel* and *camera*) (Guyard, Sabouraud, & Gagnepain, 1981). This suggests that because of an insufficient internal representation, Wernicke's aphasics have been difficulty in selecting the right phoneme at the appropriate moment. Further, the phonological errors of Wernicke's aphasics are suggestive of open-class word selection difficulties (a planning problem), as their phonologically grossly abnormal (i.e., jargonaphasic) utterance tend to occur when they look for appropriate words (Buckingham & Kertesz, 1974).

By contrast, the phonological problems of Broca's aphasics show evidence of motor impairment, such as exceptional difficulties in phoneme-to-phoneme transitions and in the selection and articulation of infrequent phonemes. As already indicated, the simplification tendencies found with Broca's, and not with Wernicke's aphasics, are probably related to their phoneme-to-phoneme transition difficulties. Further, Guyard et al. (1981) found that Broca's aphasics had a greater error susceptibility than Wernicke's aphasics for pairs of articulatorily difficult stimuli (e.g., for French "pull" [sweater], "poule" [hen], or for "truite" [trout]—"huitre" [oyster]). However unlike Wernicke's aphasics, they had relatively few problems with selecting phonemes from competing phonemes in the planned utterance segments (i.e., few difficulties with syntagmatically difficult stimuli like "couturière" or "institutrice"). Finally, the phoneme substitutions of Broca's aphasics show less evidence of contextual contamination than do those of Wernicke's aphasics (Blumstein, 1973), indicating again that these patients are impaired in the processing of the ongoing articulatory string, rather than in the selection of phonemes from the internal representation of the planned utterance segments.

Again, these characterizations are by and large in accord with previous accounts (e.g., Guyard et al., 1981, Joanette et al., 1980; Keller, 1979; 1984; Nespoulous et al., 1983; etc); however, in contradistinction to those analyses, the present account does not seek to explain processing phenomena on the basis of neurogenic data, but proceeds from a hypothesis built on normal speech behaviors and neurophysiological data to a verification of its predictions for neurogenically impaired speech. This externally motivated hypothesis, specific as to the relational nature of motor output operations, promises not only greater robustness for the proposed theoretical constructs, but also a better understanding of the causes and effects of neurogenic speech impairments.

The Difference Between Motor Programming and Motor Execution. Within motor processing, the hypothesis predicts differences in the impairments of motor programming and motor execution. However, in view of the lack of one-to-one relationships between syndromes and proposed processes, direct empirical tests of this difference are difficult to obtain. Accordingly, we must report to more indirect analyses.

The neurogenic speech disorder most clearly associated with a disorder of motor execution is spastic dysarthria (found in pseudobulbar palsy) (Darley et al., 1969, 1975). This type of dysarthria is due to a lesion in the upper motor neurons, which have their origin in the primary motor cortex. Through retrograde degeneration, an entire upper motor neuron disintegrates, if it is lesioned anywhere along its pathway from the primary motor cortex to brain stem synapses with the given lower motor neuron; spastic dysarthria is therefore a cortical as well as a subcortical disorder.

In accordance with the neurophysiologically based hypothesis for primary motor cortex function, an upper motor neuron lesion should thus cause disorders in the synergistic commands to functional groupings of speech musculature, such as those controlling respiration, laryngeal activity, lingual and labial activity. In terms of our hypothesis, this impairment occurs because of a loss or impairment of learned links between muscle commands. Clinical reports are in support of these notions. Darley et al. (1975) report on a number of studies indicating respiratory insufficiency in patients of this type, due to "too-rapid breathing, difficulty in taking a deep inhalation, difficulty in controlling a prolonged exhalatory movement, antagonistic diaphragmatic-abdominal and thoracic movements, and involuntary movements in the respiratory musculature" (p. 137), all disorders that can be interpreted in terms of an impairment of muscular synergies of local groups to muscle tissue. Further, the laryngeal muscles appear to be subjected to hyptertonus, a sign that can be interpreted as abnormal co-contraction of musculature that normally functions antagonistically. This state manifests itself perceptually in a number of prominent signs, such a harsh voice, low pitch, and a strained and strangled voice (p. 142).

