

BRAIN MATURATION
AND COGNITIVE DEVELOPMENT

Comparative and Cross-Cultural Perspectives

Edited by

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*Sponsored by the
Social Science Research Council*



ALDINE DE GRUYTER
New York

1991

*Frontal Lobe Involvement in Cognitive Changes
During the First Year of Life*

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The period of 6–12 months of age is a time of major change in the behaviors and cognitive abilities of human infants. The same changes, at roughly the same age, are found in infants in diverse physical, cultural, and social environments. This has led many to speculate that these changes may be, at least in part, biologically based. This chapter reports evidence suggesting that maturation of the frontal lobe¹ may play a role in some of the cognitive changes occurring in human infants between 6 and 12 months of age.

This line of inquiry has involved (1) studying the developmental progression of human infants and infant monkeys on tasks thought to depend on frontal cortex function, and (2) taking those same tasks and determining directly whether they are linked specifically to frontal cortex through studies of brain function in adult and infant monkeys. It has been important to supplement work on brain function in adult animals with work on infant animals because of the possibility that different neural systems might underlie successful performance of the tasks at different ages.

One of the classic markers of developmental change between 6 and 12 months is improved performance on Piaget's A \bar{B} task (pronounced "A not B") (Piaget, 1954 [1937]). Since the task was originally devised it has been used extensively with infants (for reviews see Gratch, 1975; Schuberth, 1982; Harris, 1987; Wellman et al., 1987). It turns out that A \bar{B} is almost identical to the classic test for frontal lobe function in nonhuman primates, delayed response (DR). Although both A \bar{B} and DR have been in use for half a century, the psychologists studying human infant development and the neuroscientists studying brain function did not know they were using essentially the same task and their work remained separate. The initial insight that frontal lobe maturation might underlie some of the behavior changes between 6 and 12 months was suggested by the similarity between A \bar{B} and DR and the dependence of DR on frontal cortex.

In both \overline{AB} and DR, the subject watches as a desired object is hidden in one of two identical wells, the wells are covered simultaneously, a delay of 0–10 sec is imposed, and then the subject is allowed to reach. Within-trial procedures are exactly the same on the two tasks. \overline{AB} and DR differ only in how side of hiding is varied over trials. In DR, side of hiding is varied randomly; in \overline{AB} , the reward is consistently hidden on one side until the subject is correct, then side of hiding is reversed and the procedure repeated.

Evidence Linking Delayed Response to the Frontal Lobe

Success on DR has consistently been shown to depend on frontal lobe function (specifically, dorsolateral prefrontal cortex) by virtually every anatomical, physiological, and pharmacological technique in existence. DR was first used to study functions localized to frontal cortex by Jacobsen (1935, 1936), and scores of lesion studies have replicated Jacobsen's finding that animals fail DR following bilateral lesions of frontal cortex (major reviews include Nauta, 1971; Rosvold, 1972; Markowitsch and Pritzel, 1977; Rosenkilde, 1979; Fuster, 1980). Equally large lesions elsewhere in the brain, e.g., parietal cortex, do not produce deficits on DR (e.g., Jacobsen, 1936; Meyer et al., 1951; Harlow et al., 1952). Lesions of frontal cortex that produce deficits on DR do not produce deficits on other tasks, such as visual discrimination (e.g., Jacobsen, 1936; Harlow and Dagnon, 1943; Pohl, 1973). In short, DR appears to be sensitive to damage specifically to dorsolateral prefrontal cortex and damage to dorsolateral prefrontal cortex appears to produce deficits only on specific tasks, such as DR.

These results have been replicated with techniques that enable experimenters to temporarily and reversibly interrupt functioning of a localized neural region. Thus, DR has also been linked to the dorsolateral prefrontal cortex using localized cooling (Fuster and Alexander, 1971; Bauer and Fuster, 1976; Alexander and Goldman, 1978), localized electrical stimulation (Weiskrantz et al., 1962; Stamm, 1969; Stamm and Rosen, 1969), and localized dopamine depletion (depleted using 6-OHDA, deficits reversed by L-Dopa) (Brozoski et al., 1979). Because these techniques interrupt functioning only temporarily, they effectively eliminate neural reorganization or secondary degeneration as competing explanations for observed behavioral effects. Moreover, because animals can be tested before and after cooling, stimulation, or dopamine depletion, each animal can serve as his or her own control, eliminating concerns about between-group differences.

Inferring function from dysfunction can be problematic, however. Deficits resulting from permanent damage or temporary inactivation do not always give an accurate indication of the role played by a neural region in intact, normally functioning subjects. For this reason it is important that the link between DR and the frontal lobe has been confirmed by techniques that assess patterns of functioning in the intact brain. Stamm (1969) and Stamm and Rosen (1969) con-

firmed this link by measuring surface negative steady potential shifts. Niki (1974), Fuster and Alexander (1971), and Fuster (1973) implanted micro-electrodes and recorded single unit activity, demonstrating the importance of frontal lobe firing for correct performance of DR. DR trials on which monkeys reached correctly are most often those trials on which there has been increased firing of neurons in dorsolateral prefrontal cortex during the delay period of the trial. Finally, using 2-deoxyglucose metabolic labeling, Bugbee and Goldman-Rakic (1981) demonstrated that local glucose utilization is elevated in dorsolateral prefrontal cortex during performance of DR, while other areas (e.g., motor cortex) show no changes relative to baseline during DR performance.

All of this work taken together, representing as it does such diverse experimental approaches, makes the link between DR and dorsolateral prefrontal cortex essentially incontrovertible.

Evidence of the Similarity between the Performance of Human Infants on \overline{AB} and the Performance of Monkeys with Lesions of Frontal Cortex on Delayed Response

The performance of infants from 7½ to 9 months on \overline{AB} matches that of monkeys with lesions of dorsolateral prefrontal cortex in striking detail. At delays as brief as 1–5 sec, infants fail \overline{AB} and frontally lesioned monkeys fail DR (*infants*: Evans, 1973; Gratch et al., 1974; Diamond, 1985; *monkeys*: Harlow et al., 1952; Battig et al., 1960; Goldman and Rosvold, 1970; Fuster and Alexander, 1971). This is true whether the hiding places differ in left–right location (*infants*: Gratch and Lander, 1971; Diamond, 1985; *monkeys*: Harlow et al., 1952; Goldman et al., 1970) or up–down location (*infants*: Butterworth, 1976; *monkeys*: Fuster, 1980). However, both groups of subjects succeed when there is no delay (*infants*: Gratch et al., 1974; Harris, 1973; *monkeys*: Harlow et al., 1952; Battig et al., 1960; Goldman et al., 1970; Fuster and Alexander, 1971), or when they are allowed to keep looking at, or orienting their body toward, the correct well during the delay (*infants*: Cornell, 1979; Fox et al., 1979; Diamond, 1985; *monkeys*: Battig et al., 1969; Miles and Blomquist, 1960; Pinsker and French, 1967). Both are able to learn to associate a landmark with the correct well, and to use that information to reach correctly even at long delays (*infants*: Butterworth et al., 1982; Diamond, 1983; *monkeys*: Pohl, 1973).

Another task closely linked to frontal lobe function is Spatial Reversal. Here, side of hiding is varied in a manner more similar to \overline{AB} : the reward is always hidden on one side until the subject is correct, then it is hidden on the other side and the procedure repeated. In \overline{AB} , side of hiding is reversed after the subject has reached correctly on two trials in a row. In Spatial Reversal, side of hiding is reversed after the subject has reached correctly on 90% of 30 or 100 trials, thus days of testing often occur before side of hiding is reversed. Although \overline{AB} and Spatial Reversal are similar in the manner in which side of hiding is determined,

they differ in an important within-trial procedure: in Spatial Reversal the subject does not see where the reward is hidden, whereas in $A\bar{B}$ and DR the hiding is done in full view.

Spatial Reversal requires the subject to deduce where the reward is hidden on the basis of feedback. Initially, the reward is always hidden in the same place. If the subject reaches there he gets the reward, if not he gets nothing. Animals with frontal lobe damage have no difficulty learning this initial spatial discrimination (e.g., Gross and Weiskrantz, 1962; Goldman and Rosvold, 1970). When side of hiding is reversed, however, frontally operated animals are impaired; they persist in reaching to the previously correct place (e.g., Butter, 1969; Mishkin et al., 1969; Goldman & Rosvold, 1970; Butters et al., 1969.)

This is very similar to the pattern of performance of infants on $A\bar{B}$: they are correct at the first place the reward is hidden, but when side of hiding is reversed errors appear: infants persist in reaching to the previously correct place (Harris, 1973; Gratch et al., 1974; Diamond, 1985).

Failure on DR and Spatial Reversal is the hallmark of lesions to the dorsolateral prefrontal region of the frontal lobe. $A\bar{B}$ appears to be a composite of DR and Spatial Reversal: identical to DR on within-trial procedures, similar to Spatial Reversal on between-trial procedures.

The Wisconsin Card Sorting Test was designed to be an adaptation of the Spatial Reversal task appropriate for human adults (Berg, 1948; Grant and Berg, 1948), and it has become the classic test for damage of the frontal lobe, especially dorsolateral prefrontal cortex (Milner, 1963, 1964). On this test, the subject is required to deduce the correct criterion (color, shape, or number) for sorting a deck of cards on the basis of feedback.

Adult patients with damage to frontal cortex learn the initial sorting criterion on the Wisconsin Card Sort normally but are impaired when the criterion is switched; nonhuman primates with frontal cortex damage learn the initial spatial discrimination normally on Spatial Reversal but are impaired when side of hiding is reversed: 7½- to 9-month-old infants are able to correctly find a toy at the first place it is hidden during $A\bar{B}$ testing, but err when side of hiding is reversed.

Statement of Hypothesis and Experimental Plan

Because (1) $A\bar{B}$ and DR are such similar tasks, (2) DR has been so firmly linked to frontal cortex function in nonhuman primates, and (3) the performance of human infants on $A\bar{B}$ is so similar to the performance of nonhuman primates with lesions of frontal cortex on DR, I hypothesized that maturation of frontal cortex might make possible the improved performance on $A\bar{B}$ observed in infants from 7½ to 12 months of age. Further support for this came from $A\bar{B}$'s similarity to another marker of frontal lobe function in the monkey, Spatial Reversal, and from $A\bar{B}$'s similarity to the best marker for frontal lobe function in human adults, the Wisconsin Card Sort. If maturation of the frontal lobe does underlie some of

the cognitive advances between 7½ and 12 months, then infants should improve during that age range not only on $A\bar{B}$, but on other tests requiring cognitive abilities dependent on the frontal lobe.

To test this hypothesis infants were administered two tasks, both similar to ones linked to frontal cortex function, but otherwise very dissimilar from one another. Twenty-five full-term infants (11 male, 14 female) were studied longitudinally, with testing on both tasks every 2 weeks from roughly 6 to 12 months. To control for repeated testing, another 84 children were tested only once. One of the tasks on which the infants were tested was $A\bar{B}$ (Diamond, 1985). The second task was quite different from $A\bar{B}$ to eliminate the possibility that an apparent link to frontal cortex functioning might be due to some artifact of the $A\bar{B}$ paradigm. I called the second task "Object Retrieval" (Diamond, 1981, submitted).

