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NEUROLINGUISTICS: THE STUDY OF BRAIN ORGANIZATION IN GRAMMAR AND MEANING

Reprinted from Totus Homo - Vol. 6, n. 1-2-3, 1975

Published by
Istituto Totus Homo - Milan (Italy)

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Introduction

Languages and the Cultures with which they interweave are the distinguishing features of man. Studies of the origin, organization and operation of languages are therefore of abiding interest both to scientists and humanists. Despite this, we know little of the fundamental mechanisms that allow man to communicate by way of linguistic speech. These mechanisms are perforce brain mechanisms and this paper will review some recent contributions of brain research to our knowledge about human language.

The nineteen-sixties were characterized by great interest in an attempt to understand human language by analyzing the structure of its grammar. This interest was rooted in the belief that the syntactic organization of ordinary linguistic communication is similar in construction to the programs used by digital computers (CHOMSKY, 1957; MILLER, GALANTER and PRIBRAM, 1960). More recently, however, it has become clear that semiotics, the study of the manner in which meanings are linguistically communicated, must go beyond syntax to semantics for any coherent view of what occurs when words are used in thinking and speaking.

Here the opportunity will be taken to recapitulate and extend this approach with the hope that it will strike a responsive chord among others interested in the enigma of the origins of the special powers displayed by human linguistic communications.

The basic tenet of the proposal is a simple one: grammar relates to meaning as partitions relate to the sets which they partition. The application to human language of this tenet is, however, not so simple. Although considerable progress can be reported in our understanding of the elementary syntactic structures of the partitioning process, we are only on the threshold of understanding what is that becomes partitioned. Here we will attempt understanding by tackling issues such as the distinction between information (in its strict definition) and meaning; the nature of distinctive features and of poetic connotation; and the brain organizations that dispose toward context free, and those that dispose toward context sensitive constructions.

Variety and constraint in the determination of meaning.

Let us begin with some definitions. Information measurement is based on the ability of a communication to resolve an uncertainty established by prior communications. The amount of reduction of uncertainty is measured in bits

This work was supported by NIMH Grant No. MH12970-08 and NIMH Career Award No. MH15214-13 to the author.

Neurolinguistics: the study of brain organization in grammar and meaning.

SUMMARY - This paper introduces a new and rapidly developing field of inquiry: neurolinguistics. An attempt is made to spell out some of the problems that beset the field, and to show what progress has been made relating brain to syntactic organization. The additional issue and the deeper one of delineating the brain mechanisms responsible for semantics – meaning – is shown to be also amenable to analysis. The basic tenets that are proposed are that the memory store is a distributed one and organized according to holographic principles, and that control processes, akin to computer programs, operate on this memory store. There is a variety of such syntactic structures and this variety is related to known brain mechanisms.

of information. Uncertainty describes the complexity, the number of partitions on a set necessary to specify the organization of that set. And a set is a circumscribed domain within which the communication takes place.

But all communications do not reduce uncertainty. Some merely repeat prior communications. And some in fact increase uncertainty by demonstrating a mismatch, an erroneous partitioning of the communicative domain. Early attempts to apply information theory to human linguistic communication failed to provide any basic insights largely because the theory itself remained confused on the distinction between uncertainty reduction and these uncertainty enhancing communications.

The confusion arose because "errors" were uniformly labelled "information" in the sense defined above as the reduction of uncertainty. The original definition of information was given by SHANNON and WEAVER (1949) and proved extremely useful in handling the problems of artificial communication systems such as telephone networks. But Shannon-Weaver "information" has nothing in common with "error", a mismatch: the amount of information contained in a message does not depend on processing its errors. When a longdistance telephone conversation is interrupted by a periodic beat frequency or whooshing, errors in interpretation occur which demand repetition of the communication. These repetitions, redundant communications, contain no additional information but are aimed at overcoming the errors produced by the form in which the communication occurs.

Ross ASHBY (1956) details the distinction in terms of variety and constraints. Constraints are defined as the limits on the independence of the functioning of the parts of the set. Variety indicates independence and is measured as information; constraint indicates dependence and is measured by redundancy. The relationship between information and redundancy has therefore usually been regarded as simply reciprocal. I believe that the example of the long distance telephone conversation suggests that such a simple conceptualization of the relationship is mistaken. Specification of information and redundancy, to be useful in human communication, must be sought in other terms.

