NEUROLINGUISTICS MUST BE COMPUTATIONAL[1]

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Abstract

We provide a threefold taxonomy of models in neurolinguistics: faculty models which embrace the work of classical connectionists and holists and such modern workers as Geschwind; process models, exemplified by the work of Luria, which fractionate psycholinguistic tasks and ascribe the components to particular brain regions; and representational models which use specific linguistic representations to build a psycholinguistic analysis of aphasic performance. We argue that further progress requires that neurolinguistics become more computational, using techniques from Artificial Intelligence to model the cooperative computation underlying language processing at a level of detail consonant with linguistic representations. Finally, we note that current neurolinguistics makes virtually no contact with the synapse-cell-circuit level of analysis characteristic of 20th-century neuroscience. We suggest that the cooperative computation models we envisage provide the necessary intermediary between current neurolinguistic analysis and the utilization of the fruits of modern neuroanatomy, neurochemistry, and neurophysiology.

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Introduction

In this paper we discuss and classify a number of models which relate language function to neural processes. We suggest that there is a progression to be found in such models, whose culmination would naturally lead to what we term "computational process models". We suggest that the development of such models would allow the application of cybernetics and brain theory to the study of neural mechanisms involved in language.

Our field of concern is the relation of brain to language, an emerging science which has been called "neurolinguistics". We assume that the goals of such a science are the characterization of two fundamental levels of biological reality and their interaction. The first level has as its domain the functional repertoire of an organism with respect to a particular functional subsystem. In the present case, we are concerned with the representation and processing of linguistic structures. The second level is neural, and is characterized by a theory of organic structures defined in anatomical, physiological, biochemical and other such terms.

A distinction must ultimately be drawn between those structures and mechanisms which enable humans to acquire language and those which accrue in an individual by virtue of his having acquired a particular language. In our discussion, these two classes of mechanisms are not distinguished. Nor are we concerned here with the critical question of the development of the adult system throughout ontogeny. We limit ourselves to models of the relation of language processing to neural entities in the adult.

The paper is divided into five principle sections. The first three deal with existing neurolinguistic models, for which we have provided a taxonomy based on the range of empirical data a model attempts to deal with and the linguistic and psycholinguistic analyses it adopts. In the fourth section we review work form artificial intelligence which suggests certain properties of a more adequate process model. In the fifth section, we outline the relation of such a model to neural mechanisms.

Our intention is to provide a framework for assessing the empirical adequacy of proposed neurolinguistic models, and to suggest several directions for the further development of such models. We perceive a conceptual gap between many of the existing, clinically-oriented theories of neural mechanisms pertaining to language and recent psycholinguistic approaches to the field. In our view, it is inadequate to bridge this gap by utilizing the neural aspects of one type of model and the phenomenological analysis of another. Rather, we think this gap must be filled by deepening both the phenomenological and neural analyses, and we suggest ways in which this might be accomplished. This paper does not report new observations, but attempts to clarify conceptual issues in neurolinguistics by confronting classic neurological approaches with developments in psycholinguistics, artificial intelligence, neuroscience, and cybernetic modelling.

1. Faculty Models

"Connectionist" models of neurolinguistics (which have also been termed "localist" and "topist") date from the earliest scientific work on the relation of language capacities to brain (Broca, 1861, 1865; Wernicke, 1874). They are centered on the identification of major functional psycholinguistic tasks, such as speaking, comprehending speech, etc., and tend to treat such tasks as unanalyzed wholes. The models are all derived from the study of aphasic patients, and the data involve observer judgements about the relative disruption of, and, to a lesser degree, qualitative changes in, these major tasks. A connectionist model then specifies the location in the brain of these task-defined components of language function and advances limited hypotheses as to their interaction.

Details of connectionist models were widely debated among French, German and English neurologists in the late nineteenth century (Charcot, 1863; Grashey, 1885; Lichtheim, 1885; Kussmaul, 1877; Broadbent, 1872; Bastian, 1869, 1897). Other workers rejected the observational accuracy of the empirical data upon which the model was based (Marie, 1906; Moutier, 1908); offered alternative clinical observations and models (Jackson, 1877, 1878; Goldstein, 1948); or criticized the logic by which the connectionists inferred their models, and offered alternatives (Freud, 1891). These critics have been referred to as "holists", but we suggest, contrary to common belief, that their approach is not significantly different from that of the connectionists. Geschwind (1964) has also taken the position that these models are similar, but our reasons for grouping them together are different than his. We shall view both the connectionist and holist models as being faculty models because the various components of the models tend to be identified with complete mental faculties. We view the work of Geschwind (1965, 1967a,b, 1970, 1972) as a modern statement of the connectionist approach (recalling Marshall's (1979) observation that the connectionist model "had to be re-invented in this century"). We also consider "verbal learning" approaches to language (Goodglass et al., 1964, 1966, 1967, 1969; Kawes, 1967; Geschwind & Kawes, 1962) which are linked to Geschwind's formulation as outgrowths of faculty models.

From Wernicke to Lichtheim

Broca (1861a, b, 1865, 1869) argued that the faculty for articulate speech was located in the third frontal gyrus, adjacent to the Rolandic motor strip, on the left in right-handers. He observed cases interpreted to show a lesion in the area described and a functional output consisting of scant speech but intact communicative ability as manifest by gesture and interpretable responses to the speech of others.

(Figure 1)

Wernicke (1874) published the first comprehensive model of language representation in brain based on observed aphasic symptom-complexes additional to those described by Broca. The symptom-complex which bears Wernicke's name consists of both a "receptive" and an "expressive" disorder of language. Wernicke described his first patient as "unable to comprehend a single utterance", although she was able to guess the intentions of her examiners through interpretation of their facial expressions, gestures, etc. Her spoken language consisted of fluent speech marked by neologisms, inappropriate choice of words, sound pattern errors, and agrammatical fragments. She recovered to the point of speaking fairly correctly, but her oral reading and written expression were both characterized in the chronic state by features similar to those which had affected her speech acutely. A second

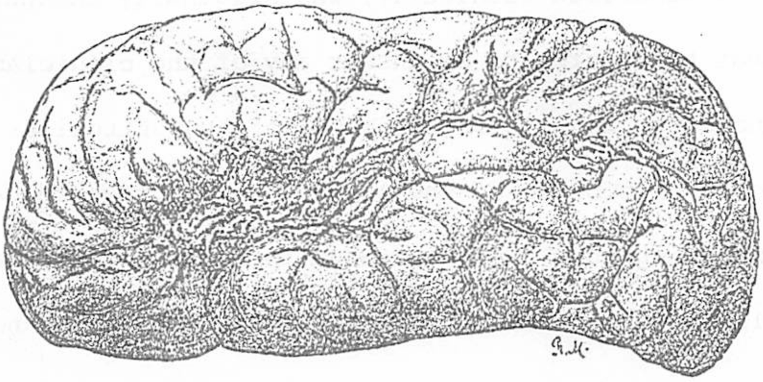
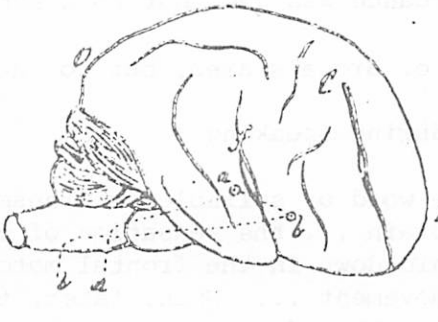


Figure 1: Broca's original case, showing lesion with its center in the third frontal convolution. Reproduced from Moutier (1908).



α: peripheral auditory pathway
a: sound center for words
b: motor center for words
β: peripheral motor pathways for speech

Figure 2: Wernicke's original diagram, showing the principle pathways for language. From Wernicke (1874).

patient, less well described clinically, was originally thought deaf because she did not appear to understand or answer any of the clinician's questions; her speech was diagnosed as aphasic on the basis of "substitutions and distortions of words". At autopsy, the brain of the second patient revealed an infarction of the first temporal gyrus, which extended into part of the second temporal gyrus, the insula and the inferior parietal lobe. There was no lesion in Broca's area.

This called for a significant re-interpretation of Broca's model. Wernicke argued for interaction between components of a neural system serving language performance. He suggested that the site of the lesion, primarily in the first temporal gyrus, was the anatomical area responsible for comprehending spoken language and storing the auditory impressions of words. He further postulated that the co-occurrence of a deficit in speech with the comprehension disturbance was due, not to a second undiscovered lesion in the region of Broca's area, but to the nature of interruption of information flow during speaking:

> ... a sound image of the word or syllable is transmitted to some sensory portion of the brain ... the sensation of innervation of the movement performed is laid down in the frontal motor areas as a representation of speech movement ... When, later, the spontaneous movement, the consciously uttered word, takes place, the associated representation of movement is innervated by the memory image of the sound. (p. 43)

This interpretation led to the first and prototypical diagram of the location of language functions in the brain. The major source of data

(Figure 2)

upon which ensuing connectionist theories were to build was the recognition that a psycholinguistic task -- speaking, comprehending spoken speech, reading, writing -- was disturbed. The psycholinguistic constructs used in the theories were these faculties themselves. Each faculty consisted of a process and memory component, not always clearly distinguished in the connectionist literature. Thus, the functional component for comprehending spoken language included a memory for the auditory patterns of words; the functional component for speaking included a memory for the articulatory sequences of words and phrases, etc. Constellations of task-defined functional deficits were grouped into "symptom-complexes", or syndromes. On the basis of inferences from pathological material, Wernicke concluded that the functional components interacted, as, for example, a destruction of the faculty for comprehension of speech and its memory store of auditory patterns led to an impairment of the component concerned with speaking. Wernicke observed that the disturbance of speaking was different in the case of dysfunction of the component primarily devoted to speech and that of the component primarily devoted to comprehension. He therefore included in the data-base for his model a very limited description of the qualitative nature of derangement of a single task-oriented function. He concluded that failure of one component would impair a second in a manner behaviorally distinguishable from a primary failure of the second component itself.

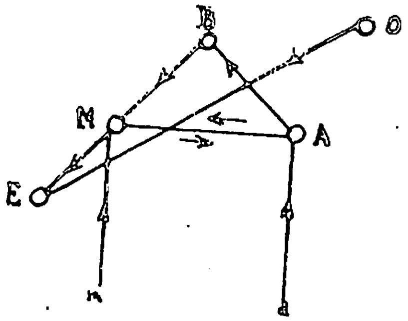
Wernicke and his followers imposed a variety of conditions on the construction of these models. Wernicke implicitly maintained that the model be consistent with theories in neuroscience and psychology. The location of his functional components -- that for comprehension of spoken speech in association cortex adjacent to the post-thalamic auditory radiations and that for speech production in association cortex adjacent to the motor area -- as well as the sensory-to-motor direction of information flow and component control which was based on the physiology of Meynert, were in keeping with the first requirement. An appeal to ontogenetic processes, viewing language development as resulting from mimicry of the language to which a child was exposed, as the source of the nature of component interaction, is in keeping with the second.

This model was expanded by a host of workers prior to the First World War. We shall present a description of one other paper which exemplifies the development of this approach.

Lichtheim's 1885 paper attempts to classify all aphasic syndromes in terms of the connectionist model. Lichtheim postulated three main cerebral "centers" involved with language: the motor programming center (M) described and located by Broca; the sensory center for auditory word memories (A) described and located by Wernicke; and the center for concepts (B), which he thought of as carrying out cross-modal and inter-modal associations of the properties of objects (and possibly of more abstract entities) to produce concepts, and which he argued to be a function of a large and unspecified region in the brain. He argued that these three centers were mutually connected and that connections to the periphery were established for language by auditory input into A and by commands for motor output from M. Thus he depicted the components and connections of the language device as in Figure 3.

(Figure 3)

The attraction of Lichtheim's diagram lay in the predictions which could be derived from it regarding the possible syndromes of aphasia. Clearly the predictions differ depending upon the nature of information flow between components. Given a unique characterization of the necessary and sufficient sequenced component activation in a particular task, and assuming that there is no possibility for substitution of alternate pathways or development of



B: Concept center
M: Motor Speech Center (Broca's area)
A: Auditory Speech Center (Wernicke's area)
E: Motor Center for control of musculature involved in writing
O: Visual Center

Figure 3: Lichtheim's diagrammatic representation of the centers and pathways involved in language use. From Lichtheim (1885).

new components after lesion, the model may be expected to predict the number and nature of aphasic disturbances. Lichtheim attempted to provide such a characterization and predicted seven distinct types of aphasia: motor and sensory aphasia, transcortical motor and sensory aphasia, subcortical motor and sensory aphasia, and conduction aphasia. He described cases of each syndrome. The clinical relevance of this classification is attested to by its survival in today's neurological literature. Benson and Geschwind (1975) present an informative analysis of the classification of aphasic syndromes on the part of some dozen or so workers, in which differences from Lichtheim's classification are clearly primarily in nomenclature and not in clinical symptomatology or site of pathology; their own classification incorporates all of Lichtheim's types and adds three additional syndromes (anomic aphasia, isolation of the speech area, and alexia without agraphia).

It is worthwhile to examine some of the details of Lichtheim's model. In discussing Wernicke's aphasia, Lichtheim argued that a lesion in A would result in loss of five linguistic functions: understanding of spoken language, understanding of written language, faculty of repetition, faculty of writing to dictation, and faculty of reading aloud. The following three faculties would be spared: writing, copying words, and volitional speech. It was Wernicke's argument that the disorder of volitional speech seen in this syndrome was due to the necessary arousal of auditory memories for words in speaking. Lichtheim's model permits a direct innervation of the motor center M from the concept center B; on superficial analysis, this aspect of Lichtheim's model seems to make the wrong prediction about speech output with posterior lesions. Lichtheim turns this possible deficit into an explanatory principle in its own right. He accepts the role of the center A in spontaneous speech. The normal production of speech thus involves a double activation of M through two pathways: a direct path from B to M, and a second from B to A and thence to M. A lesion anywhere in the arc from B to A and from A to M will give rise to paraphasia. The pathway from the concept center (B) to motor speech center (M) is sufficient to ensure that speech is produced, but it needs the additional input from the sensory center (A) to ensure that speech is correct.

The underlying principle is that where a performance is dependent upon two inputs to one center, disturbance of one input will lead to a partial performance. Thus this situation in which the motor speech area is deprived of its input from the auditory store for words, resulting in fluent but paraphasic speech, is contrasted with that in which it is deprived of its input from the concept center in transcortical motor aphasia, where there is loss of the capacity for volitional speech.

That this interpretation of the role of the two inputs to M in spontaneous speech is intended to be a principled and an an *ad hoc* feature of the model can be seen in Lichtheim's argument that the pathways for writing can be determined from analysis of the performance of conduction aphasics in this task. Lichtheim postulated a separate center (E) for skilled writing movements which would receive visual input routed via A and input from the concept center B. Lichtheim considered that "clinical facts leave no doubt that [the path from B to E] passes through M", but that "there was doubt as to whether this path was also routed via A." Lichtheim argued that the case of conduction aphasia could choose between these alternatives, assuming that the principle that paraphasia followed deprivation of M of its input from A applied equally to "paragraphia" in the case of deprivation of E of its sensory input. If the path from B to E was B-M-E, the conduction aphasic would manifest paragraphia. If the path was B-A-M-E, all input to E would be lost in a lesion of A-M and the patient would be totally agraphic. Lichtheim tentatively opted for the first of these alternatives on the basis of what he considered the best, though limited, data at his disposal.

Lichtheim's article is replete with detailed arguments of this type, and, aside from its influence on the clinical classification of aphasias, is notable for its effort to base the analysis of aphasia and neurolinguistics on as few components and as principled a set of component interactions as possible.

We leave the description of this approach with this presentation of two of the classical papers associated with it. Geschwind (1966) reviews the extension of the general connectionist approach to other syndromes, in particular those involving callosal pathways.

Modern Connectionism

It is now a commonplace observation, made originally and perhaps most forcefully by Head (1926), that the development of models along lines of these prototypes led to a "chaotic" theoretical development characterized by intricate diagrams, replete with centers and connecting tracts, whose components and connections proliferated with the discovery of new constellations of symptoms. We shall later argue that neurolinguistic models must perforce be complex. In any case, as Geschwind (1961) points out and Marshall (1979) recognizes, not only has the clinical classification of syndromes been useful to the neurologist, but the basic theoretical approach, involving the delimitation of centers and connections, has proven capable of predicting new patterns of breakdown and has been the basis of most neurolinguistic theories. Nor is it only associated with workers of the last century. The theoretical work of Norman Geschwind, to which we now turn, follows upon earlier connectionist approaches.

