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THE ROLE OF FRONTAL AND PARIETAL CORTEX IN COGNITIVE PROCESSING

TESTS OF SPATIAL AND SEQUENCE FUNCTIONS

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INTRODUCTION

SINCE Jacobsen first demonstrated that monkeys with resections of the anterior frontal cortex are unable to learn delayed-response or spatial delayed-alternation tasks (Jacobsen, 1936; Jacobsen and Nissen, 1937), there have been many attempts to interpret these findings in order to formulate a mechanism for frontal cortical control of complex behaviour. Recent interpretations have emphasized the fact that these tasks involve right-left discriminations and therefore might tap spatial memory (Goldman and Rosvold, 1970; Goldman, Rosvold, Vest and Galkin, 1971).

Although spatial cognitive processes have classically been attributed to the domain of the posterior parietal cortex in humans (Critchley, 1953), several studies in the clinical literature have also noted certain types of spatial impairments following frontal cortical damage. These studies have provided suggestive evidence for a dichotomy between the nature of the spatial impairments produced by damage to the frontal and parietal cortex. Patients with parietal cortical damage were found to have difficulty in setting a line to vertical against a conflicting background (Teuber and Mishkin, 1954) and to be unable to make conceptual spatial rotations of maps (Semmes, Weinstein, Ghent and Teuber, 1963) or visual patterns (Butters and Barton, 1970; Butters, Barton and Brody, 1970); in contrast patients with frontal damage had no such difficulty. Conversely, patients with frontal cortical damage were found to have difficulty in setting a line to vertical when their own bodies were tilted with respect to vertical (Teuber and Mishkin, 1954), pointing to the parts of their own body corresponding to those designated on a diagram (Semmes *et al.*, 1963), or making a series of right-left discriminations with respect to varying orientations on a map different from the orientation of their own bodies (Butters, Soeldner and Fedio, 1972). Patients with parietal damage also had difficulty with some of these latter tasks; however, if the parietal damage was confined

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to the right hemisphere, the patients were unimpaired. On the basis of their findings Teuber and his colleagues (Semmes *et al.*, 1963; Teuber, 1964) characterized the general impairment following parietal damage as one involving extrapersonal spatial orientation, that is, a difficulty with discriminations involving the spatial relationships among external stimuli. In contrast, they characterized the impairment following frontal cortical damage as one involving personal spatial orientation, that is, a difficulty with discriminations dependent on the accurate assessment of the body's orientation in space.

In order to specify the locus of the deficit more accurately and to correlate these clinical findings with the vast amount of information obtained from research with nonhuman primates, Pohl (1973) attempted to test the dichotomy between personal and extrapersonal spatial orientation using monkeys with dorsolateral frontal or with posterior parietal ablations. Since it had been assumed that the salient feature of the tasks defined as measures of personal spatial orientation was the necessity of making right-left discriminations, Pohl used the place reversal task (go left to a criterion—go right to a criterion) as the measure of personal spatial orientation. For comparison he used a landmark discrimination (go to the foodwell nearer the landmark) and a landmark discrimination reversal task (go near the landmark to a criterion—go far from the landmark to a criterion) as measures of extrapersonal spatial orientation. The solutions for these latter spatial tasks were based on the spatial location of an external referent, the landmark. The monkeys with frontal lesions were impaired on the place reversal but not the landmark reversal while the opposite was true for the monkeys with parietal lesions. Pohl interpreted his results to indicate that the personal-extrapersonal dichtomy is appropriate for monkeys as well as humans.

Despite the fact that both patients and monkeys with frontal damage demonstrate significant impairments on certain tasks involving right-left discriminations, there remains some difficulty with emphasizing right-left disorientation or the more general concept of personal spatial disorientation as the primary basis of the syndrome following frontal damage. First, the clinical literature indicates that right-left disorientation classically follows parietal cortical damage (Gerstmann, 1940; Critchley, 1953) rather than frontal damage. Secondly, the most striking effect of frontal cortical damage in patients is their tendency to perseverate previous responses; aspects of this syndrome have been tested empirically with card sorting (Milner, 1963), a multiple object search task (Poppen, Pribram and Robinson, 1965), and multistep instructions (Luria, Pribram and Homskaya, 1964; Luria, 1966). An emphasis on personal spatial disorientation cannot account for these findings. Thirdly, the experimental data obtained on monkeys indicate that if lesions are confined to the focus within dorsolateral frontal cortex attributed to be selectively involved with spatial function, a right-left discrimination requirement is not sufficient by itself to produce the deficit; memory must be taxed, either with imposed delays or with alternations or reversals of response requirements (Goldman and Rosvold, 1970; Goldman *et al.*, 1971).

By contrast to these theories involving spatial functions, some time ago Pribram (1958, 1961) pointed out that the delayed-response and delayed-alternation tasks require the sequencing of behaviours. He and his co-workers suggested that the function of the anterior frontal cortex is to provide a working memory in which these sequences can be flexibly ordered (Pribram, Ahumada, Hartog and Ross, 1964). The clinical literature also provides evidence that patients with frontal damage have considerable difficulty with the temporal organization of behaviour, particularly when flexibility is required. The almost pathognomonic tendency of such patients to perseverate portions of instructions occurs most notably when they attempt to perform a sequence of different behaviours (Luria *et al.*, 1964; Milner, 1964; Luria, 1966). Moreover, the difficulty similar patients have shown in identification of body parts (Semmes *et al.*, 1963), in a stylus maze task (Milner, 1964), or in a path reading task (Butters *et al.*, 1972) has been attributed to a deficit in personal spatial orientation, but the conflicting sequential response requirements are equally critical features of these tasks (Semmes *et al.*, 1963; Milner, 1971). Milner (1971) has reported that her patients with frontal damage could recognize previously-seen items but could not recall in what order they had been seen, suggesting ineffective 'temporal tagging' of information.

Pribram had earlier suggested that the difficulty monkeys with frontal resections have with sequencing tasks such as delayed alternation might be due to an inability to parse stimuli into useful patterns. He and his students were able to improve the performance of such monkeys on delayed alternation by the simple expedient of imposing a temporal pattern to the stimuli (Pribram and Tubbs, 1967; Pribram, Plotkin, Anderson and Leong, 1977). Also in Pribram's laboratory, Pinto-Hamuy and Linck (1965) directly examined the role of the frontal cortex in sequencing by teaching monkeys to press different stimulus-response panels in a particular sequential order. On the basis of earlier work by Kimble and Pribram (1963) they investigated the possibility that sequences organized by external cues and those depending on internal cues would be differentially influenced by frontal resections. They found that if the sequential order was externally imposed such that the monkeys were always required to choose the same unique sequence, those monkeys with frontal ablations were able to learn the problems at a normal rate. On the other hand, if the only rule imposed was that a sequence on any one trial must contain no repetitions, the monkeys with frontal ablations demonstrated a deficit. These authors suggested that during the latter type of sequence the monkey must internally organize the sequence within each trial by maintaining a memory of each prior press; whereas, during the externally-ordered sequence the external visual cues contained the information needed to order the responses. They concluded therefore that the frontal cortex is necessary to order sequential behaviours whenever such sequences require organization within memory.

However, another difference between the two types of sequences might have been an important variable in the study by Pinto-Hamuy and Linck. The stimuli were presented on a four-by-four stimulus-panel array such that the locations of the stimuli changed only between trials. The internally-ordered sequence could correctly be completed by simply pressing each panel once, remembering only the location of the previous press. In fact, one of the internally-ordered sequences (red, red, red) required such a spatial solution. By contrast, in the externally-ordered sequences the pattern as well as the location of the cued panel could be used to solve the problem. The deficit on the internally-ordered sequence is equally well interpreted in terms of the hypothesis that following frontal resection monkeys have a deficit in spatial memory.

An experimental analysis of both the spatial and the temporal theories was therefore undertaken and is reported here in two studies. The first of the studies attempts to clarify the relevance of a personal-extrapersonal spatial dichotomy to frontal and parietal cortical function. Monkeys with bilateral anterior frontal or with bilateral posterior parietal ablations were trained on variations of a spatial task designed to test the dichotomy as simply as possible while avoiding the use of either right-left discriminations or reversal problems. As a test of personal spatial orientation the monkey was required to press the panel next to a panel he had previously selected. As a test of extrapersonal spatial orientation the monkey was required to press the panel next to a green panel. The personal-extrapersonal spatial theory would clearly predict a double dissociation of function on these two tasks.

