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DEVELOPMENTAL DETERMINANTS OF CORTICAL PLASTICITY

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Abstract. A central problem in neuropsychology concerns the mechanisms by which functions are restored following injury to the brain. Functional recovery is particularly striking following damage to the cerebrum in early life and accordingly our studies deal with the effects of prefrontal cortical lesions performed on infant monkeys. We describe here two essentially different patterns of behavioral recovery following selective lesions of the dorsolateral and orbital prefrontal cortex. Following orbital lesions in infancy, the monkeys are impaired when tested initially between 12 and 18 months of age but give evidence of substantial recovery when they are retested at 24 months of age. In contrast, monkeys given dorsolateral resection early in life exhibit sparing of function during the initial period of testing but this impunity usually associated with dorsolateral injury in infancy gives way later to a picture of retarded development. We attribute these two patterns of recovery — progressive and regressive — to differential rates of development of the two prefrontal cortical regions involved. Our evidence suggests that while orbital cortex becomes functionally mature by 1 year of age and probably earlier, the elaboration of dorsolateral function is delayed well into the second year of life. We propose that the dorsolateral cortex, by virtue of its relative immaturity at the time of orbital excision, can come in time to subsume the functions of the orbital cortex but that the orbital cortex may be functionally "committed" too early in life to compensate reciprocally for injury sustained by the dorsolateral cortex.

The study of the dorsolateral prefrontal cortex in the adult monkey is intriguing because its removal produces selective, reliable, and on some tests, irrecoverable behavioral impairments. The investigation of this cortex in the infant monkey, by contrast, interests us precisely because its removal fails to result in such deficits. The difference be-

tween the study of lesions in the infant and the adult is more than one of a dissimilarity in outcome, however, for the two types of investigations pose quite different problems. Whereas the essential question confronting the investigator of dorsolateral function in the adult is the nature of processes intrinsic to the dorsolateral cortex itself, the task confronting the student of the early brain-injured is the understanding of the capacities of residual areas, since these are the areas presumably responsible for sustaining the functions of the damaged cortex. Thus it was that our initial approach to the problem of central nervous system plasticity began by searching for a neural substrate that could mediate the recovery of function known to occur following removal of the dorsolateral prefrontal cortex in the infant monkey.

Studies of total prefrontal removals

The area which we selected for study as a potential compensatory site was the orbital prefrontal cortex. Foremost among the reasons for this choice was the close functional and anatomical relationship existing between orbital and dorsolateral cortex. Both are granular cortical areas which receive projections from the dorsomedial nucleus of the thalamus and both are concerned, though in different ways, with performance on delayed-response tasks. In addition, we were aware that the orbital cortex had not been included in the early prefrontal removals that were shown to be compatible with normal delayed-response ability (Akert et al. 1960). As shown in the first panel of Fig. 1, the original study of prefrontal ablations in infant monkeys involved lesions which were confined primarily to the cortex in and around the principal sulcus. Later, Tucker and Kling (1967) extended the size of the prefrontal removals in their own investigations of infants to include all of the cortex on the lateral surface while Harlow et al. (1968) examined the effects of still larger prefrontal removals (Fig. 1, panels 2 and 3). Although these later studies involved lesions which included more extensive damage to the orbital cortex than previously, in neither was the orbital cortex removed entirely, and in neither was there evidence of a diminution in the sparing of delayed-response ability for monkeys operated within the first two months of life. The last panel of Fig. 1 illustrates the prefrontal lobectomy investigated in our own laboratory (Goldman et al. 1970*a*). These lesions, involving complete removal of the orbital as well as the dorsolateral cortex, were perfomed on 51-85 day old monkeys who were subsequently tested on delayed response when they were 12 months of age. The four monkeys given these total prefrontal lobectomies did indeed exhibit a delayed-response deficit.