Object Retrieval requires infants to retrieve a toy from a simple transparent box open on one side. Although the toy can be seen through the box, the infant must reach around to the opening to actually obtain the toy. The idea for Object Retrieval came from a task on which Moll and Kuypers (1977) had demonstrated impairments following lesions of the frontal lobe³ in monkeys: food could be seen beneath the center of a transparent floor plate, but the only route to the food was through a hole in the plate's side. Monkeys with lesions of the frontal lobe reached straight for the food at the center of the plate, although normal monkeys and those with lesions elsewhere had no difficulty making the appropriate detour. When a unilateral frontal lobe lesion was combined with a commissurotomy, the hand contralateral to the lesioned hemisphere persisted in reaching at the plate's center, while the hand connected to the intact hemisphere of the same monkey reached through the hole to the food!

Testing infants on $A\bar{B}$ and Object Retrieval was only the first step toward testing the hypothesis, however. No direct evidence on brain function was obtained from the infants because of lack of safe, noninvasive techniques for studying the brain. Therefore, step 2 was to administer $A\bar{B}$ and Object Retrieval, the exact tasks on which developmental progressions had been charted in infants, to nonhuman primates with lesions of the frontal lobe (Diamond and Goldman-Rakic, 1985, 1989). The critical questions were would they be impaired on these tasks and would their errors be similar to those made by the younger infants. Nine adult rhesus monkeys (*Macaca mulatta*) were tested every weekday for 15 weeks. Three animals received bilateral lesions of dorsolateral prefrontal cortex (Brodmann's areas 8, 9, and 10), three received bilateral parietal cortex lesions (Brodmann's area 7B), and three were unoperated. All ablations were bilateral, symmetrical, and performed in one stage. The prefrontal and parietal lesions were comparable in size (see Figure 1). A minimum of 2 weeks was allowed for postoperative recovery.

The next most likely neural region to be related to $A\bar{B}$ and Object Retrieval performance was the hippocampus because of the importance of the hippocam-

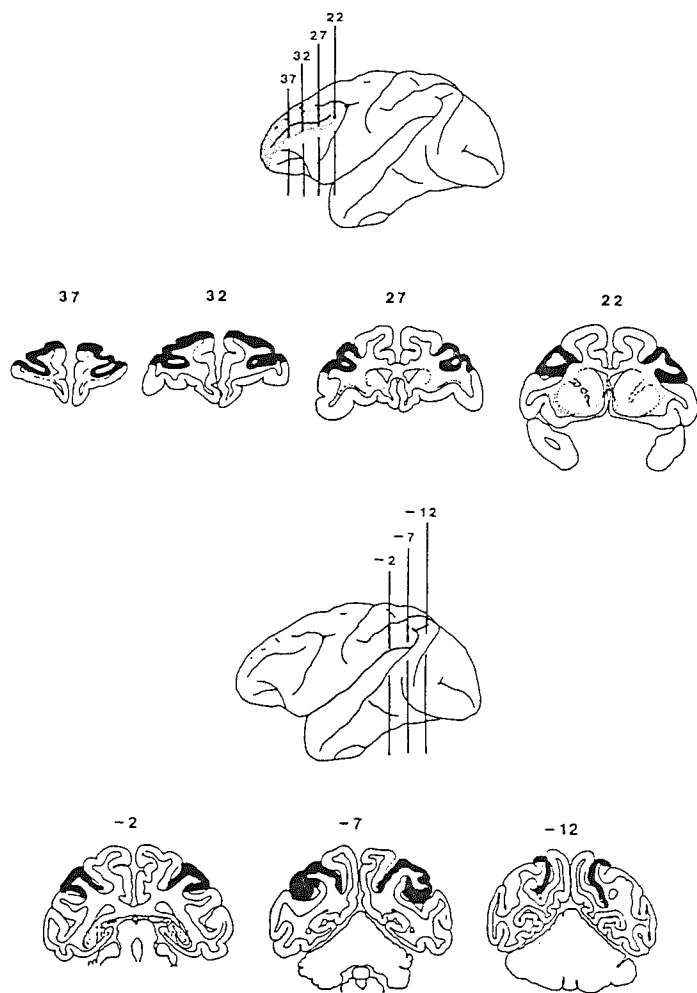


Figure 1. Diagram of intended lesions to dorsolateral prefrontal cortex and inferior parietal cortex, projected on the left hemisphere and in coronal sections. The prefrontal site is shown above and the parietal site below. The dorsolateral prefrontal lesions included cortex in both banks of the principal sulcus, the anterior bank of the arcuate sulcus, and all tissue on the dorsolateral surface rostral of the arcuate sulcus (Brodmann's areas 8, 9, and 10), similar to lesions reported in Goldman (1971). The parietal lesions included the posterior bank of the intraparietal sulcus, the anterior bank of the superior temporal sulcus for about 10 mm, and all cortex between the two sulci including roughly 4 mm of the Sylvian fissure (most of Brodmann's area 7B). All ablations were bilateral, symmetrical, and performed in one stage. These animals are still involved in behavioral experiments, and so histological verification of lesion sites is not yet available. (From A. Diamond and P. G. Goldman-Rakic, "Comparison of human infants and rhesus monkeys on Piaget's AB task: Evidence for dependence on dorsolateral prefrontal cortex," *Experimental Brain Research*, 74, 24-40. Copyright © 1990. Reprinted with permission of Springer-Verlag, Heidelberg.

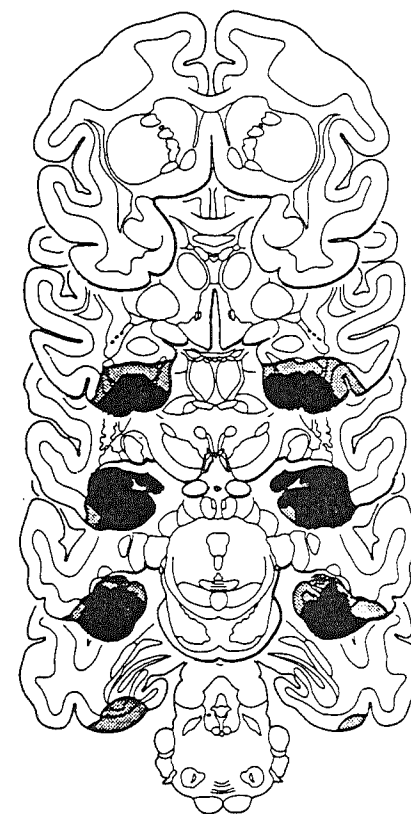


Figure 2. Representative coronal sections through the temporal lobe showing the extent of damage (shaded area) in a representative monkey in the hippocampal group. All three monkeys sustained extensive bilateral removal of the hippocampal formation. The hippocampus, including the dentate gyrus and subicular cortex, was removed for its entire extent, except for the most anterior 2-3 mm in two cases. In two monkeys, the removal also included over 90% of the parahippocampal gyrus (area TF-TH of von Bonin and Bailey) and the posterior half of the entorhinal cortex. In the third animal, damage to the parahippocampal gyrus was less extensive and the entorhinal cortex was only slightly involved. The second animal sustained slight direct damage to the amygdaloid complex, involving the ventral limit of the posterior border of the lateral nucleus. The amygdala was entirely spared in the other two animals. The caudate and the temporal stem were undamaged in all animals. The medial dorsal nucleus of the thalamus appeared normal during histological examination. Extensive gliosis was observed bilaterally throughout the fornix.

pus in memory and spatial functions. Since monkeys with lesions of the hippocampal formation could not be included in the first study, a second study was conducted with six adult cynomolgus monkeys (*Macaca fascicularis*). Three received bilateral lesions of the hippocampal formation (see Figure 2) and three were unoperated (Diamond et al., 1989b). All six were tested on AB and Object Retrieval.

Table 1. Brain Lesions and Task Performance-Literature Summary

	<i>AB</i>	<i>Delayed Response</i>	<i>Object Retrieval</i>
Human infants	Diamond (1985)	Diamond and Doar (1989)	Diamond (1990a)
Adult monkeys with lesions of frontal cortex	Diamond and Goldman-Rakic (1989)	Diamond and Goldman-Rakic (1989)	Diamond and Goldman-Rakic (1985)
Adult monkeys with lesions of parietal cortex	Diamond and Goldman-Rakic (1989)	Diamond and Goldman-Rakic (1989)	Diamond and Goldman-Rakic (1985)
Adult monkeys with lesions to the hippocampus	Diamond et al. (1989 ^b)	Squire and Zola-Morgan (1983)	Diamond et al. (1989 ^b)
Infant monkeys	Diamond and Goldman-Rakic (1986)	Diamond and Goldman-Rakic (1986)	Diamond and Goldman-Rakic (1986)
5-month-old infant monkeys, who received lesions of frontal cortex at 4 months	Diamond and Goldman-Rakic (1986)	Diamond and Goldman-Rakic (1986)	Diamond and Goldman-Rakic (1986)

The next step was to try to link developmental changes in performance of \overline{AB} and Object Retrieval to maturational changes in the frontal lobe of infant monkeys. Four infant rhesus monkeys were studied longitudinally, with testing every weekday from 40 to 150 days. At the end of testing (4½ months), two of the infant monkeys received bilateral ablations of dorsolateral prefrontal cortex (Brodmann's areas 8, 9, and 10) (Diamond and Goldman-Rakic, 1986).

Finally, to complete the \overline{AB} -DR comparison, human infants were tested on DR. Twelve infants (six male, six female) were tested every 2 weeks and another 36 infants were tested only once on DR (Diamond and Doar, 1989) (see Table 1).

Testing Procedures

The \overline{AB} Task

The \overline{AB} apparatus consisted of a testing tray with embedded wells. All subjects were tested individually in the laboratory. For testing human infants, the subject was seated on the parent's lap facing the testing table, equidistant from the wells. The experimenter was seated across the table, facing parent and child. A trial began with the experimenter holding up a toy to catch the infant's attention. As the subject watched, the experimenter slowly hid the toy in one of two wells. Particular care was taken to ensure that the subject observed this.

Both wells were then covered simultaneously and the delay period began. Subjects were prevented from straining, turning, or looking at a well during the delay. The parent restrained the infant's arms and torso gently but firmly from the beginning of the trial until the end of the delay period. Parents were instructed to look straight ahead during the delay and to release the infant's hands as soon as the experimenter said "okay." Visual fixation of the wells was broken by the experimenter calling to the infant during the delay and counting aloud, which caused the infant to look up. After the delay, the subject was allowed to reach. A reach was defined as the removal of a cover. A typical sequence of trials during an \overline{AB} testing session can be seen in Table 2. As illustrated there, trials can be characterized by whether the reward is hidden in the same well as on the previous trial or in the other well, and by whether the subject was correct on the previous trial or not.

