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Computations and
Representations

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INTRODUCTION

Gilbert Ryle (1949) has pointed out that the term "mind" is derived from "minding." When an organism minds (or does so in the negative), we are apt to endow it with all sorts of psychological attributes: Attention, perception, conception, consciousness, intention, will, satisfaction, thought, and talk are only a few of the labeled concepts that we use to identify these attributes. When brain tissue is severely damaged these psychological attributes become distorted or even destroyed. Furthermore, the distortion (or destruction) is not uniform: Damage to different parts of the brain differentially interferes with the various psychological attributes. This differential, selective interference is especially marked in man with regard to his ability to talk—to communicate audio-vocally. In most right-handed human adults speech is interfered with most critically when lesions occur in the left hemisphere, in a centrally located zone that surrounds the Sylvian fissure.

Mind and brain are thus shown to be related and we examine here the relationship with special reference to one psychological attribute—the ability to make, use, and comprehend language(s). A question that arises immediately, therefore, is whether language functions are localized in brain tissue. As audio-vocal communication becomes severely disturbed by and essentially only by lesions in a restricted portion of the brain, the question arises as to whether speech communication is synonymous with language. This question cannot be answered by fiat: Social consensus must, in the long run, decide how we are to define what we mean.

But, in the meanwhile, we can use the term language with considerable preci-

sion provided we employ some modifiers. Thus, spoken language is called the natural language; music can be considered a language-like system (see e.g. Bernstein, 1976; Jackendoff & Lerdahl, 1979; Pribram, 1981); and gestural communications are often referred to as "sign" languages (Klima & Bellugi, 1979).

When the issue is phrased in this fashion, it becomes clear that different regions of the brain partake in different sorts of language-like systems. For instance, gestural communications are not as dependent on the perisylvian cortex as are spoken natural languages. However, it might still be the case that some specific brain locus or some special brain process dependent on overall connectivity or chemistry might account for a single language ability and only its expression was dependent on diverse brain loci.

Against this possibility are observations on mentally retarded children who despite their overall incapacities can speak fluently and understand when spoken to: also, cases of idiot-savants whose incredible computational or musical abilities fail to be matched by any other form of intelligence. Though not conclusive, such observations argue strongly that the several language-like systems have diverse substrates that share, however, some overall capability that reaches its greatest development in man.

RE-PRESENTATION

What then, is this overall capability that makes man human? What brain function becomes so markedly enhanced that human languages distinguish man from all other animals? The evidence to be reviewed makes it likely that it is the brain's ability to construct hierarchies of representations that is critical.

Hierarchies imply levels. A level can be defined as a presentation (description) that is simpler than if it were made in terms of the constituents of that level. Thus each level can be characterized by a description, a presentation, and by components that are described in some different fashion—i.e., the component level of presentation is distinct from the level of the whole. Further, there would be no need for a presentation at the wholistic level were it not in some non-trivial sense, simpler. By simpler I mean simply simpler to use (see e.g. Pribram, 1971, Chapters 4 & 13 for examples). Bytes (which transform a binary code into an octal) are simpler to use than the equivalent description in bits. A presentation of a program in Fortran is infinitely simpler to use than a presentation of the successive switch settings that characterize the hardware equivalent of the program. Of interest here is whether psychological processes can be considered to be re-presentations of functions of the brain.

In the sense of hierarchical levels of presentation, the analogy between computer software (programs) and hardware can serve as a model. The psychological, mental level is described in a presentation that is analogous to the program

level. The wetware of the brain is of course analogous to the hardware of the computer (e.g., Miller, Galanter, & Pribram, 1960). There is an equivalence between program and successive switch settings. Can we therefore say that in some real sense the switch settings are re-presented in the program? And vice-versa? If so, in that same sense psychological processes re-present brain function and vice-versa.

