

PRIBRAM, K.H. (1997) The Work in Working Memory: Implications for Development. In N.A. Krasnegor, G.R. Lyon, & P.S. Goldman-Rakic (Eds.) *Development of the Prefrontal Cortex: Evolution, Neurobiology, and Behavior*. Baltimore: Paul H. Brookes Publishing Company, pp. 359-378.

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The Work in Working Memory Implications for Development

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The frontal "association areas," sometimes referred to as "the organ of civilization," are intimately connected with the limbic systems to form the internal core of the forebrain. This most forward portion of the primate frontal lobe appears to us to serve as a "working memory" where Plans can be retained temporarily when they are being formed, or transformed, or executed.

Miller, Galanter, and Pribram (1960, p. 207)

Much evidence has accrued since 1960 to bear out this proposal regarding frontal lobe function encapsulated in the term *working memory*. The paragraph from which the quotation is taken goes on to state that "this speculation appears to be consistent with the fact that animals with lesions in the frontal lobes have difficulty with the delayed reaction and the delayed alternation tests." It is also consonant with the warning issued by Jacobsen (1928, 1931, 1935, 1936) when he first demonstrated the relation between the performance of these tasks and the integrity of the far frontal cortex: The notion of an immediate or short-term memory interpretation is too simple, and some more sophisticated conception is needed. Nissen (1951) pointed out that these tasks form a category that he called *one trial learning tasks*, and Mishkin (1966) has called them *trial unique*. Further work by Jacobsen and his colleagues Wolfe (Jacobsen, Wolfe, & Jackson, 1935); Finan (1939); Nissen (Jacobsen & Nissen, 1937); and Malmo (1942) demonstrated the importance of attention to the performance of these tasks both during the predelay period and in sustaining performance in the face of distraction during the delay itself.

In this chapter, I recount the path of frontal lobe research that has been taken from the early demonstrations and recent confirmations of the importance of attention to the concept of work—that is, allocation of resources—in a working memory. Even the concept *attention* has proved to be insufficiently precise. Frontal lobe lesions lead to a susceptibility to be distracted, an appetite for novelty—in short, the

failure of the ability to disattend distraction. A similar deficit can be shown to impair the carrying out of a behavior sequence. It is as if the frontally lesioned primate becomes bored and thus distractible in tasks that control subjects pursue. Such lack of persistence can be due to a lack of motivation or to an inability to maintain concentration, disparate descriptions that may apply to the same basic phenomenon. Alternatively, the disability may be due to a deficiency in a process that flexibly organizes and reorganizes our attention (control of sensory input), intention (control of behavioral output), and even thought (memory processing). The experiments reviewed here indicate that it is this organizing function that is disturbed by frontal lesions. A computational model is presented that shows how such an organizing process might operate. Finally, data are presented that relate developmental stages in brain electrical activity to the maturation of frontal lobe function—maturation that remains incomplete as late as the ages of 17–21 years.

PARCELLATION

What, then, is working memory? How does it become implemented? A short answer given by Deeke, Kornhuber, Long, and Schreiber (1985) was that human subjects with frontal cortex damage were deficient in their ability to know what to do, when to do, and how to do. These three factors composing working memory are linked to separate subsystems of the far frontal lobe.

As was Caesar's Gaul, the far frontal cortex can be divided anatomically into three parts, and each part has been shown to have somewhat different relations to behavior consonant with the connectivity of the parts. An orbitofrontal sector can be identified with heavy connections to the amygdala, anterior insula, and temporal pole through the uncinate fasciculus. This sector has been shown to be especially involved in processing novelty and in establishing a familiar context within which subsequent processing occurs. It is this sector that is related to the functions of the visceromotor system through connections with the amygdala and hypothalamus. Visceromotor responses to novel cues (as part of the orienting reaction) were shown to be necessary to the development of familiarity. On the basis of clinical data (Konow & Pribram, 1970; Luria, Pribram, & Homskaya, 1964; Poppen, Pribram, & Robinson, 1965), the orbitofrontal sector has been shown to utilize familiarity in the service of propriety—that is, to determine what is and what is not appropriate behavior in any particular situation.

A second sector encompassing the dorsal part of the far frontal cortex is related to the hippocampal system through connections with the cingulate cortex. The hippocampal system was shown to be involved in the processing of spatial and temporal cues into a context that organizes maximally efficient action (see reviews by Pribram, 1986, 1991). It is this sector, therefore, that deals with assessing priorities. The dorsal frontal cortex modifies this organization when the situation demands flexibility to act effectively.

The third sector takes up the middle of the far frontal cortex. This sector connects to the remainder of the cortex and can be further subdivided according to the locus of connections to the various sensory modalities (Pribram, 1987). It is this middle sector of the far frontal cortex that integrates the functions of the other two sectors with those of the rest of the brain, thus ensuring practicality in the execution of actions.

The processing of propriety, priority, and practicality entails the processing of "what, when, and how" when these are not completely specified by the situation in which an action is to be undertaken (Deeke et al., 1985). The "what" must primarily be based on familiarity, a particular kind of memory. The "when" is primarily based on sustaining attention and noticing when efficient, automatic processing becomes ineffective. The "how" is primarily based on assessing what works (what is appropriate) and when it is working and when it is not. Therefore, when we state that lesions of the far frontal cortex result in defects in *working* memory, we mean that under certain conditions attentional and intentional processes necessary to the processing of "one trial learning" tasks are disrupted.

What makes a task "trial unique," and what are the conditions that must be present to make one-trial learning necessary? The short answer to these questions is flexibility in the face of spatial or temporal ambiguity, or both.

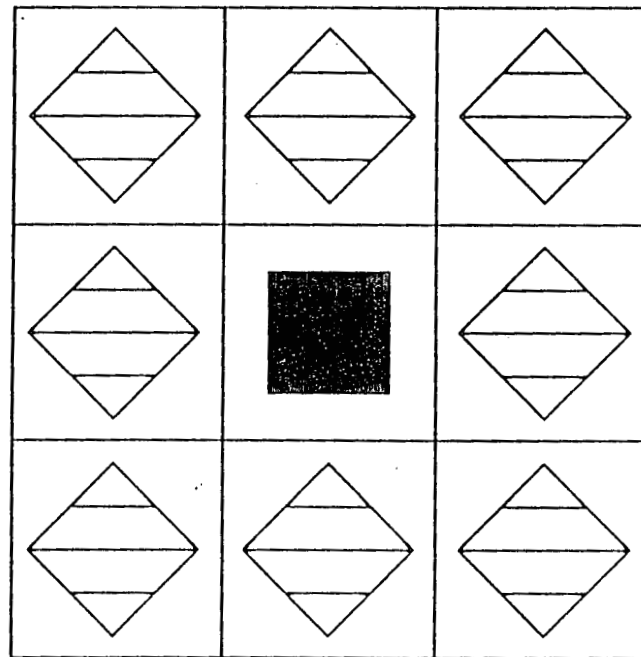
Why are spatial and temporal ambiguity so critical to bringing out the frontal lobe deficit? When I have an intention, I certainly know how to go about implementing it—if I make a mistake, I rectify my behavior; if all goes well, I proceed. Thus, it is clear that I can evaluate mistakes and successes. When we examine patients with frontal lobe pathology, they are found to be deficient in carrying out their intentions; therefore, we infer that they have difficulty in evaluating their errors and successes (Luria et al., 1964). However, when examining such patients, I noted that they were cursing whenever they made a mistake—it was obvious that they recognized the incorrect outcome of their behavior. Nonetheless, their next attempt did not profit from that recognition. I therefore concluded that such patients could not *utilize* their errors (Konow & Pribram, 1970).