Although the finding that monkeys with prefrontal lobectomies were

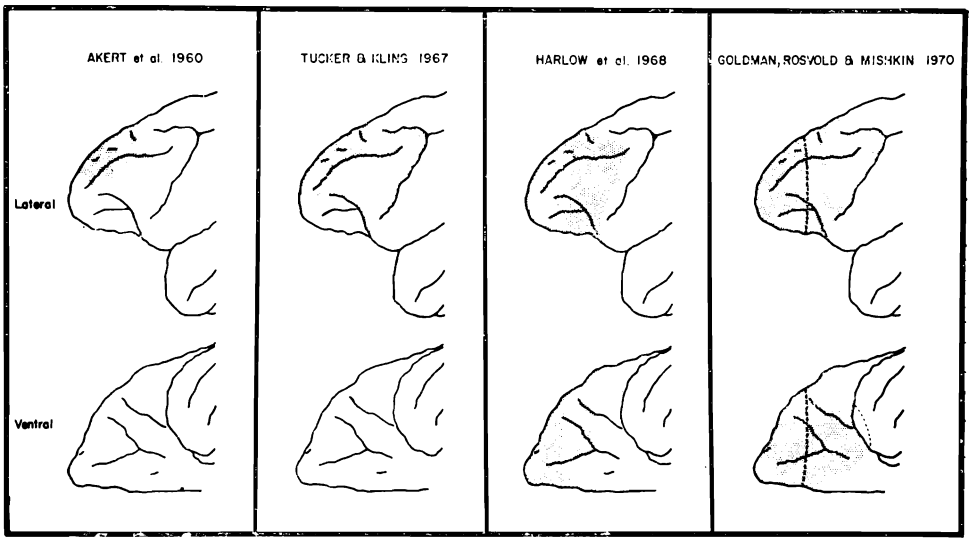

Fig. 1. Diagrammatic illustrations of the prefrontal removals studied by various investigators. The dashed line in the fourth panel of the figure indicates the plane of amputation; the remaining cortex was removed by aspiration.

impaired on delayed response could be interpreted as support for the idea that the orbital cortex played a role in the recovery of dorsolateral function, there were certain difficulties with this interpretation. The most serious, perhaps, was the fact that the deficit was only a moderate one — in spite of the size of the removal. Thus, as may be seen in Fig. 2, although the monkeys lobectomized as infants performed out of the range of unoperated monkeys of their own age on delayed response, they were still considerably less impaired than monkeys given the same lesion later in life. This was true whether the delay imposed was 5 sec in duration or was extremely brief (0-sec) as shown in the figure. Presumably, if the orbital cortex were essential to the recovery process, then its removal should have resulted in a greater loss than it did. Another difficulty with the interpretation is that it did not provide a ready explanation for other impairments exhibited by the early-operated monkeys. In addition to the delayed-response impairment, they were mildly but significantly retarded in learning a visual pattern-discrimination problem and proved to be unable to learn another delayed-response problem, delayed alternation. Within the framework of compensatory mechanisms, it was difficult to understand why the addition of orbital cortex to the dorsolateral removal should be compatible with the partial sparing of one dorsolateral measure, delayed response, and yet preclude sparing on another such measure, delayed alternation. It was also difficult to explain why the compensation of dorsolateral func-

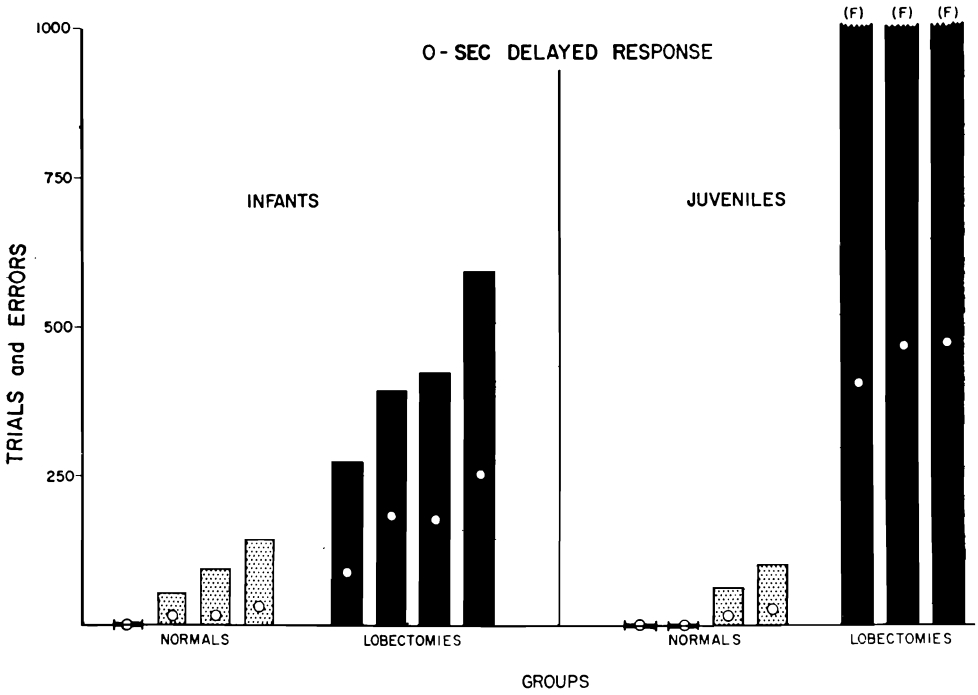

Fig. 2. Performance of individual monkeys on 0-sec delayed response. Bars indicate trials-to-criterion; circles, errors-to-criterion. The infants were operated at 51–85 days of age and tested beginning at 1 year of age; the juveniles were operated between 18 and 24 months of age and tested at 28–34 months. The normal control groups corresponded in age to the operated groups with which they were compared.

tion by orbital cortex would result in an impairment on a task such as the pattern-discrimination problem which is not itself ordinarily impaired by dorsolateral removal. We therefore explored an alternative possibility — that the orbital subdivision of the lobectomy was directly rather than circuitously responsible for the deficits. If this were the case, it would mean that the independent functions mediated by the orbital cortex, unlike those of the dorsolateral cortex, were not recoverable following lesions in the 2-month old monkey.