The purpose of the second study was to determine if monkeys with frontal ablations have deficits which are related to an inability to organize sequences independent of a spatial component and to examine the monkeys' dependence on external cues in learning such sequences. Monkeys with anterior frontal or with posterior parietal ablations were tested on sequence problems whose solutions were completely independent of the spatial locations of the stimuli. We expected that monkeys with frontal resections would show a greater deficit on internally-ordered sequences than on externally-ordered sequences. In contrast, we expected those with parietal resections to show a completely normal performance under both conditions.

METHODS

Subjects

Fourteen juvenile rhesus monkeys (*Macaca mulatta*) served as subjects; their range of weight at operation was 2·8 to 3·6 kg. Three of these remained as normal controls (Normal Group), 4 sustained bilateral posterior parietal lesions (Parietal Group), and 7 (of which only 4 were used in the spatial tasks) sustained bilateral anterior frontal lesions (Frontal Group).

Surgery and Histology

Prior to surgery all monkeys were tranquillized with Ketamine (11 mg/kg i.m.) and then anæsthetized with intravenous sodium pentobarbital until eyelid reflexes were absent. A saline drip through an intravenous catheter was maintained throughout surgery during which additional doses of pentobarbital were administered as required. All ablations were performed as a one-stage bilateral aseptic procedure. The cortex was exposed with a full calvarium flap which crossed the midline and was hinged on one set of temporal muscles. Cortical gray matter was removed bilaterally by subpial aspiration using a 19-gauge Pribram Sucker designed to avoid damage to underlying white matter. Bleeding was controlled by gentle packing with cottonoid patties or, rarely, electrocauterization. The dura was closed with individual silk sutures; and muscle, subcutaneous tissues, and skin were closed in layers. Following surgery, long-acting bicillin (300,000 U i.m.) was routinely administered to all of the monkeys, and dexamethasone (2 mg i.m.) was also given to those sustaining frontal ablations.

The anterior frontal lesion was defined by von Bonin and Bailey's (1947) areas FD, FDΔ, and FDγ, extending from the midline to the lip of the lateral surface through both banks of the sulcus principalis, and from the depth of the anterior bank of the arcuate sulcus rostrally to include the entire frontal pole.

The posterior parietal lesion was defined by von Bonin and Bailey's areas PF, PC, PE, and the more dorsal portions of areas OA and TA on the lateral surface. The lesion included the anterior bank of the lunate sulcus and extended rostrally from the lunate through both banks of the dorsal portion of the superior temporal sulcus to include both banks of the intraparietal sulcus. A several-mm-square area superior to the intraparietal sulcus at the preoccipital notch was also removed. The ventral limit of the lesion was defined by a line drawn from the tip of the intraparietal sulcus to a point several millimetres below the tip of the Sylvian fissure and then directly in a line perpendicular to the lunate sulcus. On the medial surface the lesion was defined by areas PE and OA extending ventrally almost to the calcarine fissure and including the anterior bank of the parieto-occipital sulcus and all of the tissue rostral to that sulcus for approximately 10 mm.

Following completion of behavioural testing, the monkeys were perfused intracardially under deep barbiturate anæsthesia with saline and 10 per cent formalin, and the brains were blocked stereotaxically in the coronal plane. They were hardened in formalin and 30 per cent sucrose-formalin, embedded in gelatin-albumin, and frozen; 50 μm sections were taken in the coronal plane, then mounted and stained with cresyl violet for microscopic analysis of the lesions. Lateral and medial views of the lesions were reconstructed from enlarged tracing using serial sections every 1 mm. Reconstructions of the individual brains with representative coronal sections through the anterior frontal and posterior parietal lesions are presented in figs. 1 and 2 respectively.

Apparatus

All training was carried out using a PDP-8 computer-controlled DADTA (Discrimination Apparatus for Discrete Trial Analysis; Pribram, 1969). During training the monkey sat in a testing cage measuring 45·72 cm × 50·80 cm × 50·80 cm, one side of which consisted of bars spaced at 4·445 cm intervals. This cage was placed in a small enclosure illuminated by a 15-watt house light in the ceiling. The monkey faced a 50·80 cm × 50·80 cm square panel on which there was embedded a four-by-four regular array of clear round plastic push-panels, 2·54 cm in diameter. Microswitches mounted behind each of the response panels signalled the presses to the computer, and IEE digital display projectors back-projected the stimuli through these panels. A computer program controlled the sequence of stimulus location, the intertrial interval, rewards, and the teletype which recorded the responses. A correct response caused a mechanical feeder to deliver the banana pellet food reward to a single foodwell centred just below the array of response panels. A large one-way mirror permitted observation of the monkey during training.

Procedure

Pre-operatively all monkeys were initially shaped to press only lit panels in the DADTA and were then trained on a colour discrimination problem and its reversal. Post-operatively all monkeys learned three visual discrimination problems (Brody, Ungerleider and Pribram, 1977); each monkey was then assigned to one of four training groups (*see* Tables 1–4). Each training group learned four sets of problems: Personal Spatial (P-Sp); Extrapersonal Spatial (EP-Sp); Internally-ordered Sequences (I-O Sq); Externally-ordered Sequences (E-O-Sq). The training of these problems was counterbalanced such that

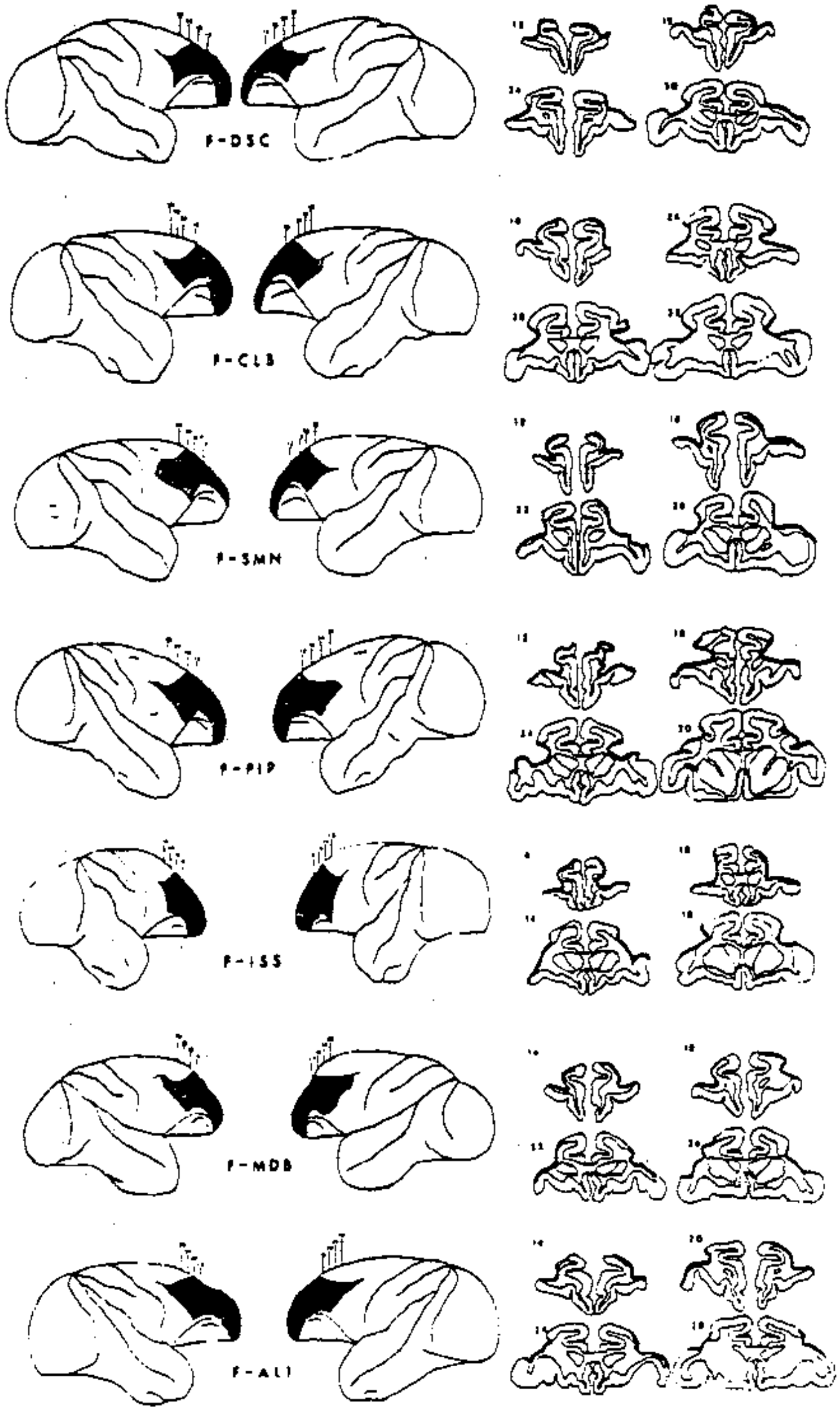

FIG. 1. Anterior frontal lesions. The extent of the individual lesions on the lateral surface was reconstructed from enlarged tracings of the coronal sections taken every 1 mm. Four representative coronal sections are presented for each brain. The dark line on the coronal sections indicates the extent of damaged or absent tissue.