In economics, a utility function is composed of the desirability of a transaction and the momentary estimation of the probability that the transaction can be executed. Could this formulation be effectively applied to all intentional behavior? If so, the experiment showing that far frontal resections disrupt the probability distribution of responses in a fixed internal experiment (see Figure 16.5 on page 368) can be taken as an indication that it is the execution of the probability distribution of a behavior, not its desirability, that suffers in the frontal lesion patient.

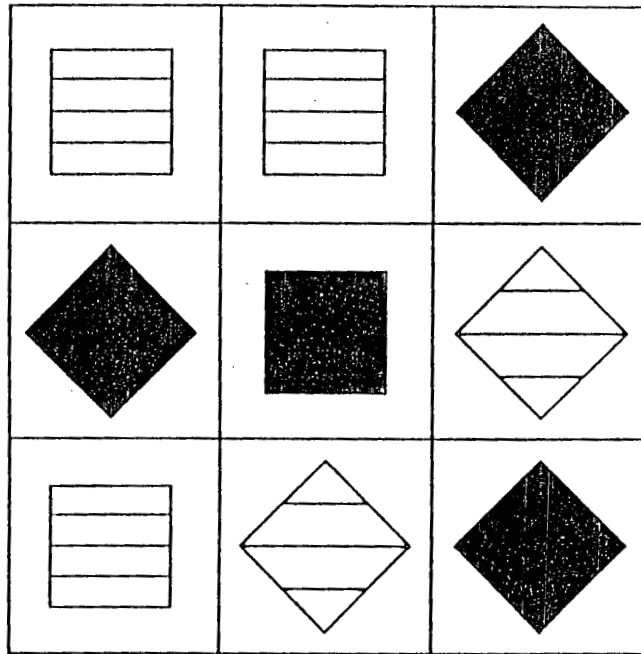
This interpretation is congruent with Milner's (1974) finding of intralist order disturbances in recall. It is serial position, the ability to monitor probability distributions, that becomes muddled; patients fail in their ability to temporally tag events. It is therefore the ability to monitor serially, whether in relation to attention or to intended behavior, that constitutes the work in working memory. The following experiments made with monkeys support and extend this conclusion.

ATTENTION

With regard to attention, Bolster and Pribram (1993), in a series of experiments, showed that recordings of brain electrical activity could be used to differentiate the brain systems involved in automatic, para-attentional parallel processing of visual stimuli from those involved in controlled, consciously attended procedures demanding an effective sampling of the feature array. A modification of Treisman's (1969) tasks was used: a distinct-feature array tested for automatic processing and a shared-feature array tested for controlled scan (Figure 16.1). Figure 16.2 shows the effect the number of shared features has on the response latency (reaction time) of



Distinct-feature array



Shared-feature array

Figure 16.1. Examples of distinct-feature and shared-feature arrays with the target (solid square) shown in the central position. (From Bolster, B., & Pribram, K.H. [1993]. Cortical involvement in visual scan in the monkey. *Perception and Psychophysics*, 53, 507; reprinted by permission.)

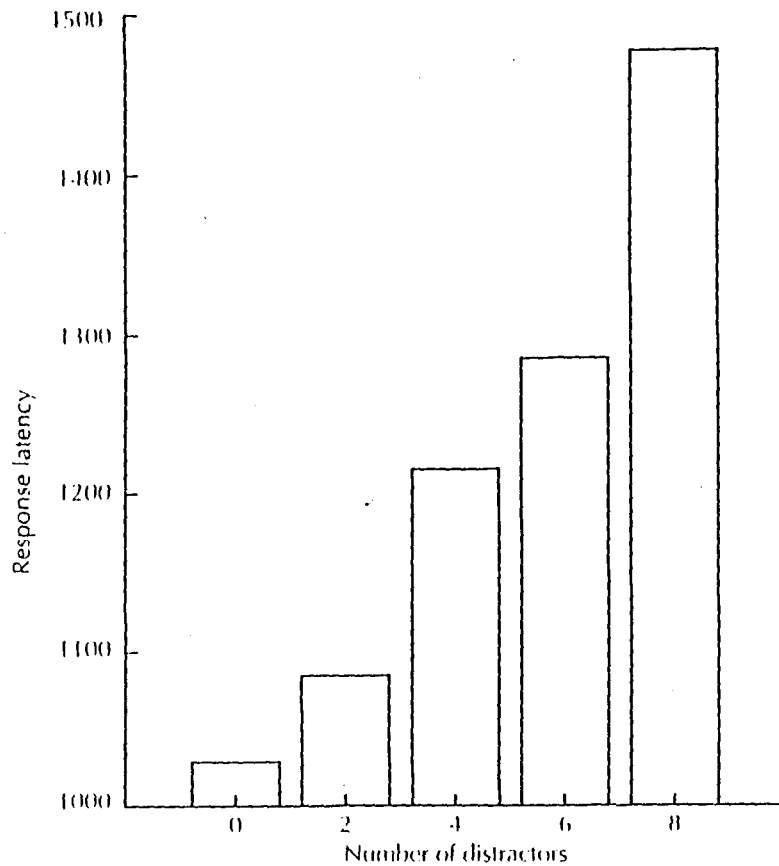


Figure 16.2. Response latency as a function of the number of shared-feature distractors present in the stimulus array. (From Bolster, B., & Pribram, K.H. (1993). Cortical involvement in visual scan in the monkey. *Perception and Psychophysics*, 53, 507; reprinted by permission.)

the monkeys tested; confirming the assumption that shared features increase search of the array.