A large part of Geschwind's work can be seen as an effort to embed the theory of language representation in brain into a broader context which includes the relation between language representation as a whole and skilled motor and complex perceptual activity (the analysis of apraxia and agnosia). We omit a discussion of this work, since it offers no principles beyond those evidenced in his extension of the connectionist approach to deal with disorders of language themselves, his views on some aspects of semantic representations, and the characteristics of the resulting model of neurolinguistics.

Geschwind (1965, 1970, 1972) accepts many of the classical analyses. Thus, he considers that Wernicke's area "functions importantly as the 'storehouse' of auditory associations" (1965). Similarly, he attributes to Wernicke the belief that, due to its proximity to the motor strip, "Broca's area contained the rules whereby heard language could be coded into articulatory form" and accepts this while cautioning that "there is no need to assume that the coding is a simple one" (1970). His emphasis on the arcuate fasciculus as the connecting pathway between these regions (1965, 1972) is well known.

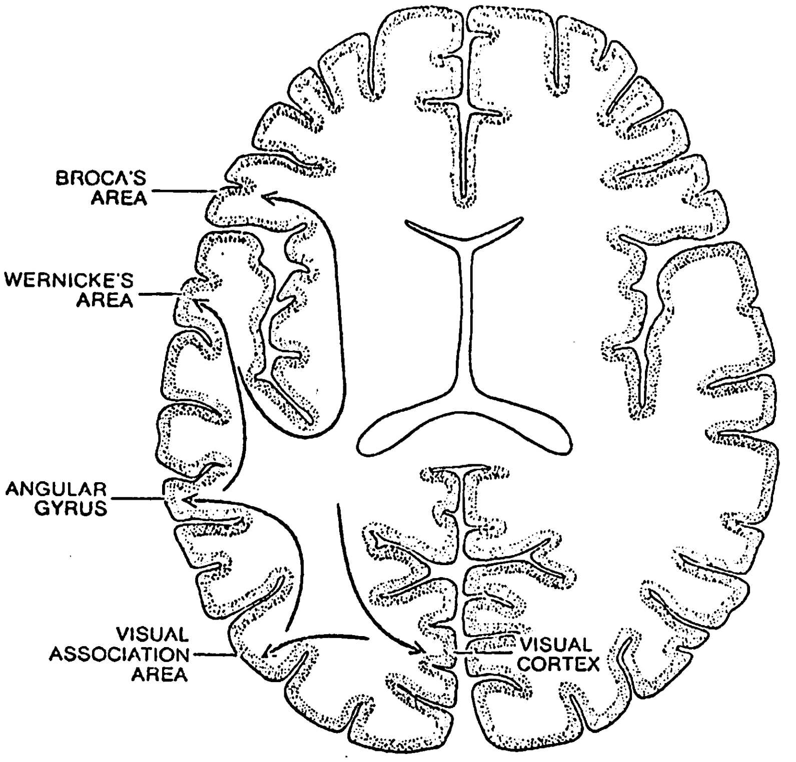
Geschwind departs in his neuropsychological model from the early connectionists in two places. The first is in his explicit account of the nature of naming and its anatomical basis. The second is in his postulation of alternate conducting pathways, particularly those from right hemisphere to the language representations in the left, but also between the left-hemisphere based components.

Geschwind (1965) argues that, in addition to the centers postulated by the theorists of the ninteenth century, there is an additional area in the inferior parietal lobe, which is peculiar to humans and consists of the angular and supramarginal gyri, an "extensive, evolutionarily advanced, parietal association area developing not in apposition to the primary projection areas for vision, somesthetic sensibility, and hearing, but rather at the point of junction of these areas." Its role is posited to be the facilitation of non-limbic cross-modal associations, in particular between the auditory stimuli of language (words) and the sensory properties of the items to which words refer. In this way, this structure assumes importance in human naming ability. Geschwind (1965) is explicit in his emphasis that the emergence of naming in man as a result of the anatomical connections just described (which are absent or rudimentary in the other primates) is a "prerequisite" for speech.

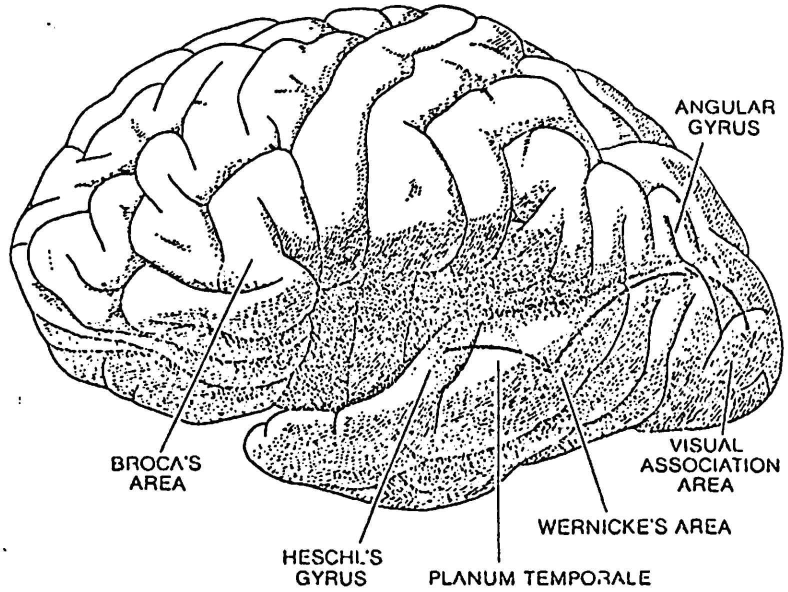
(Figure 4)

Geschwind's second addition to the basic theory is the precise description of pathways to and between the speech centers. The syndrome of alexia without agraphia (not being able to read what you can write!) may serve as an example. Patients with this syndrome, who have vascular lesions in the left occipital areas as well as the posterior callosum (Fig. 5), fail to read words, but characteristically can name objects presented visually, and also perform better on some classes of linguistic visual stimuli, such as letters and numbers. Several patients have been observed to retain their abilities to read from a card words such as "bank" or "post office" which frequently appear on public buildings. Geschwind (1965) suggests that objects and pictures are named after visual presentation because associations to the visual form are aroused in other modalities in right hemisphere areas which have intact callosal connections to the speech areas of the left hemisphere. In a later paper, Geschwind (1979) notes that the class of visual

(Figure 5)

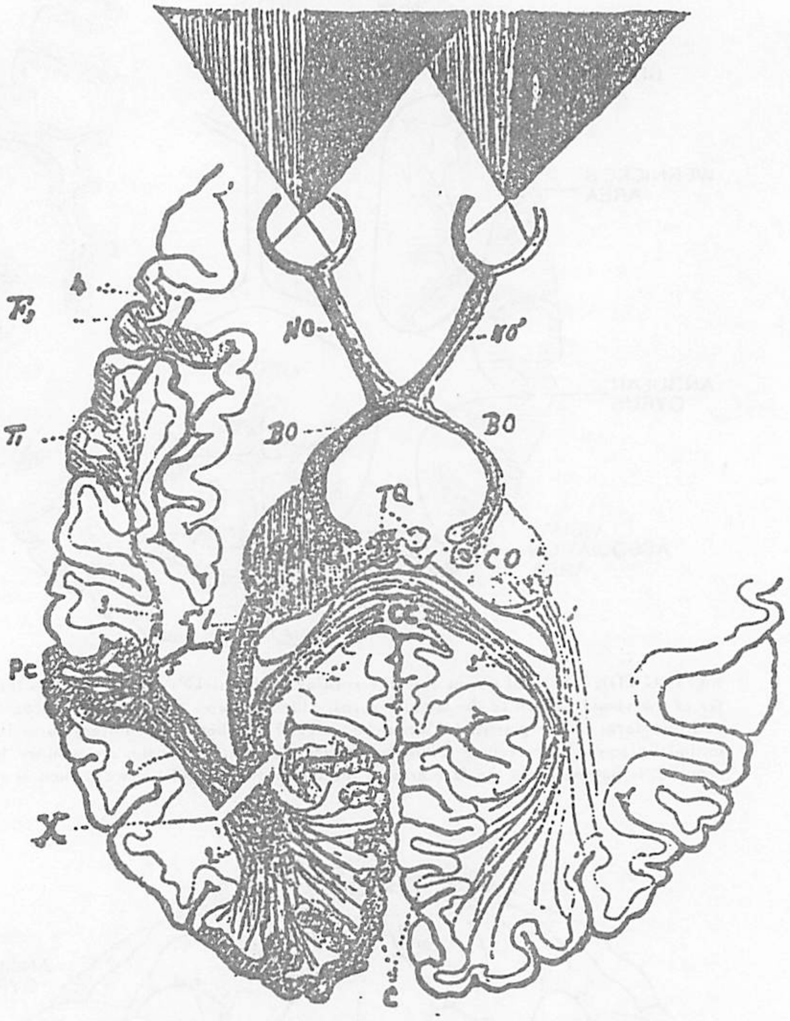


SAYING THE NAME of a seen object, according to Wernicke's model, involves the transfer of the visual pattern to the angular gyrus, which contains the "rules" for arousing the auditory form of the pattern in Wernicke's area. From here the auditory form is transmitted by way of the arcuate fasciculus to Broca's area. There the articulatory form is aroused, is passed on to the face area of the motor cortex and the word then is spoken.



UNDERSTANDING the spoken name of an object involves the transfer of the auditory stimuli from Heschl's gyrus (the primary auditory cortex) to Wernicke's area and then to the angular gyrus, which arouses the comparable visual pattern in the visual association cortex. Here the Sylvian fissure has been spread apart to show the pathway more clearly.

Figure 4: Geschwind's model of pathways involved in naming. From Geschwind (1972).



Diagrammatic horizontal cross section of cerebral hemispheres, illustrating the mechanism of pure word blindness without agraphia. NO = left optic nerve and NO′ = right optic nerve. C = left and right calcarine cortex, shown destroyed on the left (oblique lines); Pc = left angular gyrus (when destroyed as shown here alexia with agraphia results; this region is intact in pure alexia without agraphia); X = large lesion in white matter of left occipital lobe destroying fibers from the right visual cortex going to the left angular gyrus; cc = corpus callosum (although no lesion is shown here, a lesion here will be easily as effective as the lesion at X in disconnecting the right visual cortex from the left angular gyrus). Reproduced from Dejerine (1892).

Figure 5: The lesion typically producing alexia-without-aphasia. Dejerine's depiction of the lesion in his original case. Legend and figure from Geschwind (1972).

stimuli for which connections other than via the splenium must exist in normal function must include the linguistic entities just mentioned, which are preserved in this syndrome, and speculates that these items may be seen as ideographs or, at least, as items whose visuo-auditory connection does not depend upon analysis of the visual stimulus into sub-portions which are separately associated with an auditory sub-component of the total auditory entity (as is the case with graphemically and syllabary based orthographies). The relative resistance of ideographic representations to disruption in Japanese patients whose syllabary orthography is affected in this syndrome is consistent with this analysis (Sasanuma and Fujimara, 1971; Geschwind, 1972). In an important paper, Geschwind (1972b) takes up the question of the anatomical pathways underlying such connections in detail.

Geschwind's two additions to the connectionist model are of different types. The first, his analysis of naming, seeks to make explicit something of the content of one of the components of the model. The "naming center", if we can call it that, is in a sense different in kind from the centers postulated by the earlier theorists, since it deals with a function other than the "on-line" tasks of speaking, understanding, reading, and writing.

Earlier theorists considered the function of Broca's area to be the production of speech, and the linguistic representations in Broca's area to be the motor programs for speech. Similar functional/representational dualities characterized all centers. Geschwind's analysis of naming follows this pattern inasmuch as a <u>function</u>, object naming, is associated with a <u>representational system</u>, associated modality-specific information about objects and words, in an <u>anatomical site</u>, the inferior parietal lobe. It is reasonable to consider that this center may function as part of these on-line tasks, by retrieving the full lexical form of words from semantic, auditory and other cues, as each task requires. [We believe this to be an unsatisfactory approach to naming and word-meaning and to sentential meanings (see Fodor et al. (1974) for a criticism of approaches along these lines, and Chomsky (1977) and references cited there for elaboration of a different approach).]

Geschwind's model is thus made up of components fundamentally oriented to particular psycholinguistic tasks taken as a whole, though, as in the earlier models, there is provision for some limited interaction of entire components in regulating the performance of others and, perhaps in the case of the naming function, provision for embedding one component within another. This last possibility marks a possible transition from these faculty models to what we term process models. We discuss such models in Section 2. Note, of course, that our proposed classification of models is not absolute, but based on the dominant properties of each model, and that most connectionist models incorporate some process features and vice versa.

Geschwind's second point, his stress on multiple pathways, clearly enriches the theory of neurolinguistics in an important way, with partial duplication of mechanisms, some of which are arguably more efficient and hence normally utilized. Geschwind (1979) notes that these mechanisms do not always appear to operate on linguistic elements which form a natural class in linguistic theory, and that their analysis can therefore enrich the theory of linguistic and psycholinguistic taxonomies derived from work on the normal system. Such "submerged" aspects of linguistic taxonomy and psycholinguistic function have also "emerged" from other studies (e.g., Bradley et al., 1979) and appear to be a potentially significant by-product of work with abnormal populations.

"Holist" Models

We noted that there have been three general approaches to criticism of the connectionist models: disagreement with the empirical observations on which the theories are based; disagreement with the inferences drawn from the observations; and disagreement that such observations and the inferences drawn from them should form the basis for neurolinguistic theory.

Marie (1906) and Moutier (1908) provide examples of the first sort of objection. Both argued that adequate observation of all aphasic patients would reveal disorders of what they termed "general intelligence". However, we take it that observational support for different patterns of language breakdown after focal cerebral lesions is adequate, and that objections of this sort must be seen as stemming from non-linguistic impairments in aphasics. Such objections, then, do not negate the observations, and hence the models, made by the connectionists. They may be a source of additions to the models, but are not obviously controvertive evidence.

Freud (1891) argued that the inferences drawn by the main connectionist theorists were invalid. For instance, he pointed out that Wernicke attempted to limit the <u>psychic</u> entities which made up his theory to ones he deemed "simple", such as the sound pattern of words. Freud argued that it is invalid to conclude that the <u>neural</u> entities related to such mental constructs are also simple. For example, the sound pattern of a word might be "spread" over the same neural elements as associations to the sound pattern, so that a localizationist idea of centers, in an anatomical sense, does not follow from the assumption of a psychological model which has "simple" components.

The objection is a highly pertinent one, and prefigures modern, but still computationally imprecise, concepts of gradients involved in the neural representations for language (Bogen, 1976; Lenneberg, 1973; discussion following Geschwind, 1979; Whitaker and Ojemann, 1977). Its applicability is, however, not to the psychological decomposition of function utilized in the connectionist theories, but to the neural elements and events of such theories. In fact, this is one of the few examples in the literature of a possible neural mechanism of a different type from localization of functional components by gyrus, and we shall return to it later. For the present, we note that the functional analysis offered by Freud is of the task-oriented type.

Perhaps the most serious challenges to the connectionist theorists came from those who believed that neurolinguistics should rest on a totally different set of functions. As Geschwind (1964) points out, these theorists invariably concurred with the characterization of aphasic syndromes and the occurrence of particular syndromes after particular lesions. He thus suggests that nothing separates these theorists from the connectionists, ignoring the point these theorists tried to make regarding the inappropriateness of connectionist data to the construction of neurolinguistic theory.

The best examples of such work come from Jackson (1874, 1878) and Goldstein (1948). To exemplify Jackson's work, we consider his description of a sub-type of what would be considered Broca's aphasia in which patients have the following marked disturbance of speech. In ordinary conversational contexts they are usually mute. In special situations, they do speak: typically, they can repeat at least some portions of a presented utterance; they speak in emotional situations and situations of great personal significance. Jackson observed that these patients characteristically produced only certain types of responses. The most common responses were oaths, uttered in emotionally distressing situations, and "fixed utterances", which Jackson took to represent transformations of the words in the patient's mind at the actual moment of illness. What Jackson termed utterances with "propositional content", utterances in which predicative and other relations between words (and the real-world entities they referred to) were expressed and which were appropriate to but not uniquely determined by the conversational situation, were absent, with the exception of the single words "yes" and "no", which Jackson argued were the most elementary and general propositions.

