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The Frontal Cortex—A Luria/Pribram Rapprochement

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INTRODUCTION

When I began research on the functions of the anterior frontal cortex I found that neurobehavioral considerations related this part of the brain to the functions of the limbic part of the forebrain, not to the motor functions of the precentral cortex. The peri-Rolandic cortex, on the basis of neurobehavioral analysis, belonged with the remainder of the cerebral convexity. Thus a major distinction was made between the functions in behavior of the frontolimbic formations and those of the posterior cerebral convexity (see reviews by Pribram 1954, 1958a, 1958b, and the initial part of this chapter).

Alexandr Romanovich Luria conceived of the anterior frontal cortex in a different fashion. He emphasized the proximity of the anterior frontal cortex to those parts of the cortex which were electrically excitable in terms of motor functions (including those my colleagues Kaada, Epstein, and I had discovered in 1949 on the medial and basal surfaces of the hemisphere). This proximity to motor systems continued to be of considerable concern to me as well, but only recently have I hit upon an idea around which this concern can be precisely formulated.

It is this formulation which forms the core of this chapter dedicated to the memory of Luria.

The idea is simple. There is an important attribute by which the systems of the central part of the cerebral mantle differ from others: the peri-Rolandic systems are the only forebrain systems by which the organism can manipulate his or her environment. The systems of the posterior cerebral convexity primarily process sensory input in terms of "local sign", i.l. "epicritic" spatiotemporal perceptual organization for which there is no direct expression. The systems of

:e limbic forebrain primarily process input from chemical, pain and temperature :eceptors in terms of steady state "protocritic" sensibilities (see Pribram 1977; 'hin, Pribram, Drake, & Greene, 1976) which provide the basis for passion ather than action. Thus, only by relationship to the peri-Rolandic systems can 'erceptual organization and sensibility be effectively utilized.

As I hope to demonstrate, the idea of *relating* protocritic to epicritic rocessing via the peri-Rolandic somatic systems clarifies ambiguities that have itherto plagued conceptions based on either type of processing alone. Perhaps ie most important clarification has to do with the view that anterior frontal lobe inction is critical to planning. There is no doubt but that this is so (see, e.g., 'enfield, 1948). For years I held to the idea that the deficit in planning that ollows frontal lobe damage are due to the connections with the limbic forebrain hich, when disrupted, lead to interference with the serial ordering of behavior. nterference was conceived to originate in heightened distractibility. This turns ut to be only a part of the story.

Joaquin Fuster, in the initial edition of his volume on frontal lobe function, iso forwards "the disruption of serially ordered behavior" view (1980). Howev- every experimental test of this hypothesis performed in my laboratory failed confirm it (Barrett, 1969; Kimble & Pribram, 1963; Pribram, 1961; Brody & ribram, 1978). In part this is due to the fact that all behavior, by virtue of strictions in the final common path (Sherrington, 1911) is serially ordered and us brain damage that does away with ordered behavior must indeed be sizable. onetheless, something about seriality and temporal order is disturbed by anteri- frontal damage and it is that something which needs to be identified.

In the second edition of Fuster's publication the problem is recognized and ndled in a sophisticated fashion: Fuster concludes that anterior frontal damage srupts the processing of "cross temporal contingencies."

This same something is labeled "temporal tagging" by Brenda Milner and ichael Petrides (1984, 1988). These investigators have shown that, after frontal mage, recalling the *relative* recency of serially ordered events is disturbed.

In my own work, experimental results indicated that deficiencies in process- g sequences of events could be overcome by providing monkeys with a ognitive prosthesis" which "parsed" or "chunked" what would otherwise be an nterrupted flow of sensory inputs. This prothesis can be thought of as oviding tags for maintaining and recalling "serial position" within a sequence ribram & Tubbs, 1967; Mishkin, 1973).

However, as was reviewed in detail in a previous publication (Pribram, 87) it is not only the processing of cross temporal contingencies or temporal gging that is disupted by anterior frontal damage: the processing of spatial lations, i.e. the processing of cross spatial and spatiotemporal contingencies is so impaired. As in the case of processing serial position, the difficulty becomes anifest whenever an input must be processed within a context established on e basis of prior experience.

Clarification of these ideas comes when the anatomical and functional relationships between anterior frontal and other forebrain systems is delineated. Three different subdivisions based on different arrangements can be discerned: an orbital, a ventrolateral and a dorsolateral. Anatomically, the orbital subdivision, by way of the uncinate fasciculus, is related to the paleopallium; (especially the amygdala); the ventrolateral subdivison to the sensorymotor systems of the posterior convexity; and the dorsalateral, to the archipallium (especially the hippocampus). Functionally, the orbital subdivision will be shown to process *proprieties* based on limbically formulated sensibilities; the ventrolateral subdivision will be shown to be involved in *praxis* by way of processing sensory load, and the dorsolateral subdivision will be shown to deal with establishing *priorities*.