The same \overline{AB} task administered to the infants, given by the same experimenter, was administered to the monkeys. The only differences in procedures were (1) food was hidden instead of a toy, (2) visual fixation was broken by lowering an opaque screen rather than by calling to the subject and counting aloud, and (3) monkeys were not physically restrained from moving during the delay (although if they showed signs of position cueing this habit was broken).

The Delayed Response Task

The procedures used within a trial for DR were identical to those for \overline{AB} . The one difference between the testing procedures for DR and \overline{AB} was in the rule for determining where the reward would be hidden. In DR, the hiding location was

Table 2. Typical A \bar{B} Testing Session Illustrating Types of Trials

Trial No.	Side of Hiding ^a	Reach	Types of Trial ^b		
			Repeat Following Correct	Reversal Following Correct	Repeat Following Error
1	L	✓			
2		✓	..... X		
3	R	errs	.....	..... X	
4		errs	.....	.....	..... X
5		errs	.....	.....	..... X
6		✓	.....	.....	..... X
7		✓	..... X		
8	L	errs	.....	..... X	
9		errs	.....	.....	..... X
10		✓	.....	.....	..... X
11		✓	..... X		
etc.					

Performance on Previous Trial	Side of Hiding	
	Same as on Previous Trial	Changed
Correct	Repeat-following-correct trials	Reversal-following-correct trials
Wrong	Repeat-following-error trials	Reversal-following-error trials

^aSide of hiding = where toy is hidden. When toy is hidden in the same well as on the previous trial, this column is left blank. L, left well; R, right well.

^bType of trial is determined by whether side of hiding is the same as on the previous trial or not and by whether the subject was correct or not on the previous trial. Reversal-following-error trials occur in Delayed Response, but not in A \bar{B} , as reversals are administered in A \bar{B} only following a correct reach. Thus, when discussing A \bar{B} , the term "reversal trials" always refers to reversal-after-correct trials. Trial 1 above is not characterized by type of trial as there is no trial previous to it.

varied randomly, irrespective of the infant's response. In A \bar{B} , on the other hand, the reward was always hidden in the same well until the subject reached correctly.

The Object Retrieval Task

Object Retrieval is a detour task with the goal object inside a rectangular box open on one side. Three Plexiglas boxes were used for human infant testing: (1) transparent, base 6 x 6 inches square, walls 2 inches high, (2) transparent, base 4½ x 4½ inches square, walls 2½ inches high, and (3) opaque, base 4½ x 4½ inches square, walls 2½ inches high.

As with A \bar{B} , all subjects were tested individually in the laboratory. Each infant was seated on the parent's lap facing the testing table and experimenter. A trial began with the experimenter placing a toy in one of the boxes. The infant had simply to retrieve the toy. No time limit was imposed. A trial ended with retrieval or when the infant refused to try any longer. Considerable freedom of movement was permitted and if an infant became distracted, the experimenter tapped the box or toy to regain attention. The experimenter held the back of the

box throughout each trial to prevent the infant from simply lifting the box off the toy.

Experimental variables included (1) side of box that was open (front, top, left, or right), (2) distance of toy from opening (ranging from partially outside the box to deep inside the box), and (3) position of box on the testing surface (near front edge of table or far; far to the left, midline, or far to the right). The bait was always visible when a transparent box was used, but the experimental variables jointly determined whether the toy was seen through a closed side of the box or through the opening. Order of conditions was counterbalanced across testing sessions.

The same Object Retrieval task administered to human infants, given by the same experimenter, was administered to rhesus and cynomolgus monkeys. The only differences in procedure were (1) food was placed in the box instead of a toy, and (2) the box was locked into position, rather than held by the experimenter. The Plexiglas boxes used with adult monkeys were (1) transparent, base 5 x 5 inches square, walls 2 inches high, and (2) transparent, base 3 x 3 inches square, walls 2 inches high. The Plexiglas box used for infant monkey was transparent, 3 x 3 inches square, 2½ inches high.

Results for Human Infants

A \bar{B}

Confirming and extending previous work (Gratch and Lander, 1971; Fox et al., 1979), a developmental progression in A \bar{B} performance was found in infants between 7½ and 12 months of age (Diamond, 1985). The delay needed to produce the A \bar{B} error increased continuously at an average rate of about 2 sec per month (see Figure 3). At 7½-9 months, the characteristic AB error pattern occurred at delays of 2-5 sec. By 12 months, infants reached correctly at delays as long as 10 sec.

Although delay remained constant across all trials within a testing session, performance did not. Infants erred only on certain kinds of trials (reversal trials and repeat-following-error trials), while in the same session, at the same delay, they reached correctly on another class of trials (repeat-following-correct trials) (Diamond, 1985). This is the classic error pattern from which the name A \bar{B} is derived, for infants are correct at "A" but they err when side of hiding changes to "B" (reversal trial) and usually repeat that error over the next few trials (repeat following error trials) (see Figure 4a).

All children displayed the A \bar{B} error throughout the months of testing. At each age, errors disappeared when the delay was reduced 2-3 sec, and reaching became random or severely perseverative when the delay was increased 2-3 sec above the level producing the A \bar{B} error. Thus, at 7½-9 months a 10 sec delay

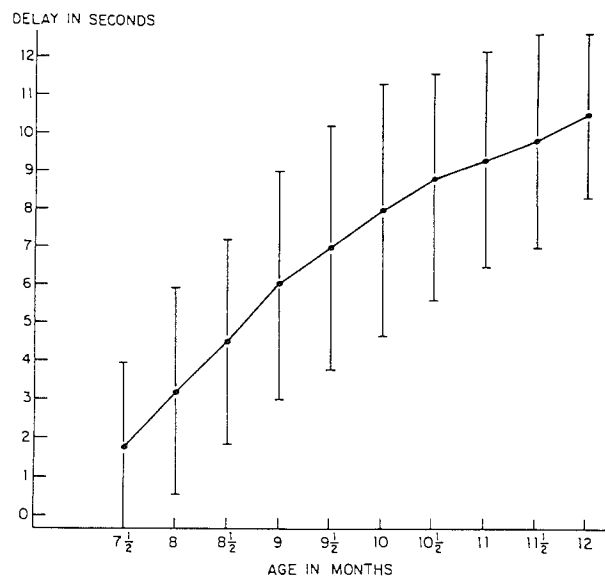


Figure 3. Delay at which the \overline{AB} error occurs in human infants as a function of age. (From A. Diamond, "Development of the ability to use recall to guide action, as indicated by infants' performance on A," *Child Development*, 56, 868-883. Copyright © 1985 by The Society for Research in Child Development, Inc. Reprinted with permission.)

produced "deteriorated performance," whose hallmarks are errors even on repeat-following-correct trials and overt signs of distress (Diamond, 1985). By 12 months, infants reached correctly even at delays as long as 10 sec. When a landmark indicated the toy's location, even young infants were able to use this to reach correctly even at long delays (Diamond, 1983).⁴

Infants in the longitudinal sample, tested every two weeks on \overline{AB} , were a few weeks ahead of infants tested only once. However, the same general developmental progression was found in infants tested cross-sectionally or longitudinally (Diamond, 1983).

Delayed Response

The developmental progression of human infants' performance in DR was almost identical to that for \overline{AB} despite the fact that these two tasks were tested in different laboratories by different testers with infants from different parts of the country (see Figure 5). In all respects, the results for DR were comparable to those for \overline{AB} . For example, the delay infants could tolerate increased at a constant rate of approximately 2 sec per month. Infants of 7 1/2-9 months failed DR at delays of 2-5 sec; by age 12 months infants succeeded on DR at delays over 10 sec. Individual differences between children of the same age were large, just as they had been on \overline{AB} . Girls could tolerate consistently longer delays than

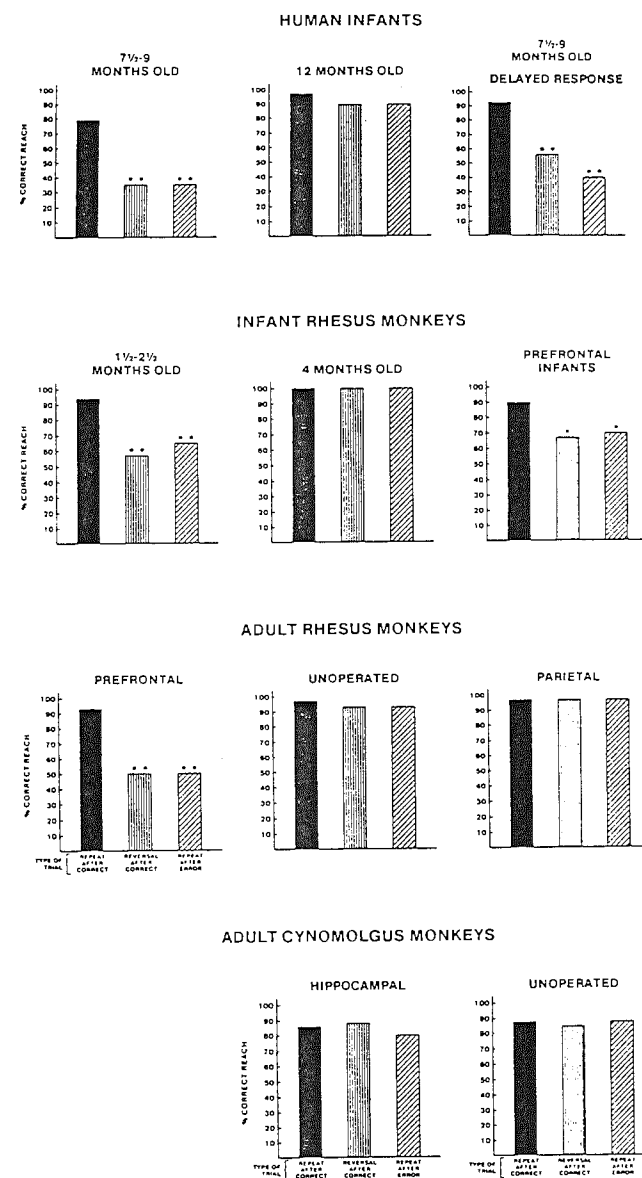


Figure 4. Percent correct by type of trial at delays of 2-5 sec. All results are for the \overline{AB} task, except where otherwise noted. The types of trials are repeat-after-correct, reversal-after-correct, and repeat-after-error. Top row: Human infants (7 1/2-9 months and 12 months of age) on the \overline{AB} task and human infants (7 1/2-9 months of age) on the Delayed Response task. Second row: Infant rhesus monkeys [1 1/2-2 1/2 months of age, 4 months of age, and those with lesions of dorsolateral prefrontal cortex (lesions at 4 months, testing at 5 months)] on the \overline{AB} task. Third row: Adult rhesus monkeys (with lesions of dorsolateral prefrontal cortex, lesions of inferior parietal cortex, and unoperated) on the \overline{AB} task. Bottom row: Adult cynomolgus monkeys (with lesions of the hippocampal formation and unoperated) on the \overline{AB} task.