Jackson argued that observations of functional repertoires of this sort would lead to a theory of language function which was not task-specific, and to a theory of brain function which did not consist of centers and connections. However, he offered no theory of the representation of propositions, nor did he distinguish between the ideational and linguistic form of propositions. In a highly similar vein, Goldstein argued that general functional principles, such as the ability to assume what he terms an "abstract attitude" (an attitude, we remark, which is probably a prerequisite for the production of a Jacksonian proposition), were lost in aphasia. A modern development of this approach is found in Locke et al. (1973) in which Jacksonian functional capacities are related to a hierarchical model of the neuraxis based on Yakovlev's work (Yakovlev, 1948).

This approach incorporates the claim that the functional capacities lost with respect to language functioning are also lost in other realms of behavior in the aphasic patient. It emphasizes the overlap of linguistic and non-linguistic functions, but uses only a rudimentary characterization of language itself. We believe this approach thus avoids the central issue in neurolinguistic theory, which consists first of the study of the representation and utilization of the <u>linguistic</u> code in and by neural tissue, and only secondarily of how this code is subject to functional factors which also regulate other cognitive and perceptual-motor capacities (although we also believe that neurolinguistics will remain shut off from recent dramatic progress in single-cell neurobiology until fruitful comparisons of linguistic behavior with other perceptual-motor behaviors are developed to the point where animal models can be introduced for relevant aspects of neurolinguistic processing).

To conclude this section, we turn to a large number of experimental and observational studies carried out on aphasic patients conceived within a framework we shall term "verbal learning" (Goodglass et al., 1964, 1966, 1967, 1969; Hawes, 1967; Geschwind & Hawes, 1962). We use this term to designate a set of factors centered around learning non-sentential verbal stimuli, as in paired-associate learning. The variables include those subsumed under general and somewhat poorly defined notions such as "salience" and "simplicity", and more specific and partially quantifiable concepts such as "frequency", "picturability" and "predictability". The frequent attempts to compare the clinical classification of patients, related to the connectionist theories, with performances with respect to these verbal learning variables indicates a close conceptual link between this approach and connectionist theories.

Such work might appear to present candidates for the detailed descriptions of language structures and psycholinguistic functions that we noted were absent in the top-down task-oriented connectionist and holist models. We believe, however, that over-emphasis of this theoretical vocabulary would be an error for neurolinguistic theory. This is because these theoretical constructs do not capture the essential aspect of language with which any linguistic theory must be concerned, namely the relation between physical event (most importantly sound) and mental representation of meaning which the linguistic system establishes. The verbal learning parameters were not devised to capture this relationship, and thus are of secondary importance to the study of language representations, and the use of such representations. The task-oriented models of Lichtheim and Wernicke made clear reference to the process of what we might fancifully call turning thought into sound and vice versa. The incorporation of verbal learning determinants into the task-oriented components of these models, or into the components of any model, will not obviate the need for a theoretical vocabulary designed specifically to capture these processes, though it is quite reasonable to suppose that verbal learning factors will interact with models incorporating these more fundamental representations. We therefore do not see the affiliation of connectionist and verbal learning approaches as an adequate response to the need for a computational neurolinguistics.

The Main Features of Faculty Models

We have suggested that the most important characteristic of the faculty models is their analysis of psycholinguistic function into major on-line language tasks, while treating each of these tasks as individual, essentially unanalyzed, components of a general language faculty. This approach is an example of purely "top-down" modelling approaches in which a designation of system components is not complemented by an account of mechanisms (whether computational or neural) whereby the component's function is realized. The process models to be discussed in the next section are also "top-down" in this sense. We can contrast both of these top-down classes of models with the models described in Sections 3 and 4, and we can contrast the present class with the process class.

The top-down models make inadequate reference to the nature of the information represented in their components to allow a view either of the exact processing of such information by each component or the utilization of the output of one component by another. When the memory aspect of a speech comprehension device is described as the "storehouse of auditory associations", without precisely describing such entities, we are unable to say how such entities enter into the process of comprehending language or influence the production of speech. Given, for instance, that Wernicke's area is, in part, a locus for auditory representations of words, it does not follow that the critical information it provides for speech production is related to the representation of sounds of words (it might be related to their syntactic or semantic features). Such theories, then, cannot provide answers to questions about the processing details of the operation and interaction of components.

There are two immediate consequences. The first is that the range of data which can be accounted for by such theories is quite small, being limited to a description of the relative deficit in one or another of the functional on-line tasks of language, and the combination of such deficits into clinical syndromes. There is no provision within the models themselves for stating the details of how these deficits come about. While aspects of the serial involvement of components are invoked to give an answer to <u>why</u> task-specific performances may differ, one needs a vocabulary in which the elements in which they differ can be stated to construct models that describe <u>how</u> such differences arise, and even <u>what</u> they are. Indeed, not only differences between task-related performances in different syndromes, but the performance of a task which is only partially performed, requires such a vocabulary. It might be the case that a total failre of a speech production component would lead to absolute mutism, but this is not characteristic of the speech of the vast majority of Broca's aphasics. To a limited extent, the theories we have considered adopt terminology drawn from a pre-theoretic linguistic and psycholinguistic vocabulary, speaking of "small, grammatical words", "sound patterns", "grammatical phrases", without specifying the nature of such terms or giving them a role in the explanation of the syndromes. The provision of these theoretically-naive elements as part of the description of aphasic syndromes is incidental to these models.

The second consequence of the limits inherent in top-down theories is that they cannot provide an account of the representation and processing of language which is adequate to approach the neural mechanisms underlying these processes. Marshall (1979) notes that it is generally agreed that the corpus callosum transmits "high-level" information and asks whether anyone would care to speculate as to the "neural code" in which such information is carried. None of "high-level information", "sound patterns of words", or "motor sequences of speech" gives us an adequate description of what the neural code is coding. A more precise, computational, vocabulary is a prerequisite for this type of neurolinguistic theory construction.

2. Process Models

The class of models included in the process category consist of those whose functional analysis is into components responsible for portions of a psycholinguistic task. The functional analysis is more detailed than in the faculty models. In every case, a component accomplishes only a portion of a psycholinguistic task, and the entirety of the task requires the interaction of several components.

Interestingly, the historical origins of this type of model within neurolinguistic pre-theoretical observations antedate 1861 (the year of Broca's landmark paper) and go back at least as far as Lordat's remarkably modern-sounding description of stages in speech production which he published as a result of introspections on his own aphasia (Lordat, 1843). In this century, we can look to the work of Head (1926) for a componential analysis of language along pretheoretical linguistic lines which intersect all psycholinguistic tasks and an effort to describe aphasic syndromes in terms of the functional components, and to Pick (1913) for a model making use of subcomponents of tasks. Brown (1977, 1979) has revived and extended Pick's analysis. In this section we shall outline the model due to A. R. Luria, which we believe exemplifies this class of models.

Luria's approach is founded upon the idea of a functional system (based on the work of Anokhin (1935) and Bernstein (1935)) in which an invariant task can be performed by variable mechanisms to bring the process to an invariant result, with the set of mechanisms being complex and, to an important degree, interchangeable. From such a background, as well as from the developmental studies of Vygotsky (1934) and his own wide experience in neurology and psychology, Luria drew the following program for neuropsychology:

> "It is accordingly our fundamental task not to localize higher human psychological processes in limited areas of the cortex, but to *ascertain by careful analysis which groups of concertedly working zones of the brain are responsible for the performance of complex mental activity; what contribution is made by each of these zones to the complex functional system; and how the relationship between these concertedly working parts of the brain in the performance of complex mental activity changes in the various stages of its development.*" (Luria (1973), pp. 33-34).

We shall consider four diagrams based on Luria's (1973) analyses of object naming, speech production, speech comprehension and repetition. Luria's analysis of the naming of objects can be schematized as in Fig. 6. Each box will correspond to a brain region and to functions suggested by clinical data. (Boxes bear the same label of a capital letter if they correspond to the same brain region -- differing only in the number of primes if they are attributed apparently different functions. In each figure, the

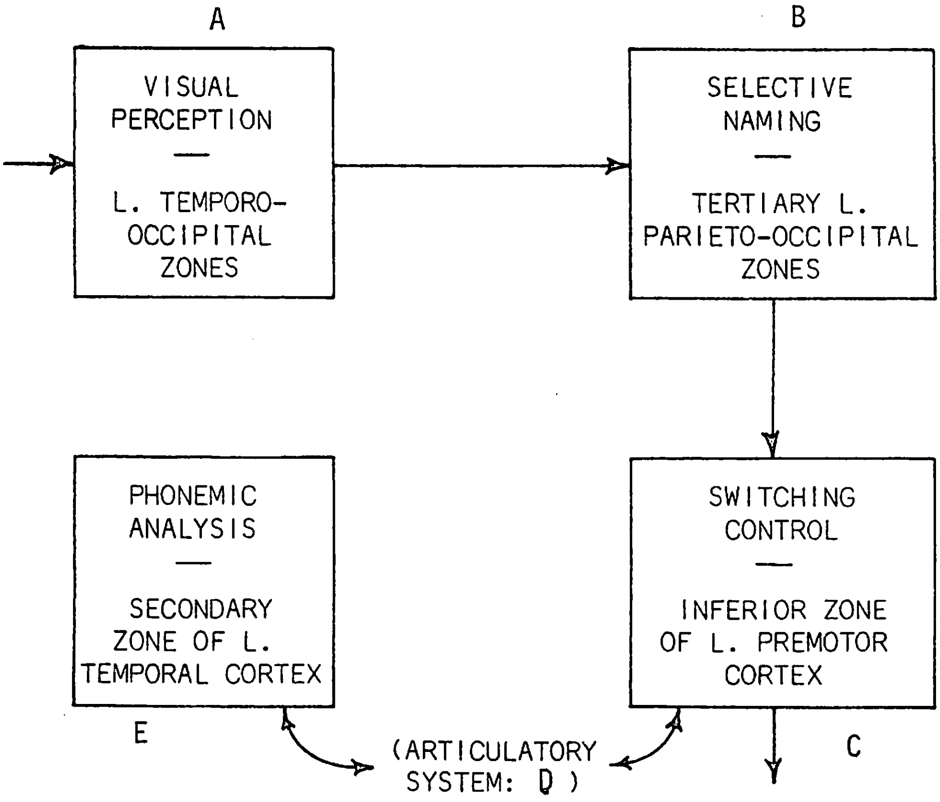


Fig. 6. Block diagram of subsystems involved in Luria's analysis of naming of objects.

functional attribution of a region is taken from Luria, whereas the arrows are our own indication of a plausible information flow.) In the object naming task, no acoustic model is given the subject. Instead, he is to look at an object, and code his visual perception of the object by an appropriate spoken word. Clearly, performance of object naming requires reasonably precise visual perception. Luria singles out as the anatomical site of this component the left temporo-occipital zone (Box A) where lesions disturb both the ability to name objects and the ability to evoke visual images in response to a given word. A patient with such a lesion cannot draw a named object, even though he can copy a drawing line-by-line. In short, lesions here seem to impair the transformation between an array of isolated visual features, and a perceptual unity into which the features are integrated.

The next step (box B) is to discover the appropriate name, and inhibit irrelevant alternatives. Lesions of the left tertiary parieto-occipital zones yield verbal paraphasias -- the appearance of an irrelevant word, resembling the required word either in morphology, meaning, or phonetic composition. Irrelevant sensory features of the object or of articulatory or phonetic information associated with its name can evoke a response as easily as correct features. It is as if the inhibitory constraints were removed in a competitive process. Such lesions do not disturb the phonological representation of language -- prompting with the first sound of a name does trigger its recall.

Luria notes that lesions of the inferior zone of left premotor cortex (box C) impair shifting from the name of one object to that of another, and that lesions in the left fronto-temporal region (not represented) affect the patient's critical attitude to the developing pathological inertia and disturb his ability to correct his mistakes. It is clear that the articulatory system (box D, see later) must also be active in the naming of objects.

Finally Luria also involves phonemic analysis (box E) in the naming of objects. Lesions of the left temporal region disturb the phonemic organization of naming, yielding literal paraphasias, in which words of similar phonemic organization are substituted. In strong contrast with the verbal paraphasias induced by box B lesions, prompting with the initial sound of the name does not help the patient with a left temporal lesion.

This model exemplifies Luria's view of the brain as a functional system and justifies our description of his work as providing process models. It is clear that box E is not just for sensory phonemic analysis; nor is box D purely for motor articulatory analysis. Rather, both systems participate in all brain functions which require exploitation of the network of representations that define a word within the brain. Convergence on the proper word can be accelerated by the cooperative exploitation of both phonemic and articulatory features, and others as well.

Luria's description of the processes involved in speech production is brief (Fig. 7). The frontal lobes are essential for the creation of active intentions or the forming of plans. Frontal lesions (box F) do not disturb the phonemic, lexical or logico-grammatical functions of speech, but do disturb its regulatory role. The patient can no longer direct his behavior with

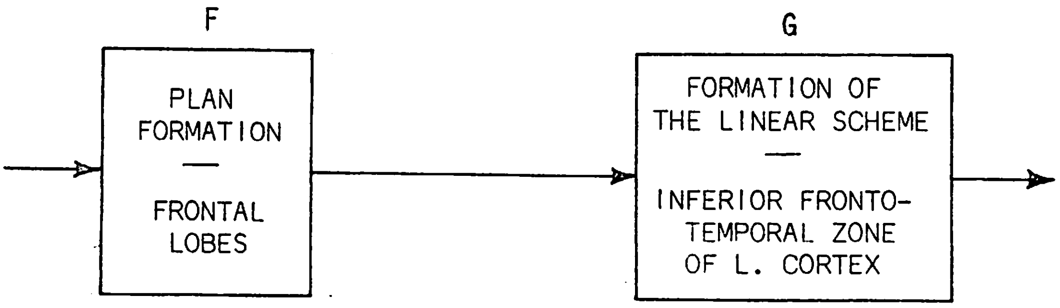


Fig. 7. Block diagram of subsystems involved in Luria's analysis of the verbal expression of motives.

the aid of his own, or another's, speech. The general adynamia of the frontal syndrome includes aspontaneity of speech. Spontaneous speech is absent, while the response to questions is passive, monotonous, and sometimes echolalic. The patient can easily respond to "Were you drinking tea?" with "Yes, I was drinking tea," but has far more difficulty with "Where have you been today?", which requires different data and structure for its answer.

Lesions of the left inferior fronto-temporal zone (box G) yield "dynamic aphasia" -- the patient can repeat words or simple sentences and can name objects, but is unable to formulate a sentence: "Well ... this ... but how? ..." Luria thus views the task of this region as recoding the plan (formulated by box F) into the "linear scheme of the sentence" which makes clear its predicative structure. In one case of dynamic aphasia, the subject was unable to make up sentences, but, if instructed to write aspects down on sheets of paper, was able to rearrange them and finally create the sentence. The output of box G feeds into the articulatory system, box D of Fig. 6.

Turning to speech understanding, we can follow Luria's analysis of the process whereby the spoken expression is converted, in the brain of the hearer, into its "linear scheme", from which the general idea and the underlying conversational motive can be extracted.