Recordings were made of event-related local field potentials placed over the primary visual projection cortex (V1) of monkeys and over parietal, frontal, and inferior temporal "association" areas. Changes in field potentials recorded from the primary visual projection cortex changed as a function of the total number of features, never as a function of shared features; by contrast, changes in the number of shared features produced changes recorded from all three "association" areas. With regard to the changes in local field potentials recorded from the frontal cortex, we concluded that the difficulty in search over the cues with the shared features was a function of the fact that these shared features composed a *distractor* set. In earlier experiments, we had found that performance of monkeys with far frontal cortex resections suffers when the location of distractors is randomized over nine positions, as in the Discrimination Apparatus for Discrete Trial Analysis (Drake & Pribram, 1976; Pribram, 1969; Pribram, Gardner, Pressman, & Bagshaw, 1962) used in those and the current experiments. The deficiency becomes especially apparent when

compared with performance on the Wisconsin General Test Apparatus, where randomization is limited to two locations (Brody & Pribram, 1978; Brody, Ungerleider, & Pribram, 1977; Pribram, Konrad, & Gainsburg, 1966). The nine-location randomization was instituted to deter monkeys (especially those with far frontal cortex resections) from falling into position habits. In this the technique was successful, but the changes in location of a cue pose an especially potent distractor for monkeys (Douglas & Pribram, 1969), especially for those with far frontal cortex damage (Grueninger & Pribram, 1969). Therefore, in the current experiments, one source of difficulty is the fact that manipulations were made of the number of shared features that constituted a *distractor set*.

A distractor set provides the context, the contingencies, within which the rewarded target must be chosen. Fuster (1988) conceptualized this context-reward relationship in terms of cross-temporal contingencies. However, experiments in our laboratory in which spatial context is manipulated, as in variants of delayed response tasks that related them to Piaget's findings on object constancy (Anderson, Hunt, Vander Stoep, & Pribram, 1976), showed that the relationship can be spatiotemporal as well as temporotemporal. In these tasks, the monkeys had to remember *where* an object had been hidden on a previous occasion. In fact, in other experiments (Brody & Pribram, 1978; Pribram, Plotkin, Anderson, & Leong, 1977), we presented data that showed far frontal cortex involvement whenever behavior is influenced by two or more distinct sets of covarying contingencies, even when both are spatial. In these experiments, the monkeys had to remember in which location they had received a reward and to avoid that location on the subsequent trial(s).

More generally, therefore, the far frontal cortex becomes implicated whenever perception entails relating current contingencies to a context computed from prior relevant contingencies. The computation of this covariation demands that cross-temporal, spatiotemporal, and cross-spatial contingencies be perceived. In classic and operant conditioning, the consequences of behavior are contiguous in time and place with the stimulus conditions that initiate the behavior. When contiguity is loosened, stimulation that intervenes between initiation and consequence has the potential to distract and thus to prevent the processing of covariation. Perception is perturbed and processing is destabilized. Perturbation is controlled only if a stable state, an established set of contingencies—that is, a stable context—instructs and directs the process (Pribram, 1987).

It is from the effects of interference on the establishment of such a stable state that one is able to discern the powerful role of context in controlling trial-unique processing. When the interfering effect of distractors is removed (e.g., by darkening the testing chamber) during trial-unique tasks such as delayed response, monkeys with far frontal cortex resections perform the task as well as their controls (Malmo, 1942; Pribram, 1961). The effects of interference occur primarily during stimulus presentation or shortly thereafter, not during the delay period (Pribram, 1961; Stamm, 1969). Interference therefore is with the organization of a perceptual context within which subsequent performance occurs.

The impairment is also shown by patients with damage to the frontal cortex. These patients fail to remember the place in a sequence in which an item occurs. They lose the ability to "temporally tag" events, that is, to *monitor* and place them within the episode. With such patients, Milner (1974; see also Petrides & Milner, 1982) performed a series of experiments demonstrating how the processing impairment affects the middle portions of an episode. In her studies, it is *relative recency*,

the *serial position* of the sequence, that becomes muddled. Other patients with frontolimbic damage, described by Kinsbourne and Wood (1975), also show that the impairment in processing serial position is due to a derangement in monitoring and therefore in organizing contextual structure of an episode.

To summarize, the involvement of the far frontal cortex in visual scans of shared feature arrays entails a stable state within which search for the rewarded target can be performed. This state is characterized as establishing and mapping (Schneider & Shiffrin, 1977), a serial search within a context of contingencies that show covariation over successive trials. In Efron's (1989) terms, this context forms a flexible yet stable "scanplan" within which shared features can be searched. Efron showed that such a scanplan does not depend on actual receptor scanning; rather, the scan is an internal process attributable to the mind's eye or ear.

INTENTION

The results of these experiments suggest that the relationship of the far frontal cortex to attention involves some deeper function. This function, a scan *plan* in the previously noted experimental results, is the intentional aspect of attention.

In an earlier series of experiments, Pribram (1960, 1961), having confirmed the earlier conclusion regarding the importance of attention, added as a result of his experiments that "frontal lesions apparently interfere with the organizational process that must take place in normal subjects when events that serve as guides to subsequent actions occur in relatively unreliable situations" (Pribram, 1961, p. 462). Some of the critical experiments that show that the far frontal cortex is involved in the organization of intention (i.e., "guides to subsequent actions") are described here.

Performance on Nonspatial Object Alternation Tasks

Twelve animals were given 50 trials a day for a total of 1,200 trials on a nonspatial object alternation. For the first 500 trials, two objects, a tobacco tin and an ashtray, were presented on a board that contained two holes 1.5 inches in diameter and 3 feet apart. For the remaining 700 trials, these objects were presented on a board that contained six holes, each with a diameter of 1.5 inches, arranged in a circle with a diameter of 2 feet. Each object could cover one hole completely, and a peanut could therefore be concealed by the object. The holes were given numbers, and on each trial the objects were placed over the holes according to a random number table. On successive trials, a peanut was placed alternately under one and then the other object irrespective of the placement of the object on the board. Trials were separated by the interposition of an opaque screen between the monkey and the test object. The animals were not allowed to correct if they made an error; that is, on any one trial, a monkey was allowed to manipulate only one object and to uncover one hole to see if a peanut was there. On the next trial, the alternative object was baited and so on throughout the 50 alternations. Trials were spaced approximately 5 seconds apart. As can be seen from Figure 16.3, monkeys with resections of the frontal cortex are impaired to a considerable extent (although not completely) in their ability to maintain their "set" to respond on each trial, a deficit that can be interpreted to be due to a change in motivation or in memory.