With respect to differences between the programming and the execution stage of motor processing, it is probably best to examine observed differences between Broca's and conduction aphasia. It will be recalled that both types of aphasics show phonemic errors, but only Broca's aphasics show phonetic impairments extending over the entire speech chain (arthric effects). Accordingly, Broca's aphasics can be expected to show disorders in both programming and execution, while conduction aphasics can be expected to show primarily programming disorders and impairments related to the copying of information from planning to motor processes (see section D.2.).

The study in this volume by Nespoulous, Joanette, Ska, Caplan, and Lecours presents a number of findings that appear to support the present hypothesis (none seem to contradict it). Let us recall that at the interface between planning and motor processings, we assume a "scan-copying" process (impaired by conduction aphasia), and at the motor processing level, a sequential organization of the speech chain in terms of movement commands, and their interpretation in terms of synergistic aphasia). Because scan-copying is essentially a process of activating selective phonemes among others (see e.g., Guyard et al., 1981; Lecours & Lhermitte, 1969), while motor processing is by and large sequential, we would expect that scan-copying errors produce phoneme substitutions which take their origin in the surrounding phonemes ("syntagmatic" or "displacement" errors), while motor processing errors should be less seriously affected by syntagmatic influences. Indeed, Nespoulous et al. (this volume) showed conduction aphasics to have more displacement errors than Broca's aphasics.

Also, the phonemic errors of Broca's aphasics showed a devoicing tendency, and a change of place of articulation when target phonemes were unvoiced, while the errors of conduction aphasics did not show such a tendency. This is in accord with the loss of synergistic muscle control over specific valves postulated for impairments of motor execution processes: in this view, a largyngeal hypertonus tends to prevent voicing, and synergistic aberrations give rise to changes in place of articulation. Conduction aphasics, who are not assumed to show any major motor execution problems, lack such selective impairment.

In summary, the major lesion effects examined here appear to be in excellent accord with predictions derived from the hypothesis. Wernicke's aphasia appears to be an impairment at the level of the planning processes, conduction aphasia seems to interfere primarily with the scan-copying process between planning and motor processes, Broca's aphasia interferes most clearly with a variety of motor programming and motor execution processes, and spastic dysarthria impairs the synergistic aspect of commands to functional groupings of articulatory musculature.

4. Predictions Concerning Lesion Effects On Speech Rate

Because it has been hypothesized that learned relations defining movement and muscle commands are stored in the motor cortex areas, a further prediction of the hypothesis is that lesions of these areas would impair the use of relations between muscle commands, in proportion to the tissue lost. The system would thus be forced to calculate movements anew by means of the remaining brain tissue.

The effect on movement is predictable from the degrees of freedom hypothesis (section A.4.). Because such a lesion would to some degree undo the effects of learning, one would expect an increase in the number of degrees of freedom, which would be reflected in a loss of speed of integrated movements and in a reduction of stereotyping of movements. In terms of articulatory movement, one would expect a slow speech rate and dyscoordinated movements in the articulators. A reduction in speech rate is particularly likely, because recalculations might have to be performed by neural tissue that previously was not involved in the calculation of articulatory events.

This prediction is well supported. Excessive slowness of speech articulation is one of the most reliable and most distinctive signs associated with impairments of the motoric aspect of speech. Goodglass and Kaplan (1972), for example, use nonfluency as one of the defining characteristics of Broca's aphasia. Also, as would be expected from the discussion in the previous section, slow speech rate is a serious impairment in the spastic type of dysarthria (upper motor neuron disorder). Darley et al., (1969, 1975), for instance, ranked spastic dysarthria (pseudobulbar palsy) as more severely affected by slowness than flaccid dysarthria (bulbar palsy, lower motor neuron disorder), hypokinetic dysarthria (parkinsonism) or ataxic dysarthria (cerebellar disorder). By contrast, cortically-lesioned patients with a minimum of impairments of processes associated with the motor phase of speech, such as Wernicke's aphasics, do not show any slowness of speech (Goodglass & Kaplan, 1972).

Moreover, it is illustrative to compare Broca's aphasia with conduction aphasia. The speech of Broca's aphasics is often described as continuously labored, in other words, the slowness affects the entire speech chain, and may be accentuated at transitions between phonemes or syllables (Luria, 1962/1966). By contrast, the slowness of conduction aphasics typically results from difficulties in chaining short utterance segments, and not in executing individual phonemes. Goodglass and Kaplan (1972) say that "the fluency may be restricted to brief bursts of speech" (p. 68). Analyzed in terms of the processes proposed above, conduction aphasics seem to run into difficulties at the point where they chain phonemes, syllables or even longer segments into a continuous speech output (interface between planning and motor processes), and Broca's aphasics suffer from an impairment of the learned characteristics of articulatory motor commands (motor programming and motor execution processes).