As we see in Figure 8, box E performs its usual role of phonemic analysis, supplying input to box H. Lesions here, in the posterior zones of the temporal region or temporo-occipital region of the left hemisphere, leave phonemic analysis unimpaired, but grossly disturb recognition of meaning. Luria very tentatively suggests that this may be due to the impairment of concerted working of the auditory and visual analyzers. The intriguing suggestion here seems to be that phonological representations, rather than directly evoking linguistic semantic representation, serve to evoke a

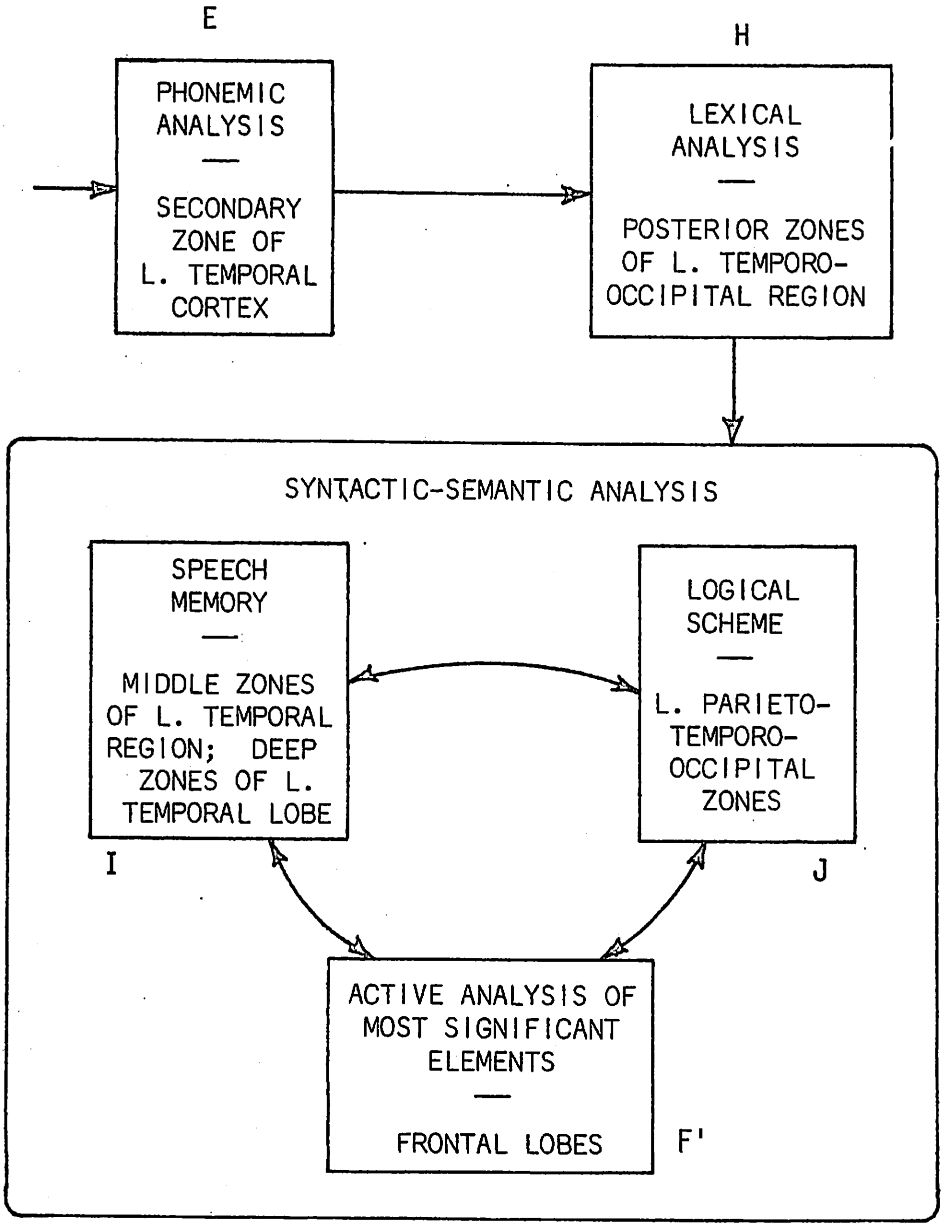


Fig. 8. Block diagram of subsystems involved in Luria's analysis of speech understanding.

modality specific representation (akin to a visual image), and this latter representation aids the evocation of the appropriate semantic and syntactic representation for further processing.

Luria identifies three subsystems involved in syntactic-semantic analysis, termed "speech memory", "logical scheme" and "active analysis of most significant elements". Disturbance of the first of these three, caused by lesions of the middle and deep zones of the left temporal lobe (adjacent to box E) yield "acoustico-mnestic aphasia". The patient cannot retain a short sequence of sounds, syllables or words in memory. This constitutes an impairment of storage of information, as distinct from retrieval of information, which was posited to be impaired by H-lesions. The patient confuses the order of words, and forgets words, recalling perhaps only the first and last. The disturbance is of retention of word series, rather than of word meaning or writing. Moreover, the problem is not so much an instability of audio-verbal traces themselves as a pathologically increased inter-inhibition of the traces. In fact, if the elements are presented with sufficient time between them (to eliminate 'mutual inhibition' between the elements) then the series <u>can</u> be retained.

Lesions of the parieto-temporal-occipital zones of the left hemisphere (box J) yield disorders of perception of spatial relationships, disturb constructional activity and complex arithmetical operations, and disrupt the understanding of logico-grammatical relationships. A sentence with little reliance on subtle syntax -- "Father and mother went to the cinema but grandmother and the children stayed at home" -- is still understood, whereas understanding of a sentence like "A lady came from the factory to the school where Nina worked" cannot be understood. Understanding of the meaning of a sentence requires not only the retention of their elements, but their simultaneous synthesis into a single logical scheme. Luria argues that data on parieto-temporo-occipital lesions give neurological evidence of a system specifically adapted to this synthesis for those constructions where identical words in different relationships receive different values. Box J plays a role when the grammatical codes -- case relationships, prepositions, word order, etc. -- are decisive in determining how the words of the sentence combine to give its overall meaning.

As we saw in our discussion of box F, the frontal lobes are required to form and maintain a program of action. In the speech understanding behavior of patients with a marked frontal syndrome, we see a deficit in the active analysis of the most significant elements in a sentence (box F'). The planned process of decoding the meaning of a complex sentence, or understanding the general meaning or undertone of a complex narrative, is replaced by a series of guesses little based on analysis of the text, or by inert semantic stereotypes based on the patient's prior information.

The block diagram of Figure 9 summarizes Luria's views of the brain regions involved when a subject repeats sentences which are spoken to him. Lesions in the left-temporal region affect the ability to differentiate the (simultaneous or consecutive) combinations of sounds involved in discriminating oppositional features yielding "acoustic agnosia" (inability to

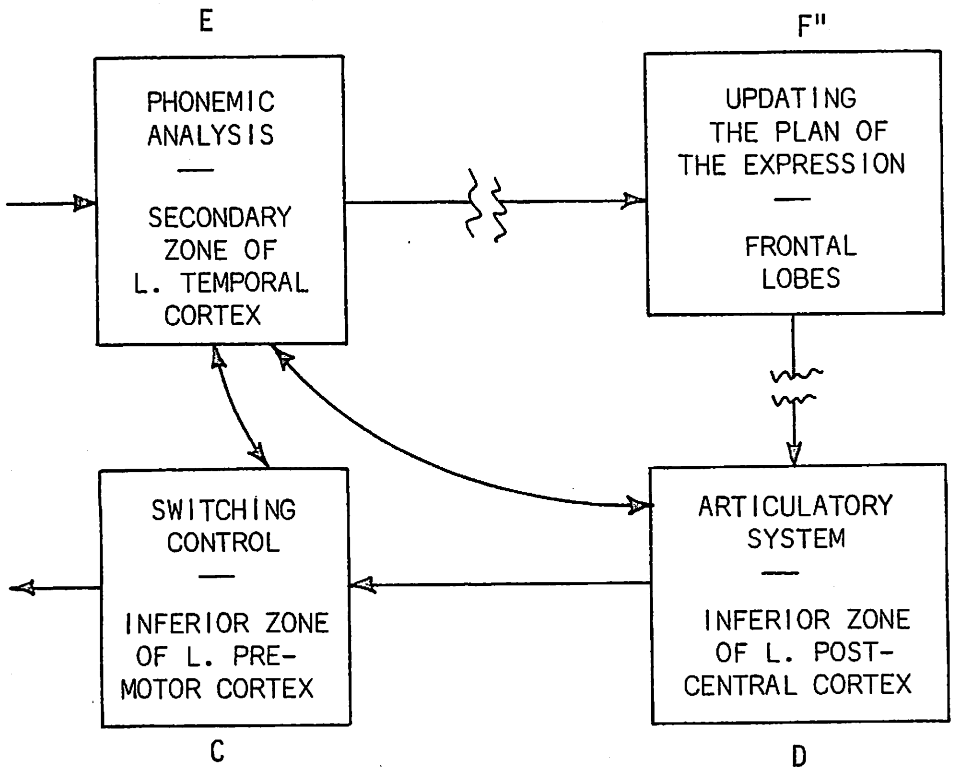


Fig. 9. Block diagram of subsystems involved in Luria's analysis of repetitive speech.

distinguish between sounds of speech) and "sensory aphasia" (the corresponding speech disturbance). With large lesions, all speech sounds are unintelligible, but with small lesions, there is an inability only to distinguish phonemes differing in a single feature: d-t, b-p, etc. Box E thus carries out basic phonemic analysis. With a lesion in E, the patient finds understanding of individual words almost impossible. However, his understanding of the general meaning of a whole utterance may be preserved because of his guesses about context, and his use of the general intonation of audible speech.

Luria insists that repetition is a complex function, requiring several components. The programming of the response requires the close participation of the frontal lobes. A frontal patient, given a logically incorrect phrase, will "persevere" with the initial interpretation and give back the more habitual correct form. With a lesion of the posterior postcentral cortical zones, the potential strength of muscles remains, but their differential timing is sharply impaired due to lack of normal proprioceptive feedback ("afferent paresis"). If the lesion of the secondary zone of the left postcentral region affects the lower zones -- our box D -- corresponding to the face, lips and tongue, the patient may be unable to determine immediately the positions of the lips and tongue necessary to articulate the required sounds of speech, an "afferent motor aphasia" of the articulatory apparatus. Small disturbances yield the confusion of articulemes which are similar in articulation even though different in acoustic properties. A secondary effect of such lesions is a disturbance of writing involving the substitution of letters corresponding to similar articulemes, an effect to be analyzed in terms of interaction between speech-evolved mechanisms and the control systems of writing. The premotor zone of cerebral cortex is responsible for playing out the "kinetic melodies" of motor stereotypes (Bernstein, 1967). Lesions here yield neither paralysis nor paresis of the contralateral limbs, but skilled movements are no longer performed smoothly, and each component requires its own isolated "trigger". When the lesion affects the inferior zones of the left premotor cortex (box C), the inertia and perseveration is shown in the patient's speech. In the resultant "efferent motor aphasia" the articulation and pronunciation of isolated speech sounds gives no serious difficulty, but the smooth pronunciation of a polysyllabic word becomes impossible. This can lead to corresponding defects in writing. Such lesions are also the basis of Broca's aphasia.

In Figure 10, we have incorporated our preceding four diagrams into a single representation of a partial specification of a neurally-based language device. Figure 10a represents the components and connections in Luria's (1973) analysis, supplemented by several additional lines representing information not specified directly but indirectly inferrable from Luria's work. In 10b we have represented the general location of these components in the brain. It should be remarked that Luria provides data for the localization of each component of Figure 10 but for few of the connections (such as A-D and A-C).

Inspection of Figure 10 makes visually apparent the features of Luria's approach which distinguish it from the models of Section 1. Each psycholinguistic task is performed by several components acting in parallel and sequential fashion. Many components are involved in several tasks. One might consider whether more shared components might be derivable from the system (G & J, for instance, might interact through some shared process) and whether some components might not be partitioned (I seems overburdened). It also seems clear that additional components might profitably be considered (the relation

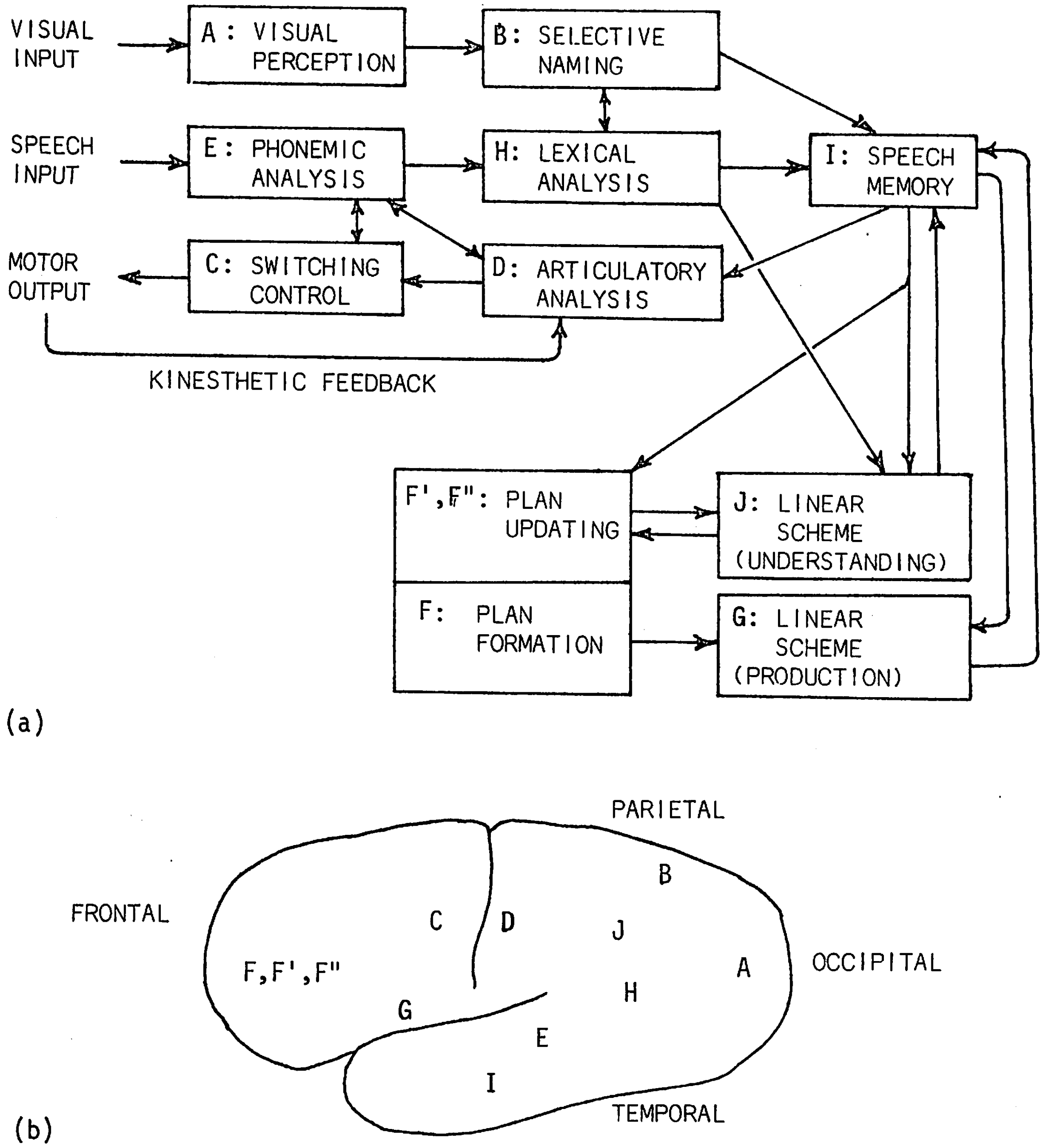


Fig. 10. (a) Synthesis of the block diagrams of Figs. 6 to 9. (b) Approximate anatomical localization of the subsystems.

of "planning" to "linear schemes", J-F in and F-G out, seems simplistic).

We may now consider the range of data the model accounts for. Because it incorporates finer functional analyses, it clearly is able to describe and explain a more detailed data-base. We noted that in the faculty models, there was no provision within the components of the model themselves for descriptive terms from linguistic, psycholinguistic, or other accounts of language. In the present model, there is provision made for such terminology. The components of the model include several whose role seems to be the conversion of one level of representation into another, and the integration of these representations into psycholinguistic tasks by means of interaction with other components. To the linguist, psycholinguist, or computer scientist concerned with representations of language, the choice of descriptive vocabulary is inconsistent and the levels of representation constructed incomplete, but we consider these to be potentially remediable defects. We note that in this model, the choice of phenomenological descriptive vocabulary is drawn from sciences whose goals are the relation of phsyical and mental representations in a linguistic system.