ISOMORPHISM

Are the equivalences between levels of presentation isomorphic to one another? Again, the answer to this question depends on reaching some consensus on the definition of isomorphic. Shepard (Shepard & Chipman, 1970) has recently suggested that processes that map into each other readily such as perspective transformations can be regarded as displaying secondary isomorphism. Where are we to draw the line between representations that display the *same* form (are isomorphic) and those that do not?

Isomorphy is not a trivial problem when one tries to understand the nature of brain representations. Köhler (1964) attempted to show that the geometry of cortical electrical activity conforms to the geometry of the physical events producing the stimulation of the organism. This line of reasoning suggested that brain representations "pictured" the significant environment of the organism or at least caricatured it.

By contrast, the computer program-hardware analogy suggests that significant transformations can occur between levels of presentation: indeed that the utility of re-presentations is derived from these transformations. Both isomorphic and transformational processing may, of course, characterize brain representations. But at least the computer analogy has liberated brain scientists from searching exclusively for "pictures" and set them to search for computations that transform sensory input and motor output and state that search in "information (bits and bytes type) processing" terms.

COMPLEMENTATION AND COORDINATE STRUCTURES

An added dividend has accrued from this new freedom. Even where isomorphism between presentations might initially be sought, the naive realism of brain "pictures" gives way to a more sophisticated view of the relationship between the sentient organism and its significant environment. Gibson (1966), Turvey (1973), and Shaw (1977), among others, have proposed that the organism becomes attuned to its environment and that the relationship between the two is one of complementation. They argue that representation suggests an *isomorphic* replica: Note that earlier I have argued the opposite—that a re-presentation involves

a *transformation*. They therefore suggest that complementation, which implies a duality, a mirror image of sorts, is more appropriate. But the distinction between complementation and representation does not clearly define the issue. A complement need not be a "picture," even a mirrored picture, any more than other presentations: Many musical instruments complement the fingers of the hand, yet a piano keyboard, violin string and clarinet stops have completely different configurations. The issue is whether the presentations are isomorphs or transforms of each other.

What types of transformational mechanism within the nervous system could be responsible for bringing it into a complementary relationship with the environment? Below the cortex these mechanisms are composed of iterative feedback loops (see Miller, Galanter, & Pribram, 1960; Pribram, 1977; Granit, 1955; Gel'fand, Gurfinkel, Tsetlin, & Shik, 1971) "coordinate structures" or TOTES (test-operate-test-exit mechanisms) that adjust the organism to changes in receptor load. At the cortex these changes in load are directly encoded (see e.g. Evarts, 1967). Anatomically there is considerable receptor-cortex isomorphism. How then can "load," which is environmentally engendered, become represented in the cortex?

Consider the anatomical connectivity of an array upon which environmental events operate. If the cortex is to encode these environmental operations there must be some transformation exerted upon the limit of the array—some transfer function that preserves an equivalence between environmental input and its cortical representation.

NEURAL HOLOGRAMS

There is good evidence that this transfer function is effected by lateral networks of mostly axonless (local circuit) neurons (Rakic, 1976) neurons whose dendrites extend perpendicularly to the receptor-cortical connectivity (see Bekesy, 1967; Ratliff, 1965; Pribram, 1977a). These networks of neurons operate in large part without generating propagated nerve impulses. Their mode of functioning is by way of graded local potentials—hyperpolarizations and depolarizations. Their operation can be considered to impose a spatial filter on the receptor-cortical pathway. The characteristics of this filter transform the input into its linear equivalent in the frequency domain. In short, the filters perform something like a Fourier transform on the input from the receptors.

Just as there is a radical difference between octal bytes and binary bits, so there is a radical difference between an input and its Fourier transform. In the transform domain frequencies are encoded and information becomes distributed—mathematically the transform is called a spread function. Further, the frequency domain allows extremely rapid correlations to be made. (This was the basis for the invention of X-ray tomography by which three dimensional brain scans can be produced.)