Some support for this notion was provided by comparing the effects of prefrontal lobectomy in infancy with that of orbital lesions alone made later in life on the three tasks mentioned above — delayed response, visual discrimination, and delayed alternation. According to the differential recovery hypothesis, the impairment profile exhibited by monkeys lobectomized as infants should closely resemble that of the monkeys given orbital lesions as juveniles. Figure 3 presents the results of this comparison along with the results of unoperated controls and

monkeys given dorsolateral resections as juveniles. As shown in the figure, the dorsolateral group exhibited the classical failure on both delayed response and delayed alternation together with normal performance on the visual-discrimination problem. The orbital group, on the other hand, though also failing delayed alternation, showed only a retardation in learning delayed response and a small but significant impairment on the test of visual discrimination. The pattern of deficits exhibited by the monkeys given orbital lesions late in life thus corresponded closely to that of the monkeys lobectomized in infancy.

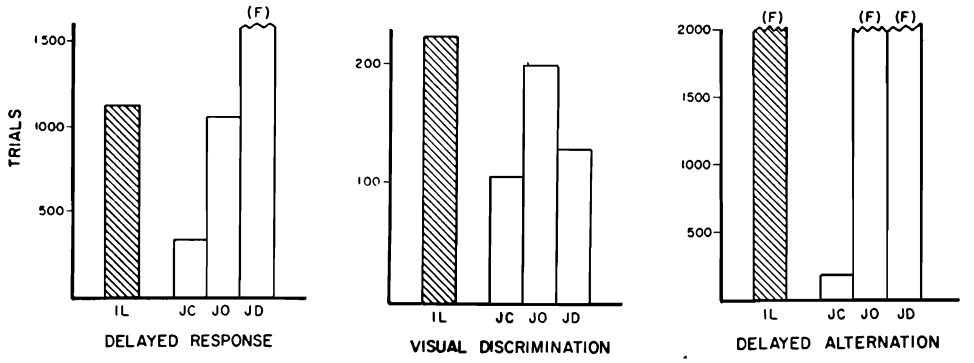

Fig. 3. Mean trials-to-criterion on each of the three tasks by the infant lobectomized group (IL) and three juvenile groups, control (JC), orbital (JO), and dorsolateral (JD). These scores on delayed response combine the results of a 0-sec condition with those on longer delays.

While the degree of impairment on delayed response was one way to differentiate the contributions of the orbital and dorsolateral subdivisions of the lobectomy, there were other tests which more sharply dissociated the functions of these two regions (Goldman et al. 1970*b*). Object discrimination reversal, for example, is a test that is selectively sensitive to the perseverative disorder produced by orbital lesions while conversely, a conditional position response test is exclusively vulnerable to the spatial disorder resulting from dorsolateral removals. Evidence corroborating this double dissociation of deficits in late-operated monkeys is presented in the upper part of Fig. 4. As indicated there, only the groups whose lesions involved the orbital cortex were impaired on object reversal, while on the conditional position response test, conversely, only the groups whose lesions involved the dorsolateral cortex exhibited impairment. The findings in monkeys lobectomized in infancy and their age-matched unoperated controls are shown in the lower half of the figure. If the functions of the dorsolateral cortex are spared while those of the orbital cortex are not, following prefrontal lobectomy in infancy,