It is also apparent from Figure 10 that the component interaction in this model is far more complex than that in the faculty models. Of course, such features of neurolinguistic models must be empirically motivated, and are not desirable in and of themselves. It seems reasonable from numerous results in psycholinguistics (Fodor et al., 1974; Garrett, 1976; Frazier, 1978; Frazier & Fodor, 1978) to consider feedback and feedforward mechanisms, parallel as well as sequential component activation, and other such interactions in neurolinguistic models. Such features of the model seem to be the natural consequence of extending neurolinguistic theory to include a more detailed and adequate range of data. Moreover, incorporation of such features into neurolinguistic models makes them far more congruent with neural models of a variety of other processes, a point to which we shall return and whose significance we consider great. Finally, we note that the expansion of task-related components into smaller divisions allows a wider range of interaction of linguistic and non-linguistic processes. We mentioned in passing that much of Geschwind's work, the analysis of apraxia and agnosia, focuses on the relation of motor and sensory systems to a general language system. In his model, such interactions occur only with the language system as a whole, and the potential for more subtle interactions is very limited. In Luria's model, there are several examples of such interactions, such as those between frontal lobe general planning mechanisms and various components of a language device directly concerned with linguistic representations. These interactions account for several aspects of aphasic syndromes, and we consider the enriched possibilities of such interactions to be a significant advantage of this model.

We close this discussion with the observation that this model still fails to be computational. There is insufficient specification of the input-output codes of the components to allow the clear conceptualization of exactly how the components function individually or how they utilize information from each other. Several components, such as E, are relatively well specified in this regard (though none are fully specified to the point, for instance, where they could be directly transposed to a computer), but others, such as G and J, are grossly under-specified and seem to involve the construction of a variety of different linguistic representations.

3. Representational Models

In the past decade, a variety of studies have provided partial analyses of aphasic syndromes which draw on the vocabulary of linguistic science to provide an explicit theory of the different representations which enter into the execution of a linguistic task. Transformational-generative grammar, as is well known, has provided detailed descriptions of a host of levels of language structure, rules relating these levels, conditions on well-formedness of the levels, hypotheses as to universal aspects of the rules and structures, and metrics for evaluation of competing hypotheses; all based on detailed descriptions and explanations of empirical observations in a large number of the world's languages. Competing analyses, many based on apparently quite disparate variants of the general theory, abound, and development and changes of theory, even within the most orthodox circles of the science, have been rapid. The impact of transformational-generative grammar upon the concerns of psycholinguists has been enormous (Fodor et al., 1974), and now a number of applications of linguistic theory to aphasiological descriptions have also been published. We shall outline two areas in which such applications have been made, each representing the work of a number of investigators: the study of phonemic paraphasias, and the characterization of the functional deficit in Broca's aphasia.

The nature of phonemic paraphasias constitutes one of the better studied aspects of aphasic production. We shall describe two studies of particular significance to the present theme. Schnitzer (1972) analyzed the dyslexic errors of a single patient, a twenty-six year old woman who manifested a prominent dyslexia as part of an otherwise mild aphasic disturbance following evacuation of a left-sided subdural hematoma. (The patient came to autopsy where a cortical contusion of the left supramarginal gyrus was the only relevant C.N.S. abnormality.) The patient's errors were most prominent in derivationally complex, multisyllabic words of Latinate etymology. Kehoe and Whitaker (1973) report that the patient was unable to read words such as "degradation" but correctly pronounced the nonsense string "maygradation" and words of Anglo-Saxon origin such as "yestermorn".

Schnitzer's analysis of the patient's errors indicates that a significant number, some forty to fifty percent, could be seen as the result of a single error mechanism. He utilizes the analysis of English phonology developed by Chomsky and Halle (1968), in which the phonological component of the grammar for English operates in a complex deterministic fashion on an input termed the "systematic phonemic representation" and yields an output which adds a number of phonological features, including stress contour, and affects others such as vowel quality. The input to this level is well defined in terms of the theory of which this is a component, and consists of the lexical phonological representation plus lexical morphological and redundancy rule effects, and a set of syntactic markings derived from the "surface structure" created by the syntactic component of the grammar, operated on by readjustment rules. The output of the phonology is equally well defined. Schnitzer argues that seemingly complex dyslexic errors can be viewed as the result of extremely simple changes in the input to the phonological component, and the subsequent operation of the rules of the phonological component on the erroneous inputs to produce observed changes which are complex transformations of the target word.

To cite an example, Schnitzer analyzes the error made in pronouncing the word "reconcile". Rather than the usual form /r$\overset{1}{\text{e}}$kəns$\overset{3}{\bar{\text{a}}}$yl/, the patient read /r$\overset{3}{\bar{\text{i}}}yk\overset{1}{\bar{\text{a}}}$nsəl/. Schnitzer points out that this "surface form ... differs phonetically from the usual form in its stress contour and in *all* of its vowels". However, a simple error in the underlying "systematic phonemic" representation, changing the underlying tense /Ī/ to lax /i/, will produce exactly this error.

In his analysis, Schnitzer makes explicit use of a computational algorithm for assigning several phonological properties to words in English. He postulates that errors occur at a particular level of representation; in certain cases (such as deletion of segments) he advances hypotheses as to restrictions on such errors. The complex patterns of observed errors are due to the complexity of the normal rules of English phonology; the actual error mechanism is relatively simple.

A rather different approach has been undertaken by Lecours and his colleagues (Lecours & Lhermitte, 1969; Lecours et al., 1973; Lecours & Caplan, 1975). He postulates a rich error mechanism to account for the phonemic paraphasias observed in spontaneous speech, reading and repetition of a large number of French "fluent" aphasics. In his model, paraphasias are due to the operation of this error mechanism on the output of the normal French phonology. Lecours utilizes a vocabulary similar to Schnitzer's for the characterization of the linguistic elements involved in errors; in both cases, these elements consist of phonemes made up of a distinctive feature analysis. Schnitzer's descriptive vocabulary is richer, inasmuch as it includes a number of different junctional elements (word boundary, formative boundary, etc.) and, as we have seen, distinguishes two levels of phonological representation. Lecours, moreover, has limited his analysis to the sequences of consonants seen in errors of this type, whereas Schnitzer focussed on both consonants and vowels and concerned himself with stress contours as well.

Lecours's descriptive and simulation studies develop a set of "aphasic transformations" of the consonants of a word. The basic operations consist of addition and deletion of elements. Several factors determine the activity of these operations. A standard base error-rate is postulated. A "paradigmatic" factor determines that elements are likely to undergo deletion or to be added in proportion to the similarity of the error and target segment, where similarity is measured in terms of number of distinctive features shared by any two consonants. A second factor, termed "syntagmatic", increases the chances of aphasic alteration in inverse proportion to the distance between two similar phonemes (distance measured in number of intervening phonemes). Particularly frequent are transformations creating identical pairs (either by reduplication or feature change in a similar consonant), metathesis, and aphasic errors bearing on existing identical phonemes and phonemes distinguished by only one distinctive feature. Accordingly, both in the descriptive and simulation work, special mechanisms are invoked to account for and create such errors.

The error mechanism is designed to apply more than once to the same input. Thus, Lecours describes complex errors as the result of several applications of the rules of error-formation to the target string. For example, the error /dekalərɔ̃/ → /kerɑdəlrɔ̃/ consists of four elementary operations in his system.

The error mechanism can apply at several levels of linguistic analysis. Lecours and Lhermitte give as examples three such levels: distinctive features, phonemes, and so-called "joint phonemes", the latter seemingly equated with consonant clusters in their work. Thus, they argue that the following errors are due to the identical error mechanism --

(1) /sɔsjɔlɔg/ → /sɔsɔlɔg/

(2) /prɔbite/ → /prɔpite/.

At the level of phonemes, the second error consists of duplication of the phoneme /p/; at the level of joint-phonemes, the first error can be seen as duplication of the joint-phoneme /sɔ/. Moreover, at the distinctive feature level (2) consists of deletion of a feature (voiced) and, at the phoneme level, (1) of deletion of the phoneme /j/. These statements embody empirically testable theories of levels of language representation.

An interesting observation, made many times and confirmed by this work, is that virtually all aphasic errors of this type conform to the morpheme-structure (phonotactic) constraints of the language. (Note that this is a natural consequence of Schnitzer's model.) Normally impossible segmental sequences are not produced as a part of the errors generated by these patients. In their simulation study, Lecours et al. were unable to achieve this feature of the errors without incorporating what might be viewed as an output filter on the error-generator, in effect stating the phonotactic constraints of French.

Despite its positive features, Lecours' model has one grave disadvantage. It is a descriptive model, seeking to use an economical set of error generators to compactly describe a varied, statistically characterized, corpus of paraphasias. This is a model which views brain damage as creating explicit "error generators". An alternate approach would seek to show what discriminations must be made in transforming some internal representation into a sequence of phonemes, and then analyze conditions in which errors would be unavoidable with limited computing resources.

A second model which makes use of modern linguistic analysis to precisely represent the relevant "data structures" is in the analysis of the deficit seen in Broca's aphasia. Kean (1978, 1979) argues that there is a linguistic characterization of the range of abnormal phenomena seen in this syndrome; namely, all errors are due to disturbances within the phonological component of a grammar. It is apparent that many aspects of the clinical syndrome traditionally recognized as Broca's aphasia may be characterized at the phonological level of a grammar. Such aspects include the dysarthric components of speech output, segmental paraphasias, prosodic abnormalities, and others. Kean undertakes to establish that a phonological characterization can -- and must -- be given for elements of the syndrome which have traditionally been conceived of in other terms. In particular, she argues that the "agrammatic" aspect of the speech of these aphasics is only formulable as a phonological deficit, not a syntactic one.

Her argument is, in its essentials, that the sharp distinction between vocabulary elements which characterizes the speech of these patients is stateable within phonological but not syntactic theory. Characteristically, these patients omit items from the minor grammatical categories in English (determiners, prepositions, pronouns, etc.) while they retain their abilities to produce items from the major grammatical categories (nouns, verbs, adjectives). This distinction, seemingly syntactic, is in fact not drawn in the theory of syntax, but in phonological theory: the minor categories are, to a very close approximation, those which do not bear main sentential stress unless emphasized. Kean then points out a formal notational similarity between the minor grammatical categories and a class of affixes which are also characteristically omitted in the speech of Broca's aphasics. These affixes, such as -ness, -ly, -er, do not alter the stress pattern of the stem to which they are attached; they are termed "word boundary" affixes. They are opposed to so-called "formative-boundary" affixes, such as -ive, -tion, and others, which do alter stress and other, segmental, features of the stems to which they are affixed.

The generalization which Kean suggests is that the speech of these aphasics demonstrates a tendency to reduce to what is psychologically construed as the minimal string of "phonological words" in the language. Kean points out that the linguistic definition and psychological construal of phonological words will differ from language to language, with the result that, if this statement is a true description of the aphasic syndrome, the speech seen in this type of aphasics may differ in different languages but still conform to the generalization.

In a related vein, a coordinated series of investigations has explored the generality of the deficit centered on phonological non-words (which we shall continue to call function words) in psycholinguistic tasks other than speech. In one experiment (Zurif et al., 1972), it has been demonstrated that Broca's aphasics do not classify these words together with major category items in tests of relatedness judgements of words in sentences. Bradley (1978) has demonstrated that the usual frequency effects and non-word interference effects found in normal populations in lexical access tasks with items from major lexical categories are not found in normal populations for function words, but that both the frequency effect and non-word interference effect are present in lexical access for function words in Broca's aphasics (Bradley et al., 1979). Goodenough et al. (1977) demonstrated a delay in reaction time to commands containing a semantic anomaly in the choice of definite or indefinite article in normals, but not in patients with Broca's aphasia. All these studies indicate a generalized deficit in psycholinguistic tasks (metalinguistic judgements, lexical access, semantic representation) centered on the "function words" omitted in the speech of Broca's aphasics.

Interesting results have also been obtained in tests of sentence comprehension. Scholes (1978) reports the results of a picture matching task in which ambiguous sentences such as (3) and their two disambiguations, (4) and (5), were presented to Broca's aphasics:

3. John showed her baby pictures.
4. John showed her baby the pictures.
5. John showed her the baby pictures.

The patients recognized an ambiguity with respect to the possible indirect object in (3) but failed to distinguish the two disambiguated versions from each other, treating each as ambiguous. The result may be interpreted as evidence of the failure of these patients to extract at least certain syntactic features from function words in sentence comprehension. Zurif and his colleagues (Zurif & Caramazza, 1976; Caramazza & Zurif, 1978) likewise argue that these patients fail to utilize syntactic information contained in function words in comprehending sentences. They presented Broca's aphasics with sentences containing center embedded relative clauses, such as (6) and (7).

6. The apple the boy is eating is red.
7. The girl the boy is chasing is tall.

Patients performed accurately in picture matching in which the foils consisted of replacement of the referents of the nouns, verbs and adjectives with other plausible items, but they performed only at a chance level in the same task when the foils consisted of reversal of predicative relations in the reversible sentences such as (7). These investigators claim that the Broca's aphasic extracts virtually no information as to the syntactic structure of a sentence from the function words, and is entirely reliant upon decoding strategies which make use of lexical semantics and knowledge of probable real-world events.

The studies by Kean define a universal set of linguistic items which are affected in Broca's aphasia, and the work on psycholinguistic processing explores the deficits in on-line language tasks of these patients. It has not yet been demonstrated that all the elements specified by Kean are affected in all psycholinguistic tasks, but all performance failures thus far have been explicable in terms of the items she includes in the linguistic definition of the syndrome.

We have outlined two areas in which partial analysis of aphasic symptoms and syndromes have been proposed in precise linguistic terms. Similar approaches to other areas of aphasiology are developing (Caramazza and Berndt, 1978) as well as to other neurologically impaired populations (Dennis and Kohn, 1975; Dennis and Whitaker, 1976; Dennis, 1979).

These models constitute, in our opinion, a significant advance over the approaches outlined in Sections 1 and 2. They explicitly designate theoretical constructs from general theory of language structure and function as the elements of a neurolinguistic theory (upon which abnormal operations can be performed in the case of language disorder), thus making it possible to construct components of a neurolinguistic theory for which input/output specifications can be stated. Such statements allow precise descriptions of the action and interaction of components. Equally important, they may serve as serious hypotheses about what the neural code actually codes.

The limitation currently visible in these models is that they are not integrated into general process models. We have chosen the term "representational" to designate these models because many, though not all, focus on the linguistic representations stored and utilized in aphasic syndromes, with less emphasis on the processing routines which involve these representations (but see, for instance, Bradley et al. (1979) and Kean (1979) for a discussion of processing). This is a remediable situation, occasioned by the nature of the models itself. The very detail and precision which makes these models appealing from the point of view of descriptive and explanatory adequacy complicates their introduction into general process models (such as Luria's) which have empirical justification. No general computational neurolinguistic process models have been proposed to our knowledge. We therefore turn to artificial intelligence to illustrate how such models of language might be developed, and to brain theory to illustrate the representation of non-linguistic phenomena in neural tissues in ways consonant with the demands of computational neurolinguistics.

4. Artificial Intelligence and Linguistics

This section reviews work in Artificial Intelligence that provides computational concepts which complement the representational advances in linguistics. We shall particularly stress those concepts that we believe are relevant to the development of neural models of language. One AI model that has already gained wide acceptance amongst psycholinguists is the ATN (Augmented Transition Network) introduced by Thorne, Bratley and Dewar (1968) and developed by Woods (1970). This model shows how a grammar may be represented not as a transformational "competence" grammar, but rather as an actual parsing system which can make initial parsing decisions with each initial segment of a word-string. Wanner and Maratsos (1978) have offered an ATN model of relative clause comprehension; Bresnan (1978) has suggested an ATN model at the heart of a radical recasting of transformational grammar which transfers most power from transformations to the lexicon; while Marslen-Wilson (1976) reports on shadowing experiments which argue for constraints on linguistic representations due to "on-line" processing by a hearer, though he cautions against uncritical incorporation of the ATN "metaphor" into psycholinguistic theory.

Winograd (1972) developed an AI system which could analyze simple English systems to obey commands, answer questions, or update a data base. He used an ATN-type grammar which could call on semantic information to cut down the number of possible parsings. The Winograd system was designed to analyze sentences about blocks on a table top. Each time the syntactic routines had posited that certain words formed a noun group, for example, the program would call a semantic routine to check whether this noun group could actually describe something in the system's table-top "world". This computational device captures something of the way in which people can cut down the number of interpretations of a sentence on the basis of pragmatic information.