By the Shannon-Weaver interpretation, variety and constraint are reciprocal, and a bit of information reduces variety and thus enhances constraint. However, in any communication system endowed with memory, i.e. the ability to compare successive communications, measures on variety

Neurolinguistique: l'étude de l'organisation cérébrale dans la grammaire et le *meaning*.

RESUME - Ce travail présente un champ de recherche nouveau et en rapide essor: la neurolinguistique. On tente de dénoncer, ici, les problèmes qui envahissent le champ et d'exposer les progrès réalisés dans la mise en relation du cerveau avec l'organisation syntactique. Il est démontré que la question supplémentaire et plus profonde, délimiter les mécanismes cérébraux responsables de la sémantique – *meaning* –, peut être également analysée. Les principes fondamentaux proposés énoncent que la réserve de la mémoire est répartie et organisée selon des principes olographiques et que les processus de contrôle, analogues aux programmes de l'ordinateur agissent sur la réserve de la mémoire. Les structures syntactiques sont nombreuses et cette variété a un rapport avec les mécanismes cérébraux connus.

Neurolinguistica: lo studio dell'organizzazione cerebrale nella grammatica e nel *meaning*.

RIASSUNTO - Questo lavoro presenta un campo di indagine nuovo ed in rapido sviluppo: la neurolinguistica. Si tenta qui di denunciare i problemi che ingombrano il campo e di esporre il progresso fatto nel mettere in relazione il cervello con l'organizzazione sintattica. Viene dimostrato che la supplementare e più profonda questione, delineare i meccanismi cerebrali responsabili della semantica – *meaning* –, può anche essere condotta ad analisi. I principi basilari proposti sono che la riserva della memoria è ripartita ed organizzata secondo principi olografici e che i processi di controllo, analoghi ai programmi del *computer*, agiscono sulla riserva della memoria. Le strutture sintattiche sono varie e questa varietà ha rapporto con i meccanismi cerebrali conosciuti.

and on constraint refer to wholly different aspects of the communication. In such systems variety entails novelty (see e.g. BRILLOUIN, 1962) and thus comes closer to the ordinary meanings of information. Further, in such systems with memory, the constraints operating on the communication deal with the form, the structural relationships among communicative events, the relationships among the parts of the communicative set. In short, in systems with memory, variety and constraint operate among relationships between partitions. When partitions produce complete independence among parts we can apply Shannon-Weaver *information* theory; when, on the other hand, the partitions are partially dependent, as in the hierarchies or net-like configurations of computer programs, a theory of *meaning*, a theory of relationships, becomes necessary. The theory of information thus becomes a special case of the theory of meaning.

The problem can be stated in another fashion. A communication can have a referent. Ordinarily, referent communication conveys information. But philosophers have for many years distinguished between reference and meaning. Meaning goes beyond reference into use, the use that the information conveyed can have to the conveyor or to the organism to whom it may be conveyed. For example, Peirce makes the statement, « We are apt to think that what one means to do and the meaning of a word are quite unrelated measurings of the word meaning ». (PEIRCE, 1934; see also PRIBRAM, 1972). He points out that meaning is always related to doing, the pragmatic, in some way. In short, meaning relates to the doings of organisms – doings that have survival value.

The relative dependence among parts of a communication and their dependence on use cannot be ascertained from the syntactical structure of the communication alone: the relationship among partitions is given in only a trivial sense by the structure of the partitioning system; thus the many popular examples of meaningless, yet grammatically correct sentences (e.g., « the pillow runs the dog ») or sentences with double meanings (e.g., « they are flying planes ») which grace the linguistic and psycholinguistic literature of the nineteen-sixties. Meaning is given by the dependence among the parts of the set and that among successive sets, not by the fact of partitioning *per se*. Thus meaning derives from some additional property of the parts which defines their relationship. It is this property which has proved so elusive.

Brain and syntax.

In an attempt to come closer to this elusive semiotic, let us proceed here as did the linguists of the nineteen-sixtees to describe first some of the properties of syntax with the expectation that in so doing we can specify more precisely what is missing. But rather than resort exclusively to an analysis of human language, let us reach into the annals of comparative behavior and of brain function for guidance.