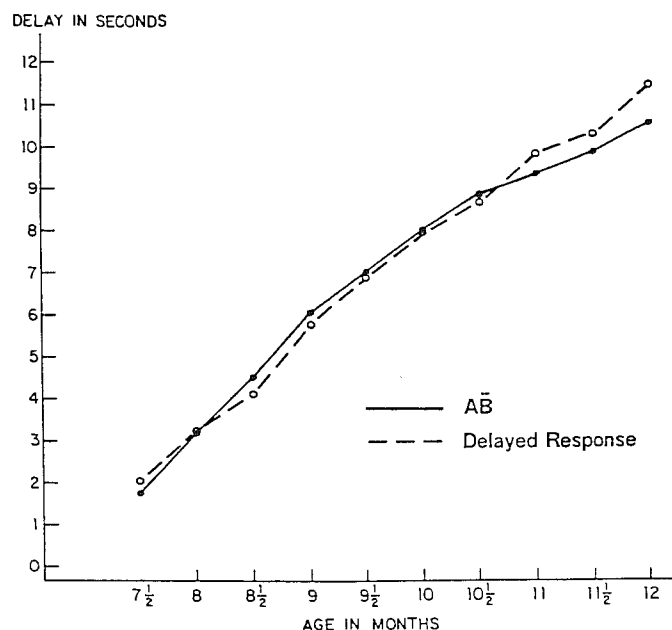


Figure 5. Delay at which human infants failed Delayed Response (dashed line) as a function of age, superimposed over Figure 3 (the delay at which the AB error occurred as a function of age; solid line). Failure on DR was defined as performance below the criterion of 88% correct. From A. Diamond and B. Doar "The performance of human infants on a measure of frontal cortex function, the delayed response task." *Development Psychobiology* 22: 278 Copyright © 1989, John Wiley and Sons, Inc. Reprinted with permission of John Wiley and Sons, Inc.

boys, not because they were improving at a faster rate (the slope of the delay \times age function on DR or AB for girls was not significantly different from that for boys), but because they got off to an earlier start. Girls could uncover a hidden object at a younger age than could boys and so could begin DR or AB testing earlier. Importantly, the same differential pattern of performance by type of trial was found for DR as had been found for AB [excellent performance on repeat trials following a correct reach; poor performance on reversals and repeat trials following an error (see Figure 4b)].

Object Retrieval

Infants were found to pass through a clear, tightly age-related series of phases in the performance of Object Retrieval (Diamond, 1981, submitted). All infants progressed through the same sequence of phases, in the same order, at approximately the same age (Diamond, 1981, 1990a) (see Figure 6). So rarely did infants deviate from this that the sequence of development fit a Guttman scale with a coefficient of reproducibility of .93. There was a small effect of repeated testing (infants in the cross-sectional sample lagged approximately 2–4 weeks

behind infants tested longitudinally) but the same phases were found in the same order.

Infants 6½–8 months, like the monkeys with frontal lobe lesions studied by Moll and Kuypers, were unable to retrieve the reward if they saw it through a closed side. They banged and scratched with considerable effort and persistence, but if their line of sight did not happen to change they tried no other route to the toy. They insisted on reaching directly to where they saw the toy. The tendency to be guided only by visual information was so strong that it overrode available tactile information and the effect of repeated reinforcement. So totally controlled was their reach by their line of sight that a fraction of an inch difference in the height of the box or in how close the box was to the baby made the difference between success and failure—everything depended on whether the infant was looking through the opening. Even if an infant's hand was already inside the box en route to the toy, if line of sight changed, the infant withdrew the hand and reached to the side through which he or she now saw the toy (see Figure 7).

The first advance on Object Retrieval was seen at 7½–8 months. It was a small change and so is called Phase 1B, rather than Phase 2. The advance is that infants, for the first time, took active steps to look at the toy through different sides of the box (e.g., learning to look through a different side of the box or moving the box). However, 7½– to 8-month-old infants still reached only at the side of the box through which they were looking. When line of sight changed, the reach changed too. The onset of Phase 1B coincided almost exactly with when infants could first uncover a hidden object (see Table 3). Phase 1B and uncovering a hidden object both require a more active, or less passive and reactive, orientation than that seen in younger infants. This marks the first time infants take active steps to change the situation with which they are presented.

The means–end behavior seen here is quite rudimentary. For example, infants were permitted to raise the front of the box (with the experimenter holding the back of the box down on the table) so that the front opening of the bottomless box became quite large and the infant could see in. Often, a 7½– to 8-month-old infant would raise the front of the box with both hands, remove one hand from the box, and attempt to reach for the toy, but the box would come down halting the reach. The reach would halt and go back to the box top because once the box was down the infant saw the toy through the box top rather than through the open front, and reaches were made at this age only at the side through which the infant was looking (see Figure 8). But why did the box come down, after all the second hand was still holding on? The problem here was that when the infants lowered one hand to reach for the toy, they had great difficulty *not* lowering the other. They would repeatedly try to raise the front of the box, but the hand left to hold up the box repeatedly failed at its task. With both hands in the raised position, when one was lowered, the other came down too.⁵

At 8½–9 months (Phase 2), the first separation of line of sight and line of reach occurred. Infants leaned and looked through the front opening of the box, sat up, then reached into the front while looking through the top of the box. For

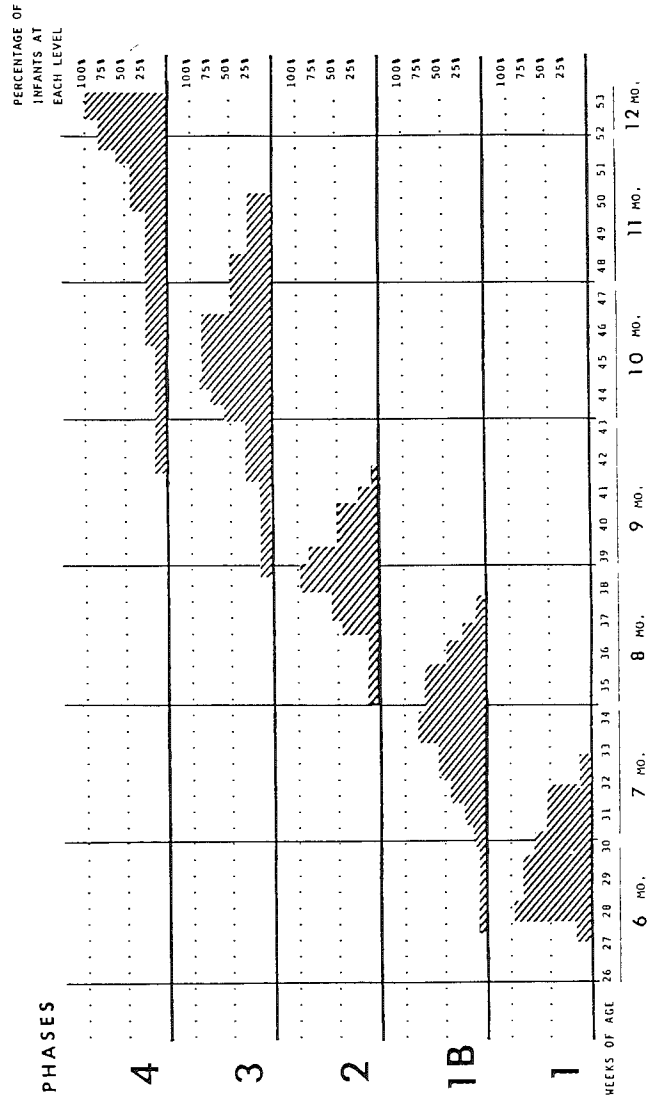
VISUAL CONTROL OF REACHING

PHASES

SIDE OF BOX THAT IS OPEN:	PHASES			
	1	1B	2	3
DOES NOT NEED TO LOOK AT TOY THRU OPENING AT ALL				
	SIDE			
NEEDS TO LOOK AT TOY THRU OPENING AT BEGINNING, BUT NOT THROUGHOUT				
	FRONT			
BEGINS TO LOOK FOR OPENING, BUT STILL REACHES EXCLUSIVELY ON DIRECT LINE OF SIGHT				
	SIDE			
REACHES EXCLUSIVELY ON DIRECT LINE OF SIGHT				
	FRONT			

(A)

Figure 6. (A) The phases through which infants progress in performance on the Object Retrieval task. (From A. Diamond, 1990.) (B) Developmental progression of performance on the Object Retrieval task with transparent barrier, showing histograms for the age distribution of each phase. (From A. Diamond, 1990.)



(B)

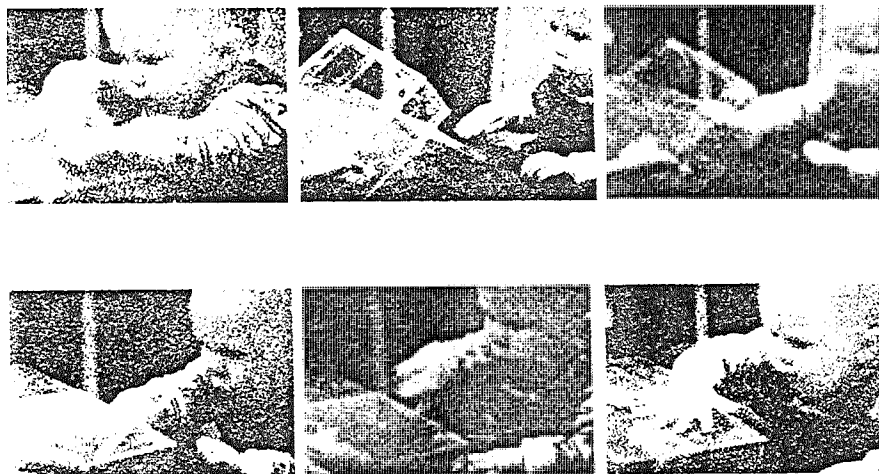


Figure 7. Infants in Phase 1 (6½–7½ months) reach at the side of the box through which they are looking. Frame 1: Front of box is open. Brian sees the toy through the top of the box and tries to reach through the top. Frame 2: Experimenter "raises" the box, enabling Brian to see the toy through the front opening. Frame 3: As soon as Brian sees the toy through the opening, he reaches into the opening. Frame 4: Experimenter lowers box back to its original position. Brian's hand is inside the box on an unobstructed line to the toy, but he now sees the toy through the closed top of the box. Frame 5: Rather than completing the reach, Brian withdraws his hand, and Frame 6: tries to reach through the top of the box to the toy. As soon as he is looking through a different side of the box, he reaches to that side. (From Diamond, 1990.)

the first time, the memory of having looked into the opening was sufficient. For the first time, infants could look through one side and reach through another. This is reminiscent of Millar and Schaffer's (1972, 1973) finding on an operant conditioning task requiring infants to push a lever to see a light display. Even 6-month-old infants succeeded when the lights and lever were in the same visual field, but not until 9 months could they look one place and reach another (Millar and Schaffer.) If the infant had not looked into the opening on that trial, he or she would still not reach there, but having once looked in, the infant did not need to continue to do so to succeed.