SUBDIVIDING THE FRONTAL CORTEX

Thalamocortical Definition of Subdivisions

The frontal cortex of primates can be divided into three major divisions each of which is made up of subdivisions. The three major divisions are the precentral (including pre- and supplementary motor), the anterior (also called prefrontal, orbitofrontal, or far frontal), and the cingulate (also called limbic). These major divisions are defined on the basis of their thalamic projections: the precentral deriving its thalamic input from the ventrolateral group of nuclei, the anterior frontal from the nucleus medialis dorsalis, and the cingulate from the anterior group (for review, see Pribram, 1958a, 1958b).

The subdivisions of these major divisions can also be defined in terms of their thalamic input: the immediate precentral cortex receives an input from the nucleus ventralis lateralis, pars caudalis, and the nucleus ventralis posterior, pars oralis, which in turn are the major terminals of cerebellar projection. The premotor parts of this division receive an input from the nucleus ventralis lateralis, pars oralis, which in turn is the major termination of input through the globus pallidus of the lateral nigrostriatal system. A further subdivision can be made between the lateral premotor and the supplementary motor systems in that the more laterally placed systems deal more with orofacial and the supplementary motor systems with the axial muscular projections (Goldberg, 1985).

The subdivisions of the cingulate cortex follow the subdivisions of the anterior thalamic nuclei: Nucleus anterior medialis projects to the anterior cingulate cortex; nucleus anterior lateralis, to the posterior cingulate cortex (Pribram & Fulton, 1954). The nucleus lateralis dorsalis (which ought to be classified as part of the anterior group) projects to the retrosplenial part of the cingulate gyrus.

Finally, the primate anterior far frontal cortex can be subdivided according to subdivisions of the nucleus medialis dorsalis: The microcellular part projects

to the dorsolateral frontal cortex, the perilamminar magnocellular part to the periarcuate cortex, and the midline magnocellular part to the orbitofrontal cortex (Pribram, Chow, & Semmes, 1953).

A Frontolimbic vs. Cortical Convexity Distinction

There are additional, hitherto ignored, interesting and important (for understanding the functional relationship to psychological processing) findings regarding the thalamocortical projections. The thalamus is a three-dimensional structure while the cortex is (from the standpoint of thalamic projections) essentially a two-dimensional sheet of cells. Thus, the projections from thalamus to cortex must "lose" one dimension. When one plots the precisely arranged "fan" of projections from each thalamic nucleus one can readily determine which dimension is eliminated.

With regard to the projections from the anterior nuclear group and the nucleus medialis dorsalis, the eliminated dimension is the anterior–posterior. An anterior–posterior file of cells in the thalamus projects to a single locus of cortex. Thus, for example, one finds degeneration of such an extended row of thalamic cells, ranging from the most anterior to the most posterior part of the nucleus medialis dorsalis after a resection limited to the frontal pole (Pribram, Chow, & Semmes, 1953).

With regard to the ventrolateral group of nuclei the situation is entirely different. Here the anterior–posterior dimension is clearly maintained: The front part of the nucleus projects to the forward parts of the cerebral convexity; as one proceeds back in the thalamus the projections reach the more posterior parts of the cortex, curving around into the temporal lobe when the projections of the pulvinar are reached. On the other hand, a file of cells extending, more or less, dorsoventrally (but angled somewhat laterally from its medial edge) projects to single locus on the cortex (Chow & Pribram, 1958).

This distinction between the anterior and medial nuclei on the one hand and the ventrolateral group of nuclei on the other, is endorsed by the fact that the internal medullary lamina separates the two classes of nuclei. Clearly, therefore, we should seek for commonality among the functions of the anterior, far frontal parts of the cortex and the limbic formations, and commonality of functions between the precentral and postcentral portions of the cerebral mantle (Pribram, 1958a, 1958b).

The close anatomical relationship of the far frontal cortex and the limbic medial forebrain is also emphasized when comparative anatomical data are reviewed. In cats and other nonprimates, gyrus prorius is the homologue of the far frontal cortex of primates. This gyrus receives its projection from the midline magnocellular part of the nucleus medialis dorsalis. This projection covers a good share of the anterior part of the medial frontal cortex; gyrus proreus on the

lateral surface is limited to a narrow sliver. It is as if there has been a rotation of the medial frotal cortex laterally (just as there seems to have occurred a rotation medially of the occipital cortex, especially between monkey and humans) during the evolution of primates.