Computers are artifacts that enact the power of hierarchically organized list structure programs. Holograms are artifacts that enact the power of transforms in the frequency domain. Holograms encode the interference patterns created by wave forms of different frequencies—much as an FM radio signal encodes information by virtue of the modulations of the frequency of an electromagnetic wave. In a hologram, however, the wave forms are two dimensional rather than unidimensional as in radio waves. Thus, considerably more information can be transmitted and stored provided the carrier frequency is high enough.

Over the past decade the evidence that the brain functions as a frequency analyzer has accumulated rapidly. Over a century ago Helmholtz (1867) supported Ohm's (1843) suggestion that the auditory system operates in this fashion. Bekesy's classical studies extended these concepts to the somatosensory modality (1957). In the olfactory mode, Freeman (1975) has presented evidence that a similar mechanism is operative. And most recently the work of Campbell and Robson (1968), of Schiller, Finlay and Volman (1976), of Movshon, Thompson, and Tolhurst (1978), of Pollen and Taylor (1974), of Maffei and Fiorentini (1973), of Ikeda and Wright (1974), of de Valois, Albrecht, and Thorell (1978), of Glezer, Ivanoff, and Tscherbach (1973), and our own work (Pribram, Lassonde, & Ptito, 1981) have established beyond any reasonable doubt that the visual system also operates in this fashion.

Two mysteries that had plagued the brain-mind problem have been resolved by these data that demonstrate a stage of processing in which the frequency domain is important. First, the resistance to brain damage of discrete memory traces is explained by the distributed nature of the holographic-like store. Second, image construction with its wealth of texture and its projection away from the receptor surface are now readily understood. Thus far there has been no other mechanism by which texture can be simulated (see Szentagothai & Arbib, 1975; Campbell, 1974). Projection is accomplished as in stereophonic high fidelity audio systems when there is disparity between the phases from two sources (see Bekesy, 1957).

For the mind-brain problem these are indeed striking contributions. The projected images are in fact the Ghosts in the Machine that Gilbert Ryle (1949) was attempting to excise in his behavioristic approach to the problem. Once images are admitted, the entire range of ghostly mental phenomena comes tumbling along bag and baggage. If brain mechanisms can generate images, why not feelings? And thoughts? And languages?

NEURAL-MENTAL RE-PRESENTATIONS

Note that this analysis concerned various levels of neural functioning: e.g., receptors, coordinate structures, cortical holograms. Only when we examine the functioning whole do we achieve the mental—and of course the whole includes the environmental events that excite the receptors and make possible effector

action. To keep faith with the spirit of the analysis we must conclude that brain is re-presented in mind and mind in brain. This does not mean, however, that the presentations of mind and of brain are identical or need be isomorphic—in fact, we have seen that they are disparate: Transformations characterize the relationship. Re-presentation is a realization in a specific domain of a presentation realized in another domain. The fact that the two presentations can be related to each other by a specifiable transformation indicates that some underlying unity is involved. In the case of complementation this unity has been suggested to be due to a symmetry structure (see Shaw & Pittenger, 1977). One type of symmetry is achieved in the complete reversibility which is the hallmark of holonomic frequency transforms (to decode a Fourier hologram the original transform—now called the inverse—needs only to be repeated). At present we have no other name than re-presentation for the unity that becomes realized in the variety of computational dualities and holonomic transformations.

INFORMATION PROCESSING

Complementation, coordination, and imaging account for a type of brain-mind relationship that in older neurological literature was called sensory-motor functioning. In this type of relationship "mind" closely binds the organism to its environment and through behavior, the environment to the organism. (This "binding" function operates through constraints similar to those that limit the distribution of hydrogen and oxygen once they are bound as H_2O , to which we give a new representational name—water.) Psychophysics, perception of Gestalts and illusions, and motor skills are the psychological processes that are studied when this aspect of mind is considered.

But there are other mental phenomena that do not fit these constraints. Cognitive problem-solving processes and social-emotional skills, for example, involve dimensions of mind that are distinctly different from those discussed in the previous sections.