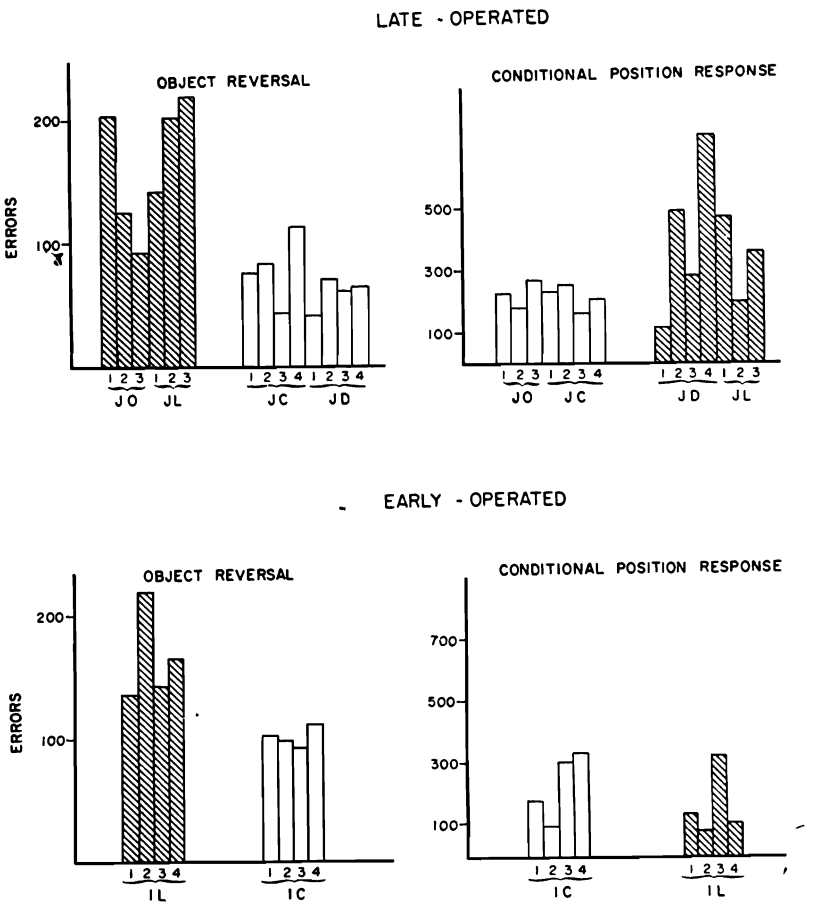

Fig. 4. Upper: error scores of the older age groups on object reversal and the conditional position response test. JO, juvenile orbital; JL, juvenile lobectomy; JC, juvenile unoperated controls; JD, juvenile dorsolateral. Lower: error scores of the younger age groups on the same tests. IL, infant lobectomy; IC infant unoperated controls.

then the early-operated monkeys should be impaired on object reversal but should exhibit sparing on the conditional position response test; and, in fact, those were the findings obtained.

Studies of selective prefrontal removals

So far all of the evidence supporting the differential recovery hypothesis had been based on monkeys lobectomized in infancy. Although this evidence was highly consistent, it was clear that a more direct test of the hypothesis was needed and could be provided by comparing the effects of selective orbital and dorsolateral lesions performed in in-

fancy with identical lesions made later in life (Goldman 1971). The prediction was straightforward: on delayed-response tasks, the monkeys given orbital lesions in infancy should be as impaired as those with the same lesions performed later in life while monkeys with early dorsolateral removals should be far less impaired than their late-operated counterparts. The monkeys in this experiment were treated exactly as those in the previous study had been: the age at surgery, the age when testing began, the order and method of testing were all the same in both experiments.

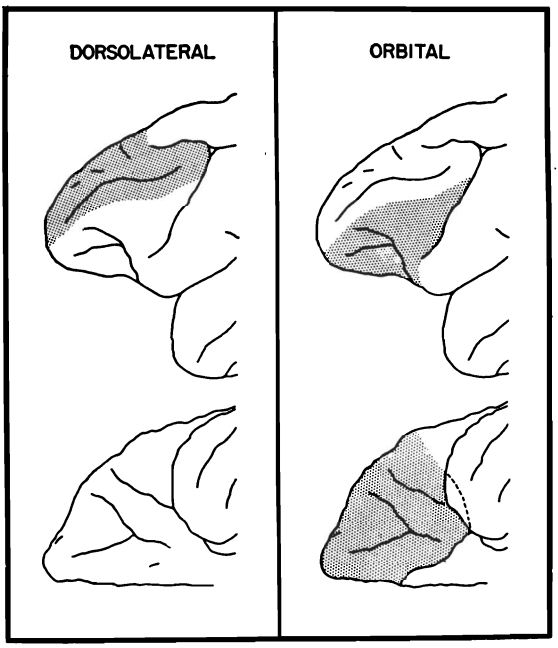

Fig. 5. Diagrammatic illustrations of the selective prefrontal lesions.

The orbital and dorsolateral resections are illustrated in Fig. 5 and the major behavioral results appear in Fig. 6–8. For purposes of comparison, the results of unoperated and lobectomized monkeys within each age category are also included in these figures. On delayed response (Fig. 6) and delayed alternation (Fig. 7), as predicted, monkeys given dorsolateral lesions in infancy were significantly less impaired than monkeys given the same operation as juveniles. In contrast, monkeys given orbital lesions in infancy were just as impaired as those with orbital lesions performed later in life. On object reversal, also, the results supported the predictions. Unlike the delayed-response tasks, object reversal is selectively sensitive to the perseverative disorder produced by orbital frontal lesions and neither dorsolateral lesions performed in infancy nor later in life should impair performance on this test. As may

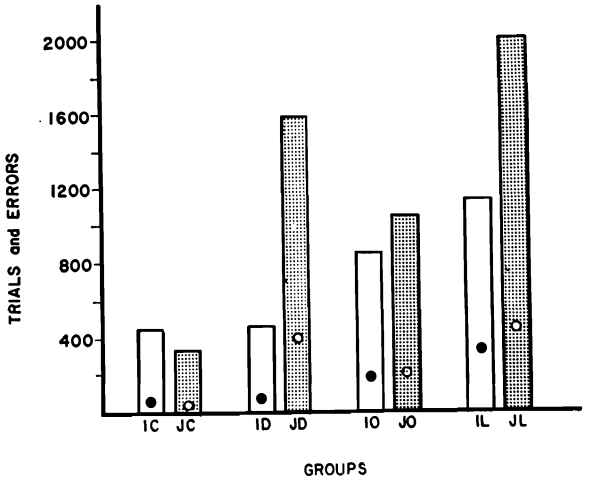

Fig. 6. Performance on delayed response. Bars indicate trials-to-criterion; circles, errors-to-criterion. IC, infant unoperated control group; JC, juvenile unoperated controls; ID, group given dorsolateral lesions in infancy; JD, group given dorsolateral lesions in the juvenile period; IO, group given orbital lesions as infants; JO, group given orbital lesions as juveniles; IL, group lobectomized as infants; JL, group lobectomized as juveniles.