At 8½–9 months, the problem of raising the box was also solved sequentially. The infant first raised the box, both hands came down, and then the infant reached in and got the toy.

Performance with the opening at the left or right side of the box always lagged one phase behind performance at the front. Hence, at 8½–9 months, infants showed Phase 1B performance when the opening was on the left or right side of the box: they leaned and looked in the opening and needed to maintain this line of sight during the reach. This leaning and looking to the left or right was accompanied by an "awkward reach," i.e., a reach with the hand contralateral to the

Table 3. Comparison of the Age of Onset of Phase 1B in Object Retrieval and the Age When Infants Can First Uncover a Hidden Object^a

	Onset of Phase 1B, Object Retrieval	First Able to Uncover a Totally Hidden Object
Jack	35 (3)	35 (3)
Lyndsey	33 (2)	33 (2)
Tyler	36 (2)	38 (4)
Jamie	34 (0)	34 (0)
Emily	34 (2)	34 (2)
Rachel	32 (4)	30 (6)
Brian	28 (3)	28 (3)
Ryan	33 (1)	33 (1)
James	28 (5)	28 (5)
Erin	30 (3)	32 (4)
Sarah	34 (6)	34 (6)
Julia	33 (2)	33 (2)
Mariama	34 (0)	36 (3)
Kate	31 (6)	33 (5)
Rusty	35 (6)	33 (5)
Todd	39 (4)	35 (1)
Nina	31 (0)	29 (0)
Isabel	32 (5)	32 (5)
Jennine	31 (4)	31 (4)
Jane	34 (5)	34 (5)
Bobby	33 (2)	33 (2)
Graham	34 (2)	34 (2)
Blair	35 (4)	35 (4)
Michael	34 (0)	36 (3)
Chrissy	32 (6)	32 (6)

^aResults are for the 25 infants studied longitudinally at 2 week intervals. Age is given in weeks, with days in parentheses.

opening. Reaching thusly with the hand farthest from the opening made the action maximally contorted and awkward.

At 9½–11 months (Phase 3), infants succeeded when the front of the box was open without looking into the opening at all. Thus, 9½ months is the turning point where infants began to succeed on trials when they had not looked in the opening at all (see Figure 9a).^a Infants of 9½–10 months were also able to raise the box with one hand and reach in with the other, or raise the box with both hands, lower one hand, and *keep the box raised* with the other. When the opening was on the left or right side of the box, 9½- to 11-month-old infants still needed to look in the opening, but they could then sit up, look through the top, and reach through the side. Awkward reaches disappeared.

Four of the 25 infants followed longitudinally departed from the typical picture of Phase 3. They reached to the left or right side opening *without* first looking in through that side. However, these four infants all failed to get their hand inside



Figure 8. Example of means-end behavior during Phase 1B (7½–8½ months). Whereas younger infants do not take any active steps to change line of sight, infants in Phase 1B begin to move themselves or the box to look at the toy through different sides of the box. However, infants in Phase 1B still reach only at the side of the box through which they are looking and have difficulty lowering one hand to reach without also lowering the other hand. **Frame 1:** Front of box is open. Nina raises the box. She can now see the toy through the front opening. (Experimenter is holding back of box, exerting downward pressure.) **Frame 2:** Nina lowered her left hand to reach for the toy. The right hand, holding onto the box, came down too, instead of remaining raised and thus keeping the box up so that she could continue to look through the opening. At this point her left hand is inside the box, a fraction of an inch from the toy, but she is looking at the toy through the closed top of the box. **Frame 3:** Nina withdraws her left hand from the box without having retrieved the toy, and reaches for the toy at the closed top of the box (the side through which she is looking). (From A. Diamond, 1990.)

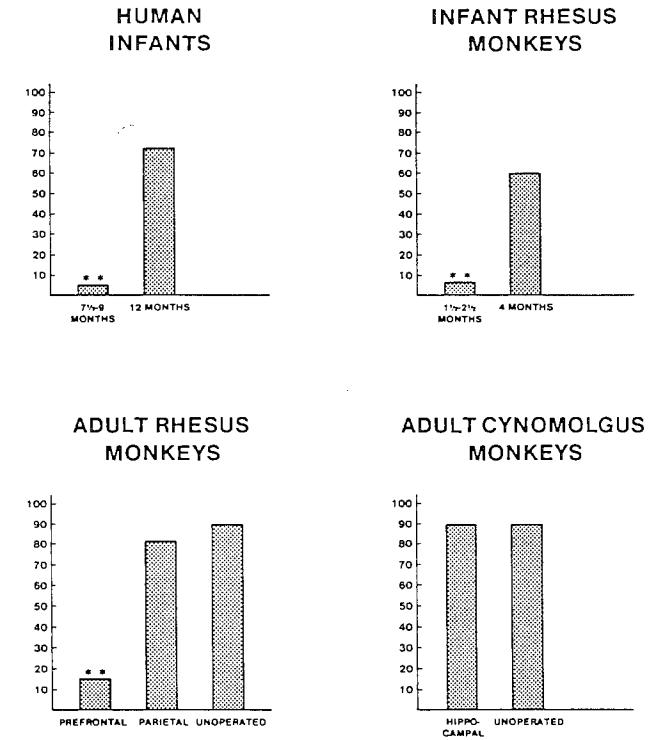


Figure 9. Percent of trials in the Object Retrieval task on which subjects reached to the box opening without having looked into the opening on that trial. (A) Human infants: 7½–12 months of age and 12 months of age. (B) Adult rhesus monkeys: those with lesions of dorsolateral prefrontal cortex, those with lesions of parietal cortex, and unoperated. (C) Adult cynomolgus monkeys: those with lesions of the hippocampal formation and unoperated. (D) Infant rhesus monkeys: 1½–2½ months of age and 4 months of age.

the opening. They misreached, going too high or too far, etc. For example, one child kept getting her thumb stuck on the top edge of the opening. To try to help her out, the experimenter tipped the box to enlarge the size of the opening, but then she reached much higher yet and still got her thumb stuck on the top edge of the opening! It was as if, although most infants appeared to attend only to vision, ignoring available tactile information, these four infants attended only to touch, ignoring the available visual information. They seemed to search for the opening the way a blind person would, by feeling for the edge. Therefore, when the opening was made very large, they still went for the edge.

Finally, by 11–12 months (Phase 4), infants were perfect at Object Retrieval. They did not need to look in the opening on any side to succeed. Their performance was efficient, quick, and accurate. One-year-old infants rarely

returned to a side to which they had reached and found closed. A single touch sufficed to tell them whether a side was open or closed.

Once infants were old enough to retrieve a hidden object (approximately 7½ months) they were also tested with an opaque box. At each age, performance was one phase ahead on the opaque box compared with the transparent box (Diamond, 1981, 1990a). Thus, when infants could not see the toy at the outset of the trial, they performed *better* than when they could. Bruner et al., (1969), Lockman (1984), and Schonon and Bresson (1984) report similar results with an opaque wall versus a transparent wall. This counterintuitive finding that the task was easier when infants could not see their goal can be understood in light of the fact that when the box was opaque infants did not need to resist reaching along their line of sight; they could not see the toy through the box.

Testing on Object Retrieval, $A\bar{B}$, and DR thus yielded clear age-related patterns of improvement over a rather brief time period in all children. Although Object Retrieval is a very different task from $A\bar{B}$ or DR, improvement on all three tasks occurred over the same age range (7½–12 months of age). Since different experiences would seem to have been necessary for mastery of these different tasks, the fact that improvement on all these tasks is seen over the same age period suggests that these improvements may be, at least in part, maturationally based. The similarities between the performance of infants tested only once and infants tested longitudinally is also consistent with a maturational component to these developmental changes.

Results for Adult Monkeys

$A\bar{B}$

Adult rhesus monkeys with lesions of dorsolateral prefrontal cortex made the $A\bar{B}$ error at delays of 2–5 sec and reached randomly at delays of 10 sec (Diamond and Goldman-Rakic, 1989), just as did 7½- to 9-month-old human infants. Again, although delay was constant across trials, performance differed systematically by type of trial with errors restricted to reversal trials and to repeat-following-error trials (see Figure 4). Like 7½- to 9-month-old infants, frontally operated adult monkeys and reached randomly at delays of 10 sec.

Unoperated and parietally operated adult rhesus monkeys succeeded on $A\bar{B}$ at delays of 10 sec or more, and showed no pattern of differential performance by type of trial (Diamond and Goldman-Rakic, 1989; see Figure 4c). Similarly, unoperated and hippocampally operated adult cynomolgus monkeys performed correctly on $A\bar{B}$ at delays of 10 sec or more (Diamond et al., 1989; see Figure 4d). The excellent performance of monkeys with lesions of the hippocampal formation at short delays is consistent with extensive findings of good performance by hippocampal monkeys at delays of 10 sec or less, even on tasks particularly sensitive to damage of the hippocampus (Diamond, 1988; Squire and

Zola-Morgan, 1983; Zola-Morgan and Squire, 1986; Zola-Morgan et al., 1989). Amnesic patients, including patients with known hippocampal damage, similarly perform well at short delays provided that the material to be retained does not exceed short-term memory capacity (Squire, 1987; Zola-Morgan et al., 1986).

As the delay increased above 10 sec, monkeys with lesions of the hippocampal formation made progressively more errors on $A\bar{B}$. Finally, at delays of 30 sec they made roughly as many errors overall as frontally operated monkeys had made at delays of 2–5 sec. Monkeys with lesions of the hippocampal formation never showed the $A\bar{B}$ error pattern, however, not even at the 30 sec delay (see Figure 4d). The $A\bar{B}$ error pattern consists of errors confined to reversals and to the trials immediately following reversals. The performance of hippocampal monkeys was not significantly worse on reversal trials, even at the 30 sec delay, than on repeat-following-correct trials. Thus, they did not show the fundamental characteristic of the $A\bar{B}$ error. Their performance was significantly worse, however, on repeat-following-error trials than on repeat-following-correct trials. Were they perhaps showing some aspects of the $A\bar{B}$ error? The answer is no. Repeat-following-error trials simply indicate a string of errors. These can begin on a reversal trial or on a repeat-following-correct trial. Because errors on reversal trials are indicative of the $A\bar{B}$ error, a string of errors immediately following a reversal might reasonably be taken as further evidence of the $A\bar{B}$ error. A string of errors following a correct reach when side of hiding has not changed, however, would *not* be indicative of the $A\bar{B}$ error. Monkeys with lesions of the hippocampal formation performed roughly at chance on *both* kinds of repeat-following-error trials (46% correct on those following a reversal trial and 53% correct on those following an error on a repeat-following-correct trial). Their low score on repeat-following-error trials thus reflects poor performance in general, not a selective tendency to repeat errors after reversals. In contrast, at delays of 2–5 sec, monkeys with lesions of dorsolateral prefrontal cortex performed significantly worse on reversal trials and on repeat-following-error trials than on repeat-following-correct trials, and their errors on repeat-following-correct trials were largely confined to those trials immediately following a reversal (40% correct on repeat-following-error trials following an error on a reversal trial; 72% correct on repeat-following-error trials following an error on a repeat-following-correct trial). Thus, frontal monkeys showed the $A\bar{B}$ error at brief delays and hippocampal monkeys never showed the $A\bar{B}$ error at either brief delays or long delays. When frontal monkeys erred at brief delays they did so by reaching back to where they had previously been correct, and by repeating that error over the next several trials, as if the experience of successfully retrieving the reward at the old location was having more influence over their behavior than the sight of where the reward had just been hidden. Hippocampal monkeys, on the other hand, showed excellent performance at brief delays, and when they finally erred at long delays, they did so by reaching randomly, not by showing a preference for the previously correct location.