5. Predictions Concerning Lesion Effects On Interarticulatory Organization And Synergistic Muscle Action

Another predicted effect of a motor aphasia is a breakdown in sequential relations within organized command aggregates. As a result, one would expect impairments in the (a) coordination of the action of various speech

tract valves and (b) synergistic action of the musculature of such valves. As an example of an interarticulatory coordination problem, one would expect disorders in voice onset time (VOT, coordination of the linguo-palatal and the laryngeal valves), and as an example of a breakdown in muscle synergy, one would expect co-contractions of normally antagonistic musculature.

To the degree that this prediction has been investigated, it is well supported. Recently, two research teams have examined the VOT performance of patients with and without motoric impairment. Blumstein and her colleagues (Blumstein, Cooper, Goodglass, Statlender, & Gottlieb, 1980) report that a sample of American Broca's aphasics failed to clearly differentiate VOTs for voiced and unvoiced stops, which indicates that the sequential relations between the linguopalatal articulatory valve and the laryngeal valve were impaired. By contrast, Wernicke's patients did differentiate VOTs in the voiced and the unvoiced condition, although it must be noted that in comparison to normal subjects, their differentiations were exaggerated. Itoh and his colleagues (Itoh, Sasanuma, Tatsumi, Murakami, Fukusako, & Suzuki, 1982) (Fig. 6.3) document similar results for comparable groups of Japanese patients.

Itoh, Sasanuma, Hirose, Yoshioka, & Ushijima (1980) also present X-ray microbeam measurements for velum and tongue dorsum action in a patient with a motoric impairment. For the sound *n* in [*d*ɛ:nɛ:], a normal person lowers the velum at the same time as he raises the tongue tip towards the hard palate and depresses the tongue dorsum (top panel of Fig. 6.3). However, the patient with motor impairment does not show this relationship. Unfortunately, no data on the tongue tip is available. Yet with respect to the relationship between the velum and the tongue dorsum, the patient is seen to raise his tongue dorsum, instead of lowering it, at the time that the velum is lowered (bottom panel of Fig. 6.3).

With respect to a breakdown of muscular synergy, Fromm, Abbs, McNeil, and Rosenbek (1982; Fig. 6.4) present direct EMG evidence from a comparable patient showing pathological co-contraction in muscles which in normals function antagonistically (orbicularis oris inferior and depressor labii inferior in bilabial closure). These data illustrate very powerfully the neurophysiological calculation errors which are at the basis of the articulatory errors of these patients.

6. Predictions Concerning Processing In The Primary And Secondary Motor Cortex

The differences between phonetic disorders found in patients showing arthric effects, and phonemic disorders found in aphasia patients without anarthria probably relate to the difference between primary and secondary motor cortex impairment. In view of the direct control over individual muscle groups