In addition to providing the words of the input with syntactic labels in a manner consistent with the rules of the grammar -- with the string being accepted as a sentence just in case such a labelling can be found -- text understanding involves a translation process which yields a representation of the intention behind an utterance. If the input is a command, the system must recognize it as such and translate it into a program for carrying out the command -- which may well involve first translating the command into an internal representation, and second calling upon planning processes to translate this into a detailed program of action tailored to the current situation. If the input is a question, the system must recognize it as such and translate it into a program for retrieving relevant information from its data base. A second translation is then required to express this information as an answer in natural language. Transferring this perspective from the computer to the human, we can suggest that the task of speech perception is to organize a string of words into pieces which map naturally into the internal processes that constitute the person's response to the utterance; while production serves to recode a "brain representation" into a syntactically correct string of words. We thus stress translation between "internal" and linguistic representations of meaning.

While the above material indicates the growing utility of AI studies for psycholinguistics, it does not address the specifically neurolinguistic question of how a performance may be mediated by the interaction of a number of concurrently active processes. We thus devote the rest of this section to an exposition of HEARSAY (Erman and Lesser, 1975, 1979; Lesser et al., 1975), an AI speech-understanding system which is explicitly based on the cooperation of multiple processes. It has not yet fed into psycholinguistic, yet alone neurolinguistic, theory but we shall indicate in Section 5 a number of ways the model could be modified to better fit it as a test-bed for simulating the neural basis of language.

The HEARSAY-II system has a very explicit representational structure, based on a set of different levels of representation. The raw data, whose interpretation is the task of the system, is represented at the "parameter" level as a digitized acoustic signal. The system will, via intermediate levels, generate a representation at the "phrasal" level of a description according to a grammar which contains both syntactic and semantic constraints. The combination of phrasal and lexical information can then be used to generate the appropriate response to the verbal input.

HEARSAY uses a dynamic global data structure, called the "blackboard" which is partitioned into the various levels. At any time in the system's operation, there are a number of hypotheses active at the various levels, and there are links between hypotheses at one level and those they support at another level. For example in Figure 11 we see a situation in which there are two surface-phonemic hypotheses 'L' and 'D' consistent with the raw data at the parameter level, with the 'L' supporting the lexical hypothesis "will" which in turn supports the phrasal hypothesis "question", while the 'D' supports 'would' which in turn supports the 'modal question' hypothesis at the phrasal level. Each hypothesis is indexed not only by its level but also by the time segment over which it is posited to occur, though this is not explicitly shown in the figure. We also do not show the "credibility rating" which is assigned to each hypothesis.

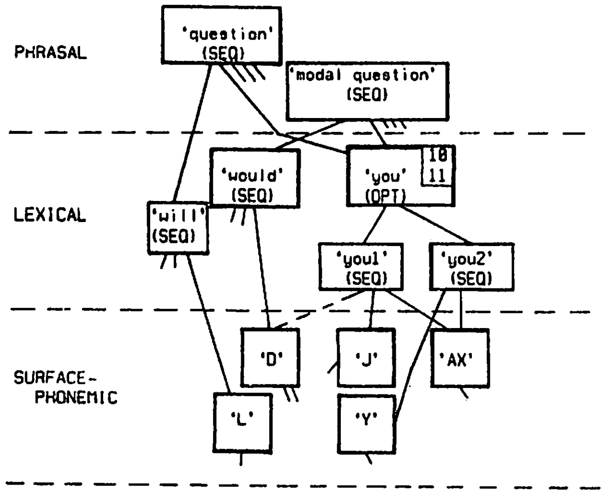


Fig. 11. Multiple hypotheses at different levels of the HEARSAY blackboard (Lesser et al., 1975).

HEARSAY also embodies a strict notion of constituent processes, and provides scheduling processes whereby the activity of these processes and their interaction through the blackboard data base is controlled. Each process is called a knowledge source (KS), and is viewed as an agent which embodies some area of knowledge, and can take action based on that knowledge. Each KS can make errors and create ambiguities. Other KS's cooperate to limit the ramifications of these mistakes. Some knowledge sources are grouped as computational entities called modules in the final version of the HEARSAY-II system. The knowledge sources within a module share working storage and computational routines which are common to the procedural computations of the grouped KS's.

HEARSAY is based on the "hypothesize-and-test" paradigm which views solution-finding as an iterative process, with each iteration involving the creation of a hypothesis about some aspect of the problem and a test of the plausibility of the hypothesis. Each step rests on *a priori* knowledge of the problem, as well as on previously generated hypotheses. The process

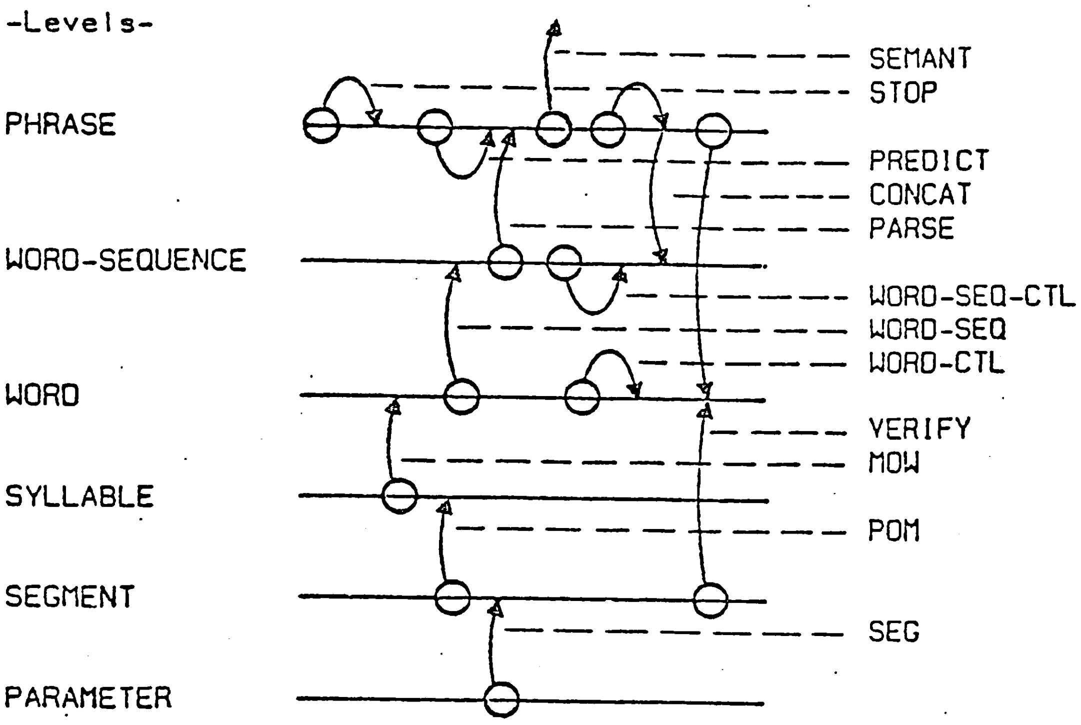


Fig. 12. The C2 configuration of HEARSAY-II. The levels are represented by the solid lines, labelled at the left. The KS's are represented by the circle-tailed arrows, and are linked to their names by the dashed lines. Each KS uses hypotheses at the tail-end level to create or verify hypotheses at the head-end level. (Erman and Lesser, 1979).

terminates when the best consistent hypothesis is generated satisfying the requirements of an overall solution.

The choice of levels and KS's varies from implementation to implementation of HEARSAY, which is thus a class of models or a modelling methodology rather than a single model. (In fact, the HEARSAY methodology has been used in computer vision with picture point/line - segment/region/object levels replacing the acoustic/phonetic/lexical/phrasal levels of the speech domain (Hanson and Riseman, 1978).) The C2 configuration of HEARSAY-II is shown in Figure 12. We see that each KS takes hypotheses at one level and uses them to create or verify a hypothesis at another (possibly the same) level. In this particular configuration processing is bottom-up from the acoustic signal to the level of word hypotheses, but involves iterative refinement of hypotheses both bottom-up and top-down before a phrasal hypothesis is reached which is given a high enough rating to be accepted as the interpretation of the given raw data.

As we have seen, the KS's cooperate in this iterative formation of hypotheses via the blackboard. In HEARSAY, no KS "knows" what or how many other KS's exist. This ignorance with respect to other KS's is maintained to achieve a completely modular KS structure which enhances the ability to test various representations of a KS as well as possible interactions of differing combinations of KS's.

The current state of the blackboard contains all current hypotheses. Subsets of hypotheses represent partial solutions to the entire problem. A subset of hypotheses is defined relative to a contiguous time interval. A given subset may compete with other partial solutions, or subsets having time intervals which overlap the given subset.

We thus regard the task of the system as a search problem. The search space is the set of all possible networks of hypotheses that sufficiently span the time interval of the utterance connecting hypotheses directly derived from the acoustic input to hypotheses which describe the semantic content of the utterance. The state of the blackboard at any time, then, comprises a set of (possibly overlapping) partial elements of the search space. No KS can singlehandedly generate an entire network to provide an element of the search space. Rather, we view HEARSAY as an example of "cooperative computation": the KS's cooperate to provide hypotheses for the network providing an acceptable interpretation of the acoustic data. Each KS may read data; add, delete, or modify hypotheses and attribute values of hypotheses of the blackboard. It also may establish or modify explicit structural relationships among hypotheses. The generation and modification of hypotheses on the blackboard is the exclusive means of communication between KS's.

Each KS includes both a precondition and a procedure. When the precondition detects a configuration of hypotheses to which the KS's knowledge can be applied, it invokes the KS procedure, i.e., it schedules a blackboard-modifying operation by the KS. The scheduling does not imply that the KS will be activated at that time, and/or that the KS will indeed be activated with this particular triggering precondition since HEARSAY uses a "focus of attention" mechanism to stop the KS's from forming an unworkably large number of hypotheses. The blackboard modifications may trigger further KS activity -- acting on hypotheses both at different levels and at different times. Any newly generated hypothesis would be connected by links to the seminal hypothesis to indicate the implicative or evidentiary relationship between them.

There are essentially two operations which generate hypotheses: Synthesis or abstraction which results in additional hypotheses at a higher level based on conjoined lower-level hypotheses which have already been substantially validated; and analysis or elaboration resulting in the creation of lower-level hypotheses which, when verified, tend to confirm or refute a higher-level hypothesis. Analysis or elaboration can also decompose hypotheses from a higher level into more explicit hypotheses whenever stagnation occurs in the system.

A jump over several levels is the equivalent of constructing a major step in the plan, helping to significantly prune the search space. Partial solutions can be combined to create hypotheses which skip several intermediate levels on the blackboard. This concatenation of contiguous partial solutions is validated by consideration of the desirability of the conjoined partial solution at a higher level.

Each hypothesis has an associated set of attributes, some optional, others required. Several of the required attributes are: (i) the name of the hypothesis and its level; (ii) an estimate of its time interval relative to the time span of the entire utterance; (iii) information about its structural relationships with other hypotheses; and (iv) reliability ratings.

The reliability measure reflects the plausibility of a hypothesis. It is calculated by a weighted functional composition of the validity of the hypothesis (an integer between -100 and 100: from maximally implausible to maximally plausible); and the conditional strength of the hypothesis as an inference represented by its implication value (ranging from 100, maximally confirming evidence, to -100, maximally disconfirming evidence). The validity of a hypothesis is a function of the validity of the hypotheses directly supporting it via implicative links and the implicative strengths associated with those links. Changes in validity ratings reflecting creation and modification of hypotheses are propagated automatically throughout the blackboard by a rating policy module called RPOL.

The actual activation of the knowledge sources occurs under control of an external scheduler, the "schedule KS" (Figure 13). The schedule KS constrains KS activation by functionally assessing the current state of the blackboard with respect to the solution space and the set of KS invocations that have been triggered by KS preconditions.

The focusing strategy module, in a manner consistent with the desired search policy (bottom-up, breadth-first, best-first -- determined heuristically and by current state considerations), calculates a weighted functional value based on: (i) validity of the hypothesis on which an inference is based; (ii) the implicative strength of the inference (that of the permanent knowledge on which the inference is based); and (iii) the estimated validity of the results.

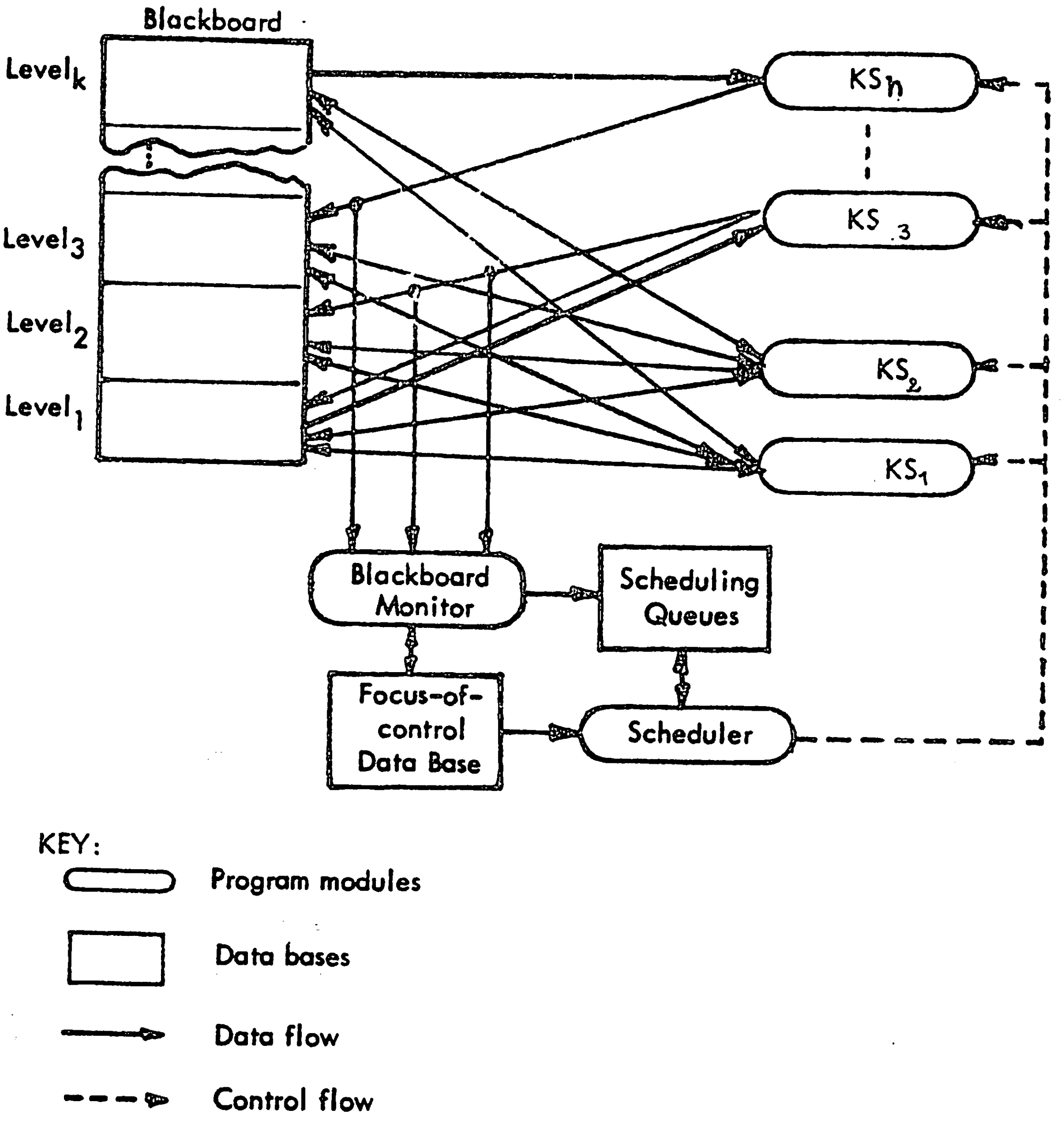


Fig. 13. HEARSAY-II Architecture. The blackboard is divided into levels. Each KS interacts with just a few levels. A KS becomes a candiate for application if its precondition is met. However, to avoid a 'combinatorial explosion' of hypotheses on the blackboard, a scheduler is used to restrict the number of KS's which are allowed to modify the blackboard. (Lesser & Erman, 1979)

The KS having the highest functional value becomes the best-first knowledge source and is the one that is activated by the scheduler (Hayes-Roth & Lesser, 1977). The highest overall rated KS reflects the activation level of the hypotheses relevant to the KS instantiations. The scheduler supplies the external input which actually activates the specific KS most likely to aid in attaining the complete parse of the utterance.