Performance on a Multiple-Choice Task

To further explore this relationship between memory and motivation, a multiple-choice task reward reversal was devised. Reversal was instituted after five trials as

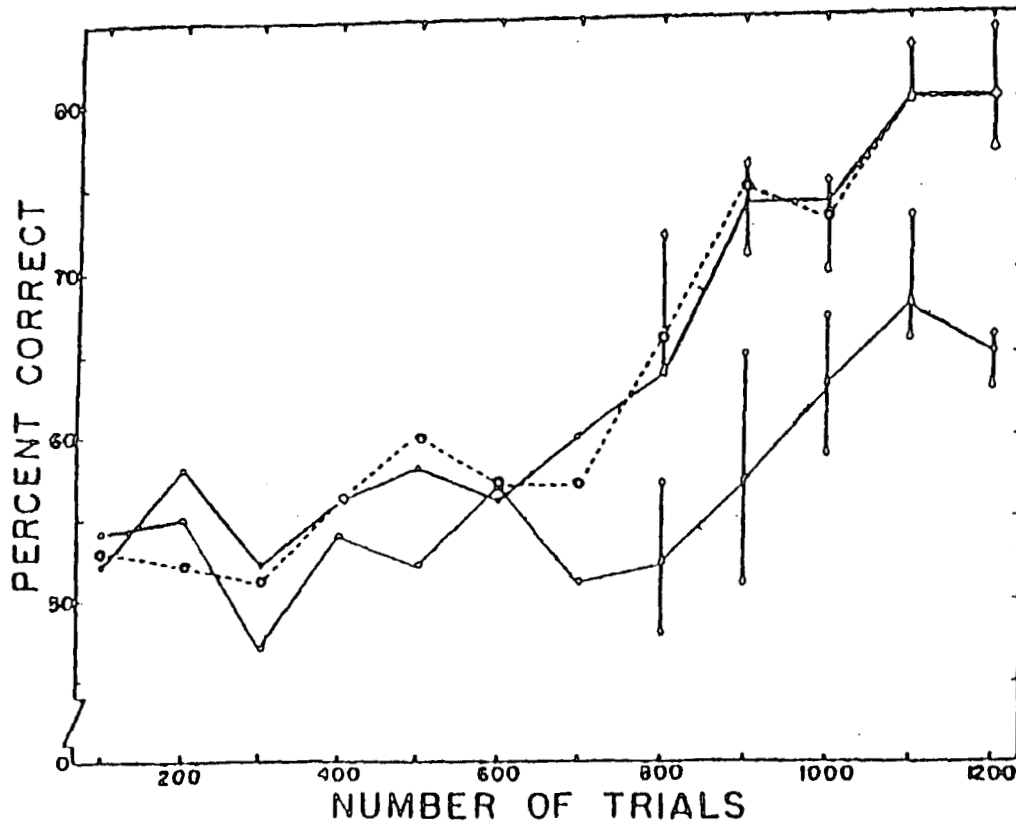


Figure 16.3. Results of comparing frontally lesioned monkeys on a nonspatial object alternation task with unoperated and temporal cortex resected controls. Monkeys with frontal resections reach only a 65%–70% performance level, indicating that the spatial parameter is not the only one responsible for the frontal lobe deficit in alternation performance. (□—□, normals; ○—○, temporals; ○—○, frontals; [], range.)

in the previous experiment, but now a sequence of 12! (twelve factorial) tasks was given in which, after each set of reversals among a given number of cues was completed, a novel cue was added until a total of 12 cues were presented to the monkey on each trial. The locations of the cues were randomized from trial to trial among 12 possible positions. The results showed that the monkeys with far frontal cortex resections responded immediately to the novel cue when it was introduced, whereas the control subjects tended to respond more to the previously rewarded (familiar) cues (see Figure 16.4). Furthermore, the monkeys with frontal lesions failed to sustain their intention to respond to the rewarded cue for the five consecutive trials necessary to reach criterion before reward reversal was instituted (see Figure 16.5), despite the fact that they have shown (statistically) that they "know" which one shelters the reward. These results show that the reinforcing consequences of the monkeys' behavior had less impact on their future behavior than these consequences had on that of the control subjects. Alteration in intention (organizing behavior on the basis of consequences, i.e., reinforcement) was thus shown to affect "memory."

The results of these experiments also tell once more the twice-told tale. After the completion of search [see Figure 16.7 on page 370], frontal lesions produced perseveration of the set of responses that had proved useful to the subject in the imme-

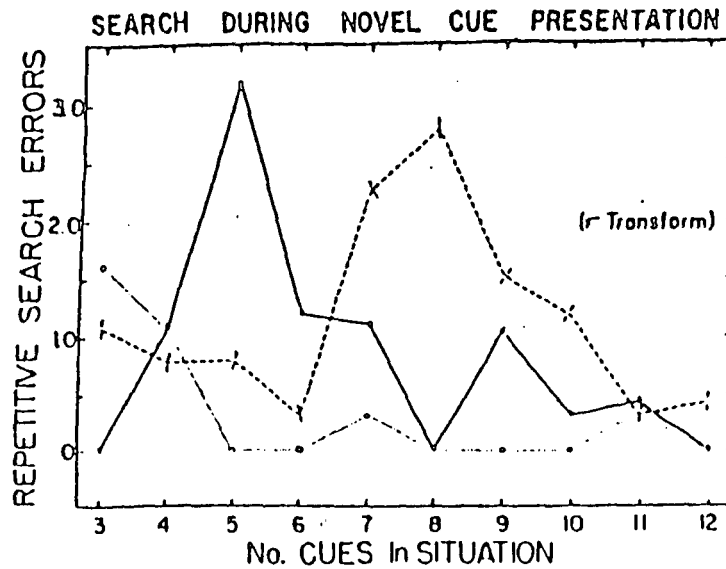


Figure 16.4. Graph of the average of the number of repetitive errors made in the multiple-choice experiment during the search trials when the novel cue is presented. (— = normals, - - - = temporals, = frontals.) Note that, although records of the control groups show peaks that indicate confusion between novel and familiar cues, the monkeys with frontal lesions are not confused.

diately preceding circumstance. During search, in contrast, the frontally lesioned monkeys tended to shift their responses.

What features distinguish search and postsearch situations? After search, the reward contingencies are held constant for the duration of a problem, then changed. During search, the reward situation varies. Specifically, the cue-reinforcement contingencies had remained consistent during a period sufficient for the subject to develop an identifiable (adaptive) response pattern; perseveration (response to the novel cue) occurs in frontally lesioned primates when the cue-reinforcement contingencies are then changed to another but equally consistent cue-reinforcement configuration. During the postsearch period, characterized by varying cue-reinforcement contingencies trial by trial, frontally lesioned monkeys react with an increased (compared with controls) variability in response pattern. In general, therefore, these results can be summarized by stating that perseveration occurred with *interproblem* change and an increased tendency to shift occurred with *intraproblem* change of the cue-reinforcement configuration.