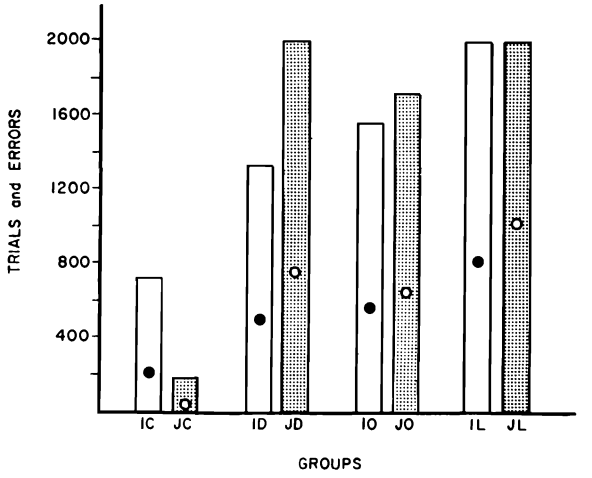

Fig. 7. Performance of the eight groups on delayed alternation. Bars indicate trials-to-criterion; circles, errors-to-criterion. Abbreviations as for Fig. 6.

be seen in Fig. 8, again as predicted, only those groups whose lesions involved the orbital cortex were impaired while monkeys with dorsolateral removals, irrespective of age at surgery, performed as well as controls.

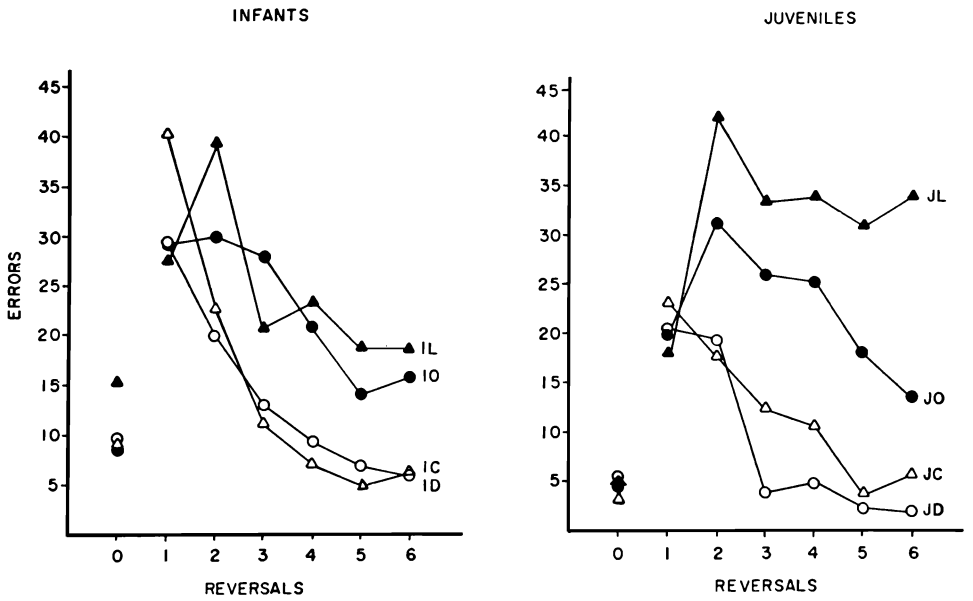

Fig. 8. Performance of the eight groups on object reversal. Scores on the initial discrimination (reversal 0) and each of the subsequent six reversals are shown. Abbreviations as for Fig. 6.

Although the results obtained following the selective lesions were in good agreement with the predictions and thus seemed to provide strong support for the differential recovery hypothesis, nevertheless, there was some indication that these data were not as confirmatory as they might at first appear. Despite the statistically significant findings, there were important exceptions to the group trends in the performance of individual monkeys on the delayed alternation task. Of the four monkeys given dorsolateral lesions in infancy, two learned the task within normal limits, a third, though failing to reach criterion, performed at 82–87% correct throughout most of the training, and a fourth was severely impaired. Of the four monkeys given orbital lesions in infancy, the result was different but the pattern of variability was the same: two failed the task, one was moderately impaired — learning only after 1840 trials – but the fourth learned the task well within the normal range of scores. It was this last monkey's performance that presented a particularly serious problem for interpretation since it was difficult to maintain the notion that orbital function cannot be spared in light of his excellent score. At the same time, it seemed unreasonable to relinquish the notion merely on the basis of one animal's score on one test when by far the greater bulk of evidence seemed to support it.