It is easiest to begin with problem-solving processing because a quantitative measure of what constitutes a problem can be given in terms of "information." A bit of information reduces uncertainty in half—uncertainty being a measure of the number of specified alternatives that characterize the choices an organism faces in a situation. The measure on uncertainty and information is therefore identical and simply reflects the choices made with respect to possible choices.

Note that alternatives, choices, break up, partition an organism-environment relationship into segments (sets and subsets). In order to do this, segments must be differentiated. This is the problem of similarity and of categorizing—a problem recognized as fundamental to cognitive psychology, (see e.g. Tversky, 1977).

The brain locus involved in information processing is distinctly separate from

that in which complementation takes place. Complementation as we have seen is a function of the sensory-motor projection systems of the brain. Information processing, differentiation among alternatives is disrupted by resections of what is usually called "association" cortex of the posterior convexity of the brain (for review, see Pribram, 1974). In man, lesions of these areas produce agnosias, deficits in recognizing, in cognitive processing. Experimental analysis has shown that resection of this cortex reduces the ratio of possible alternatives sampled by the organism (Pribram, 1960).

As noted earlier, one of the most pressing problems in psychology is to decipher the transformations that re-present images as information (and vice-versa). The linear complementary functions of the sensory-motor systems must be transformed into nonlinear choices. How do the "association" systems of the brain effect these nonlinear transformations? We do not as yet know, but to date we have shown that the operation of this cortex in making discrimination possible is intimately dependent on its efferent, downstream connections to the basal ganglia of the brain and from there to the sensory-motor systems (Spinelli & Pribram, 1967; Lassonde, Ptito, & Pribram, 1981).

Several possibilities for research are opened by these results. Radar operators have faced the problems of digitizing holographic presentations. They have relied on the mathematics of Hadamard and Walsh transforms to differentiate the infinitely multivalued Fourier domain into a finite multivalued one (Hadamard, 1972) and then into a bivalued (binary) system (Walsh, 1972). The efferent operators from the association cortex that have been found to modify the lateral connectivities in the projection system may convert an essentially continuous "field" into a binary matrix (see Wilson & Cowan, 1973). Or, these efferent operators may be band-limiting in such a manner that logons, units of information suggested by Gabor (1946), are produced (see MacKay, 1969; Brillouin, 1962, for review).

EPISODIC PROCESSING

There is an entirely different mode of central processing that is reciprocal to the information and cognitive mechanism just described. Resection or electrical excitation of the frontolimbic forebrain almost always produces effects on projection cortex opposite to those produced by these methods applied to the convexal association cortex (see Spinelli & Pribram, 1967; Lassonde, Ptito, & Pribram, 1981). According to the analysis pursued here, frontolimbic processing should therefore result in integration rather than differentiation.

According to the results of neurobehavioral experiments, the frontolimbic forebrain subserves context dependent, episode specific constructions (see Pribram, Ahumada, Hartog, & Roos, 1964; Pribram & Luria, 1973; Pribram, 1977c). This type of construction involves taking the continuum of experience

and "chunking" it into coherent episodes (see Miller, 1956; Simon, 1974). The chunks are, of course, arbitrary but effective in enhancing the utility of the re-presentation. Encoding binary bits into octal bytes is such an operation. Experimental evidence (see Pribram & Tubbs, 1967; Pribram, Plotkin, Anderson, & Leong, 1977) has been obtained to show that frontal cortex is in fact critical to such parsing or chunking operations.