Thus, only lesions of dorsolateral prefrontal cortex produced the \overline{AB} error. Prefrontal lesions produced the \overline{AB} error pattern at *the same length of delay* as that seen in human infants of 7½–9 months (2–5 sec). In every way, the performance of human infants of 7½–9 months and of monkeys with lesions of dorsolateral prefrontal cortex was comparable: the errors of both groups were confined primarily to reversals and to the trials immediately following reversals; they performed well if allowed to circumvent the memory requirements by staring at, reaching toward, or positioning their body toward the correct well during the delay, and they immediately tried to correct themselves after an incorrect reach. At delays of 10 sec, their performance deteriorated: they showed overt signs of distress, and there was no longer a differential pattern of performance by type of trial; instead performance was poor on all types of trials.

It should be noted that the monkeys with lesions of the hippocampal formation exhibited the classic memory deficits associated with lesions to this region (e.g., they performed poorly both before and after AB testing on Delayed Nonmatch to Sample, a memory test often used to assess hippocampal deficits). Thus, their success on AB cannot be attributed to lack of impairment or to recovery of function, nor can the pattern of errors of infants and prefrontal monkeys be attributed solely to poor memory, for the hippocampal monkeys had a severe memory impairment and yet never showed the AB pattern of error.

Delayed Response

It was already known that the DR performance of monkeys with lesions of dorsolateral prefrontal cortex closely resembles the \overline{AB} performance of human infants aged 7½–9 months. The same monkeys had never been tested on both DR and \overline{AB} , however. Diamond and Goldman-Rakic (1989) demonstrated that in the same monkeys performance on these two tasks are remarkably similar. Unoperated rhesus monkeys and those with parietal lesions showed excellent performance on both tasks at delays well over 10 sec. Monkeys with lesions of dorsolateral prefrontal cortex, on the other hand, failed DR and \overline{AB} even at delays as brief as 2 sec. The performance of frontally operated monkeys on DR was fully comparable to the performance of 7½- to 9-month-old human infants on DR.

Object Retrieval

Adult rhesus monkeys with lesions of dorsolateral prefrontal cortex showed the same pattern of performance on Object Retrieval as 7½- to 9-month-old human infants (that is, they showed the behaviors characteristic of Phases 1B and 2) (Diamond and Goldman-Rakic, 1985). No monkeys displayed Phase 1 behavior (seen at 6½–7 months of age in human infants) as they all actively tried to look through more than one side of the Object Retrieval box. However, frontally operated monkeys, like human infants of 7½–9 months, needed to have seen the

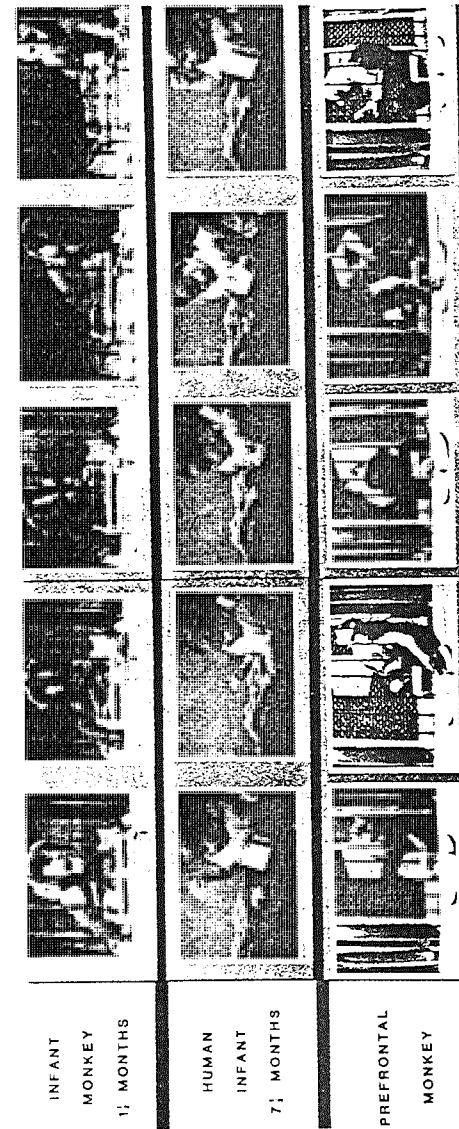


Figure 10. Failure after pushing the bait inside the box themselves: infant monkey of 1½ months, human infant of 7½ months, and adult monkey with lesion of dorsolateral prefrontal cortex. Frame 1: Bait is partially out of box, S reaches immediately for the part that is sticking out of the box. Frame 2: S accidentally pushes bait into the box. Once bait is inside the box, S is unable to retrieve it, even though S was touching the bait, S pushed the bait inside the box himself, and S was at the opening. Frame 3: S withdraws hand from opening and goes to the side of the box through which he sees the bait. Frame 4: S looks at bait through front of box and reaches to the front. Frame 5: Unable to retrieve the bait, S gives up.

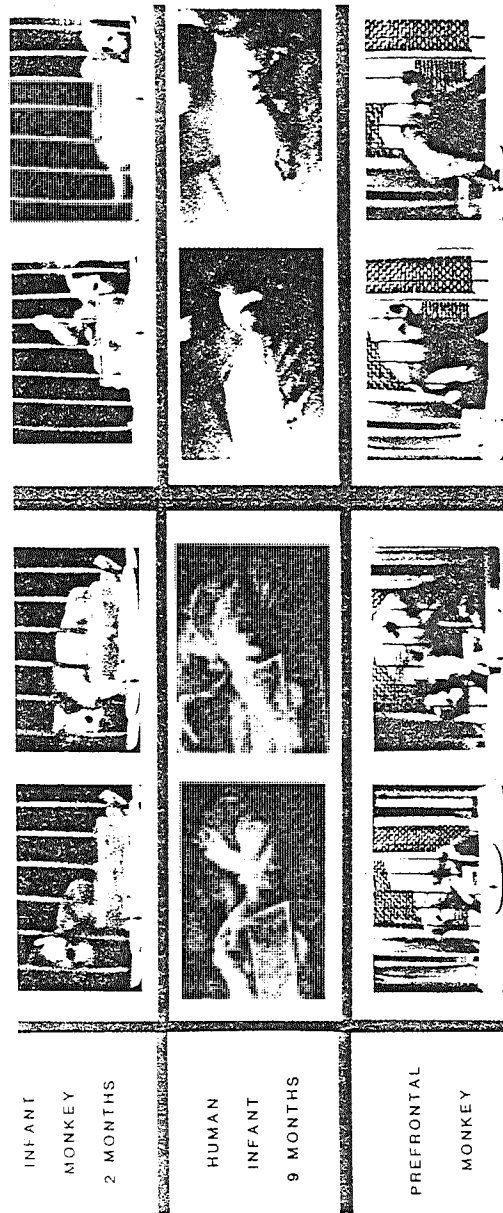


Figure 11. The "awkward reach" in infant monkey of 2 months, human infant of 9 months, and adult monkey with lesion of dorsolateral prefrontal cortex. Frame 1: S leans and looks at bait through opening of box. Frame 2: S reaches in awkwardly with the far hand. Frame 3: Opening is on the other side of the box. Performance is the same. S leans and looks into the opening. Frame 4: S reaches in awkwardly with the far hand.

bait through the opening of the box to reach in and retrieve it. When the bait (toy for children, food for monkeys) was partially out of the box they reached for it straightaway, but if in so doing they accidentally pushed the bait inside the box, they could no longer retrieve it. Deserting the opening, they tried to reach through the transparent wall of the box through which they now saw the bait, even though they had pushed the bait inside the box themselves! (see Figure 10).

Monkeys with lesions of dorsolateral prefrontal cortex also showed the "awkward reach": they reached to the left side of the box with their right hand and to the right side of the box with their left hand, seeming to make the task maximally difficult for themselves (see Figure 11).

In contrast, unoperated monkeys, and monkeys with lesions of parietal cortex or of the hippocampal formation reached to the opening on all trials straightaway, as do human infants of 11–12 months (see Figure 7b and c). They did not need to have looked through the opening and they reached into the left or right side effortlessly with the hand nearest the opening. A single touch served to tell them whether a side was open or closed; they did not persist at a closed side and did not return to sides already tried and found closed.

Thus, on all three tasks (Object Retrieval, AB , and DR) monkeys with lesions of dorsolateral prefrontal cortex performed as do human infants of 7½–9 months. They failed under the same conditions and in the same ways. Monkeys with lesions of the hippocampal formation or parietal cortex performed well on all tasks, as do human infants of 12 months.

It should be noted that the monkeys with lesions of the hippocampal formation exhibited the classic memory deficits associated with lesions to this region (e.g., they performed poorly both before and after AB and Object Retrieval testing on Delayed Nonmatch to sample). Thus, their success on AB and Object Retrieval cannot be attributed to no loss of function or recovery of function, nor can the pattern of errors of infants and prefrontal monkeys be attributed solely to poor memory, for the hippocampal monkeys had a severe memory impairment and yet never showed the AB pattern of error.