A Rolandic vs. Extra-Rolandic Distinction

A further lesson can be learned from an analysis of the precise arrangement of thalamocortical projections and from comparing nonprimate with primate cortical anatomy. In tracing the thalamic projections to the precentral cortex, a surprising finding came to light. The dorsoventral arrangement of terminations, both pre-and postcentrally, is diametrically opposite to the arrangement of the projections farther forward and farther back. The dorsoventral terminations of the Rolandic projections reflect a lateral-medial origin from the thalamus; the dorsoventral terminations both forward and back of the peri-Rolandic cortex reflect a medial to lateral origin (Chow & Pribram, 1956).

Again comparison of nonprimate with primate cortical anatomy clarifies this surprising finding. In nonprimate species such as the carnivores, the suprasylvian and ectosylvian gyri extend the full length of the lateral surface of the cerebral convexity. The cruciate sulcus, the homologue of the Rolandic fissure, is mainly found on the medial surface of the hemisphere with only a minimal extension onto the lateral surface. It is as if in the evolution of primates this sulcus has migrated laterally to become the prominent central fissure (that becomes so intimately related to the cerebellar system).

Such a migration has split the supra- and ectosylvian gyri into anterior and posterior segments. That such a split has occurred is supported by the fact that terminations of thalamocortical projections to the anterior and posterior segments originate in adjacent parts of the ventrolateral nuclei. Should this conjecture regarding a split be correct, it would go a long way toward accounting for the difficulty in making a differential diagnosis between apraxias that are due to frontal, and those that are due to parietal damage.

Skill vs. Praxis

Jason Brown (1987) in a review of frontal lobe syndromes, defines apraxia as "a substitution or defective selection of partial movements with lesions of the left premotor cortex [which] is due to an alteration of motor timing or a change in the kinetic pattern for a particular motor sequence" (p. 37).

In order to test whether in fact damage to both parietal and frontal (premotor) systems can produce apraxia and to pin down in a quantitative fashion just what changes in timing, in the kinetic pattern of movement occurs in apraxia the following (Pribram 1986) was performed: Monkeys were trained (using peanuts

as reinforcements) to move a lever in a T-shaped slot beginning at the juncture of the arms of the T with its stem. The movements were then to be directed to the right, to the left, and finally down and up, in that order. Records were kept of the monkeys' ability to perform the movements in the correct order and the number and duration of contacts with the sides of the slots that formed the T. (This was done by having the sides and the lever lined with copper and wiring them so that contact could be recorded.)

Resections were made of precentral cortex, of the cortex of the inferior parietal lobule and of the premotor cortex, and of the latter two lesions combined. Precentral resections led to many more and briefer contacts along the path of the lever within the T slot, a loss of fine motor skill. No change in overall sequencing occurred. Both the parietal and the premotor resections produced a breakdown in the sequencing of the movements but only insofar as the same movement was carried out repetitiously, interpreted as evidence of apraxia. There was no observed difference between the effects of the anterior and those of the posterior resection and the overall order of the act was not disturbed. When the parietal and premotor resections were combined this deficit was enhanced; still there was no change in overall ordering of the action. More on this distinction between the systems that deal with skill and with praxis in the summary and synthesis.

ANTERIOR FRONTAL SUBDIVISIONS

When lesions occur in the Rolandic and premotor parts of the frontal lobe neurological signs and symptoms occur which are relatively easy to spot. By contrast, the lesions of the anterior frontal cortex are essentially "silent" unless specific and sophisticated inquiries are addressed to the organism. Such inquiry has been greatly aided by the deployment of nonhuman primate models of anterior frontal lesion-produced deficits in behavior.

Description of Tasks

The tasks which have been found most useful in delineating the deficit following anterior frontal damage are all characterized by a delay between stimulus presentation and the opportunity for a response to occur. During this delay distractors are introduced and the cue to the correct response disappears. The tasks fall into two main categories: delayed response and delayed alternation. Further, variations in the tasks have produced several subcategories of each category, variations which have been found to be extremely useful both as tools for subdividing the anterior frontal cortex and for understanding the nature of the deficit.

The delayed response task, in its direct form, involves hiding within sight of the subject, a reward in one of two identical-looking boxes set side by side, bringing down a distracting opaque screen for at least 5 seconds and then raising the screen to provide the subject with a single opportunity to locate the reward. The boxes are immediately withdrawn beyond the subject's reach and the next trial begun. Should the subject have failed to find the reward on the just-completed trial, the trial is repeated (correction technique), that is, the reward is again hidden within sight of the subject in the same box as in the previous trial. Should the subject succeed in finding the reward on the previous trial, the location (i.e., the box) for the hiding of the reward is chosen according to a pseudorandom table.