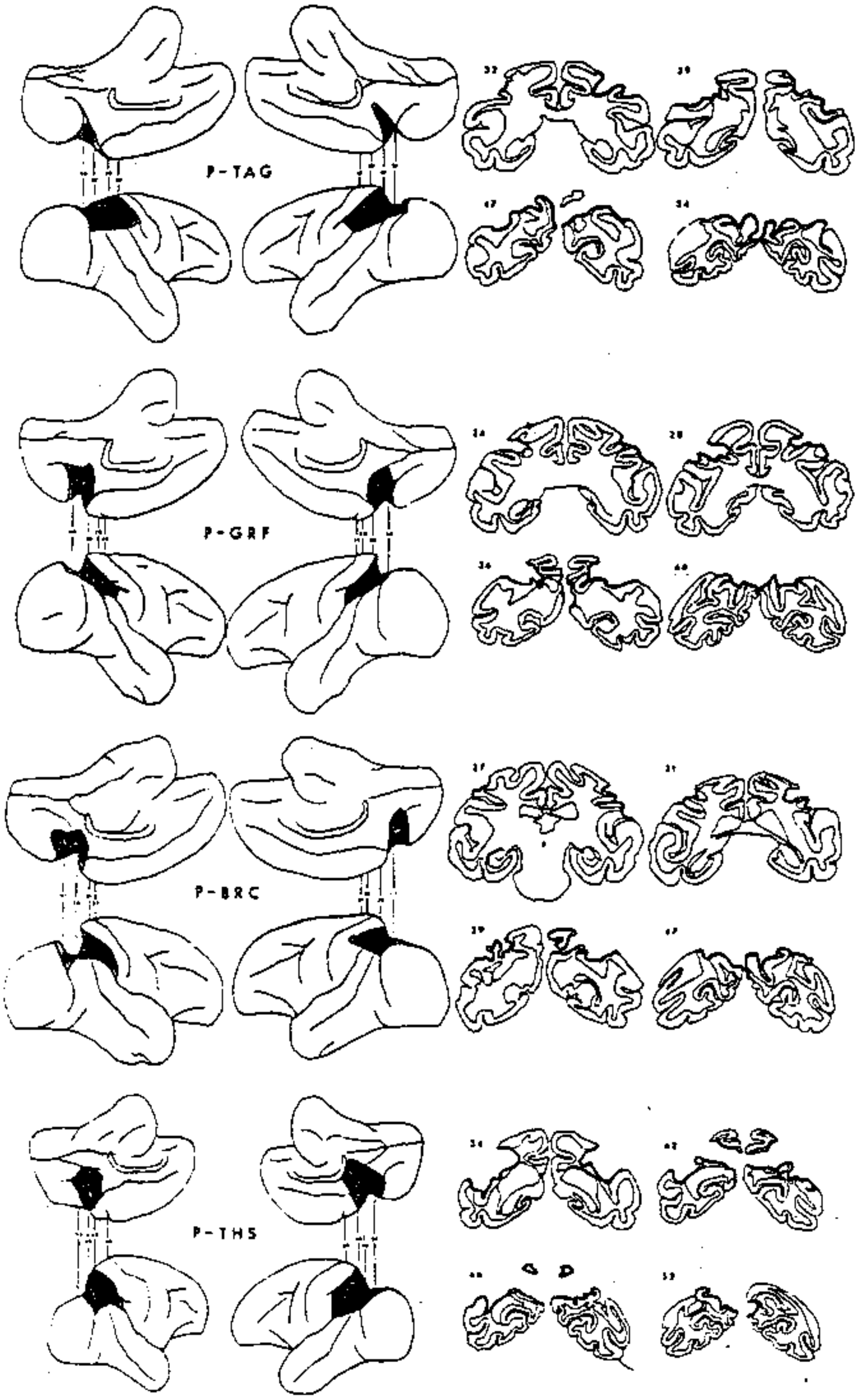

FIG. 2. Posterior parietal lesions. The lateral and medial extents of the individual lesions were reconstructed from enlarged tracings of the coronal sections taken every 1 mm. Representative coronal sections are presented as in fig. 1.

Groups A and C learned the spatial problems first and Groups B and D learned the sequences first. The order of training was further counterbalanced as follows:

Training Group A:	EP-Sp	P-Sp	E-O-Sp	I-O-Sq
Training Group B:	E-O-Sq	I-O-Sq	EP-Sp	P-Sp
Training Group C:	P-Sp	Ep-Sp	I-O-Sq	E-O-Sq
Training Group D:	I-O-Sq	E-O-Sq	P-Sp	EP-Sp

Three of the 7 monkeys given frontal resections were trained as members of Group B for the discrimination and sequence problems only; all the other monkeys completed all problems. All monkeys worked 100 trials a day, six days a week to a criterion of 90 correct out of 100 consecutive sets of 10 trials (100 trials) for each problem. Detailed description of the testing procedure follows:

Extrapersonal Spatial Tasks: Free-Start. The monkey was required to press consecutively two (or in the case of the 3-element task, three) contiguous panels in any one horizontal row of the array in order to obtain a pellet. For the initial tasks the monkey was permitted to start anywhere, press a panel, then *press the panel next to the one he had just pressed.* All active and lit panels displayed the stimulus '1' (a white pattern against a dark field). After each correct press the stimuli disappeared, then immediately reappeared as before, except that *the panel the monkey had just pressed turned green.* The trial ended and an eight-second intertrial interval began whenever the monkey made an incorrect press or successfully completed the two or three consecutive presses required. There was no time limit for responding at any point during the trial, but rewards occurred only following the last correct press.

The monkeys were trained in successive steps beginning with just two contiguous panels lit. Since repeat presses were ignored, no errors were possible and only 50 trials were given. The monkeys were then trained to the 90 per cent criterion with 4, 8, and 16 panels lit, beginning with a 2-element version in which they were permitted to start anywhere and then required to press one panel next to their starting panel. They were then trained to the 90 per cent criterion again with 4, 8, and 16 panels lit on a 3-element version in which they were required to press three panels starting anywhere. The third press was correct if it was made directly next to either the first or the second panel just pressed. Three correct presses were therefore not necessarily contiguous presses, but any correct press after the first one was always next to a green panel.

Extrapersonal Spatial Tasks: Forced Random-Start. In order to avoid the tendency of the animals to simply press the same two or three panels each trial, at the beginning of the trial only two panels appeared lit with the '1' stimuli in random positions on the array. A press on either panel caused 15 of the panels to display the '1' stimuli and one of the panels to display a green circle. The monkey was then required to *press the panel next to the green panel* in the same horizontal row. This 2-element version was also followed by a 3-element version in which the first correct press caused all panels to be extinguished and then reappear immediately with 14 of the panels lit with '1's and two consecutive panels lit with green circles. The monkey was again required to press one panel next to either of the green ones. Pressing either a green panel or any other incorrect panel terminated the trial without reward. The initial two '1's, the green cue, and the two consecutive green cues in the 3-element version all appeared in different locations from trial to trial according to three independent pseudo-random sequences. That is, the location of the green cue was independent of the initial press. Thus, all monkeys learned eight versions of the extrapersonal 'next-to' task to the same 90 per cent criterion in the following order: 2-4, 2-8, 2-16, 3-4, 3-8, 3-16, 2-2R, 3-2R. The first number indicates the number of responses required within one trial, the second number indicates the number of consecutive panels initially lit, and the 2R indicates two panels initially lit in random locations on each trial.

Personal Spatial Tasks: Free-Start. This task had exactly *the same requirements as the free-start extrapersonal task.* The monkey was permitted to start anywhere on the array and then required to press two or three consecutive panels in a horizontal line. The third press of the 3-element version was permitted to be next to either the first or the second panel just pressed. However, in this task when the monkey pressed a panel, *all of the panel lights disappeared then reappeared exactly as before, that is all displaying '1's.*

Personal Spatial Tasks: Forced Random-Start. As in the extrapersonal random-start version the initial display consisted of only two randomly lit panels. A press on either of these panels caused all 16 panels to display '1's. The monkey was then required to *press the panel next to whichever of the panels he had chosen initially.* For the 3-element version he was required to press three contiguous panels starting with whichever panel he chose initially, and again the third press was permitted to be next to either the first or second panel pressed. In addition, repeat presses were not permitted. Any repeat press as well as any other incorrect press terminated the trial without reward. Again all monkeys learned all eight versions of the personal 'next-to' tasks in the same order: 2-4, 2-8, 2-16, 3-4, 3-8, 3-16, 2-2R, 3-2R.