In his address of acceptance of the chair at Edinburgh and also elsewhere, VOWLES (1970; 1970a) has suggested that perhaps phylogeny could be characterized by the development of a grammar of behavior. He proposed that invertebrates show finite-state Markov-type constructions; vertebrates develop phrase-structure hierarchies; and that man is distinguished by transformational capacities. Though perhaps wanting in detail (which is gradually being provided by other ethologically oriented scientists – see e.g. BEER, 1963), this sweeping theoretical statement struck a responsive chord since, at the time, Peter Reynolds, working in the Stanford Neuropsychological Laboratories, was organizing his observations on the development of primate play by attempting to specify the rule structure, the syntax, which characterizes the interactions (REYNOLDS, in press). The grammar of play is but a specific instance of a search for the plans, programs, syntax by which behavior becomes organized.

The essence of a grammar is that it orders sequential dependencies among behaviors – including communicative behaviors. In Vowles' proposal, when the behavior reflects only the immediate state of the organism, then that behavior or communication can be thought of as determined by a Markov process, very much as a set of dice or the image produced in a kaleidoscope depends only on the configuration of the parts at the moment that they cease to be perturbed. On the other hand, when a behavior or communication becomes organized according to some rules that determine the order in which the communications take place, then, in the terminology of linguistic grammarians, a phrase-structure grammar is involved. It is quite obvious, however, that such phrase structures do not occur only in human linguistic communications. A good deal of the concatenation of egg-rolling behavior or of mating and maternal behavior in birds, for instance, depends on "phrases" of behavior that trigger some state in the communicant to whom the behavior is addressed; this state then gives rise to another set of behaviors, which in turn change the state of the original communicant (e.g. Hinde, 1959; 1966). The important thing here is that it is not just one communicative act or one behavior that is triggered by the change of state; a whole sequence is generated. The idea of a generative grammar, so popular in current linguistics, is therefore applicable to certain forms of animal communication as well. What is believed to be unique to human communication is the ability to transform these rules that determine sequence. When one writes a paper or presents a lecture, one does it differently every time, even though the material covered may be the same. In order to achieve this flexibility, transformational rules seem to be imposed upon the more primitive phrase-structure rules.

Brain research has distinguished two types of rule structures, those that are context-free and those that are context-sensitive: there are specific brain mechanisms that have been identified for each of these types.

To begin with context-free constructions: these are ordinarily produced by way of making a discrimination: a visual discrimination, an auditory discrimination, a somatosensory discrimination, a taste discrimination – in other words, various sensory discriminations. Discriminations allow one to identify events and objects and ultimately to name them irrespective of the environmental situation or even the subjective situation in which they occur. In a context-free construction, a rose is a rose is a rose is a rose, whether it appears on one's lapel, in a garbage can, or in a vase on a table.

About twenty years ago a part of the monkey brain that dealt with context-free constructions was discovered (Blum, Chow and Pribram, 1950; Harlow, et al., 1952). For vision this area is located in the inferior part of the temporal lobe. It had been known for many years that lesions of the temporal lobe gave rise to visual disturbances in man, but it had always been thought that this was due to the involvement of Henle's loop, a portion of the optic radiation that was assumed to course around the anterior portion of the temporal horn of the lateral ventricle. When neurosurgeons began to perform anterior-temporal lobectomies without producing any visual defects, the existence of Henle's loop was called into question. In fact, the visual difficulties that occur in man, especially from the subdominant hemisphere, arise from involvement of the temporal cortex itself, just as they do in the monkey (Milner, 1971; 1974).

Behavioral analysis of the discrimination deficits in monkeys is therefore relevant to our problem. What this analysis has shown is that the cortex that lies in the posterior part of the hemispere, in between all the projection areas, can be divided into zones, each of which is associated with one of the primary sensory modalities: somesthesis, taste, audition, and vision (Pribram, 1969). The disturbance in the sensory discrimination is not due to inability to distinguish the features that allow the two objects to be discriminated. For instance, monkeys who have learned to make a visual discrimination between an ashtray and a tobacco tin in a simultaneous discrimination, albeit with a deficit as compared to their normal controls, cannot use this ability to discriminate in another situation, e.g. in a successive discrimination in which the tobacco tin and ashtray are placed in a central location and the monkey has to go right whenever the ashtray is present and to go left whenever the tobacco tin is present (PRIBRAM and MISHKIN, 1955). Other tests have shown that it is the utilization of the distinctive features that the monkey finds difficult. In fact, the deficit has been quantitatively related to the number of such features utilized by the operated as compared to control monkeys (PRIBRAM, 1960; BUTTER, 1968).