The indirect form of the delayed response task is more often called a delayed matching from sample. In this task a cue is presented instead of the reward during stimulus presentation; at the time of choice this cue and some other are available and the subject must choose the same cue as that initially presented in order to obtain the reward. A further variant of this task is the delayed nonmatch, in which the subject must choose the cue which was not present at the time of stimulus presentation. This version combines the attributes of the delayed response task with those of the delayed alternation procedure.

In the delayed alternation task the subject is not shown where the reward is located, he is simply given the opportunity to choose between two boxes. On the first trial both contain a reward. After the choice has been made, a distracting opaque screen is interposed between the boxes and the subject for at least 5 seconds and the next opportunity for choice is given. On this second trial the subject will find the reward in the box other than the one he chose initially and if he continues to choose successfully he will do so by adopting a win-shift strategy. Should the subject choose the empty box, the trial is repeated (correction technique). Unless this correction procedure is used, monkeys when they are the subject fail to learn the alternation task (at least in 5,000 trials, Pribram, unpublished data).

Three variants of delayed alternation which have proved especially useful are a go/no-go version, the object alternation procedure and discrimination reversals. In the go/no-go task the subject must alternately go to fetch the reward on one trial and withhold his response on the subsequent trial. Failure to go or failure to withhold result in the repetition of the trial (correction procedure). In the object alternation procedure the reward is alternated between two different objects rather than between two different locations. In this variant the spatial aspect of the task is reduced, a reduction which is enhanced when the objects are placed among 6, 8, or 12 locations, according to a random number table (Pribram, 1961b). Discrimination reversals are, in fact, alternations which vary the numbers of trials that occur between the shift of reinforcement that signals the alternation. There is a gradual transition between alternation, double alternation, triple alternation, and so on, and the ordinary nonreversal discrimination task.

The inflection point occurs at three nonalternation trials in normal subjects, but is raised to four to five such trials after frontal lobe damage. (Pribram, 1961b).

Description of Lesion Sites

Earlier an anatomical rationale for subdividing the anterior frontal cortex was given in terms of the thalamic projections which terminate in different parts of this cortex. Unfortunately all of the investigators involved in pursuing the parcellation experiments did not adhere to this particular mode of subdividing: Many experimenters simply divided the anterior part of the frontal lobe into a dorsal part centered on the sulcus principalis and a ventral part, which included both the lip of the lobe and the entire orbital surface. Furthermore, surgical result does not always match surgical intent. The fibers in the depth of the sulci (medial, orbital, and principal) in the anterior part of the frontal lobe are separated by only millimeters and can be differentially spared only by exercising the greatest care and skill.

Despite this, meaningful conclusions can be teased out of the results of such experiments, provided the various lesions are kept clearly differentiated by appropriate labels. It is therefore necessary to adopt a uniform terminology for the resections that often differs from that used in the original reports because different investigators used the same term to describe different lesions or different terms to describe the same lesion.

The greatest problem arises from the use of the term "orbital." Here the convention will be followed that the term orbital refers to the general expanse of the ventral part of the lobe and that when specific parts of this cortex are referred to, orbital will be conjoined to a modifier. Thus posterior orbital refers to the agranular cortex located in the most posterior part of the orbital cortex (Area 13 of Walker, the projection of the midline magnocellular portion of nucleus medialis dorsalis of the thalamus). This cortex is intimately related through the uncinate fasciculus to the anterior insula, temporal pole, and amygdala.

The term medial orbital will be used to refer to the dysgranular cortex of the medial orbital gyrus, which is continuous with the cortex on the medial surface of the lobe and receives a projection from the anterior thalamic nucleus (Pribram & Fulton, 1954). In keeping with the agranular and dysgranular cytoarchitecture of the posterior and medial orbital cortex, it was found to be electrically excitable, that is, head and eye movements and a host of visceral responses (respiratory, heart rate, blood pressure) are obtained when this cortex (as well as that of the anterior cingulate gyrus with which it is continuous) is electrically stimulated (Kaada, Pribram, & Epstein, 1949). This finding gave rise to the concept of a mediobasal motor cortex, the existence of a limbic system motor cortex in addition to the more classical Rolandic and precentral systems (Pribram, 1961a).

The eugranular cortex on the lateral orbital gyrus is continuous with that forming the ventral lip and adjacent ventral gyrus of the frontal lobe. This cortex is part of the projection of the microcellular part of n. medialis dorsalis. When a lesion of this cortex is reported in conjunction with a lesion of posterior and medial orbital cortex the lesion is here labeled as orbitoventral. When a lesion of this cortex is made in isolation the lesion is referred to as ventral. When the resection extends laterally up to the gyrus adjacent to the sulcus principalis, the lesion is called ventrolateral.