Thus in both the personal and extrapersonal 'next-to' tasks the monkeys were first trained using a series of displays in which all of the possible response panels were initially lit (free-start versions). The appearance of the display was stable and the monkeys were permitted to establish stable response patterns. They were then transferred to random-start versions of the task in which the relevant stimuli shifted spatial location from trial to trial. This change prohibited the monkeys from using stable response patterns with the same sets of panels every trial.

Externally-ordered Sequential Task. The three problems in the order in which all monkeys learned them were 'red-green' (large solidly coloured circles); '0'-'2'; and '0'-'2'-'6' (white patterns against a dark field). On each trial the two stimuli (or three in the case of the 3-element sequence) appeared in randomly-placed locations on the four-by-four panel array. In order to receive a reward the monkey pressed first the red and then the green panel irrespective of their location. The stimuli disappeared after each press within a trial and reappeared immediately in a new random configuration according to a programmed 100 trial pseudo-random sequence, thereby making spatial strategies irrelevant. The trial ended and an 8-second intertrial interval began when the monkey either made an incorrect press or successfully completed the sequence. There was no time limit for responding at any point in the sequence, but rewards occurred only at the end of a complete sequence.

Internally-ordered Sequential Task. The three problems in the order in which all monkeys learned them were 'blue'-'yellow' (a blue filled plus and a yellow filled triangle); '4'-'5'; and '4'-'5'-'7' (white patterns against a dark field). This task was presented in exactly the same manner as the externally-ordered sequence task except that the monkey was permitted to choose different orders from trial to trial as long as any given sequence contained no repetitions. Thus, for the 2-element 'blue'-'yellow' sequence task either the order of responses blue-yellow or yellow-blue was acceptable. For the 3-element sequence on any given trial there were six acceptable orders: 4-5-7, 4-7-5, 5-4-7, 5-7-4, 7-5-4, and 7-4-5. Because of its difficulty, this last problem was trained for a minimum of 5,000 trials and a maximum of 10,000 trials.

RESULTS

Spatial Tasks

The data obtained from the various 'next-to' tasks reveal four striking results:

First, there were no significant differences among any of the groups in the initial free-start version of either the personal or the extrapersonal task (Table 1).

Secondly, on the random-start version of the personal task (fig. 3) the Frontal Group had a deficit compared to both the Normal and Parietal Groups, while the monkeys in the Parietal Group performed well within the normal range. This difference only attained significance for the 3-element version of the task. The Kruskal-Wallis nonparametric one-way analysis of variance by ranks (Siegel, 1956) for three independent samples gave a nonsignificant $H = 0{\cdot}89$ for the two-element version and an $H = 6{\cdot}05$, $P < 0{\cdot}05$ for the three-element version. Paired comparisons using the Mann-Whitney U test for two independent samples (Siegel, 1956) indicated that this overall group difference was due to the poor performance of the monkeys with frontal lesions. The comparison of the Frontal and Parietal Groups gave a $U = 0$, $P = 0{\cdot}014$, and the comparison of Frontal and Normal Groups gave a $U = 1$, $P = 0{\cdot}057$.

TABLE 1. TRIALS TO 90 PER CENT PERFORMANCE LEVEL
'NEXT-TO'
FREE-START TASKS

	Training		*Extrapersonal*		*Personal*	
Subjects	*Group*		*2-press*	*3-press*	*2-press*	*3-press*
N-Lns	A		90	250	50	70
N-Zld	B		80	100	60	0
N-Gld	C		90	170	2640	1830
		Mean	87	173	917	633
P-Brc	A		320	190	20	30
P-Ths	B		230	160	150	310
P-Grf	C		30	680	880	1510
P-Tag	D		0	0	230	100
		Mean	145	258	320	488
F-Dsc	A		450	470	310	2070
F-Pip	B		250	20	100	430
F-Smn	C		90	0	2890	8630
F-Clb	D		0	0	310	0
		Mean	198	122	902	2782

• N = Normal Group; P = Parietal Group; F = Frontal Group.

Thirdly, on the random-start versions of the extrapersonal task (fig. 4) both the Frontal and Parietal Groups demonstrated a significant impairment compared to the normal performance. The Kruskal-Wallis analysis of variance indicated significant overall differences among the three groups for both the two-element and three-element versions of the task. For the 2-element version $H = 6{\cdot}20$, $P < 0{\cdot}05$, and for the 3-element version $H = 6{\cdot}40$, $P < 0{\cdot}05$. For the 2-element version the Mann-Whitney U test gave a $U = 0$, $P < 0{\cdot}028$ for comparisons between both the Frontal and Normal Groups and between the Parietal and Normal Groups. For the 3-element versions the comparison between the Parietal and Normal Groups gave a nonsignificant $U = 2$, $P = 0{\cdot}114$. There was complete overlap between the Frontal and Parietal groups on both versions of the extrapersonal 'next-to' tasks.

Fourthly, on the random-start tasks, the performance of all monkeys, including the impairment shown by the Frontal Group, was independent of the level of testing sophistication they had attained prior to beginning these tasks. On the free-start

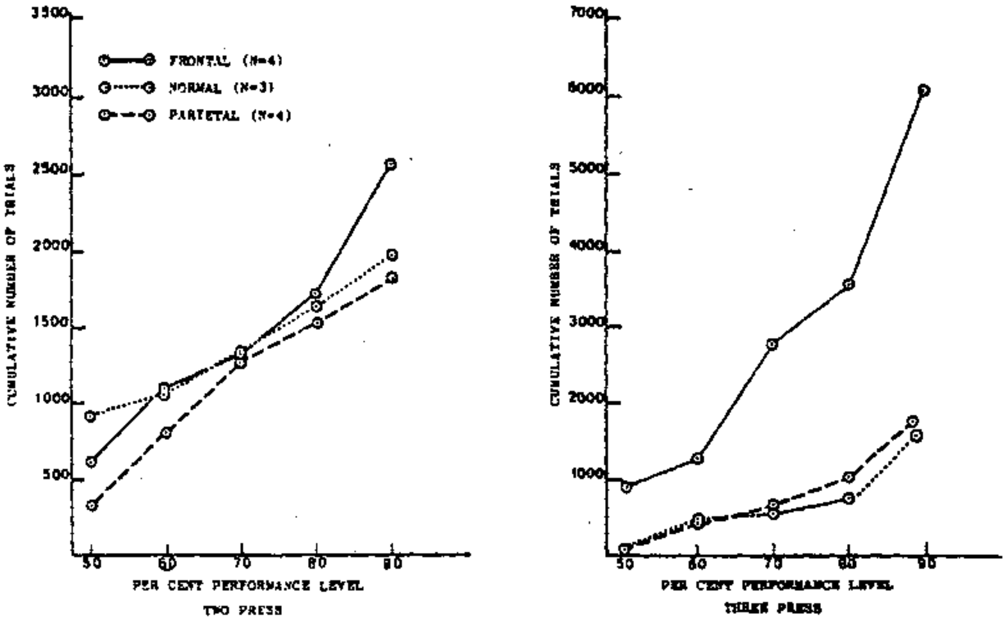

FIG. 3. Personal 'next-to' task. The cumulative number of trials required to reach each successive performance level (percentage correct) during acquisition of two versions of the task are presented for each experimental group. Two-press version—initialize press, then press the panel next to the panel just pressed. Three-press version—initialize press, then press the panel next to the panel just pressed, then press the panel next to either one of the two panels just pressed. All monkeys learned the two-press version first and then the three-press version.