Neurological analysis of the mechanism involved in utilizing distinctive features shows that the pathways involved course downward from the temporal cortex into the visual system, as far down as the retina itself (SPINELLI and PRIBRAM, 1966; SPINELLI and PRIBRAM, 1967). The temporal cortex may be thought of as a mechanism for generating rules that categorize more primitive stochastic imaging processes determined by input within the primary visual system (PRIBRAM, 1974). These rules allow invariances in the input to be identified (PRIBRAM, 1960). When the temporal cortex is removed and the environmental context is altered, these invariances can no longer be utilized to guide behavior. Context-free constructions are therefore dependent on the rules (phrase-structure rules) generated by the temporal cortex. The significance of differences in sensory input is a function of such rules of utilization. Significant meanings, or signs, are therefore due to context-free phrase-structure-type constructions, and the mechanism involved is the generation of such rules by the temporal cortex and their imposition through efferent control on sensory input.

There has also been a great deal of work done on context-dependent constructions. Context-dependent communications are the basis of poetic connotation and in animal behavioral studies have as their paradigm the delayed response or delayed alternation performance that has been used so extensively in physiological psychology. In these tasks, the usefulness of a particular behavioral act, or of the stimulus, depends not only on the situation of the moment, but on what went before: on the context in which the performance occurs. Context may be spatial or temporal, or even the familiarity or novelty of the situation (PRIBRAM, 1959; ANDERSON, HUNT, VANDER STOEP and PRIBRAM, in press; Pribram, Plotkin, Anderson and Leong, in press). Over the years, research has also shown that the limbic portion of the forebrain is involved in the proper performance of these tasks (PRIBRAM, WILSON and CONNORS, 1962; PRIBRAM, LIM, POPPEN and BAGSHAW, 1966). If these parts of the brain are removed, monkeys can no longer alternate. The limbic systems and the frontal lobe are anatomically related (PRIBRAM, 1958).

Some years ago the delayed response paradigm was modified, in this way: instead of showing where a piece of food might be hidden and then asking the animal at some later time to find it, a token was placed in sight of the animal, then removed, and the animal was asked to find food in the location where the token had appeared. In turn, this so-called indirect version of the delayed response problem was made more complex, until the animals were shown to be capable of working for tokens that could be used at a later occasion, depositing them in a "chimpomat" which would deliver food (PRIBRAM, 1971). Tokens whose use is very specific to the situation in which they occur are usually referred to as symbols.

Symbolic meaning differs from significant meaning in this very fact of context dependence. Significance is context-free; symbolism is highly context-sensitive.

A shortcoming in the tests that have been used in brain research to establish that primates are capable of significant and symbolic behavior and to trace the brain mechanisms that are involved in this behavior is that we have asked the animals to communicate with us only through some very simple instrumental act. This deficiency was overcome recently in two studies done with chimpanzees. The GARDNERS (1969) at the University of Nevada, taught their chimpanzee, Washoe, to use American Sign Language and succeeded in constructing a vocabulary of approximately 150 words by which the chimpanzee could communicate with them. In another experiment, PREMACK (1970), at the University of California at Santa Barbara, developed the token technique and showed that his chimpanzee, Sarah, could organize tokens in several orders of complexity to communicate with her trainer. As might be expected from the context sensitivity of tokens, Premack found that Sarah's behavior was highly sensitive to any change in the training personnel. The meaning of the tokens was too dependent on the specifics of the training situation. In short, subhuman primates have been taught to communicate with both signs and symbols, using both context-free and context-sensitive constructions.