Finally a dorsolateral resection is identified as including the eugranular cortex surrounding the sulcus principalis. Such lesions usually extend to and include the marginal gyrus. The dorsolateral cortex is the termination of the remaining projection of the microcellular part of nucleus medialis dorsalis.

When smaller lesions are reported, for example, periarcuate, around the arcuate sulcus; periprincipalis, around the sulcus principalis, and so on, the nomenclature is reasonably clear. When larger lesions are made they are simply referred to as lateral frontal when they excluded the posterior and medial orbital gyri. The resections are referred to as medial frontal when they are restricted to these gyri and the medial surface of the lobe. When the entire anterior frontal cortex is removed, the lesion is referred to as anterior frontal.

The Orbital Contribution: Propriety

A good subject to begin with is the orbital contribution to psychological processing because it is so closely linked to that of the limbic forebrain. Damage limited to either the medial orbital (Pribram, Mishkin, Rosvold, & Kaplan, 1952) or the posterior orbital (Pribram & Bagshaw, 1953) does not produce any impairments in performance of the direct form of the delayed response task. Damage to both the medial and posterior orbital cortex does, however, produce a deficit in delayed alternation performance (Pribram, Lim, Poppen, & Bagshaw, 1966; Pribram, Mishkin, Rosvold, & Kaplan, 1952; Pribram, Wilson, & Connors, 1962). This deficit is due to the accumulation of many repetitive errors of both commission and omission which become apparent especially in the go/no-go version of the task. In fact these lesions produce a greater deficit in this variant of the task than on the right/left version (Pribram, 1973), a result which is opposite to that obtained when lateral frontal resections are made (Mishkin & Pribram, 1955).

Other effects observed after resections of the medial and/or posterior orbital damage are a decrease in aggression (Butter, Mishkin, & Mirsky, 1968; Butter, Snyder, & McDonald, 1970), and an increased tendency to put food items in their mouths (Butter, McDonald, & Snyder, 1969). Both of these effects had previously been observed when posterior orbital lesions are combined with those

of the anterior insula, temporal pole and amygdala (Pribram & Bagshaw, 1953). It is such results which link the effects of orbital lesions on behavior to those of the limbic forebrain.

The question arises as to what such changes in behavior are due to? Brutkowski had argued that the orbital lesions in monkeys and dogs produce disinhibition of ordinarily present drive inhibition rather than the more obvious perseverative interference (see the extensive reviews of the conditioning literature by Brutkowski, 1964, 1965; and Konorski, 1972). The findings that monkeys with orbital resections continue to work harder than normals for nonfood items despite a normal preference for food items (Butter, McDonald, & Snyder, 1969), a result similar to that obtained with amaygdalectomized monkeys (Weiskrantz & Wilson, 1958), would seem to support Brutkowski's hypothesis, which was mainly based on work with dogs.

However, data showing that the response rates following orbital or lateral frontal resections are the same as those of normal monkeys during conditioning of an intermittently reinforced bar press response (Butter, Mishkin, & Rosvold, 1963) plus the additional data that monkeys with orbitoventral lesions stop responding for longer than do monkeys with dorsolateral frontal resections when novel stimuli are introduced during a similar bar pressing task (Butter, 1964) cast considerable doubt on a disinhibition hypothesis based solely on an increased drive for food.

The fact that failure in delayed alternation is characterized by proportionately as many errors of omission as of commission also indicates that the drive disinhibition hypothesis is untenable (Pribram, Lim, Poppen, & Bagshaw, 1966). Similarly damaging to a drive disinhibition hypothesis were the results of an experiment testing the object reversals using the go/no-go technique with monkeys who had sustained resections of orbital cortex (McEnaney & Butter, 1969). Once again the animals not only made more errors of commission than normals but also more errors of omission. They perseverated their refusal to respond to the previously negative stimulus.

Further evidence along these lines comes from the fact that monkeys with large orbitoventral lesions show a greater resistance to extinction of a bar press response even in the absence of food reinforcement (Butter, Mishkin, & Rosvold, 1963). These results confirmed and extended those obtained earlier with total anterior frontal and limbic (posterior orbital, insula, temporal pole, and amygdala) resections (Pribram, 1961a; Pribram & Weiskrantz, 1957) and are consistent with the finding that frontal and limbic lesions enhance the extinction of a conditioned avoidance response (Pribram & Weiskrantz, 1957).