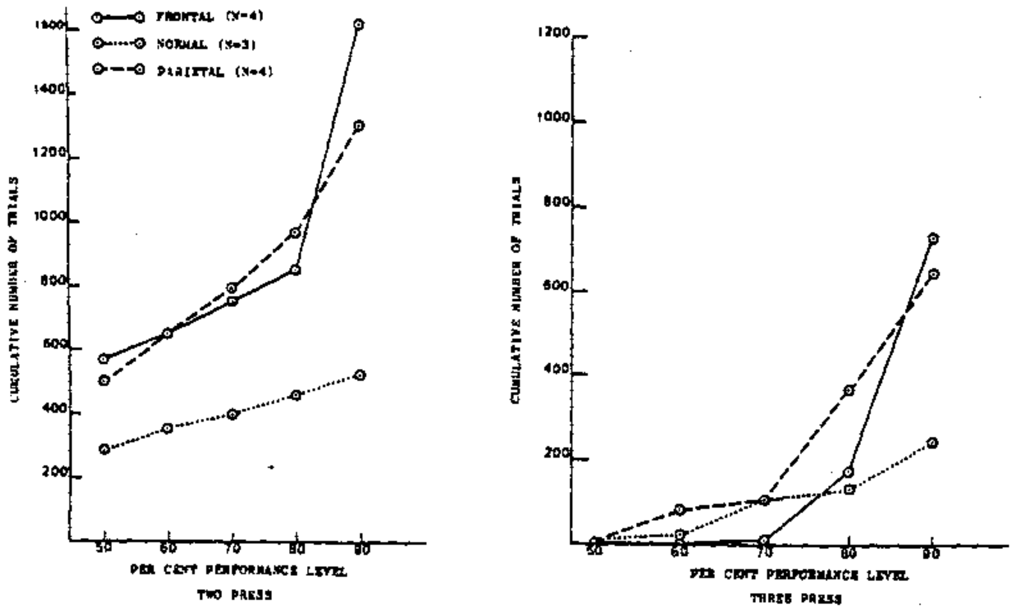

FIG. 4. Extrapersonal 'next-to' task. Learning curves are presented as in fig. 3. Two-press version—initialize press, then press the panel next to the single green panel. Three-press version—initialize press, then press the panel next to the single green panel, then press the panel next to either one of the two adjacent green panels. All monkeys learned the two-press version first and then the three-press version.

tasks there was a significant tendency for the monkeys who learned the extrapersonal tasks before the personal tasks (Training Groups A and B) to reach criterion more slowly ($U = 2$, $P = 0{\cdot}02$, $N_{1,2} = 6,5$ two-tailed) on the extrapersonal tasks and more quickly on the personal tasks ($U = 1$, $P = 0{\cdot}008$) than those who learned the tasks in the reverse order (Training Groups C and D). However, there were no differences among the lesion groups in this tendency, and the effect became insignificant by the 3-element version of each task. Similar comparisons for the random-start tasks indicated extensive overlap among the performances of the training groups (Table 2).

TABLE 2. TRIALS TO 90 PER CENT PERFORMANCE LEVEL
'NEXT-TO'
RANDOM-START TASKS

	Training		*Extrapersonal*		*Personal*	
Subjects	*group*		*2-press*	*3-press*	*2-press*	*3-press*
N-Lns	A		530	0	340	610
N-Zld	B		480	490	1680	2570
N-Gld	C		550	230	3890	1530
		Mean	520	240	1970	1570
P-Brc	A		820	10	1520	510
P-Ths	B		1910	640	2720	1790
P-Grf	C		980	850	2310	2310
P-Tag	D		1470	1080	780	2180
		Mean	1295	645	1832	1698
F-Dsc	A		2630	1360	2160	2550
F-Pip	B		880	630	2090	3100*
F-Smn	C		1350	330	2330	13580
F-Clb	D		1590	600	3620	5130
		Mean	1612	730	2550	6090

* Training stopped after 80 per cent but before 90 per cent criterion attained.

In order to detect any further difference in the nature of impairments produced by frontal or parietal cortical damage, several types of error analyses were performed on the data from the random-start versions of both 'next-to' tasks.

While learning the personal task the monkeys made many of their errors by pressing the other one of the two 'initialize' panels. The number of incorrect presses on the 'other-initialize' panel was tallied for the first 100 non-repeat errors made in learning the 2-element version. The expected frequency of such an error in 100 trials is 7. The means of the observed frequencies for the Normal, Parietal, and Frontal Groups gave Z scores respectively of 9·04, 16·7, and −0·2. That is, both the monkeys of the Parietal and Normal Groups, but not the Frontal Group, made significantly more of such errors than would be expected by chance.

For the extrapersonal 'next-to' task where the Frontal Group was as impaired as the Parietal Group, none of the error analyses revealed any differences in behavioural strategies. The first 100 trials in which each monkey made exactly 50 correct responses were tallied according to the location to the right or left of the green cue for the correct responses and the spatial location for the incorrect responses. The data indicated that all monkeys distributed their correct responses relatively equally to the right and left of the green cue, and there were no group differences. There were no differences among the groups in the tendency to incorrectly respond to the green cue itself, to incorrectly press panels that were on the same horizontal row but separated from the cue by one panel, or to incorrectly press panels that were vertically or diagonally next to the cue. Furthermore, there were no differences among the groups in the tendency to continue incorrectly pressing the panel next to the 'initialize' panel.

Sequence Tasks

The data from both the externally-ordered and internally-ordered sequence problems reveal several striking results. *First, the level of sophistication was quite clearly the most important variable in determining the ease with which rhesus monkeys were able to learn such sequences regardless of the type of brain damage they sustained. Second, the monkeys with frontal ablations showed a striking impairment which was dependent on their level of sophistication.*

However, sophistication apparently needs to be defined differently for the two types of sequences. In the case of the externally-ordered sequences, any extended experience with the automated apparatus produced sophistication. Not only did the two training groups (C and D) which had learned the internally-ordered sequences first perform well on the externally-ordered sequences, but the monkeys in Group A, who had finished the spatial tasks, also performed equally well despite the fact that the externally-ordered sequences were the first sequences they experienced (Table 3). In the case of the internally-ordered sequences, general sophistication apparently did not suffice. Only those two training Groups (A and B) which had previously learned externally-ordered sequences were able to learn the two 2-element sequences significantly faster than either of the other two training groups regardless of their level of general sophistication (Table 4).

The learning curves of the monkeys with parietal damage showed complete overlap with the curves of the normal monkeys at each criterion level; this was true for both the sophisticated and the naive monkeys (*see* Tables 3 and 4). Therefore, in order to determine which factors were contributing to the differences between the groups, two-way analyses of variance were calculated on each of the sequences at the 90 per cent criterion level with the Parietal and Normal Groups combined to form a single Control Group. The two factors analysed were (a) level of sophistication and (b) presence or absence of frontal cortical damage. A significant effect due to level of sophistication was obtained on the three easiest of the six sequences trained; that is, the 'red'-'green' ($F = 48{\cdot}8$, d.f. $= 1/10$, $P < 0{\cdot}001$)

TABLE 3. TRIALS TO 90 PER CENT PERFORMANCE LEVEL EXTERNALLY-ORDERED SEQUENCE TASKS

Subjects	*Training group*		*Red-green*	*0-2*	*0-2-6*
Naive					
N-Zld	B		1780	670	4150
P-Ths	B		1990	670	4380
		Mean	1885	670	4265
F-Iss	B		2420	1100	5160
F-Pip	B		2180	2040	12160
F-Ali	B		2410	2050	4000
F-Mdb	B		2880	1670	6670
		Mean	2472	1715	6998
Sophisticated					
N-Lns	A		610	590	1400
N-Gld	C		1520	830	7180
N-Brc	A		370	550	2830
P-Grf	C		410	140	1400
P-Tag	D		680	600	4570
		Mean	748	542	3476
F-Dsc	A		390	630	2380
F-Smn	C		640	670	4830
F-Clb	D		1060	110	3030
		Mean	697	470	3413

and the '0'-'2' ($F = 14$, d.f. $= 1/10$, $P < 0{\cdot}004$) externally-ordered sequences and the 'blue'-'yellow' ($F = 42$, d.f. $= 1/10$, $P < 0{\cdot}001$) internally-ordered sequence. There was both a significant lesion effect and a significant interaction between level of sophistication and lesion for the '0'-'2' sequence ($F = 7{\cdot}1$, d.f. $= 1/10$, $P < 0{\cdot}024$; and $F = 9{\cdot}3$, d.f. $= 1/10$, $P < 0{\cdot}012$ respectively) and for the 'blue'-'yellow' sequence ($F = 12{\cdot}9$, d.f. $= 1/10$, $P < 0{\cdot}005$; and $F = 10$, d.f. $= 1/10$, $= < 0{\cdot}010$ respectively).