In this experiment, paradoxically, perseveration consisted of responding to a novel cue. This suggests that frontally lesioned primates are especially susceptible to distraction (see also results obtained by Grueninger & Grueninger, 1973; Grueninger & Piibram, 1969), which accounts for both the increased variability and the perseveration obtained in these and other experiments. Distractibility interferes with working memory—but the question remains as to whether this is due to lowered motivation or to a more rapid decay in a memory trace. Or both? Or neither?

Performance on a Fixed Interval Task

The results of these experiments were inconclusive regarding the relationship of the anterior frontal cortex to motivation and of motivation to memory. To resolve

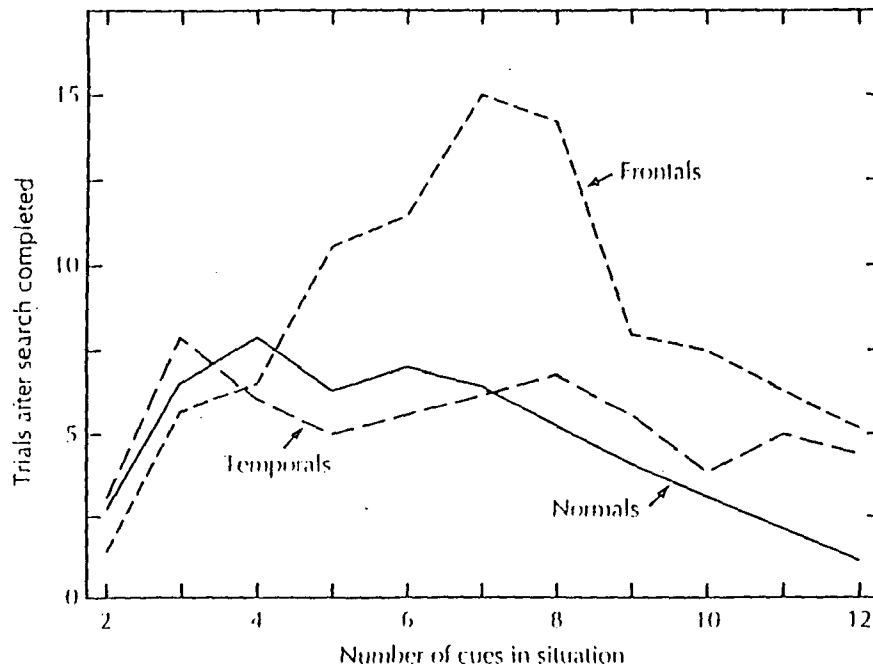


Figure 16.5. Graph of the average of the number of trials to criterion taken in the multiple-object experiment by each of the groups in each of the situations after search was completed (i.e., after the first correct response). The difference between the curves for the controls and for the frontally operated group is significant at the .05 level by an analysis of variance ($F_{2,6} = 8.19$) according to McNemar's procedure performed on normalized (by square-root transformation) raw scores.

these issues, a set of experiments was undertaken in which the effects of starvation were compared with the effects of frontal cortex resection. Twelve rhesus monkeys were trained to press a lever in an experiment where a reward was delivered on a "fixed-interval" schedule. The monkeys were fed a sufficient amount of laboratory chow immediately after each training session to maintain them at approximately 80% of the weight they had attained after a 3-week period of *ad libitum* feeding.

In addition to the usual cumulative record obtained, counters were so arranged as to sum the number of responses an animal made during six equal periods into which the total 2-minute interval was divided. From the numbers recorded on the counters, performance graphs were constructed. These graphs show the distribution of responses across as many of the 2-minute intervals as desired. Therefore, the total performance of any monkey could be measured—an advantage not given by inspection of the ordinary representative cumulative curve. Also, in this way, averages of the responses of groups of animals could be taken and the variations between individual animals statistically analyzed.

The actual experiment consisted of the following procedure. Ten 2-hour sessions were given. Then each animal was subjected to a 72-hour fast and retested for one session, after which the usual feeding schedule was immediately resumed and testing continued as in the prefast period for 10 sessions. The entire procedure was repeated another time with the interposition of 118 hours of fasting before the critical test session.

The results are shown in Figure 16.6. As can be clearly seen, the effect of food deprivation (i.e., of starvation) is upon the rate and not upon the distribution of

monkeys' responses during an interval. The percentage of total responses made during any particular portion of the interval appears to remain remarkably constant despite marked changes in the total number of responses an animal makes. Also, there is remarkable consistency of results and little variation between animals. When monkeys are starved for 3-5 days, their total rate of response increases—but the way in which they distribute these responses during an interval does not change. (Similar changes are observed when monkeys are sated. Fixed-interval performance when the animals are kept in an *ad libitum* feeding situation shows a lower overall rate.)

The same group of animals were used to assay the effect of selective brain resections on performance in the fixed-interval operant task. Three of them were given ablations of the frontal eugranular isocortex, and three others were given control lesions that consisted of resection of the inferior portion of the temporal isocortex. Four of the remaining animals served as unoperated controls.

Figure 16.7 graphs the results obtained following these procedures. When rate of response of the operated and control groups is compared, no differences are apparent. However, for the frontally operated group, the *distribution of responses across the interval* is markedly different, whereas that of the control monkeys remains unchanged. This effect of the frontal lesion is in direct contrast to the effect of starvation. Here, instead of a deficit in monitoring, in constructing a scanplan that relates to searching the environment, the deficiency in planning entails instrumental behavior. Neither motivation per se nor the ability to remember per se is affected by the frontal resection. The frontally lesioned monkeys respond *precisely* to the timing of the reward. Therefore, neither timing nor general memory is affected [see also Stamm, 1963]. Rather, it is monitoring the distribution and therefore *the allocation of effort* that constitutes the work in working memory.

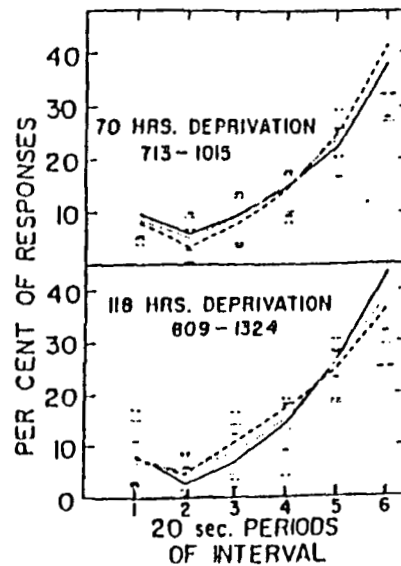


Figure 16.6. Graph showing the effect of food deprivation on monkeys' rates of lever-pressing response to food (a small pellet of laboratory chow), which became available every 2 minutes. (— = pre-hunger, = hunger, - - - = post-hunger.) The change in total rate is indicated by numbers under the deprivation label. The lack of change in the distribution responses is shown by the curves. Each curve represents the average of the responses of 10 monkeys; each point represents the average rate during a period of the interval over 10 hours of testing. Variance is indicated by the short horizontal bars.