Some conclusions important to the understanding of the meaning of human communication can be drawn from these studies of brain function. Several orders of constraint among communicative events, of "use" of syntax have been distinguished: finite state, significant and symbolic. It is customary to think of these orders as being hierarchically organized, and perhaps this is so. But the fact that the limbic and frontal parts of the forebrain are so intimately related in delayed alternation and delayed response problems, while the posterior cortex seems to deal with discriminations of every sort, suggests that instead of there being a trichotomy, as outlined by Vowles (discussed above), there are actually four fundamental processes which can be distinguished. The relationship between sign and referent when discriminations are involved seems to be a straightforward one: the sign refers to an invariant part of a stochastically determined kaleidoscopic image. Perhaps there is a similar relationship between some finite-state-type processes and the symbolic domain. One of the puzzles that has plagued brain research on the frontal lobes and the limbic system is that, although delayed alternation is disrupted by lesions of any limbic or frontal system, delayed response is not (MISHKIN and PRIBRAM, 1954). Delayed response behavior seems to be more specific to the frontal cortex than to the limbic forebrain. Could it be that the more ubiquitously involved delayed alternation behavior represents a finite-state-type process? If so, what is the difference between the state that determines alternation and the finite state process involved in discrimination? As noted, referent behavior addresses the invariant in the communication. It is tempting to suggest that alternation addresses some variances, but not all variances: only those that recur with some regularity. Recurrent regularities are ubiquitous in the internal environment of the organism. They lead to "steady" states characterized by alternation of satiety with hunger, thirst, sexual and respiratory need, and the like. Hence homeostatic, rather than stochastic, properties determine these states.

Basic to homeostatic processes are the spontaneously recurrent cyclicities of neuronal networks. Circadean rhythms and other biological clocks derive from such cyclicities and PITTENDRIGH (1974) has suggested a description of such rhytmicities in terms of systems of mutually coupled oscillators. In such systems dominant foci of pacemakers evolve by virtue of "entrainment" or capture of neighboring oscillators into a single periodicity. PATTEE (1971) has constructed a functioning model of such a system and has developed a set of theoretical views that link this model with linguistic modes of operation. Thus "entrainments" can be viewed as primitives of symbolic processes, just as stochastic, Markov mechanisms are conceived as basic to significant referents. In such a scheme entrainment deals with recurrent variances, while stochastic mechanisms serve to process invariances. A good deal is becoming known about entrainment; the thesis put forward here should therefore readily yield testable hypotheses. A guide to their formulation can be taken from Sherrington's classical analysis of spinal cord mechanisms, in which he discerns the difference between the organization of antagonistic and of allied reflexes.

An attempt was made to pursue this insight some years ago (Pribram, 1960), but it might be worthwhile to look at the distinction once again in the light of more recent knowledge.

Mathematically, the difference between stochastic and entrainable systems is that stochastic processes can be described in finite hierarchical terms while entrainable ones fall into the domain of heterarchical infinite algebras. Mathematical learning theories of the nineteen-fifties and sixties developed in detail the potentialities of stochastic processes (e.g. Bush and Mosteller, 1955; Estes, 1959). G. Spencer Brown has more recently provided a simple calculus for understanding some of the logical paradoxes that occur in the «infinite» entrainable, context-dependent domain (1972), and the formal properties of context-dependent processes have been explored in terms of graph structures (Harary, Norman and Cartweight, 1965) and by computer programmers such as Quillian (1967). But perhaps the most penetrating insights have come from Shaw (Shaw and Wilson, in press) who has applied the mathematics of symmetry groups to the problem. Shaw points out that such groups are infinite rather than finite and thus can handle the persistent puzzle of the generative properties of grammars. Such generativity derives from the fact that an infinite set «provides a structure for which it is true that a proper subset is equal to the total set». Thus symbols can apply to a potentially infinite equivalence class of instances. Shaw's proposals are well worth pursuing in detail.

Brain organization and meaning:

These insights into the structure of syntax obtained from studies of brain function do not, however, directly address the fundamental issues of the organization of meaning. In Chomsky's terms, what has been discussed so far concerns superficial rather than deep structure. In Jakobson's vocabulary, a question that remains to be explored is the nature of features and what makes them distinctive.