These last results would readily fit a response disinhibiton hypothesis (one that plagued limbic system research for many years) were it not for the finding of errors of omission in the delayed alternation task. Also, monkeys with large orbitoventral resections take longer to habituate to novel stimuli (Butter, 1964), as do monkeys with total anterior frontal resections (Pribram, 1961a) and those

with amygdalectomy (Schwartzbaum & Pribram, 1960). These results and those from a long series of conditioning experiments led Mishkin to propose that anterior frontal resections produce perseveration of central sets of whatever origin. Subsequent experimental results (Butter, 1969) showed, however, that monkeys with orbital resections do not perseverate in place or object reversal tasks. Furthermore, the definition of central set, when it is extended to include a failure to habituate to novelty, tends to lose its meaning.

The enhanced distractibility and sensitivity to pro- and retroactive interference, which accounts for the failure to habituate (see Malmo, 1942; Pribram, 1961b) may well be dependent on the organization of drive states, provided we understand by this that such states are composed of endocrine and other neurochemical systems (Estes, 1959). The limbic forebrain has been found to be a selective host to a variety of neuroendocrine and neurochemical secretions which can form the basis of a neural representation of the internal state of the organism by way of which neural control over peripheral endocrine and exocrine secretions is exerted (McGaugh et al., 1979; Martinez, 1983; Pribram, 1969b).

The import of this research for this review is that such neuroendocrine and neurochemical factors influence the organization of attention and intention. Habituation to novelty (registration and consolidation in the face of distraction) and therefore the organization of what is responded to as familiar is disturbed by the lesions. Experimental psychologists test for familiarity with "recognition" tasks and recently Mishkin (1982) has used the delayed nonmatching from sample as an instance of such a recognition procedure. Not surprisingly, he has found deficits with limbic (amygdala and hippocampus) resections and drawn the conclusion that these structures are involved with recognition memory. For those working in the neurological tradition where agnosias, since the time of Freud and Henry Head, have been related to lesions of the parietal convexity, this conclusion is confusing. The confusion is resolved when it is realized that the delay tasks, as do the "recognition" tasks used by experimental psychologists to test humans, test for the dimension "familiarity," not the identification of objects which is the neurologist's definition of recognition. In short, the orbital contribution based on processing both interoceptive and exteroceptive inputs to psychological processing is to provide a critical facility the evaluation of propriety, to the feeling of familiarity.

The Lateral Frontal Cortex: Praxis and Priority

The results of attempts to subdivide the lateral frontal cortex have been reviewed recently in great detail (Pribram, 1986). As in the case of the orbitofrontal cortex reviewed above, much of the evidence appeared initially to be in conflict. To avoid undue repitition this detail is omitted from the current essay.

When the nuances of test procedures and lesion sites were carefully, analyzed the following conclusions emerged. (insert see pg (4–18)

The major part of the lateral frontal cortex centering on its ventral lip, influences all types of alternation performance and can be further subdivided according to modality by tests involving variants of alternation (e.g., object alternation, discrimination reversal). Using these variants, dorsal periarcuate auditory, anterior periarcuate visual, and posterior periarcuate kinesthetic subdivisions have been identified. The deficits produced by lesions in these subdivisions is sensitive to the *sensory load* imposed as a requirement for performing adequately. This suggests that some sort of sensory servocontrol feedback mechanism is involved. Connections between lunate (area 8) and arcuate (area 8) are well known (see e.g., Bonin & Baily 19XX). Goldman-Rakic (1979; Goldman-Rakic & Schwartz, 1982) has elegantly worked out the connections between frontal and parietal cortex and these with the corpus striatum, connections which can serve such a sensory servosystem. The ventrolateral subsystem is thus ideally situated to fine tune praxis especially where current action depends on the sensory consequences of prior actions (as in the variants of the alternation procedures).

Finally, there is a dorsolateral focus centering on the sulcus principalis which influences performance on both the spatial delayed response and the spatial delayed alternation task but *not* on the go/no-go or object versions of alternation. This suggests that a spatial factor important to task performance has been interfered with by the lesion of this cortex. However, the presumed kinesthetic basis for this spatial deficit proved not to be related to the spatial aspects of these and other tasks but rather to the temporal aspects (Pribram 1986). This left the spatial deficit unexplained.

Still, an explanation *can* be provided when connections between the cortex surrounding the sulcus principalis and the hippocampus (Nauta, 1964) are considered. It is this dorsolateral part of the anterior frontal cortex which has resisted fractionation with respect to sensory mode but which is especially sensitive to the "spatial" aspects of the delay task. This is exactly the situation with regard to hippocampal function. In fact the deficits produced by resections of the primate hippocampus and those produced by resections of the primate hippocampus and those produced by resections of the cortex surrounding the sulcus principalis mimic (with the critical exception that spatial delayed response remains intact after hippocampectomy) each other to such an extent that it is hard to distinguish between them.