One can conceptualize the difference between behavioral differentiation and chunking in terms of the distinction between mathematic differentiation and integration. Differentiating a wave form emphasizes consistent changes (invariances). Each invariant can become an alternative—a bit (binary digit) of information. Integration, by contrast, encompasses the entire area contained by the wave forms. All that needs to be specified are the limits over which the integration should proceed, and these limits—the windows—are established arbitrarily or on the basis of some extraneous (contextual) criterion. Episodic integration is thus context sensitive. Arbitrary (token) rules for integration must be established—e.g. as by social convention. But brain states (such as the neurochemical states that are regulated by limbic system functioning and responsible for basic emotional and motivational feelings) also furnish the momentary contextual limits for integration. In economic theory, these contextual parameters are called "probable availability" (social and arbitrary) and "desireability" (based on attraction between available input and need). The frontolimbic forebrain deals with the organism's economy (Pribram, 1965)—sometimes wisely while the posterior cortical convexity is involved in formulating knowledge (informs cognitions).

COGNITIVE CONTROLS

A model of brain function emerges from these considerations. This model envisages complementation between brain and the environment. Complementation takes place via sensory transduction on the one hand and behavioral adjustment on the other. Hierarchically organized coordinate structures in the peripheral and central nervous system become organized to re-present the transductions and adjustments. This is in part accomplished by transformations of the presentations into the frequency domain in which correlations are readily performed.

The encoded frequency representations are in turn operated upon by controls from the "association" systems of the brain. Two classes of such systems, operating reciprocally have been identified, one originating in the posterior cortical convexity and the other in the frontolimbic forebrain. Control from the convexity tends to differentiate the representation making possible, "choices" among its "bits" and therefore information and cognitive processing. By contrast, control from the frontolimbic forebrain tends to integrate portions, epi-

sodes, of the complement, chunking it according to felt needs and/or environmental contingencies.

HUMAN LANGUAGES

The transformations produced by these information (cognitive) and episodic (economic, sapient) controls can, in man, serve as the basis for re-presentation at still another level of presentation. Neurally this level is probably made possible by the increase of the proportions of cortex not directly committed to complementation (see Young, 1962; Pribram, 1962; also, Pribram, 1971). Encoding this level in an enduring culture is equally important (see Pribram, 1964, 1975b, 1976, and Popper & Eccles, 1977). The re-presentation now partakes both of the structure of information process and that of the arbitrary chunking of the episodic process. At a deeper level, its semantic store re-presents the distributed frequency domain and even the coordinate structures that compose complementation.

The nature of transformations that re-present cognitions (knowledge) and context sensitive episodic constructions (wisdom) in language and language-like process is not at all clear. Chomsky has chosen to emphasize syntax (1980) and there is good evidence that this approach to natural language and to musical phrasing (Bernstein, 1976; Lerdahl & Jackendoff, 1977; Pribram, 1981) can be fruitful. However, this emphasis on syntax fails to point out that equally important syntactic advances characterize all cultural achievements (Pribram, 1971). This, then poses the problem of what distinguishes them—what is the difference between natural languages, musical compositions, sport, dance, architecture, and painting? I have in a preliminary fashion attempted to frame this question by examining the relative roles of semantics (cognition) and pragmatics (sapience) with regard to natural languages (Pribram, 1976; 1978; 1980) and music (1981).

Much more needs to be done—languages, cognitions, and wisdom apparently do not spring from the isolated operation of any single neural mechanism—still, there is the haunting evidence of the linguistically competent retardates and of the savants to continually remind us of the uniqueness of the combinations that characterize each of these mental processes.

EPILOGUE

Since this was written a great deal of interest has been devoted to the problems of cognitive computations and psychological representations. For instance, a recent issue of *The Brain and Behavioral Sciences* (Spring, 1980) was devoted to these problems, as is Volume III of the Pennsylvania State Series on Ecological Psy-

chology (1981). The views expressed in my presentation here can be readily compared with others, therefore. On the whole, there appears to be considerable agreement overall, but with sharp differences in detail (such as whether brain facts are critical—see, e.g., the excellent discussion by Churchland of Pylyshyn's otherwise superb contribution in *The Behavioral and Brain Sciences*), and definition (as to whether by representation is meant an isomorph or a transform or both).

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