COMPUTER SIMULATION

In order to determine how such a process might operate, I turned to computer simulations, which, much as *in vitro* experiments in biochemistry, can often help to clarify processes that are difficult to examine *in vivo*. The following is an excerpt from a paper presented during a conference on frontal lobe function in 1964:

Because simulation can be made precise with the use of computers, erroneous or vague models can be readily rejected. The experimentalist is therefore given a limited number of models, i.e., hypotheses about mechanism, that are found to fit the data. These he can then test against the real nervous system. By the use of this intervening step of model building, the neurological scientist can test notions about neural mechanism instead of notions directly derived from behavioral observation such as "perseveration of set," "tendency to shift," or even "immediate memory."

A model worth serious consideration derives from the work of Newell et al. (1958). These investigators have simulated the human cognitive, i.e., problem-solving, process by devising a hierarchically organized computer program composed of lists of items, each item capable of referring to another list. The structure of such programs can be variously represented as an English teacher's outline, a mathematician's branching set theoretical tree, or a systems engineer's flow diagram. Once such a computer program has been engaged it runs its problem-solving course relentlessly. Erroneous or nonsense solutions indicate errors in programs, errors that must be painstakingly sought out and corrected.

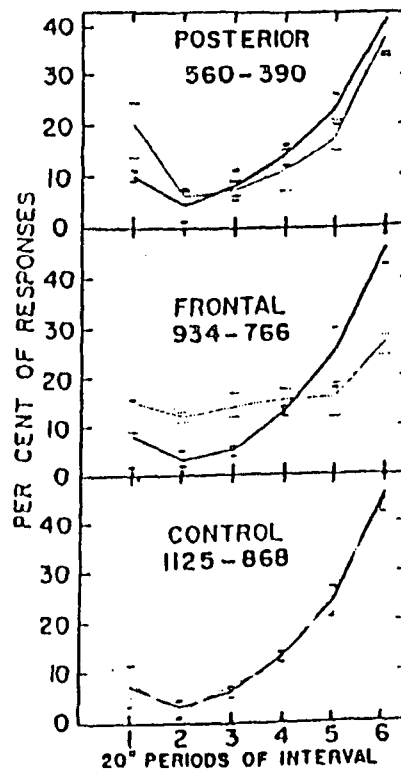


Figure 16.7. Graph showing the change in distribution on monkeys' response rates following frontal ablation (three monkeys). (---- = preoperation, = postoperation.) Note that the distribution of rate over the interval is not affected in the controls (four monkeys) and after inferotemporal (posterior) ablations (three monkeys). Also note that the total rate of response did not increase; rather, the rate was somewhat decreased in all groups, probably as a result of the *ad libitum* feeding period that all groups were given prior to operation—approximately 2 weeks before postoperative testing.

Instruction Programs

One of the most recent of these continually evolving problem-solving programs is EPAM II (Feigenbaum, 1959, 1961; Feigenbaum & Simon, 1961a, 1961b, 1961c; Newell, 1961). In this program, as in most others, a recurrent difficulty had to be met. Once the stored lists that compose a complex program reach a certain number, access to the list structure needs itself to be programmed to "get the show on the road," as it were. Three types of such instruction programs have to date been found useful.

The first type (type I) of instruction is contained in the problem itself; for instance, in its simplest form it will be an instruction that reads "find item X." This instruction both sets the problem and indicates that the computer's stored list structure is to be systematically searched until an item that matches X is found.

The second type (type II) of instruction program is closely related to the first, but is more complicated. This instruction reads that the first step in problem solving is to run the problem program through the computer's *permanently stored* list structure and to report the items on the problem list that match the items in the stored program. The residue, the items that fail to match, are also reported as such and stored in new locations in the permanently stored list structure.

The third, and for our purposes the most interesting, type of instruction program (type III) has an "iffy" nature. This type is a somewhat complex and hierarchically organized list structure independent of both the problem programs and the computer's stored list structure. The lists that comprise this program contain items such as "(1) take the problem program and search part A of the stored list structure for its match; (2) if no match is found, search part B; (3) and so on until a match is obtained." However, this routine is not fixed. Another set of items states: "Shuffle the order in which these items of instruction are to be tried in such a way that the instruction that has proved repeatedly successful is tried first, i.e., is placed first on the list." This is accomplished by temporarily storing the information about the outcome of prior searches (through A or B or . . .). This temporary storage must take place not in the computer's permanent memory where it would do little good, but in the instruction program itself. Needless to say, there is a limit to the complexity which such a flexible set of temporary instructions can attain if they are to remain an efficient tool for problem solving.

These temporary instruction programs are called *noticing orders*; those that shift the order of the items on their lists on the basis of the outcomes of searches through their memories are known as *flexible noticing orders*. Noticing orders and the current problem program are kept separate from the computer's main storage facility in a "working" or temporary memory that is at all times immediately accessible to the programmer and computer.

To pursue the analogy: the primate brain must solve the same tasks that the computer has been programmed to solve. Since the computer processes were composed in order to simulate "primate" problem-solving processes, the processes are likely to be similar if not yet identical. However, this does not mean that the brain mechanism need mirror the computer mechanism that is set up to accomplish a particular process.

Noticing Order in a Working Memory

Noticing order is a process used by EPAM II and other problem-solving programs based on list structures. If noticing order is a process used by the primate brain when the subject is solving problems, several statements can be made about noticing order and the performance of frontally lesioned monkeys.

First, on problems where noticing order is unimportant, or where it is determined by the situation, frontally lesioned monkeys have no difficulty. This is especially apparent when the situation is novel.

Second, on problems where noticing order is determined by running the problem through the subject's fixed store of representations of past experiences, the frontally lesioned monkeys also have no difficulty. Discrimination performances and discrimination learning have repeatedly been shown [to be] unaffected by frontal lesions. Matching from sample remains unimpaired. And, in the multiple-choice problem analysis, sampling and search, though different from controls because of irrelevant interproblem changes, are also essentially unimpaired.

When, however, problem solution demands a noticing order that is not contained in the problem itself nor in the permanently fixed store of representations of past experience of the subject, frontally lesioned primates have difficulty. Such problems have in common the factor of change, not in the stimuli per se, but in the way in which the already-experienced stimuli (e.g., cues and reinforcements) covary to form the context for the new problem. The organism must react to these changes much as does the computer program: it must reshuffle the order in which the stimuli are processed. When change is occasional, i.e., when the change occurs between problems, the frontal defect is minimal and shows up as perseveration of set since noticing order within each problem proceeds, once the frontally lesioned subject catches on that a change has taken place, according to the type I or type II process of noticing order. When, however, the change occurs within a problem; i.e., when the appropriate behavior sequence depends solely on the outcome of the immediately preceding application of the noticing order, the frontal defect shows up full-blown.