I have extensively reviewed (Pribram, 1986) the evidence for considering the difficulty with "spatial" problems as due to an increase in sensitivity to distraction under certain specifiable conditions. Briefly, the essential evidence is that when such interference is minimized, as when the delay interval is darkened, monkeys with frontal resections can perform the delay task (Anderson, Hunt, Vander Stoep, & Pribram, 1976; Malmo 1942). Further, spatial cues have been

found to be more distracting than visual and auditory cues for normal monkeys and especially so for monkeys with resections of the anterior frontal and to a somewhat lesser extent (thus the sparing of delayed response?) hippocampal cortices (Douglas & Pribram, 1969; Grueninger & Pribram, 1969). Whatever the interpretation of the "spatial" deficit the data are consonant with the conclusion that the cortex surrounding the sulcus principalis is derived from an archicerebral primordium.

The key to understanding the contribution of the lateral frontal cortex to processing is provided by the proposals made by Goldberg (1985, 1987) regarding the functions of the premotor systems which, in turn, are based on the concepts of Sanides (1966; which are also reviewed and extended by Pandya & Barnes, 1987). These proposals divide the premotor cortex into a medial, supplementary premotor region and a lateral, periarcuate premotor region. The medial region is, on the basis of evidence from comparative anatomical studies, shown to be derived from archicortical origins, the lateral region, from paleocortical primordia. The two regions are suggested to function differently: The medial is concerned in developing models which program behavior in feedforward fashion; by contrast, the lateral region programs behavior via a variety of sensory feedback mechanisms.

This analysis can be readily extended to the remainder of the motor cortex: The evidence regarding the difference in orientation of the projection fan of thalamocortical connections, presented in the initial part of this review, indicates that the primary somatosensorimotor cortex also derives from the medial surface of the hemisphere, perhaps from the cortex of the cingulate gyrus. Accordingly, it would seem that the supplementary motor cortex participates in the sketching the outlines of the model while the precentral cortex implements its finer aspects. Such a scheme is supported by the fact that the supplementary motor cortex receives an input from the basal ganglia (known to determine postural and sensory sets) while the precentral motor cortex, in its involvement with the cerebellum, provides the details necessary to carry out a feedforward regulated action. I have elsewhere (Pribram, Sherafat, & Beekman 1984) provided a review of the evidence and a mathematically precise model based on one developed by Houk & Rymer, (1981) by which such a feed-forward process operates.

The lateral premotor region is the one so intimately interconnected with the inferior-posterior parietal cortex as indicated by Schwartz and Goldman-Rakic (1984), Goldberg (1985), and the thalamocortical and comparative anatomical data reviewed in the initial parts of this chapter. As indicated, it is damage to this system that produces apraxias, which according to Goldberg's thesis should devolve on faulty feedback processing. It is not too farfetched to wonder whether the repetitions which the lesioned monkeys made in the task reported in the first section of this review might not have been due to the necessity for gaining additional sensory feedback before proceeding.

There is one further speculation regarding apraxia that is worth considering. Elsewhere (Pribram & Carlton, 1987) I have described the neural mechanism that is involved in the construction of objects from images. Essentially this mechanism operates to extract invariances, constancies, from sets of images by a process of convolution and correlation. An object is experienced when the resultant of the correlation remains constant across further transformation of the set of images.

When objects are constructed in the somatic sensorimotor domain they are of two kinds. One sort of object is the familiar external "objective" object. Damage to the peri-Rolandic cortex (including the superior parietal gyrus) results in object agnosia. When, however, the lateral premotor and inferior parietal cortex is damaged, apraxias and neglect syndromes develop. Could the apraxias be thought of as a mild form of neglect in the sense that the "object" which is constructed by this premotor-parietal system is the "self"? If this hypothesis is correct, apraxias result from a failure in the appreciation (based on feedback?) of self: an awkwardness more pervasive than the impairment of skills. Thus one can envisage a gradually increased impairment ranging from apraxia through Parkinsonian tremors at rest, and so on, to neglect. This syndrome can be clearly distinguished from the one produced by cerebellar-Rolandic damage which is characterized by loss of skill, intention tremor, and paresis.

A word of caution. The statements made above could be interpreted as a denial of distinctions between such syndromes as Parkinson's, neglect, and apraxia. This is definitely *not* what is meant. Even apraxias of frontal origin can be expected to differ subtly from those of parietal origin, and it may well be as Jason Brown (1985) suggests that the lesions which produces apraxia must invade the limbic forebrain as shown by the work of Terrence W. Deacon (personal communication). Parietal and frontal cortex, though reciprocally connected, show an upstream–downstream relationship to one another. According to Deacon, a downstream corticocortical connection terminates most heavily in layers iiic–iv; an upstream connection terminates in layer i and sometimes in bands in vb. Thus there is a clear hierarchical connectivity from anterior cingulate to anterior frontal to periarcuate to premotor and motor cortices. At the same time parietal cortex is upstream from posterior cingulate, as well as from all of frontal cortex.