Again brain physiology recently has had a good deal to say about these issues. Units in the nervous system have been discovered which are sensitive to features of the environment (e.g. Mountcastle, 1957; Hubel and Wiesel, 1962; Barlow and Hill, 1963; Evarts, 1967; Spinelli, Pribram and Bridgeman, 1970; Werner, 1974). Further, these features appear to be organized into different configurations in each of the hemispheres of the human brain. Thus after the age of seven or thereabouts, damage to the right hemisphere of most people impairs primarily spatial relationships while damage to the left hemisphere impairs the linguistic abilities which are the concern of this paper. Sperry (1970), in an elegant series of experiments, has demonstrated the separateness of these functions in patients whose hemispheres have been severed from one another by sectioning of the major commissure, the corpus callossum, that ordinarily connects them.

But these important contributions also pose problems of interpretation to neurolinguists. Are we to search for a different brain cell for each distinctive feature of a language? If so, do these brain cells respond to the feature innately or do they become responsive only through experience? If by experience, what is that experience? Further, most of the feature sensitive units that have been discovered so far deal with the spatial aspects of input. How do such feature sensitivities relate to linguistic structure in a hemisphere that supposedly does not process these features?

Many of these puzzling problems are resolved if we look at the evidence from a somewhat different theoretical perspective. The ordinary interpretation that feature sensitive cells in the brain serve as "detectors" for that feature has been found wanting. Thus, for instance, POLLEN and TAYLOR (1974) have shown that the output of "complex" cells of the visual cortex (which are assumed to be detectors of lines of specified length and orientation) is not invariant across all transformations of input other than orientation. In fact, changes of luminance, width of line, number of lines and their spacings all influence the cell's output. Thus only a network of neurons could separate their orientation specificity from that to luminance, for example. Several groups of investigators (POLLEN and TAYLOR, 1974; CAMPBELL and ROBSON, 1968; GLEZER, IVANOFF and TSCHERBACH, 1973) have shown that such cells are in fact more accurately stated to be sensitive to spatial frequencies than to lines *per se*, and that it is therefore an error to think of them as simple line "detectors".

The change from sensitivity for line orientation to one for spatial frequency has major consequences. As discussed elsewhere (PRIBRAM, 1971; 1974; PRIBRAM, NUWER and BARON, 1974) a spatial frequency sensitive mechanism allows image reconstruction with a richness and resolution of detail not possible when only the detection of outline features is used. But perhaps of greater importance, the spatial frequency analysis of light, just as the temporal frequency analysis of sound (by the auditory system) is accomplished in the domain of wave mechanics and not in the digital, quantal domain in which present-day computers operate almost exclusively. This shift in emphasis allows alternate hypotheses to be formulated as to what might distinguish a feature in speech and what the organization of deep structure might look like in the brain.

Phoneticians have in fact already made it clear that the distinctive features of spoken language are most readily analyzed in terms of the wave forms generated by the vocal apparatus – the vocal cords, larynx, oral cavity, tongue and lips. For example, one recent study was able to decompose speech sounds into some six to eight components by performing a Fourier analysis taking into account both spatial and temporal relations (Port, personal communication). And the Haskins group has for years been simulating sounds by using spectral techniques (e.g. LIBERMAN, COOPER, SHANKWEILER and STUDDERT-KENNEDY, 1969).

If, in fact, the distinctive features by which linguistic communications take place are to be identified as wave forms, perhaps the deep structure of such communications is to be found in the wave mechanical domain. The computer, with its programmable digital information processing capabilities, has been of great service both as a model and in data analysis with regard to syntactic superficial structure. Is there not an information processing system that can serve with equal value as a model (and perhaps in due time in data analysis) in our search for the deep semantic structure of meaning?

Optical information processing systems are just beginning to be recognized as useful analogues in studies involving the wave mechanical domain. Aside from their image constructing capacity, they partake in organizations characterized by the distribution of information produced by interference among wave fronts. This distributed aspect of their organization makes them attractive to brain scientists who have been puzzled for years by the apparent distribution of input for storage over reaches of brain surface which makes their functions resistant to local damage.

Organizations of optical information processing systems in which information is distributed are called holograms (GABOR, 1969; STROKE, 1969). The proposal has been made therefore that the spatial and temporal frequency analyses performed by the brain are indicative of a holographic-like brain processes (Pribram, 1966; 1971; in press; Pribram, et al., 1974). But it must be borne in mind, of course, that for neural holograms only the organization of the paths taken by light in optical systems serves as the model. The energy involved in neural excitation is electrical, not photic.