Additional findings

A resolution to this quandary was suggested by some additional findings. Early in our investigations we had begun to retest the monkeys on delayed alternation after they had completed the test battery and just before they were sacrificed. We did not anticipate any appreciable changes in performance but thought that retesting on one of the measures, particularly one that gave the least evidence of recovery, would be a reasonable control for maturational effects if there were to be any. Thus, we had available retest scores on the delayed-alternation problem for all but one of the 35 monkeys that had served as subjects since the inception of these experiments. When the monkeys were first tested on this problem, the early-operated groups and their unoperated controls were approximately 15 months of age while the older operated and unoperated groups ranged from 31–37 months of age. All groups were retested on the problem about 9 months later when the younger monkeys were 24 months old and the older ones now 40–46 months of age. The only difference between the initial and retest procedures was that the former allowed 2000 trials for learning whereas the latter limited the training variously to 500 or 1000 trials. Retesting the monkeys on delayed alternation turned out to provide some largely unexpected but illuminating results. These appear in Table I.

As may be seen in the Table I, the orbital monkey (IO-1) that had learned the task within normal limits at the 15-month stage was no longer the exception — but rather was simply precocious. By 24 months of age, all of the monkeys given orbital lesions in infancy were able to solve the problem, as IO-1 had done at the earlier stage, and their retest scores were not significantly different from those of the unoperated controls. In contrast to the rather consistent success of the monkeys with orbital lesions in infancy, variability still characterized the retest scores of the monkeys given dorsolateral lesions in infancy. Two of the monkeys in this group reached criterion but two others failed the retest even though one of them had previously learned the task. Their error scores, moreover, were greater than and did not overlap with those of the unoperated controls. Although the lobectomized monkeys and most of the juveniles had not been given as extensive an opportunity for relearning as the groups with selective lesions performed in infancy, it is doubtful that more than one or two of these monkeys would have succeeded in reaching criterion even with more extended training. Despite this procedural difficulty, these data are more than adequate to indicate a change during development in the relative status of the two groups given dorsolateral and orbital lesions in infancy. Thus, when the early-operated monkeys were tested on delayed alternation at 15 months of

TABLE I

Initial and retest performance on delayed alternation

Subjects	Infants				Subjects	Juveniles			
	Initial (15 months)		Retest (24 months)			Initial (15 months)		Retest (24 months)	
	T[a]	(E)[b]	T	(E)		T	(E)	T	(E)
IC-1	340	(85)	420	(97)	JC-1	240	(48)	30	(3)
IC-2	260	(79)	20	(3)	JC-2	380	(90)	0	(0)
IC-3	850	(250)	500	(86)[c]	JC-3	10	(2)	30	(8)
IC-4	600	(146)	20	(7)	JC-4	50	(15)	0	(0)
IC-5	950	(250)	210	(78)					
IC-6	800	(207)	290	(92)					
IC-7	660	(159)	500	(124)					
IC-8	610	(218)	250	(96)					
IC-9	1380	(463)	190	(47)					
ID-1	2000	(934)[c]	1000	(364)[c]	JD-1	2000	(614)[c]	500	(138)[c]
ID-2	430	(144)	1000	(246)[c]	JD-2	2000	(778)[c]	500	(215)[c]
ID-3	870	(252)	500	(125)	JD-3	2000	(768)[c]	—	—
ID-4	2000	(643)[c]	650	(197)	JD-4	2000	(837)[c]	1000	(401)[c]
IO-1	410	(148)	660	(237)	JO-1	1160	(378)	500	(194)[c]
IO-2	1840	(567)	270	(97)	JO-2	2000	(542)[c]	500	(225)[c]
IO-3	2000	(908)[c]	910	(287)	JO-3	2000	(1033)[c]	1000	(489)[c]
IO-4	2000	(681)[c]	140	(74)					
IL-1	2000	(619)[c]	500	(108)[c]	JL-1	2000	(971)[c]	500	(244)[c]
IL-2	2000	(853)[c]	500	(214)[c]	JL-2	2000	(1002)[c]	500	(201)[c]
IL-3	2000	(924)[c]	500	(243)[c]	JL-3	2000	(1102)[c]	500	(265)[c]
IL-4	2000	(877)[c]	500	(241)[c]					

a Trials-to-criterion.
b Errors-to-criterion.
c Failed to reach criterion within the limits of testing.

age, those given dorsolateral lesions did not differ significantly from unoperated controls and were considerably less impaired than juveniles with identical removals while early-operated monkeys with orbital lesions were significantly worse than controls and exhibited impairments as substantial and definitive as those shown by monkeys given orbital lesions as juveniles. At the 24-month stage, however, the two groups reversed standing: the group with dorsolateral lesions failed to keep pace with the unoperated monkeys whereas the monkeys with orbital lesions had caught up with them to an impressive degree. The reversal in findings obtained when the monkeys were retested at 24 months of age resolved the dilemma created initially by the precocious monkey. Although the differential recovery hypothesis could be considered cor-

rect insofar as the effects of the early lesions on behavior at the one-year level were concerned, it was not, after all, comprehensive enough to deal with the longitudinal spectrum of effects produced by these lesions.