Specific comparisons indicate that naive monkeys with frontal ablations had a significant deficit in reaching the 90 per cent criterion compared to the naive controls; for 'red'-'green' ($t = 2{\cdot}56$, d.f. $= 4$, $P < 0{\cdot}05$); for '0'-'2' ($t = 3{\cdot}12$, d.f. $= 4$, $P < 0{\cdot}05$); and for 'blue'-'yellow' ($t = 2{\cdot}54$, d.f. $= 3$, $P < 0{\cdot}05$). In contrast, the sophisticated monkeys with frontal ablations performed extremely well. Their learning scores were completely within the range of those of the sophisticated monkeys from the Parietal and Normal Groups. The differences between the mean scores of the naive and sophisticated monkeys with frontal ablations were highly significant; for 'red'-'green' ($t = 7{\cdot}44$, d.f. $= 5$, $P < 0{\cdot}005$); for '0'-'2' ($t = 4{\cdot}09$, d.f. $= 5$, $P < 0{\cdot}005$); and for 'blue'-'yellow' ($t = 5{\cdot}01$, d.f. $= 5$, $P < 0{\cdot}005$).

TABLE 4. TRIALS TO 90 PER CENT PERFORMANCE LEVEL INTERNALLY-ORDERED SEQUENCE TASKS

Subjects	*Training group*		*Yellow-blue*	*4-5*
Naive				
N-Gld	C		1390	9450
P-Grf	C		2510	350
P-Tag	D		3320	2200
		Mean	2406	4000
F-Smn	C		4700	4230
F-Clb	D		8900	1320
		Mean	6800	2775
Sophisticated				
N-Lns	A		30	80
N-Zld	B		500	240
P-Brc	A		140	790
P-Ths	B		310	330
		Mean	245	360
F-Dsc	A		90	290
F-Iss	B		20	—
F-Pip	B		50	7040
F-Ali	B		610	650
F-Mdb	B		1830	—
		Mean	520	2660

The learning curves for the three externally-ordered sequences (fig. 5) suggest that the naive controls became sophisticated faster than the naive monkeys with frontal ablations. However, there were too few subjects in the Control Group for the interaction effect to attain statistical significance in a three-way analysis of variance with repeated measures on the three sequence problems.

The ease with which each monkey was able to solve the internally-ordered sequences correlated highly with the degree to which the monkey limited the number of possible sequences he actually used during a session. The monkeys were ranked according to the number of times each monkey used the same one of the two possible correct sequences during the first 100 trials in which he made exactly 90 correct responses. The Spearman rank correlation (two-tailed) between that ranking and the ranks on trials to a 90 per cent criterion was Rho $= 0{\cdot}68$, $P < 0{\cdot}01$ for 'blue'-'yellow' and Rho $= 0{\cdot}63$, $P < 0{\cdot}05$ for '4'-'5'. The sophisticated monkeys had means of 88 and 87 responses of the same order for the 'blue'-'yellow' and '4'-'5' sequences respectively while the naive monkeys had respective means of only 62 and 69 responses of the same order. Moreover, those monkeys who had previously learned the fixed sequence 'red'-'green' began the 'blue'-'yellow' sequence

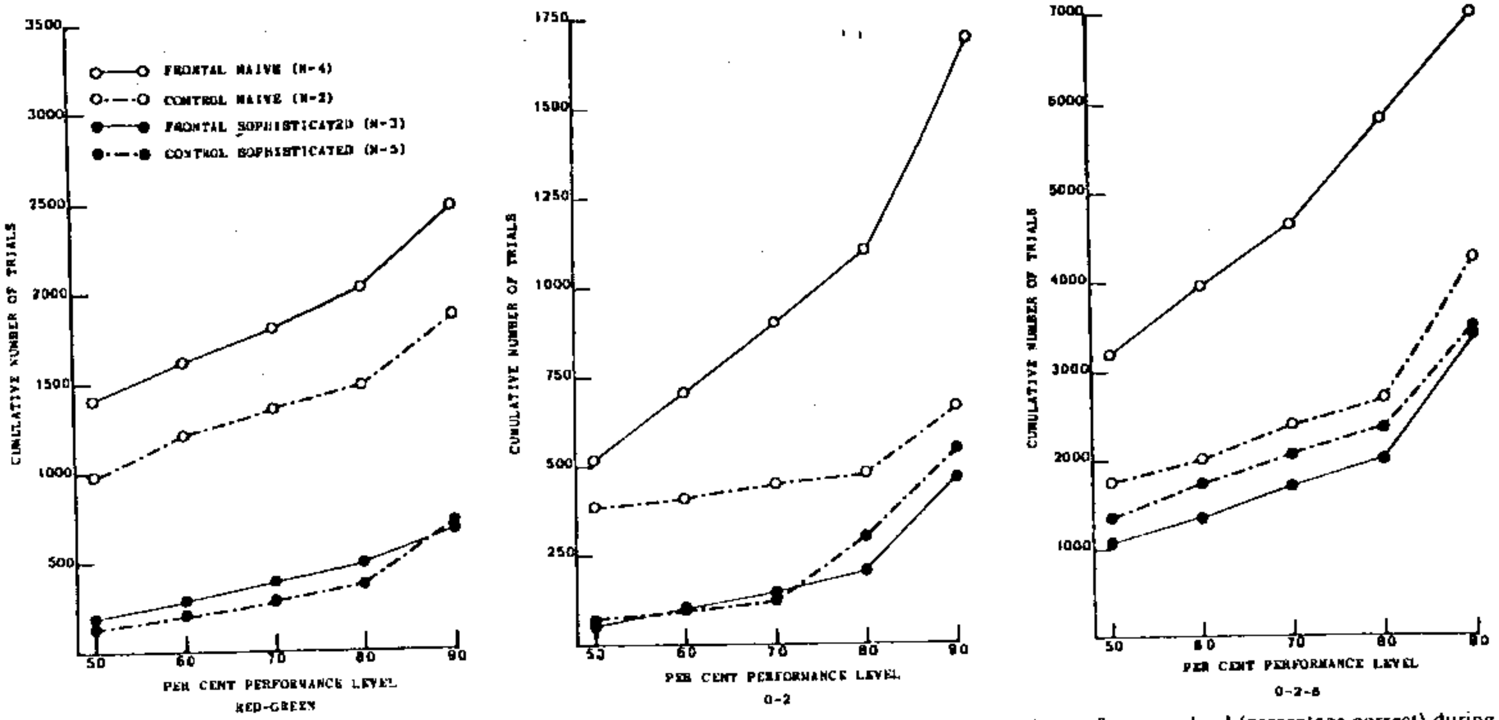

FIG. 5. Externally-ordered sequence tasks. The cumulative number of trials required to reach each successive performance level (percentage correct) during acquisition of the three sequence problems are presented separately for the naive and sophisticated Frontal and Control Groups. The Control Group consists of the monkeys with parietal lesions and the normal monkeys. All monkeys learned all three problems in the order 'red'-'green'; '0'-'2'; '0'-'2'-'6'.

using almost exclusively the yellow-blue order even though either order was correct. There was no particular tendency for the monkeys with frontal ablations to limit the number of possible sequences they used more or less than the control monkeys. Only 3 (one monkey each from the naive Frontal, sophisticated Frontal, and sophisticated Parietal Groups) of the 11 monkeys trained on the 3-element internally-ordered sequence showed any tendency to limit their choices among the six correct possible sequences. Each of these 3 showed a significant tendency to begin the trial with the stimulus '5'. Moreover, these 3 plus one additional normal sophisticated monkey were the only monkeys able to reach an 80 per cent criterion within the allotted 10,000 trials. The remaining 8 monkeys required between 7,000 and 10,000 trials to reach a performance level of 70 per cent correct, and there was complete overlap in the learning curves of all training groups regardless of lesion or level of sophistication.

For the 3-element externally ordered sequence there were six possible incorrect responses: '2', '6', '0'-'0', '0'-'6', '0'-'2'-'0', and '0'-'2'-'2'. For the 3-element internally-ordered sequence there were three types of incorrect responses: XX, XYY, or XYX. An analysis of the type of error made at the 50 per cent performance level for both sequences also failed to reveal any consistent differences among groups.

DISCUSSION

Spatial Tasks

The purpose of this part of the study was to re-examine the relevance of a personal-extrapersonal spatial dichotomy to frontal and parietal cortical function by training monkeys on conceptually simple 'next-to' tasks. The results did not provide the double dissociation predicted by this dichotomy: while the Parietal Group was impaired only on the extrapersonal 'next-to' task, the Frontal Group was impaired on both the personal and extrapersonal 'next-to' tasks, but only under a random-start condition.