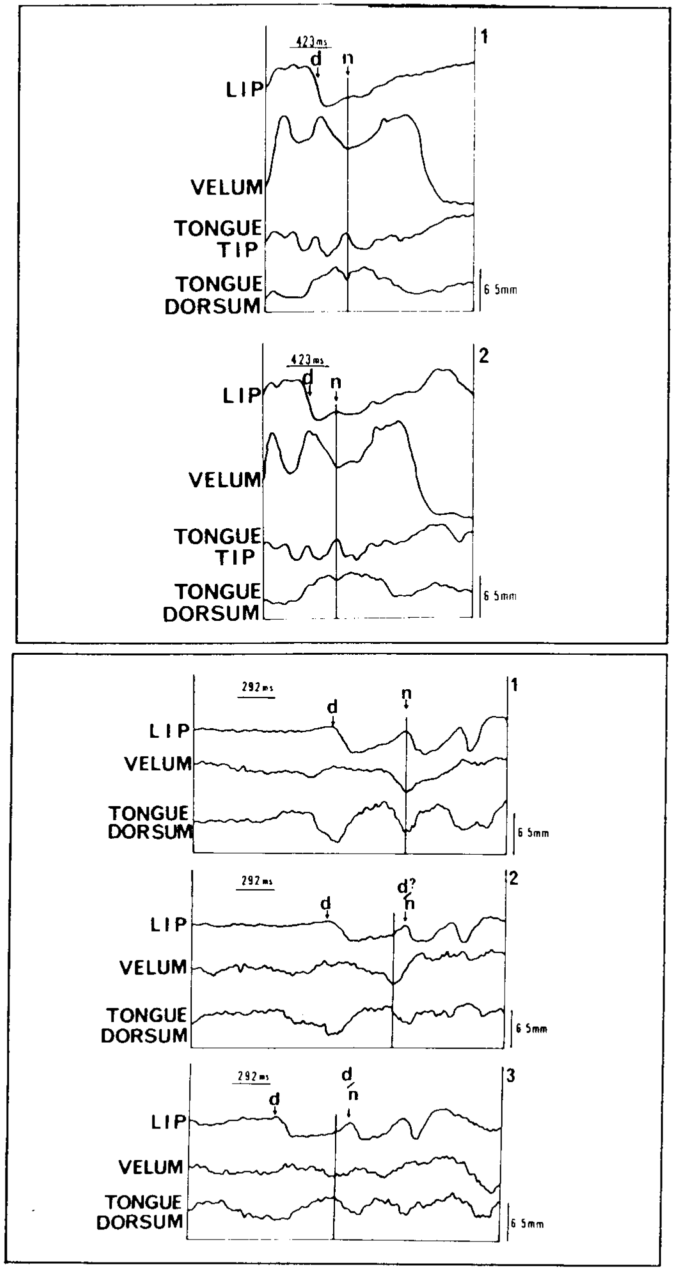

FIG. 6.3. Displacements of several articulators for the Japanese stimulus [dɛ:nɛ:] (top panel: a normal subject; bottom panel, a patient with Broca's aphasia ["apraxia of speech"]). The vertical lines indicate the moment of maximal velar lowering for the nasal consonant [n]. The time scale for the top panel is different from that for the bottom panel. It can be seen that the patient raised his tongue dorsum, instead of lowering it, at the time that the velum was lowered. (Itoh, Sasanuma, Hirose, Yoshioka, & Ushijima, 1980.)