A reformulation

These additional findings go far beyond calling attention to the limitations of the differential recovery hypothesis, however. More importantly, they provide some clues to the nature of plasticity and to the mechanisms by which the central nervous system can respond to early insult. The findings obtained following selective lesions in infancy provide examples in functionally related cortical systems of two expressly different patterns of recovery — one, exemplified in the group with early orbital lesions, in which initial deficits were followed by subsequent recovery — and the other, exemplified by the monkeys with early dorsolateral lesions, in which initial sparing effects gave way to a picture of retarded development. On the basis of these results, we have proposed (Goldman 1971) that there is a central principle governing whether or not recovery will occur and whether it will follow the progressive or the regressive pattern.

The principle involved has to do with the maturational status of functionally related areas that remain undamaged by the early brain injury. If such residual areas are functionally immature, i.e., relatively "uncommitted" to their own course of development, then they may be more susceptible than otherwise to modifications induced by injury to a related part. If, on the other hand, surviving tissue is already "committed" or relatively mature, then presumably it will have lost this capacity for reorganization, and hence will be unable to assume new responsibilities.

Regarding the prefrontal cortical areas, the available evidence suggests that the orbital cortex develops considerably earlier in ontogeny than the dorsolateral cortex. When the monkeys given orbital lesions in infancy were tested between 12 and 18 months of age, they exhibited impairments that were just as severe and just as selective as those exhibited by monkeys with identical removals made later in life. Although the early-operated group eventually recovered the capacity to perform delayed alternation, their deficits at the one-year stage indicate clearly that the orbital cortex is well developed by that age, if not earlier. Turning to the dorsolateral cortex, several lines of evidence converge to indicate a later course of development for this prefrontal subdivision. In the present study, evidence of deficiencies resulting from dorsolateral removal in infancy first became apparent only when the

monkeys were retested at 24 months of age. Also in the present study, 15-month old unoperated monkeys were not as proficient on the delayed-alternation problem as were older unoperated monkeys (*see* Fig. 7). Since delayed-alternation performance depends on the integrity of both the orbital and dorsolateral cortical areas and given the evidence for the prior development of orbital cortex, the poorer performance of the unperated monkeys at 15 months of age could well reflect the immaturity of the dorsolateral contribution at that age. Finally, Harlow et al. (1968) studied the effects of dorsolateral lesions (topectomies) made at different stages of early life and found that such lesions were not effective in producing substantial delayed-response deficits unless they were made as late as 18 or 24 month of age. (A 12-month operated group performed consistently more poorly than either younger or older groups with identical or larger removals; their deviant behavior was attributed by Harlow to an unfortunate sampling bias). These various lines of evidence suggest that whereas the orbital cortex may become functionally mature by one year of age, the dorsolateral cortex, by contrast, does not approach functional maturity until well into the second year of life. Extrapolating to the infantile period, it seems reasonable to suppose that the dorsolateral cortex would be far less "committed" than the orbital cortex and hence should have a greater potential for assuming a compensatory function.

This analysis permits us to explain both the dramatic recovery at 24 months of age exhibited by monkeys given orbital lesions as infants and the less impressive performance at this age by the monkeys given dorsolateral lesions as infants. We propose that the dorsolateral cortex mediates the recovery of function demonstrated by the early-operated orbital monkeys, and that it derives its capacity for compensation both by virtue of its relatedness to orbital cortex and its relative immaturity at the time of brain injury. The full expression of this compensatory capacity, to be sure, is delayed until the dorsolateral cortex itself becomes functionally mature — sometime between 18 and 24 months of age. Supporting this interpretation is the finding that when the dorsolateral cortex is removed along with the orbital cortex in infancy, as it was in case of the monkeys lobectomized in infancy, recovery at the 24-month period does not ensue.

It would seem reasonable to suppose that if the dorsolateral cortex can compensate for the loss of orbital cortex in infancy, the reverse should also be true. The compensatory relationship does not appear to be reciprocal, however. If the orbital cortex develops earlier in ontogeny, as we have suggested, then presumably its development is sufficiently advanced at the time of dorsolateral removal that assumption of other