The fact that the monkeys of the Parietal Group were significantly impaired on a task which required them to press a panel next to a green cue but were unimpaired on a more difficult task which required them to press the panel next to their own previous press supports the usefulness of the extrapersonal-personal spatial distinction with respect to parietal function. It is true that the Parietal Group did not show the expected deficit on the initial free-start version of the extrapersonal task. However, in that version the 'initialize' panel itself became green so that the task could be solved by ignoring the green cue and simply pressing the panel next to the 'initialize' panel, that is, by treating the task as if it were a personal 'next-to' task. It is interesting that these findings from monkeys parallel the findings from patients with parietal damage confined to the right hemisphere. Such patients show only extrapersonal spatial deficits even though patients with left parietal damage show both personal and extrapersonal spatial deficits (Semmes *et al.*, 1963; Teuber, 1964; Butters *et al.*, 1973).

The surprising result in this study was that the Frontal Group was as impaired as the Parietal Group on the random-start extrapersonal 'next-to' task. Neither an emphasis on spatial memory impairments (Goldman *et al.*, 1971) nor on personal spatial orientation (Semmes *et al.*, 1963; Pohl, 1973) would have predicted that monkeys with frontal damage should have any deficit on a task which simply required the monkey to press a panel next to a visible green cue. The task required neither memory nor personal orientation.

The importance of the spatial factor with respect to frontal cortical control mechanisms was first suggested by Mishkin and Pribram (1955, 1956) when they found that several non-spatial variations of the delayed-response and delayed-alternation tasks improved the performance of monkeys with frontal resections. Although a spatial hypothesis became less tenable when they next demonstrated that frontal resections produced deficits on an extremely difficult right-left alternation task that were as severe as those on spatial alternation, an unusually good performance on object alternation by one monkey in the Frontal Group called for further analysis (Pribram and Mishkin, 1956). To this end, Pribram (1961) devised a multiple location object alternation test which was more readily learned by monkeys. However, he continued to find a deficit after frontal lesions although performance (70 per cent) was better than on spatial alternation (50 per cent). Mishkin, Vest, Waxler and Rosvold (1969), using Pribram's new test, then found a dissociation between object and spatial alternation by making more restricted resections within the frontal cortex. They demonstrated that monkeys with lateral frontal resections confined more dorsally to the region of the sulcus principalis continued to have a profound deficit on spatial alternation but were able to attain a performance level of 80 per cent on object alternation. In contrast their monkeys with more 'ventral' resections, including both orbitofrontal and ventrolateral frontal cortex showed profound deficits on both the spatial and object alternation tasks suggesting the monkeys were disturbed by the reversal factor involved in both tasks.

These results indicate that different functions may be differentially localized within the frontal cortex. Despite this, we chose to utilize the larger dorsolateral resection defined by the projection of the parvicellular portion of the *nucleus medialis dorsalis* (Pribram, Chow and Semmes, 1953) thus invading the ventrolateral cortex. This choice was made because we wanted to evaluate both spatial factors (on the basis of the above data presumably located around the *sulcus principalis*) and temporal factors (possibly located more ventrally). As we were interested in analysing the nature of the deficit rather than its localization, we utilized the small number of subjects available to such a study to control for test variables rather than to subdivide the group according to a variety of lesions. However, because the resections did include the entire anterior lateral surface, possible effects specifically due either to damage to the frontal eye fields (area 8) or to invasion of the ventrolateral surface must be considered.

Results of earlier studies indicate that an explanation in terms of peripheral inattention or neglect due to damage to the frontal eye field is unlikely to account for the observed data. Monkeys with unilateral damage to area 8 do demonstrate transient neglect of the contralateral visual field, but they do not show neglect after bilateral damage (Kennard, 1939; Pribram, 1955). Presumably if frontal damage caused an attentional neglect of the peripheral field of vision, the errors made by the Frontal Group would centre around whatever point on the response panel array the particular monkey tended to fixate. Fixation points were not measured in this study; however, the Frontal Group demonstrated the same error patterns as did the Parietal and Normal Groups on the extrapersonal 'next-to' task. This pattern of error was in fact random with respect to both the green cue and the 'initialize' panel.

Mishkin and others have postulated that the ventrolateral surface is part of the frontal cortical region in which damage produces perseverative interference (Mishkin, 1964; Butter, 1969; Iversen and Mishkin, 1970; Passingham, 1972). In the present study, the method of training the monkeys to learn the extrapersonal 'next-to' task involved a shift from the free-start version in which the green cue appeared on the panel the monkey had just pressed (necessitating a response to the panel next to the first press) to a random-start version in which the green cue appeared in random locations (generally necessitating responses away from the 'initialize' panel). This shift in the response pattern requirement could have created deficits due to perseverative response tendencies. However, error analyses revealed that there were no differences among groups in the tendency to perseverate the response next to the 'initialize' panel. By the time the monkeys had attained a 50 per cent correct performance level such perseverative errors constituted less than 15 per cent of the errors for each group. Furthermore, when the monkeys from this study were trained on a landmark reversal problem, the Frontal Group demonstrated a normal performance (Ungerleider and Brody, 1977). Reversal learning tasks in general have been shown to be extremely sensitive to perseverative interference errors (Mishkin, 1964; Iversen and Mishkin, 1970). Therefore, if the monkeys had sustained sufficient damage to the ventrolateral surface to account for their deficits on the basis of perseverative interference, they should also have demonstrated significant perseverative interference on the landmark reversal task.

Thus neither a peripheral inattention hypothesis nor a perseverative interference hypothesis adequately accounts for the data. However, other details of the performance of the monkeys with frontal lesions suggest an alternate explanation for the unexpected difficulty the Frontal Group had with the random-start extrapersonal task.

First, the data indicate that the Frontal Group demonstrated an impairment on the personal 'next-to' tasks only if the 'initialize' cues shifted spatial location randomly from trial to trial and only during the 3-element version of the task. Observation of the monkeys during the learning of this task indicated that this impairment was due to their inability to flexibly shift their response patterns from a left-right movement to a right-left movement, or *vice versa*, when the location of the 'initialize' cues on the response-panel display demanded the direction of movement opposite to the individual monkey's preferred direction. Only the 3-element version in which three consecutive panels had to be pressed within a four-panel row required frequent shifts in the response pattern.

In addition, still other aspects of the data indicate that the Frontal Group might have been relying heavily on movement stereotypes to solve the personal 'next-to' task. When the monkeys were first learning the task, the Frontal Group made significantly fewer errors by pressing the other one of the two 'initialize' panels than either the Normal or Parietal Groups. Unlike the other monkeys, they made that error at chance frequency. The occurrence of such an error at a level greater than would be expected by chance implies that the monkey remembered correctly where the location of the stimulus was before all the panels became identically lit. The fact that the Frontal Group showed no evidence of remembering where the initialize cues had been strongly suggests that their normal performance on the random-start 2-element personal task was dependent on movement stereotypes learned in the initial free-start versions. Moreover, the lack of a significant group effect in the 2-element random-start task was due more to the increased variance of the ability of the Normal Group to solve this more difficult task than to a particularly inspired performance by the Frontal Group.

Thus, the ability of the monkeys in the Frontal Group to depend on movement stereotypes could explain their normal performance on the free-start and the 2-element random-start personal task. These movement patterns failed in the 3-element version of the personal 'next-to' task specifically because flexibility of response was required. Perhaps then the deficits of the Frontal Group were *unrelated* to spatial processes in both the personal and extrapersonal 'next-to' task.

Recent neurophysiological findings provide evidence relevant to this question. There is a population of single units in posterior parietal cortex which responds when arm movements towards relevant stimuli are co-ordinated with visual fixation of those stimuli in space (Hyvarinen and Poranen, 1974; Mountcastle, Lynch, Georgopoulos, Sakata and Acuna, 1975). These data support the view that the posterior parietal region is specifically concerned with spatial orientation. In contrast single units in dorsolateral frontal cortex do not respond in relation to arm movements but rather respond when the monkey must *hold* relevant information *in memory* prior to making a response in a delayed response or delayed alternation paradigm (Fuster, 1973; Kubota and Niki, 1971; *see also* Stamm and Rosen's macroelectrode analysis, 1969). Thus neurophysiological data as well as the behavioural data of this study suggest that the frontal cortex is involved in higher-order control functions. Such functions are easily tapped by personal spatial tasks but may also be tapped by other problems, such as the extrapersonal 'next-to' task and the sequence tasks which constitute the other part of this report.

Sequence Tasks

The purpose of this part of the study was to evaluate the importance of anterior frontal cortex in controlling sequences of behaviour when such sequences are completely independent of spatial location and to re-examine the effect of forcing a monkey to internally organize his own sequence at each trial rather than providing him with a predetermined externally imposed set of rules to guide his responses.