We now give a more detailed account of the syntactic and semantic components of HEARSAY-II. The C2 configuration (September 1976) of the HEARSAY-II system will be used throughout the subsequent description. In HEARSAY-II, both syntactic and semantic operations are implemented via the SASS module. The SASS module is comprised of three independent KS's, PARSE, PREDICT, and CONCAT. It utilizes a semantic template grammar to effect the parse of the utterance. Efficiency considerations led to much of the partial working results being stored internally to SASS. The only information placed on the blackboard at the phrasal level is the recognized and extended word sequences, with their maximal partially-matched template and missing constituents as attributes. Note then that there is much data flow and updating within SASS which is not mediated via the blackboard -- a departure from the initial HEARSAY design procedure. SASS seems to correspond to the input side of Winograd's system -- if one equates a SASS parse with Winograd's Planner representation. Once the best parse is achieved, KS's SEMANT and DISCO operate to produce the required interpretation and initiate the desired response.

The PARSE KS of the SASS module relies heavily on an ACORN (Automatically Compilable Recognition Network) representation of the semantic template grammar (to be described later). A parse is effected through cooperation in a top-down and bottom-up manner, by extensive interaction among the KS's of the HEARSAY-II system.

The language recognized by HEARSAY-II is described by a semantic template grammar. Each template describes a context-free language of expressions with a common interpretation class. For example, the template $REQUEST ($ precedes a non-terminal) is defined as the sequence

TELL $ME $RE $TOPICS

and describes a set of typical requests which might be made to an information retrieval system.

TELL is a hypothesis at the word level, while $ME, $RE, $TOPICS, and $REQUEST are hypotheses at the phrasal level. Here is an example of data at one level being used to confirm hypotheses at the same level. The system (via the KS's SEMANT and DISCO) must have an explicit access to the hypotheses confirming $REQUEST if the request is to be understood.

A template combines syntax and semantics. It consists of ordered, linked terminal and non-terminal nodes. Each terminal node has associated with it a description of all possible instances. Node names representing networks, i.e. the non-terminal nodes, can occur within a template network. Figure 14 provides an example.

The partial hypotheses which match the terminal elements are combined into phrasal node hypotheses and each has associated attribute values. The grammar is "speech act" based in that in its definition, the frame of an inquiry discourse is explicitly and restrictively utilized. The pragmatics of the discourse permit evaluation of possible sentence types which are likely to occur. This limits the number of possible high-level templates. (The DISCO KS network contains these as its nodes -- there are 13 of them in

```
<SENT> ::= [<SS>]

<SS> ::= <$WHATIS>  THE SIZE OF THE DATABANK
         <$QUANTITY> PLEASE

<$WHATIS> ::= WHAT IS
              WHAT'S

<$QUANTITY> ::= THE <LAST> <$NUMBER 1-99>
                THE <LATEST> <$NUMBER 1-99>
                THE <LATEST>
                <$NUMBER 1-99>

.
. .

<LAST> ::= LAST
           NEXT
           FIRST

<LATEST> ::= EARLIEST
             LATEST
             NEWEST
             OLDEST
             MOST RECENT

<$NUMBER 1-99> ::= <NUMBER2>
                   <TEENS>
                   <DIGITS>
```

Fig. 14. Part of the template of the AIX15 Semantic Template Grammar. Note that alternatives are represented on separate lines. TEENS, DIGITS, AND NUMBER2 are subsequently rewritten.

addition to the semantic registers.) Each template is expanded with respect to all sentences possible within the narrowly defined problem space of 1011 words in an information retrieval frame. The definition of subsequent nodes and their related substructures is thus determined by grouping like subphrases and creating additional subnodes. Ultimately, all possible meaningful combinations of word sequences are evaluated to create tables used by the word sequence KS to produce 'islands of reliability' from the bottom-up acoustic phonetic KS's.

Parsing with a semantic template grammar is used to produce the most consistent network of hypotheses spanning the entire utterance. Once this occurs the SEMANT KS reparses the blackboard information using the same grammar, but incorporating semantic information at the nodes that are parsed. This second parse produces a semantically-tagged representation of the utterance which the DISCO KS, a finite state network of the solution space, decomposes into appropriate actions. DISCO also maintains a pragmatic, current semantic register list to determine pronoun reference and current frame reference in a manner similar to the Winograd system.

In the HEARSAY-II environment, each instantiation of a template is accomplished by a separate execution of the SASS knowledge source. The scheduling execution is controlled by the focussing strategy of the system -- the template supported by the highest rated information will be instantiated first.

The omission of a symbol at word junctures, background noise or poor speaker enunciation result in incorrect words being hypothesized with high ratings, while the correct word may be hypothesized with low ratings, or not at all. Because of the scheduler focussing strategy, a correct word with low validity may never be considered unless the alternatives are exhausted.

According to Hayes-Roth et al. (1977), "present statistics" show that only 80% of the words in the utterance are supplied to the ACORN. Techniques of prediction, partial matching and filtering are used to supplement the bottom-up processes.

This account by no means exhausts the details of HEARSAY-II, but it does make explicit a number of features which suggest that it contains the seeds of the proper methodology for combining the best features of the faculty and process models with those of the representational models. First, we see in it the explicit specification of the different levels of representation, and an interpretive strategy wherein components interact via the generation and modification of multiple tentative hypotheses. This process yields a network of interconnected hypotheses which supports a satisfactory interpretation of the original utterance. Second, HEARSAY exhibits a style of "cooperative computation" (Arbib, 1975, Section 5). Through data-directed activation, KS's can exhibit a high degree of asynchronous activity and parallelism. HEARSAY explicitly excludes direct calling of one KS by another, even if both are grouped as a module. It also excludes an explicitly predefined centralized control scheme. The multi-level representation attempts to provide for efficient sequencing of the activity of the KS's in a nondeterministic manner which can make use of multiprocessing, with computation distributed across a number of concurrently active processors. The decomposition of knowledge into sufficiently simple-acting KS's is intended to simplify and localize relationships in the blackboard.

Two other observations come from the studies of AI models in general and from recent psycholinguistic approaches: First, a grammar interacts with and is constrained by processes for understanding or production. Second, linguistic representations and the processes whereby they are evoked, interact with information regarding how an utterance is to be used, in a "translation" process. AI and psycholinguistics thus provide a framework for considering an ever-widening domain of concern, beginning with the narrowly constrained mediation by the linguistic code between sound and meaning, and widening to include processing and intentional concerns.

5. Computational Neurolinguistics and Neuroscience

We have proposed a taxonomy of theories of language representation and processing in the brain. We have characterized these theories with respect to the range of data they account for, the linguistic representations they utilize, and the level of detail of processing. We have, in addition, suggested that the most detailed computational models of language are found in linguistics (concerning representations) and artificial intelligence (concerning processing), and that the principles found in these models can serve as the basis for extending existing neurally-constrained process models.

We now turn to a consideration of the neural mechanisms involved in these theories. It is immediately apparent that the models we have considered utilize a limited set of neurological concepts in the description of the neural basis for language, all centered around the idea of localization of components of a language processing device in areas of the brain. Historically, the greatest controversies in aphasiological theories have centered on the question of the appropriateness of a "localizationist" or a "holist" model of representation of language in the brain. As we have noted, Geschwind's observation that there has been virtually no disagreement regarding the correlation of aphasic syndrome and locus of lesion, and other uncontested statements such as the facts of cerebral dominance, indicate that a completely holist position is untenable. The lesson of the faculty and process models is that the brain can be approximated as a network of interconnected regions for each of which a function in a language processing device can, in principle, be delineated. Variations on this theme, emphasizing the role of areas outside the peri-Sylvian cortex (Brown, 1979) and the concept of gradients (Bogen, 1979) modify but do not fundamentally challenge this general view.

We therefore begin with a consideration of the implications of the computational process models we have outlined for this sort of regional analysis of neural organization pertinent to language. We turn to the HEARSAY model as a well-defined example of a cooperative computational model of language comprehension, and observe that incorporating it into a neural framework raises several important conceptual questions. We present four of these, along with a brief discussion which sheds light on possible neural mechanisms at this regional level.

First, in HEARSAY, changes in validity ratings reflecting creation and modification of hypotheses are propagated throughout the blackboard by the rating policy module, RPOL. These ratings are the basis for the determination, by a single schedule KS, of which blackboard-manipulating KS will next be activated. This use of a single scheduler seems "undistributed" and "non-neural" -- in a brain region, one may explore what conditions lead to different patterns of activity, but not of scheduling. However, the particular scheduling strategy used in HEARSAY is a reflection of the exigencies of implementing the system on a serial computer. Serial implementation requires us to place a tight upper bound on the number of activations of KS's, since they must all be carried out on the same processor. The HEARSAY methodology can, however, be extended to a parallel "implementation" in the brain, in which we may view each KS as having its own "processor" in a different portion of the brain. When viewing a HEARSAY system as a neural model, we can think of RPOL as a subsystem within each schema or KS, so that propagation of changes in validity ratings can be likened to the relaxation procedures in neural nets that we shall discuss below.

Second, we have seen that the processes in HEARSAY are represented as KS's, and that certain KS's may be aggregated into modules. In would be tempting, then, to suggest that in HEARSAY-style implementations of process models such as that of Luria in Figure 10, each brain region would correspond to either a KS or a module. Schemas would correspond to much smaller units both functionally and structurally -- perhaps at the level of application of a single production in a semantic template grammar (functionally), or the activation of a few cortical columns (neurally). But a major conceptual problem arises because in a computer implementation, a KS is a program, and it may be called many times -- the circuitry allocated to working through each "instantiation" being separate from the storage area where the "master copy" is stored. But a brain region cannot be copied ad libitum, and so if we identify a brain region with a KS we must ask "How can the region support multiple simultaneous activations of its function?" We may hypothesize that this is handled by parallelism (which presumably limits the number of simultaneous activations). Alternatively we may actually posit that extra runnable copies of a program may be set up in cortex as needed.

Such a proposal can be found in Arbib's suggestion for DIPM (Arbib, 1966, 1970), a Distributed Information Processing Machine which provided a new mode of computer organization, originally designed to offer a perspective on certain patterns of recovery following brain lesions. In the original formulation, the computer was divided into a central program area in which programs are stored, and a surrounding computation area. To execute a program, DIPM had to assign to it a region in computation space, so that data would be appropriately transformed as they passed through this region of the network. If the program were used at all frequently, it would come to "own" a specific computation region, thus reducing switching time. However, were

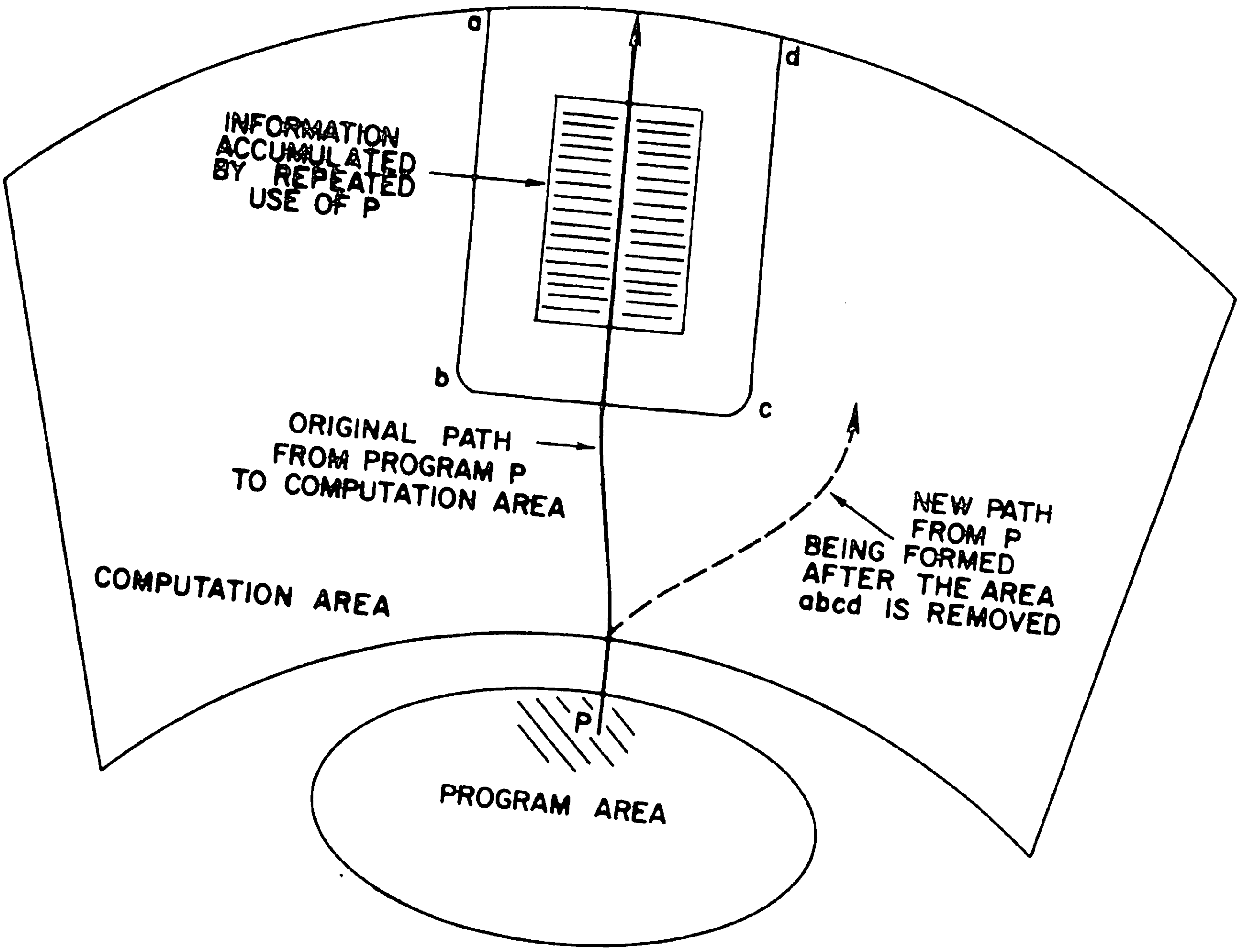


Fig. 15. The DIPM (Distributed Information Processing Model) of cortical reallocation of computing area for different programs.

this specific computation area to be damaged, DIPM still had the mechanisms available for assigning a new area to the program. Whereas the DIPM model segregated program space from computation space, the view of cooperative computation sketched above suggests that we recast the model -- forming DIPM Mark II, as it were -- to no longer require such a strict separation. Instead, we balance the cooperation of the subsystems in achieving overall goals by the competition, via normal growth and learning rules, of the subsystems for computing resources (cf. Norman and Bobrow (1976)).

So far we have taken no account of learning. Conventional accounts of learning in neural nets (e.g. Arbib, Kilmer & Spinelli (1976)) emphasize that neural nets can tune their parameters in response to reinforcement, and can self-organize ('learning without a teacher') to classify inputs into a relatively small number of classes, thus providing a 'vocabulary' in terms of which states of the environment may be analyzed. The DIPM model posited that a program will, with repeated use, store in its computation area much useful material which will ease later computation. For example, if a function is repeatedly evaluated for certain values of the argument, the machine will store a table for these values. Using this table, later computations will be both faster and more precise (Figure 15).

If a lesion damages the computing area of a program but leaves the program itself undamaged, the program has to compete for more computing space in order to resume its action. Then if only a small part of the computing space is removed, this will cause little trouble. However, if the area removed is large -- even if the program remains in some sense intact -- there may be major problems of competition for the remaining resources, as well as routing problems caused by the severing of major anatomical pathways carrying messages in and out of the relevant computation area. In short, such damage may be relatively non-specific, but will increase as the area removed increases. At the other extreme, if the sole "copy" of a program is destroyed, then that function will be lost save to the extent that the system can approximate it with other functions. We mentioned that, with use, a program might build up a table of useful values. If we destroy this 'table', performance will be impaired -- both in speed and precision -- even if the program itself is undamaged and gets access to sufficient new computing space. However, as repeated use gradually re-established the lost table, performance will better and better approximate the level of performance prior to damage. This approach accords well with those situations in which a series of small lesions yield less functional impairment than a single lesion of the same magnitude (Eidelberg & Stein, 1974).