The suggestion to be entertained here is therefore that deep structure is, in the final analysis, semantic structure and that semantic structure derives from a distributed neural organization akin to that found in the holograms of optical information processing systems. Note that deep structure is conceived to be derived from a holographic organization and is not synonymous with it. Syntactic structures, as delineated in the earlier parts of this paper, partition – map – the holographic distributed store of information into useful, meaningful organizations.

In biology, this mapping of a distributed more or less homogeneous matrix into useful hierarchical and heterarchical organizations is commonplace. Thus, the morphogenetic field becomes organized into useful structures by the action of inducers which derepress the potentialities of DNA molecules embedded in those fields. New mathematical approaches to these age old problems have provided new insights which have been noted in the section on grammar, although a fuller appreciation must await their publication and translation. Thus, Thom (1972) has recently developed a topological mathematics to describe the mappings of the morphogenetic field. Although mathematically different, the approaches of Pattee (1971) and Shaw (Shaw & Wilson, in press) described in the section on grammar achieve the same end with even more powerful techniques. These related techniques emphasize heterarchies and generative capacities and can therefore be used to define the origin of the distinctive features of language. Each feature would be occasioned by continuous interactions (i.e. wave forms generated in the vocal apparatus) but the ensuing stabilities, the distinctive features *per se*, would result when the interactions – the relationships – temporarily get into non-linearities, a process Thom calls a «catastrophe».

The difference between right and left hemisphere function is ordinarily conceptualized in terms of whether processes leading to image formation or to non-linear catastrophic processes are emphasized. But more likely a simpler distinction based on sensory (e.g. auditory-verbal vs. visuo-somato-sensory) and especially motor mode is responsible. Reynolds (in press) has suggested that differential use of hands by primates has necessitated specialization of function between their cerebral hemispheres. Abler (personal communication) has suggested further that when such specialization occurs, a problem arises for innervation of midline structures such as the tongue. He has experimentally demonstrated that one innervation (usually the right in right-handed persons) must dominate, or conflicting signals from the two hemispheres disrupt function. In short, once hemispheric specialization has occurred, dominance must follow if the midline structures involved in speech are to function harmoniously. And dominance entails some catastrophic-like "decisional" mechanisms which more or less stably "take over" the innervation of the midline. In discussion, we have even entertained the possibility that the left hemisphere has the edge in achieving dominance because the heart is located on the left side of the body and thus provides some slight advantage to the embryo's circulation. Wada (Wada, Clark & Hamm, 1973) has shown that asymmetries in the size of the cortex of the supratemporal plane already exist at birth – although some puzzling sex differences also emerge in these studies: the difference is greater in males. There are, however, as yet no data on differences in early cerebral circulation to support such a hypothesis.

Conclusion

This essay has attempted to show that neurolinguistics in the near future may contribute as richly to classical problems in the study of human language as did psycholinguistics in the immediate past. This essay began with definitions of variety and constraint within the framework of information measurement and processing theory. These concepts were then used to provide defining properties of grammar and meaning. Next, comparative behavioral conceptualizations were invoked to relate some details of the syntactical structure to brain organization. Three levels and two modes of organization were identified. Significant (context-free) and symbolic (context-dependent) modes each could operate on a transformational, a phrase-structure or a primitive level. The primitive in the significant mode was suggested to be stochastic and finite state; in the symbolic mode entrainable, infinitely recurrent regularities were the most likely candidates. The application of finite state mathematics to the problems of hierarchy in language was pursued during the 1950's and '60's; infinite state applications have begun in the 1970's. Finally, some problems concerning brain organization and semantic structure were covered. Specifically, the concept of distinctive features was analyzed in the light of recent neurological evidence and the nature of deep structure viewed from the vantage of our knowledge of the characteristics of information storage in the brain. Models of linguistic organization based on digital computers and on optical information processing systems were invoked and the relationship between programs and distributed holographic-like neural stores was outlined in the light of our knowledge of the functions of other biological systems. The hope is that these outlines and proposals will serve as rudimentary formulations of some of the hitherto intransigent problems that have continued to plague linguistics despite rapid strides in understanding so recently achieved.

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