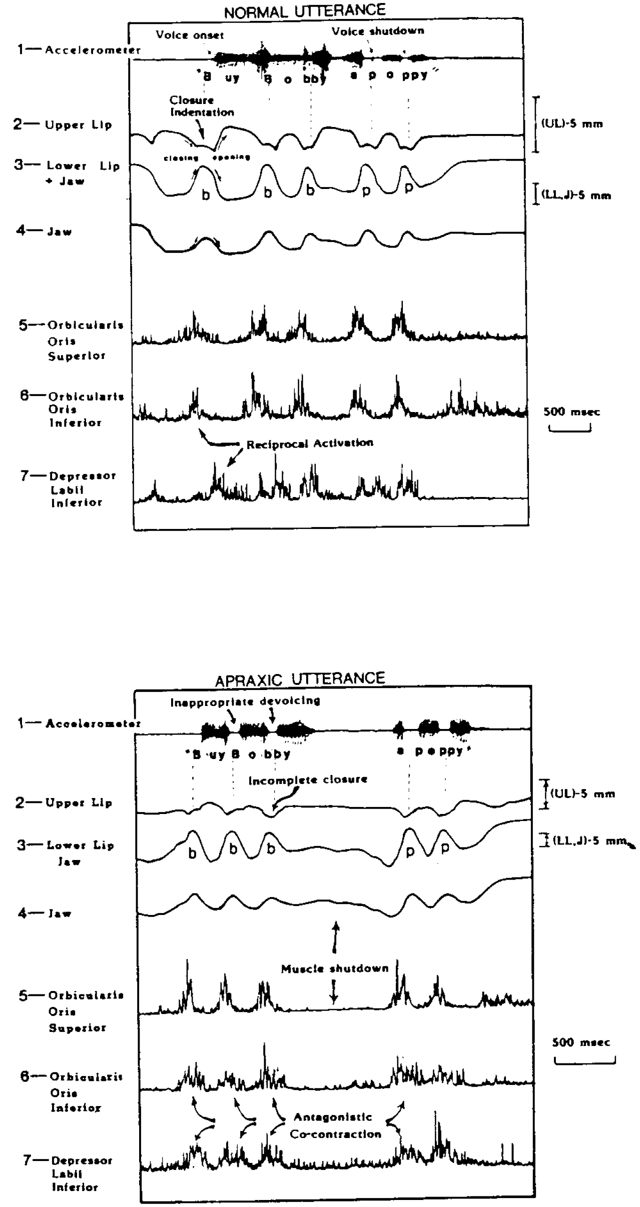

FIG. 6.4. Muscle activity and labial-mandibular movement signals obtained from a normal subject (top panel) and a patient with Broca's aphasia ("apraxia of speech") (bottom panel). The bottom three traces of each panel show the integrated EMG. The patient showed co-contraction in muscles which in the normal subject functioned antagonistically. (Fromm, Abbs, McNeil, & Rosenbek, 1982)

reported for primary efferent zones in higher mammals, the function of the primary motor cortex was seen to be concerned with synergistic relations between commands for individual muscle contractions, whereas the secondary cortex was seen to be concerned with the sequential organization of larger aggregates of movements.

In speech, a disorder of synergy due to primary cortex lesion should result in a continuous impairment of muscular execution in specific speech valves; this would correspond to the phonetic impairments in dysarthria and in the arthric effects found in Broca's aphasia. By contrast, a lesion of the secondary motor cortex should impair sequential relations between command aggregates for the entire speech musculature, to produce substitutions, omissions, additions and repetitions of phonemes, syllables or larger utterance stretches. We recall that these are the signs of phonemic motor disturbances in aphasia (see also Johns & Darley, 1970).

In further support of the difference between impairments of the primary and the secondary motor cortex, we would predict a predominance of phonetic over phonemic impairments with lesions of the non-dominant hemisphere. This prediction receives some support from a study of 42 patients with cortical lesions in the right, non-dominant hemisphere; 7 of the patients were affected by marked arthric effects, while none showed frequently recurring phonemic disturbances (Joanette, Lecours, Lepage, & Lamoureux, 1983; Joanette, personal communication, 1985).

7. Predictions Concerning The Impairment Of Feedback-based Speech Motor Processing

The fourth aspect of the hypothesis concerned the flexible status of feedback in motor learning and processing. One of the few examples in the literature of the impairment of speech motor learning or processing due to a lesion of feedback pathways, is found in Linke (1976). He describes a relatively clear case which illustrates the crucial role feedback plays in compensating perturbations, at the same time as it demonstrates the non-use of feedback under predictable circumstances.

A patient with bilateral operative lesion of the trigeminal nerve (cranial nerve V), which provides primarily sensory input from the face, was found to be incapable of lip control for eating, for holding a cigarette, or for liprounding on command; at the same time, there was no demonstrable impairment for normal speech, even when speaking in a white noise condition. The movements involved in eating, holding a cigarette, and liprounding on command probably involve calculations for muscle contractions based on momentary circumstances in the vocal tract, fed back to the central nervous system via the sensory input; speech in predictable circumstances probably involves the use of learned relations defining articulatory movement, relatively independent of sensory input.

As expected, this patient experienced difficulties when speaking in inhabitual conditions; indeed, he was found to have excessive difficulties when speaking with a pencil in his mouth, a condition which normal speakers can easily compensate. Further, when a non-painful electrical stimulation was applied to the lips, normal subjects were able to compensate the perturbation easily, while this patient reacted with a complete breakdown of speech for the ensuing 300 to 500 ms.

Although these results provide good support for the present hypothesis, more extensive studies on the use and importance of feedback in speech motor processing are clearly called for.

E. CONCLUSION

In this chapter, a synthesis of findings derived from the functional and neurophysiological studies of speech motor control, and tested with respect to findings on neurogenic impairment of speech, has led to an hypothesis of cortical functioning with respect to normal and neurogenically impaired speech.

It was proposed that the acquisition of speech motor control involves the abstracting of relations between those commands for muscle contractions that have been previously successful in implementing perceptually circumscribed speech targets. Skilled speech, by contrast, was seen as involving the retrieval of stored relations, and the calculation of additional movement biases in order to compensate for unpredictable and infrequent conditions in the vocal tract. The difference between the acquisitional and the skilled stage of speech production necessitated a flexible view of the contribution of the feedback mechanism. Finally, it was proposed that these functions were mediated primarily by the cortex; the secondary motor cortex in the speech-dominant hemisphere was seen to be concerned primarily with the sequential organization of command aggregates involving the entire speech musculature, while the bilateral primary motor cortices were seen to be concerned principally with synergistic relations between constituents of functionally related muscular structures (speech tract valves).