As a rule, the monkey returns to random behavior since his apparatus for shifting noticing order is broken down with the result that the various behaviors tried all result in the same number of reinforcements. But perseveration may also be shown, when frontally lesioned monkeys are tested in the delayed-response or delayed-alternation situation, they frequently—more frequently than their controls—develop a position habit, since this behavior mode obtains as many reinforcements as random behavior does. The results of the experiment show that frontally lesioned monkeys are no more prone to position habits than unoperated monkeys are. My view is that frontally lesioned monkeys, just as unoperated monkeys, take position habits whenever they need not or cannot cope with a task, i.e., whenever the number of reinforcements they gain remains constant irrespective of their responses. Since frontal lesions impair delayed response and alternation learning, the operated subjects tend to take position habits—but *no more so than their controls would if they could not cope with the problem*. Support for this view comes from the observation that inferotemporally lesioned monkeys, when they have difficulty with visual discrimination problems, also slip easily into position stereotypes. At present, however, there is as yet no quantitative comparison of the relative proneness to stereotypy by frontally and inferotemporally lesioned monkeys in an insoluble problem.

In a sense, this explanation of the frontal defect in terms of impairment of a flexible noticing order is in partial agreement with the explanation made by Brush et al. (1961). They hypothesize that regression to a more primitive innate performance set occurs whenever the frontally lesioned primate cannot change this innate response tendency through learning. When, however, a task has already been learned, *this performance is perseverated*. As already noted, we could say the same, even for our results with respect to tendency to shift, were we to interpret the data in the multiple choice experiments as perseveration of some initial "set to explore" or set to behave randomly, which is overcome by the controls as a result of reinforcing contingencies which do not affect the frontally lesioned group. As Wilson points out, however (1962), the notion of perseveration of set so conceived can be stretched over any data set since all that need be done is to specify after the fact which response tendencies are resistant to change. Does not the stretching go too far when it is made to cover random responses and response to novelty? The explanation in terms of impairment of a flexible noticing order is considerably more predictive, yet captures the spirit of the intent of the perseveration of set hypothesis.

The suggestion is, therefore, that the frontally lesioned primate is defective in problem solving whenever a process that corresponds to a flexible noticing order is demanded. From the analysis made above, it follows that a disruption of the mechanism that allows monitoring of stimuli that temporarily covary would impair this process. It follows also that this temporary flexible monitoring of stimulus-covariation is separable from the process that allows more permanent storage of invariant representations of experiences, (e.g., in a discrimination tree).

Stimulus Covariation and Dominant Foci

Neurologically, the search is shifted. Earlier notions of the short or immediate memory process led to hypotheses about memory trace formation and decay, and to experiments aimed at uncovering reverberatory circuits in the brain. The concept of a flexible noticing order within a working memory leads instead to tracking down the mechanism of tempo-

rary, flexible stimulus covariation, perhaps through the formation of readily shifted dominant neural foci (see review by E.R. John, 1961; Pribram 1971). Such dominant foci can be manipulated in a classical Pavlovian situation, for instance, by training a dog to raise his right hind leg to a signal. When the response had been well established, the dog's right motor cortex was exposed and a patty of strychnine sulfate-soaked filter paper was placed over the area that controls the left foreleg. While the strychnine was effective, the dog was placed in a conditioning situation. Now he raised his left foreleg instead of his right hind leg whenever the signal was given.

The production and shift of dominant foci have recently been repeatedly studied (Morrell, 1961; Rusinov, 1956; Ukhtomski, 1927). Could frontal lesions be shown to alter the time course of the establishment or of the shift of such dominant foci? If for no other reason than that the direction of experimentation has been altered, the experiments and analyses reported here may thus be shown by future events to have been worthwhile. (Pribram, Ahumada, Hartog, & Roos, 1964, pp. 47-52)

With currently available tools, noticeably 128-electrode geodesic scalp recording arrays with which to assay brain electrical activity, a first step toward demonstrating a frontal influence on an evoked visual response in the occipital cortex has been taken. Tucker, Liotti, Potts, Russell, and Posner (1994) have shown a "reinforcement" of an occipitally evoked response by a "reprise" that issues from that response to the frontal cortex and then back again to the occipital cortex. The relationship of the reprise to working memory must now be shown.

IMPLICATIONS FOR DEVELOPMENT

Thatcher (1994a, 1994b; see also Chapter 5) has analyzed the process of maturation of brain electrical activity and correlated it with a variety of anatomical and other physiological indicators. In his analysis, Thatcher has mapped coherence among recordings from different brain sites. The maturation process was shown to proceed in cycles, each cycle consisting of rapid change (spurts) followed by a plateau. Three "stages" were identified: one occurring in early childhood, a second during what is sometimes called the latency period, and another following puberty.

Specifically, the physiological processes observed in the study are 2-year growth spurt cycles in the strength of intrahemispheric couplings, which are nested within 4-year interhemispheric rotations. Figure 16.8 is a diagrammatic representation of the structure of cycles and subcycles as observed in the electroencephalographic coherence data. In summary, there are three main cycles separated by at least two bifurcations or phase transitions (see also a bifurcation between ages 4 and 5 in the right frontal regions; Thatcher, 1994b). Phase transition 1 occurs in the left hemisphere between ages 5 and 7, and phase transition 2 occurs in the right hemisphere between ages 9 and 11. Cycle I is from approximately age 1.5 years to age 5.0, cycle II is from approximately ages 5 to 10, and cycle III is from approximately ages 10 to 14. For continuity, the Fischer (Fischer, 1980; Fischer & Ferrar, 1987) and Case (1985, 1987) descriptions of cognitive development are used.