The third "non-neural" feature of current HEARSAY implementations is the use of a centralized blackboard. But this is not, perhaps, such a serious problem, for examination shows that the levels of the blackboard are really quite separate data structures, and that they are only linked via KS's. For each level, we may list those KS's that write on that level ("input" KS's) and those that read from that level ("output" KS's). From this point of view, it is quite reasonable to view the blackboard as a distributed structure, being made up of those pathways which link the different KS's. One conceptual problem remains. If we think of a pathway carrying phonemic information, say, then the signals passing along it will encode just one phoneme at a time. But our experience with HEARSAY suggests that a memoryless pathway alone is not enough to fill the computational role of a level on the blackboard; rather the pathway must be supplemented by neural structures which can support a short-term memory of multiple hypotheses over a suitable extended time interval.

Finally, we note that the HEARSAY methodology requires that "no KS knows what or how many other KS's exist" -- a KS is simply activated whenever data meeting its precondition appear on the blackboard, and it writes the result of its procedures at some appropriate level. In particular, this approach is said to preclude one KS directly activating another. But this restriction would seem to vanish once we "neuralize" HEARSAY, for if we decentralize scheduling, and reconceptualize levels as pathways from "input" to "output" KS's, we may certainly view an "input" KS as sending a signal along the pathway to directly activate an "output" KS.

An immediate research project for computational neurolinguistics, then, might be to approach the programming of a truly distributed speech understanding system (free of the centralized scheduling in the current implementation of HEARSAY) with the constraint that it include subsystems meeting the constraints such as those in our Figure 10 reanalysis of Luria's data. To date, there seems to be no detailed simulation of this kind, though Patrick Hudson's Ph.D. thesis (1976) contains a (non-implemented) analysis of neurolinguistic/psycholinguistic data which is in the spirit of the present paper. Hudson's Chapter XI offers a somewhat ad hoc flow diagram for normal performance without reference to neurological data and then, in Chapter XII, he defines the effects of neural damage as "buffer threshold alternations", relating these to brain regions to see if his model predicts the clinical effects. One can expect that psycholinguistic tests will be increasingly integrated into the study of aphasic and other patients -- as in the work reviewed in Section 3 -- so that our neurolinguistic models can fully exploit psycholinguistic cues to 'mental structure'. But we must expect that our localizations will evolve with our concepts -- we may localize a function in a region only to later conclude that there we can only localize some aspect essential to that function.

In the remainder of this section we shall address the possibility of broadening the range of neural mechanisms involved in linguistics beyond this type of regional analysis. It is striking that the neural mechanisms specified by neurolinguistic theories are all derived from pre-Sherringtonian neuroscience. The start of the 20th century saw the establishment of the neuron doctrine by Cajal and that of the concept of the synapse by Sherrington. The last 30 years, since the introduction of the microelectrode, have seen tremendous strides in the neuroscientific analysis of synapses, cells and circuits. Yet none of these levels of analysis have come to play any serious role in neurolinguistics. One might say that neurolinguistics is a branch of psycholinguistics rather than of neuroscience as we now know it -- distinguished from the rest of psycholinguistics only by the fact that subjects have brain damage and that certain components of the model are given anatomical labels.

We shall use the term "cybernetic" for models which seek to explicate neural mechanisms at the level of detailed neural circuitry. As we see it, there are two reasons for the lack of cybernetic models in linguistics. The first relates to the technical problem involved in making the relevant neurophysiological observations in man. Microelectrode single-cell recordings, the major technique employed in animal studies, are almost never applicable to human subjects. Grosser neurophysiological observations involving event-related potentials (Desmedt, 1977) and sub-seizure stimulation of exposed cortex (Whitaker and Ojemann, 1977) provide the first steps towards observation of the physiological events we believe responsible for language processing, but empirical investigations in this area are limited.

The second impediment to the development of cybernetic models is conceptual. As long as neurolinguistic theories employed faculty models of language, or process models which failed to specify the linguistic representations and computational logic of their components, it was impossible to suggest how neural elements might represent linguistic items or effect psycholinguistic processes. As we have mentioned, without a characterization of the linguistic code, we can have no characterization of the neural code for language.

To see how cooperative computation models may provide the bridge from neurolinguistics to synapse-cell-circuit neuroscience, we must first address the fact that modern neuroscience is based on animal experiments, while language is in the main a particularly human attribute. While it would require another lengthy paper to develop this theme, let us here simply outline the thesis that there are important processes between visual perception and speech understanding on the one hand, and between speech production and motor control on the other. The basic notion is that visual perception like speech understanding requires the segmentation of the input into regions, the recognition that certain regions may be aggregated as portions of a single structure of known type, and the understanding of the whole in terms of the relationship between these parts. We use the term "schema" to refer to the internal representation of some meaningful structure, and view the animal's internal model of its visually-defined environment -- and the human's internal model of the state of a discourse -- as an appropriate assemblage of schemas (Arbib (1977); cf. the slide-box metaphor of Arbib (1972)). The generation of movement then requires the development of a plan on the basis of the internal model of goals and environment to yield a temporally-ordered, feedback-modulated, pattern of overlapping activation of a variety of effectors (Arbib, 1980) -- so that the word-by-word generation of speech may be seen as a natural specialization of the general problem of motor control. A key concept in the analysis of perception and movement is that of the action/perception cycle -- we perceive to get the information on which to base action, but each action extends our sampling of the environment. A theory of schemas must include an account of the input-matching routines which determine schema activation and of action routines which enable the system to use the knowledge rendered available by this activation.

This cycle corresponds to the role of one speaker in ongoing discourse. We suggested at the end of Section 4 that one can view the deployment and decoding of the linguistic signal as responsive to a series of constraints. The first are those inherent in the structure of the linguistic code itself, and their characterization is the goal of the theory of lingistic competence. We presently have far more information about these constraints than about the remaining levels. The second type of constraint arises from psychological limitations of the human language-processing systems. Recent work (Fodor, 1978; Frazier and Fodor, 1978) has advanced hypotheses regarding the intrinsic nature of these psycholinguistic devices, and suggested interactions between the nature of human processing routines and the nature of language structures. A third type of constraint results from the social and pragmatic facts of conversational situations. Other levels can be suggested. We can view the utilization of language, at each of these levels, as consisting of the interaction of a stored long-term representation of the items and processes at some level and the analysis of the incoming and outgoing signal at the same level to yield a fluid and continually updated current model of the total language act. Seen this way, there are no direct one-to-one correspondences between sensory-motor and language computations, but there are overall similarities which allow us to investigate aspects of the neural mechanisms of language by examining the neural mechanisms relevant to perceptual-motor activity.

Neuroscience has taught us how to trace the coding of information in the visual periphery (Hubel and Wiesel, 1977; Lettvin, Maturana, McCulloch & Pitts, 1959); how to view the cerebral cortex as composed of columns or modules intermediate in complexity between single cells and entire brain regions (Hubel and Wiesel, 1974; Mountcastle, 1978; Szentágothai & Arbib, 1974); how to analyze spinal circuitry involved in motor outflow, and the later stages of its cerebral and cerebellar control (Phillips & Porter, 1977; Granit, 1970; and Eccles, Ito & Szentágothai, 1973). To some extent these analyses may be integrated into models of perceptual and motor processes (Figure 16).

We have good neuroscientific data on retinal response to neuronal stimulation, and of the different "feature extraction" processes in a number of visual systems within different animals. At the motor periphery, we have good neuroscientific data on basic motor patterns, their tuning by supraspinal mechanisms (the Russian school has been particularly productive here), and the spinal cord rhythm generators and feedback circuitry which control the musculature. This partial list could be extended and could be complemented by a list of major open problems at these levels: the important point here is that near the visual and motor peripheries there is a satisfying correspondence between single-cell analysis and our processing concepts.

In between, the results are fewer and tend to be somewhat more speculative. By what process are the often disparate activities of feature detectors wedded into a coherent "low-level" representation of the world?

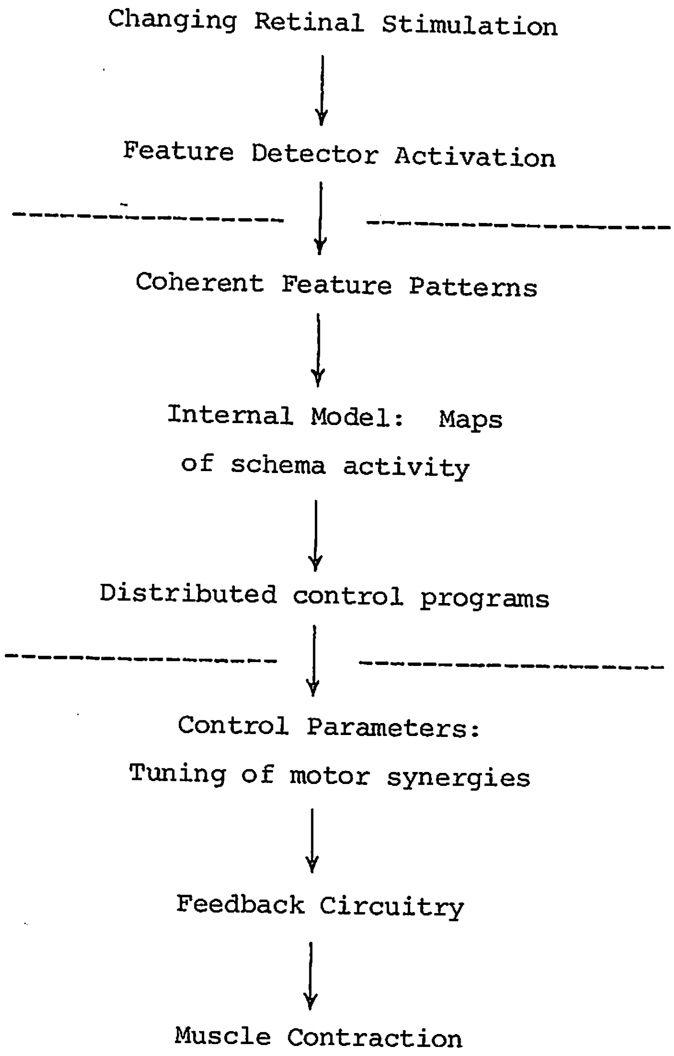


Fig. 16. Stages in visual perception and control of movement. Many aspects are omitted, as are all of the important "return" pathways.

How is the representation integrated into the ongoing internal model (the "schema-assemblage" as we have posited it to be)? How are the internal model and goals of the organism combined in a planning process which yields the distributed control programs which orchestrate the motor synergies? We have models for all these processes (Arbib, 1980), but many are couched in a language closer to AI than to neurophysiology, and the body of available neuroscientific data with which they can make contact is still relatively small. Nonetheless, it does seem to us that progress is well under way in the neural analysis of "perceptual structures and distributed motor control". We briefly sketch one effort of this kind.

The problem of visuomotor coordination in frog and toad has yielded to a behavioral analysis coupled with lesion and single-cell analysis (Ewert, 1976; Ingle, 1976). Ingle (1968) had observed that a frog confronted with two fly-like stimuli would normally snap at one, but would sometimes snap at neither even though each stimulus alone was "snap-worthy". This suggests a process of competition between the internal representation of the "flies" (and in this case an identification of the "schema" with localized cellular activity does seem justified) and Didday (1970, 1976) offered a model of competitive interaction in neural nets consistent with the data of 1970. The intervening ten years have seen developments in both theory and experiment. Amari and Arbib (1977) developed a general theory of competition and cooperation in neural nets, and this has proved to have much similarity with the relaxation and constraint satisfaction techniques that have become popular in the artificial intelligence literature for the resolution of conflicting hypotheses (Rosenfeld, Hummel & Zucker, 1976; Shortliffe, 1976; Waltz, 1978). Experiments have shown patterns of interaction between tectum and prethalamus, demonstrated the interaction between prey-approach and predator-avoidance, isolated processes of facilitation and habituation, and have shown how obstacles in the environment can modify appetitive and aversive behaviors. These observations have been integrated into new models (Lara et al., 1979) in which visuomotor coordination is achieved by competition and cooperation in neural nets which meet some constraints of anatomy and physiology at the synapse-cell-circuit level.

Given the development of such models of visuomotor coordination, one can suggest that the neural circuitry which carries information of this sort in non-human species is homologous to that involved in information systems in the human. Microscopic and macroscopic differences between human and non-human brains will doubtless play a role in providing the particular computational content of each species (cf. the discussion of Geschwind in Section 1), but, in the absence of evidence to the contrary, we may adopt the view that the basic information-carrying elements (membranes, synapses, cells, circuits, etc.) will be closely related. The task is to provide more empirical support for particular neural models in animals and to relate the models developed in the animal to comparable perceptual-motor systems in man, and thence to systems involved in language.

The last of these tasks requires determination of points of contact between the language system and perceptual-motor systems. We have noted that many workers have been concerned with the relationship of aspects of language to perceptual, motor, and other cognitive systems. In this connection, we refer to our comments on Jackson's views of propositions, Geschwind's approach to the agnosias and apraxias, and Luria's concern with start/stop mechanisms shared between linguistic and non-linguistic motor activities. We also note the influence on Luria of Bernstein (1967), whose work has had such a profound influence on the Moscow school which combines neurophysiological and mathematical analyses of motor control with the construction of actual robots (Feldman and Orlovsky, 1972; Gelfand and Tsetlin, 1962; Okhotimskii et al., 1979).

We believe that pursuit of these connections will require a framework of cooperative computation in which, in addition to interaction between components of a language processor alone, there are important interactions between components of linguistic and non-linguistic systems. Consider, for example, Luria's analysis of naming of visually-presented objects (Fig. 6, Section 3). The link between a representation of an object derived from visual information and a representation of the object in a linguistic code must be made. We have seen that, unlike the simple, unanalyzed analysis of this operation as a "non-limbic cross-modal association" offered by Geschwind, Luria's view is that the linguistic system utilizes multiple components to arrive at the appropriate item. Some of these components, e.g. Box D related to articulatory analysis, include representations at remote linguistic levels. The retrieval of the appropriate word involves exploitation of the entire network of representations which define a word, and convergence on the proper word is accelerated by cooperation of the entirety of the components of the language device. Similarly, one can imagine a comparable cooperative mechanism for the assignment of a representation to an object from visual data. A fuller analysis of such a process would involve, for example, distinguishing the 3-D shape of an object from its functional role (Warrington and Taylor, 1973), and might utilize these different sorts of information in different routines (one of which, in this example, might plausibly involve information of a "motor" sort).

Careful analysis of the components of such tasks and of their patterns of breakdown can lead to the identification of a (presumably limited) number of components which share and/or compare linguistic and non-linguistic representations. One might then be able to infer something of the cellular neural events underlying language from an appreciation of the neural mechanisms underlying these directly related non-linguistic processes. Again, we are confronted with the need for explicit representational systems, in this case for non-linguistic as well as linguistic entities, coupled with a co-operative computational analysis of processing which determines which representations are "translatable" and "shared" between linguistic and non-linguistic systems.

Thus, we suggest that parallels in the overall organization of language and non-language activities indicate that animal models of non-language capacities are relevant to the study of neurolinguistics. In particular, they provide evidence for the ways in which neural tissue stores and processes information, at the cellular level, and for modes of organization of brain with respect to functional systems, both of which give clues as to the nature of the neural process involved in language representation and utilization. To exploit these 20th century neuroscientific models will require a computational process model of language, which might then be tested in one of two ways: Technological advances may allow the observation of the hypothesized neural events relating to language in man. Alternatively, points of contact in computational vocabularies and routines between linguistic and non-linguistic systems in man and parallels between non-linguistic systems in man and other species may allow hypotheses to be formed regarding the role of these neural entities in language.

It is interesting to consider to what extent our suggestions are similar to those recognized as constraining factors in neurolinguistic theory by its first exponent, Wernicke. In Section 1, we pointed out that Wernicke insisted that neurolinguistic theories be consonant with plausible accounts of psychology and physiology. We have, in essence, reiterated his insistence on these constraints. What distinguishes his theory from the outline of theories we have proposed is the greater appreciation a century later of just how rich the accounts of psychology of language and neurophysiology of information-carrying are. Plausible neurolinguistic theories will have to integrate these discoveries, in a synthesis as rich as the concepts in the contributing fields.

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