Predictions arising from this proposal with respect to patients with neurological cortical damage were shown to be supported by available data. It was seen that classical expressive symptoms of various groups of aphasic patients were well predicted by the theoretical framework elaborated from non-aphasic evidence. Further, some specific predictions relating to speech rate and interarticulatory organization were seen to be borne out. Since the hypothesis suggests that relations between muscle commands are learned in order to obtain a speed advantage associated with a reduction of the system's degrees of freedom, it can be expected that the impairment of such relations through cortical damage leads to a slowing of the speech rate; indeed, slowness of speech is one of the most reliable symptoms of the motor control disorder found in Broca's aphasia and in spastic dysarthria.

Also, available direct indications on the breakdown of the sequential organization and synergistic contraction patterns in neurogenic speech disorders show the hypothesis to be supported. Recent VOT and cinefluorographic experiments show that patients with Broca's aphasia suffer more directly from errors in the sequential coordination of different speech articulators than other types of aphasics. The predicted breakdown of synergistic relations between muscle commands were also briefly documented.

The difference between primary and secondary motor cortex responsibilities, derived from animal studies and from electrical stimulation of the exposed cortex, are supported by the difference between phonemic and phonetic types of articulatory breakdown, associated respectively with impairments of sequential organization of speech tract motor commands, and synergistic commands to speech tract valves.

Finally, the proposed flexible view of feedback was shown to be further supported by a rather unusual and illustrative case of bilateral (sensory) trigeminal nerve ablation who showed intact speech in predictable speech conditions, but in contrast to normal subjects, was unable to deal with inhabitual vocal tract conditions or unexpected perturbations.

Despite its comprehensiveness, it is evident that the present account leaves many unanswered questions. It may be useful to list just a few:

1. The central hypothesis, that the acquisition of speech motor control is fundamentally the learning of relational information, should be examined systematically, preferably by means of EMG and kinematic records in children, adults and adults with various types of neurological lesion.

The present hypothesis predicts that disorders based on a breakdown of relational muscle command specifications would be seen primarily with disorders of the primary and secondary motor cortices; what are the VOT characteristics of various types of subcortically-impaired dysarthric patients? Of patients with lesions in non-speech areas? Do they back up the present theoretical notions?

2. What are the theoretical implications of viewing agrammatism as a motor disorder due to a breakdown in learned automaticity? Is it possible to apply the relational paradim elaborated here for the muscular command structure, to the context of grammatical relations?

3. At present, the empirical basis for verifying the predicted lack of stereotypy of articulatory movement is relatively weak. Recently-developed, improved recording techniques for articulatory movement (e.g., X-ray microbeam, ultrasound, magnetic tracking, etc.) may be successfully applied to this question.

4. The exact extent of a "functional grouping of speech musculature," here globally characterized as a "speech tract valve," should be explored for each group. Can cases be found in which the abnormality affects just one speech tract valve? If so, what is the anatomical extent of affected musculature?

5. Unaffected portions of the speech production system probably adjust their operations to the effects of a disorder "further up" or "down" in the system. What is the nature of this adjustment?

6. How does the present account articulate with other models of speech production, such as those derived from normal speech errors in spontaneous speech?

7. What are the speech motor functions of various subcortical brain structures, such as the extrapyramidal loop involving the basal ganglia and the thalamus, the cerebellum and the brain stem nuclei? How do they integrate with the processes proposed here?

Despite the many unanswered questions and the (fully avowed) great uncertainties about what has been proposed here, it would seem that the present account makes an attempt to present an integrated view which coherently explains findings from a large number of experiments, from observations on normal and neurogenically impaired speech, and from the neurophysiology of motor control in general. It provides logical and responsible links between a variety of related scientific domains, and furnishes a global conceptual framework for normal, acquisitional and disordered processes in speech motor control.

The major challenges awaiting these hypothesis are, first of all, intensive direct testing of its specific predictions by means of experiments on the learning and the utilization of motor control in normal and impaired speech condition; and secondly, the theoretical integration of these findings into a larger model of speech production.

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