Results for Infant Monkeys

AB

Infant rhesus monkeys of 1½–2½ months made the AB error at delays of 2–5 sec (Diamond and Goldman-Rakic, 1986),⁷ as do human infants of 7½–9 months and adult rhesus monkeys with lesions of dorsolateral prefrontal cortex (see Figure 12). The infant monkeys also showed the familiar AB error pattern: excellent performance on repeat following correct trials, with errors confined to reversals and repeat following error trials, even though the same delay was used on all three types of trials (see Figure 4, line 2). Like 7½–9-month-old infants and frontally operated adult monkeys, infant monkeys of 1½–2½ months

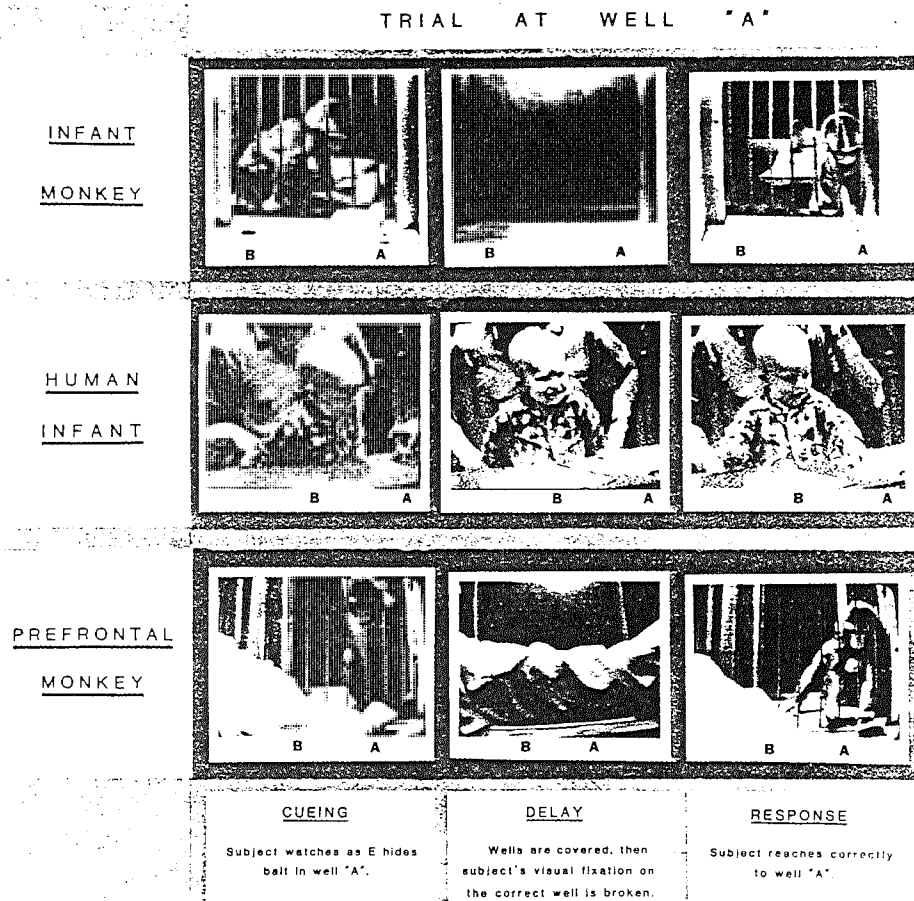
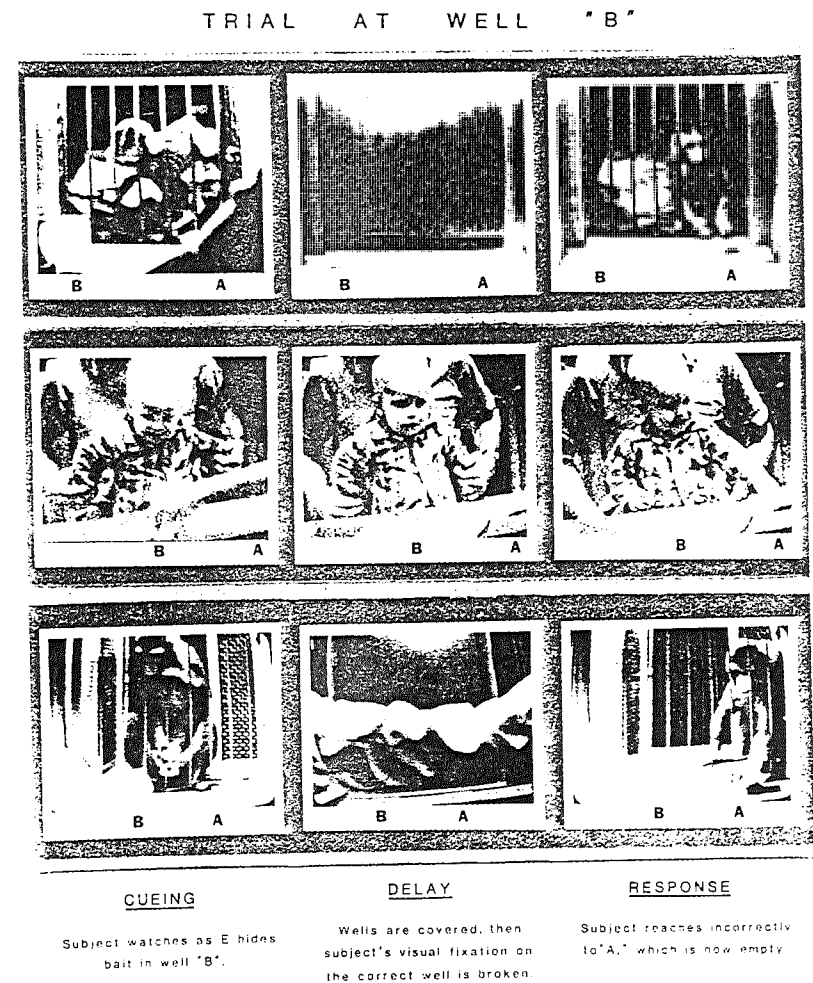


Figure 12. Comparison of performance of infant monkeys, human infants, and adult monkey with bilateral lesions of dorsolateral prefrontal cortex on the AB task. All succeed on the trial at A, but when the side of hiding is changed to well B, they all err by reaching back to A, even though they all saw the bait being hidden at B.

reached randomly at delays of 10 sec, but reached correctly if allowed to stare at the correct well, or sit in front of it, throughout the delay. By 4 months, infant monkeys reached correctly on \overline{AB} even at delays of 10 sec or more, as do 12-month-old human infants.

Lesions in the infant do not always produce the same effect as lesions in the adult. If a neural region is late maturing, lesions of that region may produce deficits in the adult, but not in the infant (e.g., Goldman, 1971, 1974). It has been suggested that lower areas of the brain might mediate infants' performance on a task, even though performance of that task by adults is mediated by a later maturing area of the brain. Thus, although prefrontal cortex seems to mediate



\overline{AB} performance in the adult, it might not be involved in improved \overline{AB} performance in the infant. To determine whether prefrontal cortex is necessary for success on AB in infant monkeys, two of the infant monkeys who had been tested longitudinally on AB from 1½ to 4 months of age received bilateral lesions of dorsolateral prefrontal cortex at 4½ months and were retested on \overline{AB} at 5 months. Although these monkeys had considerable postoperative training on \overline{AB} , and had performed perfectly on \overline{AB} at delays greater than 10 sec preoperatively at 4 months, after lesions of dorsolateral prefrontal cortex they failed \overline{AB} at delays of 2–5 sec and showed the differential pattern of performance over trials characteristic of the \overline{AB} error (see Figure 4, line 2). That is, the lesion produced the same effect in infant monkeys as it did in adult monkeys: the \overline{AB} error at delays of 2–5 sec.

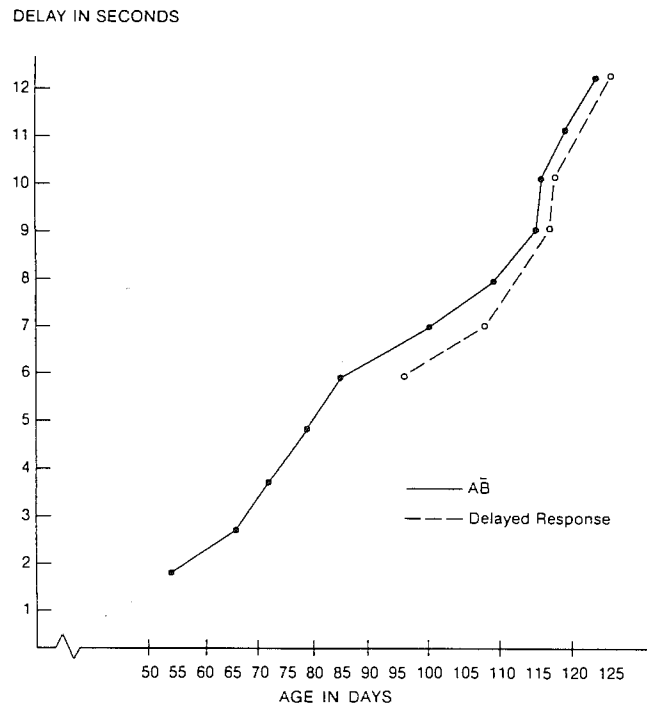


Figure 13. Developmental progression of infant monkeys' performance on Delayed Response and AB. The delay at which infant monkeys failed Delayed Response as a function of age is shown by the dashed line, and the delay at which they made the AB error as a function of age is shown by the solid line. Failure on Delayed Response was defined as performance below the criterion of 88% correct. Testing on Delayed Response did not begin until 80 days of age, but note that performance on this task quickly became comparable to performance on AB.

Delayed Response

The same infant monkeys tested longitudinally on AB were also tested longitudinally on DR during this same period (Diamond and Goldman-Rakic, 1986). The developmental progressions on both tasks were identical (see Figure 13). Infant monkeys improved in their performance of Delayed Response over the same age period and at the same rate as they did on the AB task. For example, they reached criterion on AB with a 10 sec delay at a mean age of 112.75 days and the reached criterion on Delayed Response with a 10 sec delay at a mean age of 113.80 days. They progressed on both tasks at the rate of approximately 1 sec a week.

Infant monkeys of 4 months succeeded on DR at delays over 10 sec. The two infant monkeys who received bilateral lesions of dorsolateral prefrontal cortex at 4½ months, following all of this longitudinal testing, once again failed DR at delays of 2–5 sec, despite their excellent performance on DR at delays over 10

sec just before surgery. Thus, lesions of dorsolateral prefrontal cortex appeared to have the same effect on DR performance at 4–5 months of age as they did in adult monkeys.

Object Retrieval

Infant monkeys of 1½–2½ months showed behaviors characteristic of Phases 1B and 2 on Object Retrieval. They needed to have seen the bait through the opening of the box to retrieve it. When the bait was partially out of the box, if they accidentally pushed it back inside the box, they were unable to retrieve it, even though they themselves had been the one to push the bait in the box (see Figure 10 above). When the opening was on the left or right side of the box, if they leaned and looked in the opening they could retrieve the bait, but in this position they reached with the hand contralateral to the opening, displaying the "awkward reach" (see Figure 11). These behaviors are the same as those shown on Object Retrieval by human infants of 7½–9 months and adult monkeys with lesions of dorsolateral prefrontal cortex.

No infant monkeys displayed Phase 1 behavior (characteristic of human infants at 6½–7½ months). From the start, infant monkeys actively tried to look through more than one side of the box (Phase 1B behavior). Whereas, human infants below 7½ months rather passively accepted the task as presented, infant monkeys of even 1½ months moved quite a bit. (Monkeys below the age of 1½ months cannot reach and retrieve a piece of food and so cannot be tested on Object Retrieval). Monkeys are more advanced at birth than are humans and very shortly become quite mobile and agile.

By 4 months, infant monkeys reached to the opening of the box on all trials straightaway. The task was trivially easy for them, just as it was for human infants of 12 months.

Thus, infant monkeys showed developmental progressions on all three tasks (Object Retrieval, AB, and DR) between 1½ and 4 months quite comparable to that seen in human infants between 7½ and 12 months. Note that in monkeys, just as in humans, even though Object Retrieval is quite different from AB or DR, and so one might think different experiences would be relevant to acquiring mastery, improvement on all three tasks occurred over the same age period. This is consistent with there being a maturational component to these changes.