What I *am* trying to convey is that a *class* of disorders due to damage of systems of paleocerebral origin can be discerned. Within that class a variety of syndromes traceable to differences in neuroanatomical and neurochemical substrates can be made out.

How does this approach to the problem help connect the functions of the anterior frontal cortex to those of the somatosensorimotor regions? As noted in this review, there seems to be a gradient of relationships of delay problem performance to sensory mode reaching from a periarcuate auditory and visual to a more anterior kinesthetic location. These relationships fit with the general

hypothesis that the function of the anterior frontal cortex is to relate the processes served by the limbic forebrain to those of the somatosensorimotor systems, broadly as defined. Furthermore the results also support the suggestion that these relationships are of a feedback nature, viz Stamm's experiments in which kinesthetic feedback was manipulated (1987).

Furthermore there are the strong connections through the uncinate fasciculus with the structures of the temporal lobe which are derived from paleocerebral systems (amygdala, pyriform cortex, and adjacent temporal polar juxtallocortex) which indicate that these parts of the anterior frontal cortex are to be considered as relatives of the lateral premotor rather than as relatives of the precentral motor systems.

CONCLUSION

One final word. Jason Brown (1987) has suggested that the mechanism for feedback and feedforward depends on the operation of sets of tuned relaxation oscillators that constitute the brainstem and spinal cord systems which are influenced by the various frontal lobe processes under consideration. The evidence for the existence of such tuned oscillators has been repeatedly presented from the time of Graham-Brown (1914) through von Holst (1937, 1948) and Bernstein (1967) and his group (Gelfand, Gurfinkel, Tsetlin, & Shik, 1971). This evidence has been thoroughly reviewed by Gallistel (1980). The mechanism whereby a cortical influence can be imposed on such systems of oscillators has also been worked out within the concept of an "image of achievement". Such "images" must operate within the spectral frequency domain. Pribram (1987) and Pribram et. al. (1984) have presented evidence that neurons in the motor cortex are tuned to different frequencies of movement (independent of velocity and acceleration). These authors also detail the mechanism whereby such tuned cortical cells can program the subcortical motor systems.

The profusion of data collected by hard labor over the past half century can thus be fitted into a tentative scheme. No longer are we stuck with vague concepts of frontal lobe function. The role of the anterior frontal cortex in emotion and motivation is seen as relating protocritic (interoceptive plus pain and temperature) to epicritic processes in the feedback mode. Evaluation (what Arnold, 1970 calls appraisal) of proprieties is the function of the periarcuate and ventrolateral portions of this cortex (Konow & Pribram, 1970). Evaluation is a sort of internal rehearsal, a feedback by way of which proprieties become refined, that is, more in keeping with current sensory input and with the consequences of actions.

The role of the anterior frontal cortex in processing priorities (planning) relates protocritic to epicritic processing in the feed-forward mode. This is the function of the dorsolateral frontal cortex. In the feed-forward mode current and

consequent input form the context within which "models" are constructed in "fast time," models which in turn are used to modify subsequent behavior. One definition of praxis given by the Century Dictionary (1914) is "an example or collection of examples for practice; a model." Thus the role of the frontal cortex in one form of "short-term memory" is clarified: the close connection between the dorsolateral frontal cortex and the hippocampus; the similarity of the cytoarchitecture of the hippocampus and that of the cerebellum; the close connection of the peri-Rolandic cortex (which is most likely derived, as noted, from the archicerebrum as is the hippocampus) and the cerebellum; and the known function of the cerebellum as a feed-forward mechanism (see, e.g., Ruch, 1951; Pribram, 1971, 1981) all attest to the likelihood that the dorsolateral frontal cortex is indeed involved in such "projective" processes.

It is of course, these "models" obtained through praxis that allow the processing of serial position in a remembered sequence—and the extrapolation of serial position into the future. It is this aspect of planning which is impaired by anterior frontal damage. When combined with defective evaluation and appraisal of proprieties regarding projected action, the full-blown anterior frontal deficit becomes manifest.

A prodigious amount of research has been accomplished since the initial findings obtained with experiments on nonhuman primates in the Yale laboratories headed by John Fulton and Robert Yerkes led to the, to my mind unjustified, practice of leukotomy performed on thousands of human subjects (see Valenstein, 1986). This procedure and continued observations of patients such as those made by Luria has fired the curiosity of a dedicated group of neuropsychologists who continued the research begun in the Yale Laboratories until the present. Only now, with continued input from the clinic and the laboratory are we beginning to understand the effects of damage to the primate frontal lobe.

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