Hudspeth and Pribram (1992) performed a somewhat different analysis using the increase in desynchronization of brain electrical activity as our indicator. We found three stages spanning much the same age ranges as those found by Thatcher. The first stage of maturation, which spans the period between 1 and 6 years of age, is characterized by rapid maturation in all brain regions. The frontal executive (FT), visuospatial (PO), somatic (CC), and visuoauditory (TT) functions reach their respective peaks almost simultaneously (i.e., within 6-month intervals of each

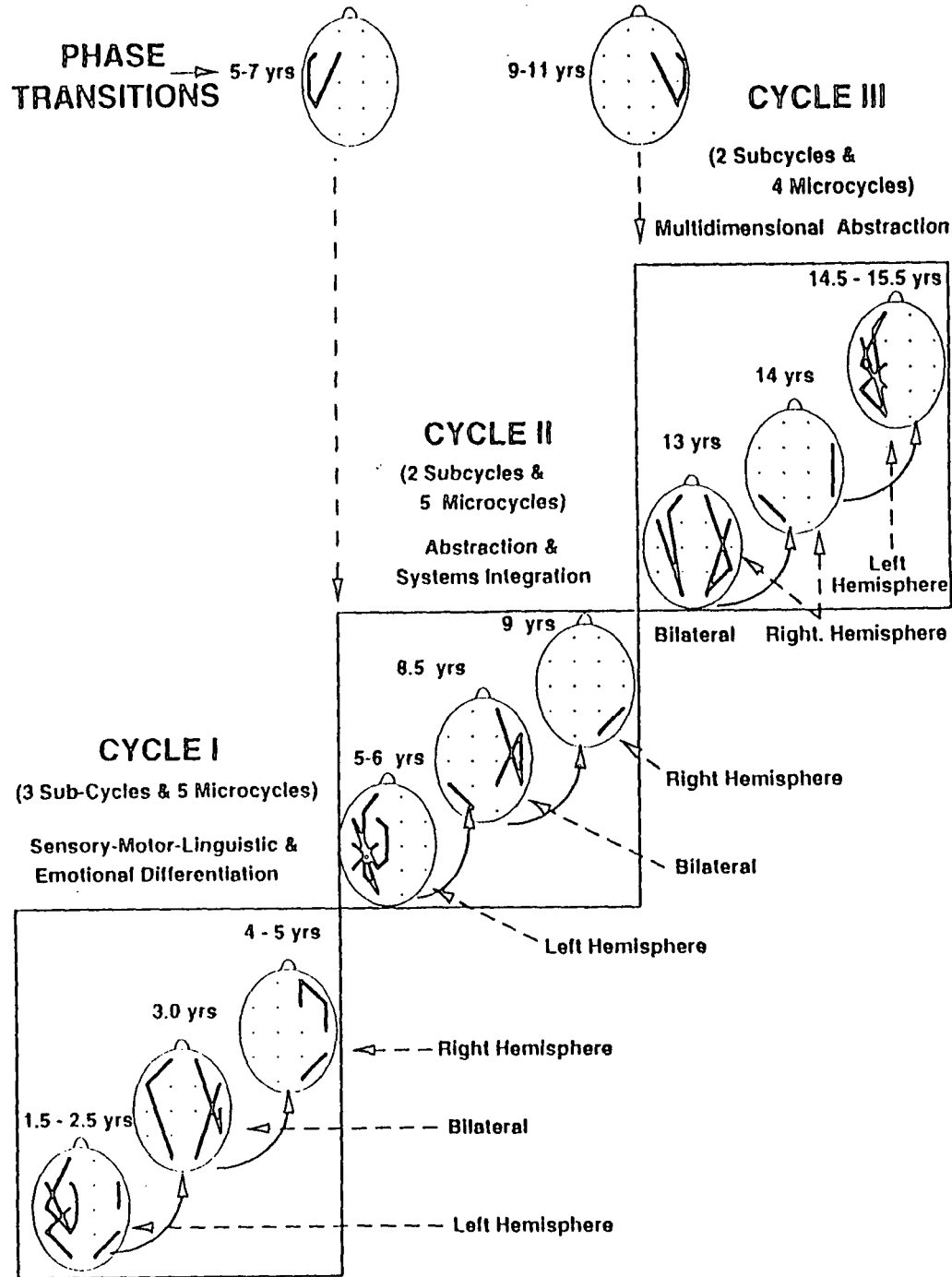


Figure 16.B. Diagrammatic representation of the predominant developmental cycles and subcycles of neocortical reorganization. A designation of "Left hemisphere," "Bilateral," or "Right Hemisphere" emphasizes the predominant growth spurts during a given age range. This figure illustrates the combination of punctuated equilibria and the presence of a "spiral staircase" process of cyclical reorganization during postnatal cerebral development. (Adapted from Thatcher [1994].)

other). This suggests that the executive control exercised by the far frontal cortex is primarily directed toward regulating body functions (e.g., going to the toilet at appropriate times and places).

In a second stage of maturation that spans the period between 6 and 10.5 years of age, rates are synchronized across the sensory and motor systems (PO, TT, CC), with all reaching a peak at 7.5–8 years of age. A mild acceleration in development in the frontal executive region (FT) starts only then (7.5 years) but terminates synchronously with that of the rest of the brain at 10.5 years. The early part of this period is therefore a continuation of the maturation of sensorimotor functions, whereas the latter part, beginning at age 7.5, heralds some enhancement of executive control, perhaps over sensory input (attention).

The third stage of maturation spans the period between 10.5 and 17 years of age. The third stage appears to be initially devoted to the elaboration of visuospatial (PO) functions. At the same time, however, maturation of the visuoauditory (TT) function starts and slowly accelerates, to be followed by successive maturation of another phase of visuospatial (PO) and somatic (CC) functions, with each region reaching its maturational peak with 1-year intervals (i.e., at 14, 15, and 16 years, respectively). The frontal executive region remains unchanged at this time.

However, our data permitted us to extend our analysis to age 21. Much to our surprise, a sizable acceleration of maturation of the electrical activity recorded from the frontal cortex occurred during the ages of 17–21 years. These changes can be attributed to the development of monitoring the controls over behavior, that is, the development of intentions. This is the age range of students in college, a period of intense cognitive and social activity. It is at the college level that many students become exposed to the variety of viewpoints, the variety of subcultures with which they must cope during life. It has been said that the far frontal cortex is the organ of civilization. Should our findings hold up, they emphasize the importance to our civilization of college and university education—the period when the plasticity of the frontal cortex can be challenged to provide a responsible, rich, and productive life in an environment replete with ambiguities and change.

These stages are in close correspondence with those delineated by Piaget and Inhelder (1966) [see also Kramer, 1983; Riegel 1973, 1975]. Other stage-based theories for the maturation of emotion (Freud, 1932; Sullivan, 1953), moral judgment (Kohlberg, 1969), and psychosocial adaptation (Erikson, 1963) delineate roughly the same age boundaries as those described in this chapter (however, see also critique by McGuinness, Pribram, & Pirnazar, 1988). The theories are based on a wide range of observed behaviors. Therefore, a considerable amount of variation is to be expected when attempts are made to delineate maturational stages with behavioral criteria alone. The fact that stages could be gleaned from such evidence at all strongly suggests that biological factors are entailed in the processes denoted by these behavioral indices. Further refinements in these biobehavioral relationships would be expected when maturation in specific brain subsystems can be linked to maturation in specific behavioral subsystems.

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Development of the Prefrontal Cortex: Evolution, Neurobiology, and Behavior

edited by Norman A. Krasnegor, Ph.D., G. Reid Lyon, Ph.D.,
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