The results indicate that *neither spatial memory nor* the different types of *temporal memory* demands inherent in the two kinds of sequence problems *are critical factors* in determining the ability of monkeys with anterior frontal ablations to solve complex problems. First, the naive Frontal Group demonstrated a clear impairment in learning both the externally and simplest internally-ordered sequences, but that impairment did not appear on any of the sequence problems if the monkeys had previously acquired extensive testing experience. Second, regardless of presence or locus of lesion the sophisticated monkeys learned the externally-ordered sequences significantly faster than the naive monkeys.

With respect to the externally-ordered sequence the results of this study are therefore in agreement with those of the study by Pinto-Hamuy and Linck (1965), but they provide an alternative explanation. The monkeys in that earlier study all had had extensive experience with internally-ordered sequence problems prior to learning the externally-ordered sequence. Hence they were sophisticated by the definition used here, and like the monkeys in the present study, the Frontal Group learned the latter sequence as quickly as the normal controls.

Pinto-Hamuy and Linck had concluded on the basis of their results that monkeys with frontal ablations are impaired on sequence problems specifically when the elements of the sequence must be internally ordered by the monkey. However, it now appears that there are three possible factors which could account for the poor performance of the Frontal Group on their internally-ordered tasks: (1) the task-tested spatial memory; (2) the internally-ordered sequence task required a different type of memory organization than the externally-ordered sequence task; and (3) the monkeys had no prior DADTA testing experience, and were therefore naive.

The results of the present study suggest that in fact the third factor was the critical one. First, the spatial memory factor can be ruled out since the present data indicate that under certain conditions the Frontal Group showed a significant impairment on sequence problems even though demands on spatial memory had been eliminated. It is more difficult to rule out one or the other of the remaining two possibilities on the basis of the current results. Although general testing experience with the DADTA enabled all of the monkeys to learn the externally-ordered sequences quickly, it was not sufficient to enable them to learn the internally-ordered sequences quickly. For these latter sequence problems only those monkeys who had learned the former sequence problems were aided by their previous testing experience, and in those cases the transfer seemed to be directly from performing the 'red'-'green' sequence in the required order red-green to invariantly performing the 'blue'-'yellow' sequence in the order yellow-blue. The effect of sophistication therefore seemed mainly to predispose the monkeys towards restricting their own alternatives. Such restrictions actually changed the internally-ordered sequences into externally-ordered ones. It is therefore impossible to determine from the data if an intact frontal cortex would have been necessary to allow the monkey to perform the internally-ordered sequences normally while choosing different orders for those sequences on each trial. The data do indicate that when faced with such difficult sequences the sophisticated Frontal Group was able to impose the restrictions on their own choices as quickly as the sophisticated Control Group. Thus there is some evidence that the critical factor in determining the relative performance of the Frontal Group was not the type of memory required by the sequence tasks but rather was the level of testing experience in the DADTA the monkeys had attained before beginning any particular sequence.

If the previous level of testing experience affected the performance of the Frontal Group more than that of the Control Group, the implication is that frontal cortical ablations made the monkeys less able to integrate or compensate for some feature of the training situation. That feature appears to be the continuous shifting of the spatial location of the stimuli. Like the solutions to the random-start 'next-to' problems, the solutions to the sequences were made independent of absolute spatial location by having the stimuli appear in random spatial locations from step to step within each trial. Moreover, this same Frontal Group showed a significant deficit in learning simultaneous two-choice discrimination problems in the DADTA where again the stimuli appeared in random spatial locations from trial to trial but learned similar problems at a normal rate in a Wisconsin General Testing Apparatus where the stimuli remained within the same two locations each trial (Brody, Ungerleider and Pribram, 1977).

Concluding Remarks

The normal performance of the Frontal Group on the initial and the 2-element personal 'next-to' tasks and of the sophisticated members of the Frontal Group on the sequences indicate that neither sequencing *per se* nor personal spatial orientation or spatial memory *per se* is dependent on intact functioning of the frontal cortex. The frontal cortex must be involved in higher-order control of stimulus-response correlation and organization.

A clue to the nature of that higher-order function lies in the difference between the good performance of the monkeys with frontal damage on the free-start versions and their consistent poor performance on the random-start versions of both the extrapersonal and personal 'next-to' tasks. The critical factor producing the frontal deficit on the 'next-to' tasks is the variable nature of the relevant stimulus or the required response—in one case the location of the green cue and in the other the starting location or the direction of movement required.

Moreover, the data strongly suggest that damage to the frontal cortex causes monkeys to be adversely affected by lack of stability in the spatial location of relevant stimuli even when the spatial location provides a context which is irrelevant to the solution of the problem. In order to solve the sequence problems the monkey must learn that the spatial context is not relevant; he must eliminate all hypotheses based on spatial location. However, if the monkey is especially sensitive to spatial distractors, he will have greater difficulty in learning to ignore that aspect of the stimuli. An earlier study utilizing the DADTA (Grueninger and Pribram, 1969) had indicated that irrelevant spatial distractors (an irrelevant stimulus appearing in novel spatial locations) were particularly potent in disrupting the performance of monkeys with frontal ablations on a well-learned task. The present study suggests that when the variable aspects of the stimuli are irrelevant, the disruptive effect of such variability can eventually be circumvented even by monkeys with frontal lesions. When the monkeys with frontal damage finally did learn to ignore the irrelevant shifting spatial context, they had no further difficulty in learning nonspatial discrimination problems (Brody, Ungerleider and Pribram, 1977) or in ordering nonspatial sequences. This ability to eventually ignore irrelevant spatial variabilities may explain why such monkeys are better able to learn object alternations than spatial alternations (Pribram, 1961; Mishkin *et al.*, 1969) despite the fact that both tasks represent unparsed sequences of regularly varying correct choices.

In contrast to the sequence problems, the critical issue for the 'next-to' problems was where to press, not what to press. The spatial context remained relevant to the solution of the problem, but that context varied from trial to trial. It is interesting that although the solution required abstracting the concept of relative spatial position, 'next-to', it was the shifting of the absolute spatial locations which constituted the unreliable context. Thus, in the current 'next-to' tasks, just as in the case of the delayed-response task where the spatial context is relevant but unreliable (Anderson, Hunt, Vander Stoep and Pribram, 1976), frontal damage produced a deficit. The data therefore indicate that *the frontal cortex is essential to the ability to perform tasks in which context varies*. This ability is essential to allow flexibility in response (Pribram, *et al.*, 1964) appropriate to the demands of such tasks. The effect of frontal damage can be seen as a lack of flexibility of response when the context prohibits stable or routine response patterns (as with the 3-element personal 'next-to' task) or it can be manifest as a deficient ability to abstract the relevant stimulus parameters when the cues constituting context vary (as in the sequence tasks, discrimination problems, or the extra-personal 'next-to' task). The interpretation of the current finding as indicating that frontal cortex is essential to an ability to perform tasks in which context varies is not only consistent with other data obtained from monkeys but also provides a framework for understanding the classic finding that patients with damage to the frontal cortex have difficulty generating flexible response patterns in the face of changing environmental demands (for example, Ackerly and Benton, 1948; Milner, 1964; Pribram, *et al.*, 1964; Luria, 1966).

SUMMARY

Normal monkeys and monkeys with resection of anterior frontal or posterior parietal cortex were trained to press a panel next to a green panel as a test of extrapersonal spatial orientation and to press a panel next to their own prior press as a test of personal spatial orientation. All monkeys also learned two sets of sequence problems in which the solutions were made independent of spatial location by randomly shifting the locations of the stimuli after each response within a trial. The Parietal Group was significantly impaired on the extrapersonal 'next-to' task but not the more difficult personal 'next-to' task. The Frontal Group was impaired on both the personal and the extrapersonal 'next-to' tasks but only when the relevant cues shifted spatial locations from trial to trial. The performance of the Parietal Group completely overlapped that of the Normal Group on the sequence problems regardless of the level of testing sophistication the monkeys had attained. In contrast, the Frontal Group demonstrated a significant impairment in learning sequences but only when the monkeys were naive. Once they became sophisticated, they learned each sequence at a normal rate. Their poor performance was attributed to the lack of stability in the spatial location of the stimuli. The data support the view that a distinction between personal and extrapersonal spatial orientation is relevant to posterior parietal function but indicate that neither sequencing *per se* nor personal spatial orientation or spatial memory *per se* is dependent on intact frontal functioning. Rather, the frontal cortex is involved with a higher-order control essential to allow the monkey to perceive the reliable aspects of stimuli contained in a stimulus context full of unreliable noise and to further allow for flexible response pattern appropriate to the demands of a variable context.

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