functions is precluded. Indeed, it is difficult to think of any area remaining after dorsolateral removal at 2 months of age that could meet the postulated requirements (functionally related, developmentally "uncommitted") necessary for taking over dorsolateral function. Until now, however, it has been generally assumed that the instances of sparing following dorsolateral lesions in infancy did indeed reflect just such a reparative process. Kling and Tucker (1968), for example, have provided evidence that the caudate nucleus may be involved in such a process since when the caudate is removed along with the dorsolateral cortex in infancy, the sparing of delayed-response capacity obtained with the cortical ablation alone is completely abolished. An alternative interpretation of these phenomena which emerges from the present analysis is that the dorsolateral cortex was not contributing materially to delayed-response functions in the first place because it was not functionally mature and that the caudate nucleus alone is responsible for mediating these behaviors at the earlier testing ages usually employed. Indeed, we have found that small lesions of the caudate alone in infancy are sufficient to produce serious impairments at 1 year of age on just those tests that at the same age are not impaired by dorsolateral lesions in infancy (P. S. Goldman and H. E. Rosvold, unpublished data). In this view, the caudate nucleus, already functionally "committed" by one year of age, does not "take over" the functions of the damaged cortex in a compensatory sense but at that age is the structure responsible for mediating many of the behaviors that the dorsolateral cortex will ultimately assume. In the course of development, the dorsolateral cortex would come to play a more dominant role in mediating delayed-response functions and as it did, its absence would become increasingly more evident. Thus, the idea that the dorsolateral cortex has a protracted development, extending well into the second year of life, can account for why the monkeys with dorsolateral lesions in the present study failed to improve with age, just as it also accounts for why those with orbital ablations did.

Other issues

The present reformulation provides a conceptual framework for dealing with several important issues surrounding the plasticity problem. For one, it points to what may be the essential difference in capacity of the infant and adult nervous systems for compensation. Only in the infant brain-injured would there be the possibility of areas still "uncommitted" at the time of injury and therefore capable of modification while in the adult, all pathways remaining after injury would presumably be "fixed". It may be that the adult brain relies more heavily on

"strategic" modes of recovery wherein various tasks can be accomplished by alternative strategies involving neural substrates performing as they normally would, whereas the infant depends more on a "structural" mode in which functions are subsumed by structures not normally concerned with them. Evidence of structural reorganization in developing nervous systems as a consequence of injury is now beginning to appear (Hicks and D'Amato 1970, Schneider 1970). A structural remodeling of the nervous system, assumed to be possible only when residual areas are not yet "committed", would seem to provide the kind of basis needed to explain the more striking restitution of function following equivalent injuries in the young than the old.

Another commanding issue concerns the apparent difference in the effect of early lesions in nonhuman primates and in man. Teuber and Rudel (1962) have aptly pointed out that whereas the results of animal studies have given a rather uniform picture of less disability from early than from late lesions, the consequences of early brain damage in children are more complex — indicating more severe as well as less severe effects of early as compared with later brain damage. Their study provided evidence in children of behaviors for which the effects of early injury appear only with delay, as development progresses and of other behaviors for which there is an immediate effect which disappears with age. Interestingly, the function which Teuber and Rudel identified as becoming increasingly more impaired by early injury as development proceeded turns out to be one associated with frontal-lobe damage in adults. It is tempting to speculate that the patients in these experiments had sustained damage to the dorsolateral prefrontal cortex and that the impairment in question involved spatial-mnemonic abilities analagous to those associated with such lesions in monkeys.

Happily, the present results parallel the findings in man by establishing evidence in monkeys for both progressive and regressive sequelae of early injury to the brain. The theoretical formulation based on these finding also provides for heterogeneous effects, suggesting as it does that recovery of function is not an immutable consequence of early injury and that it will occur only under certain specifiable conditions. This kind of correspondence between findings in monkeys and man raises the hope that the outcome of investigations on nonhuman forms can ultimately be extrapolated to conditions of developmental neuropathology in man.

Perhaps it would not be inappropriate to conclude this discussion by attempting such an extrapolation. No discussion of cerebral plasticity would be complete without at least touching upon its clearest manifestation in man: the sparing of language abilities after early brain injury.

It is well known (Penfield and Roberts 1959, Lenneberg 1968, Teuber 1970) that damage sustained by the hemisphere dominant for language within the first 2 years of life fails to produce the severe aphasic disorders that result from such cerebral injuries in adulthood. This phenomenon provides an excellent example of functional plasticity in the human brain wherein one part appears to have the capacity for assuming the functions of a damaged part. It is generally believed (Penfield and Roberts 1959, Lenneberg 1968, Teuber 1970) that the contralateral hemisphere is involved in the mediation of this recovery, at least under certain conditions. Our analysis of plasticity in monkeys would lead us to suppose that the intact hemisphere in these cases derives its capacity for compensation of language function because some part of it, association cortex presumably, is relatively "uncommitted" at the time the hemisphere destined to be dominant is injured. The association areas of both hemispheres could develop slowly so that injury to either would be compensated by the other or the more interesting possibility could apply — that there is actually an asymmetry in their functional development. Thus, if the nondominant hemisphere were to develop later in ontogeny than the dominant hemisphere, the former should be relatively immature and capable of subsuming the functions of the latter. On the other hand, however, the dominant hemisphere, to the extent that it were to become "committed" relatively early in life, should not compensate reciprocally for early damage to the nondominant side. This hypothesis of asymmetrical development could be tested by determining whether or not the nonverbal, visual-spatial, perceptual functions of the right hemisphere are spared to the same degree that the language functions of the left hemisphere are, after selective injury at early ages.

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