Monkeys are born more neurologically and physically mature than humans and show more rapid postnatal development. Hence, 1½- to 2-month-old monkeys performed on these tasks as do 7½- to 9-month-old human infants, and while human infants required roughly 5 months to attain mastery, infant monkeys required only about 2 months. The progression on Object Retrieval was truncated in the monkey: human infants progressed through Stages 1, 1B, 2, 3, and 4; infant monkeys progressed from Stage 1B–2 to Stage 4.

Lesions of dorsolateral prefrontal cortex in infant monkeys disrupted performance of these tasks, just as these lesions do in adult monkeys. Thus, these tasks appear to test an aspect of frontal lobe function that matures very early in life.

Indeed, many had believed that prefrontal cortex did not subserve any cognitive functions until much later in life.

Evidence of Maturation of the Frontal Lobe

The human nervous system is not fully mature at birth, and frontal cortex is one of the clearest examples of a structure that matures postnatally (e.g., Schade and van Groenigen, 1961; Yakovlev and Lecours, 1967; Dekaban, 1970).

Although all neurons in frontal cortex are generated before birth (Rakic, 1974), they remain immature for some time. The immaturity of frontal cortex early in life, like that of many other regions of the brain, has been shown by diverse indicators. For example, most of the layers of frontal cortex are narrower in the infant than in the adult and the subregions are cytoarchitecturally less distinct (Larroche, 1966). The dendritic systems of pyramidal neurons in layers 2, 3, and 5 are rudimentary and lack extensive branching (Schade and van Groenigen, 1961). Synaptic density in frontal cortex is low at birth, as is the number of synapses per neuron (Huttenlocher, 1979). Available staining methods have not been able to detect evidence of axonal myelin sheaths in frontal cortex during the early months of life (Yakovlev and Lecours, 1967).

Developmental changes in performance of $\bar{A}\bar{B}$, DR, and Object Retrieval coincide with maturational changes in frontal cortex: (1) Neurons, at least in layer 3 of the middle frontal gyrus, have probably acquired their full complement of synapses by the end of the first year (Huttenlocher, 1979). (2) The mean number of synapses per neuron in this region increases rapidly from roughly 10,000 at birth to roughly 100,000 by 1 year of age; increase thereafter is much slower (Huttenlocher, 1979). (3) The density of neurons here declines markedly during the first year. After one year the decrease proceeds more gradually (Schade and van Groenigen, 1961; Huttenlocher, 1979). (The neonatal brain appears to have more neurons in regions such as frontal cortex than does the adult brain. Thus, neuronal loss is an aspect of maturation. For example, the average number of neurons per mm^3 in layer 3 of the middle frontal gyrus in the neonate is about 10^5 , while in the adult it is only slightly over 10^4 .) (4) The density of synaptic contacts across all layers of dorsolateral prefrontal cortex in the rhesus macaque increases during the first $1\frac{1}{2}$ – $2\frac{1}{2}$ postnatal months; thereafter density declines (Bourgeois et al., 1985). (2) The dopamine concentration in the brain increases during this period in rhesus macaques as well (Brown et al., 1979). Dopamine is particularly concentrated in frontal cortex. When levels of dopamine are low in dorsolateral prefrontal cortex, monkeys are unable to succeed at DR (Brozoski et al., 1979). Their performance returns to normal following a return to normal dopamine levels (Brozoski et al., 1979). Thus, increasing levels of dopamine with age may help make possible improved performance with age.

A potential mechanism by which frontal cortex maturation might result in improved Object Retrieval performance is through frontal inhibition of collicular

mechanisms. The frontal lobe (including both dorsolateral prefrontal cortex and premotor cortex specifically) projects directly to the superior colliculus in monkeys and probably in humans (Goldman and Nauta, 1976; Kunzle, 1978) and indirectly via the substantia nigra. If the inhibitory projections to the colliculus are interrupted, frogs (who readily detour around a transparent barrier ordinarily) try to go straight through a transparent barrier to the reward instead of detouring around the barrier (Ingle, 1973).

Plans are now underway to explore this hypothesis in human infants. Interruption of inhibitory projections to the superior colliculus in monkeys results in saccadic intrusions during the smooth pursuit of a slow moving target (Hikosaka and Wurtz, 1983, 1984, 1985). That is, instead of the eyes smoothly following the target, they dart away momentarily and then continue tracking. Infants of 3–4 months show saccadic intrusions during smooth pursuit (Aslin, personal communication). If saccadic intrusions disappear because of frontal inhibition of the colliculus and if this inhibitory projection becomes functional between $7\frac{1}{2}$ and 12 months of age in humans, then human infants of 5–7 months should still show saccadic intrusions during smooth pursuit, but infants of 12 months should not. This prediction will be tested in collaboration with Naomi Wentworth and Marshall Haith.

Performance of Brain-Damaged Human Adults on Tasks Similar to $\bar{A}\bar{B}$, Delayed Response, and Object Retrieval

Human adults with damage confined to dorsolateral prefrontal cortex have never been tested on any of these tasks. Human adults with more diffuse brain damage have, however, been tested on DR (Freedman and Oscar-Berman, 1986). Freedman and Oscar-Berman used DR with delays of "0", 10, 30, and 60 sec, summing the results over all delays. Patients with bilateral frontal lobe damage, which included dorsolateral prefrontal cortex in some cases, failed DR, while amnesic patients (some of whom were reported to have signs of frontal lobe dysfunction) and alcoholic control subjects performed well. Performance on DR was correlated with performance on the Wisconsin Card Sort, as it should be if both are measures of dorsolateral prefrontal function.

Schacter et al. (1986) tested amnesic patients with signs of frontal lobe dysfunction on tasks similar to $\bar{A}\bar{B}$. In one task, an object was either hidden in a room rich in objects and landmarks ("Room Search") or in one of four drawers, each drawer being a different color ("Container Search"). The delay for both tasks was 150 sec ($2\frac{1}{2}$ min). The amnesic patients correctly retrieved the object from the first hiding place (location A), but when the object was hidden at a second location (B) they continued to search at A (similar to the $\bar{A}\bar{B}$ error). Unlike human infants, however, these patients were as likely to err when the object was uncovered as when it was covered. Human infants make very few errors when there are no covers (Butterworth, 1977). Patients with damage to

medial frontal cortex succeeded on these tasks and perseverated less on the Wisconsin Card Sort than did the amnesic patients. This is as it should be if errors on AB and the Wisconsin Card Sort result from damage specifically to the dorsolateral region of frontal cortex.

The good performance of the amnesic patients in the Freedman and Oscar-Berman (1986) study and the poor performance of the amnesic patients in the Schacter et al. study (1986) may have been due to the difference in length of delay. The 150-sec delay used by Schacter and colleagues may have taxed the memory of the amnesic patients, while the shorter delays used by Freedman and Oscar-Berman did not. A second possibility is that the amnesic patients tested by Schacter et al. may have had more severe frontal lobe dysfunction than the amnesic patients studied by Freedman and Oscar-Berman.

Three points should be noted from these two studies. First, patients with dorsolateral prefrontal cortex damage failed DR even at relatively short delays (Freedman and Oscar-Berman, 1986), just as do monkeys with lesions of dorsolateral prefrontal cortex and as do infants. Second, the amnesic patients who failed tasks similar to \overline{AB} had signs of frontal lobe dysfunction, as indicated by their poor performance on the Wisconsin Card Sort task (Schacter et al., 1986). Third, patients with medial frontal cortex damage succeeded on the \overline{AB} -like tasks (Schacter et al., 1986), as they should if the critical neural locus for the performance of AB is dorsolateral prefrontal cortex.

Adult patients with frontal lobe damage are also impaired on other delayed comparison tests (Prisko, cited in Milner, 1964). On one such test, patients were presented with a color or a sound, the stimulus was removed, then a second color or sound was presented and the patients were asked if that color was the same shade or the sound the same intensity as the first stimulus. Frontal lobe patients performed well when there was no delay between the stimuli, but failed when a delay of 60 sec was used.

Adults have never been tested on Object Retrieval. However, there is evidence that vision exerts a pull on the behavior of frontal patients similar to that seen in monkeys with lesions of dorsolateral prefrontal cortex and in infants. Vision exerts a strong pull in all of us (e.g., Rock and Harris, 1967), but most of us with intact frontal lobes are able to inhibit or counteract that tendency when necessary. The power of vision over the behavior of adult frontal patients can be seen, for example, if asked to hold up a finger when the examiner makes a fist, and to make a fist when the examiner holds up a finger. Most of us might be tempted to copy what we see but would manage to follow the instructions. A patient with frontal lobe damage, on the other hand, cannot resist mimicking what he sees and so upon seeing the fist, makes a fist, even though he can repeat the instructions back correctly (for other examples of echopraxia see Luria, 1966).

In short, although adults with damage restricted specifically to dorsolateral prefrontal cortex have not been tested on precisely the same tasks on which we have tested infants and monkeys, the performance of patients on similar tasks is

fully consistent with the conclusions about brain function drawn from the work with monkeys.

Abilities Required for Success on \overline{AB} , Delayed Response, and Object Retrieval and Which Depend on the Frontal Lobe

Object Retrieval, on the one hand, and \overline{AB} and DR, on the other, would appear to share little in common. Object Retrieval is a detour task with a transparent barrier so the bait is always visible. In \overline{AB} and DR the bait is hidden. However, the fact that the human and simian infants improve on all three tasks over the same period and the fact that all three tasks have been linked to frontal cortex suggest that \overline{AB} , DR, and Object Retrieval probably require common abilities.

\overline{AB} and DR have usually been thought to be measures of memory or perseveration (e.g., memory: Fox et al., 1979; Jacobsen, 1936; perseveration: Bremner and Bryant, 1977; Mishkin, 1964). However, neither of these interpretations works very well for Object Retrieval. Object Retrieval does not appear to require memory as the box is transparent. Instead of infants perseveratively repeating what they did on the previous trial, they *fail* to repeat the previous trial's performance if a change is made in the variables controlling line of sight. For example, following three successful retrievals from the *front* of the box, if the box is moved forward 1 inch and the toy moved $\frac{1}{2}$ inch deeper into the box (so that the infant now sees the toy through the top), infants below 8½ months reach only at the top of the box, although the perseverative response would be to reach at the front. Infants fail by not repeating their previous response (Diamond, 1981, submitted). Thus, the search for common abilities required for \overline{AB} , DR, and Object Retrieval required rethinking what might be involved in the \overline{AB} and DR tasks.

It is suggested that the frontal lobe subserves two principal abilities that develop between 7½ and 12 months and are required for performance of \overline{AB} , DR, and Object Retrieval.

Relating Information Separated in Time or Space

Object Retrieval requires the subject to relate the box opening to the bait over a spatial separation. When bait and opening are superimposed (as when the bait is in the opening, partially out of the box) even the youngest infants succeed. However, as the spatial separation between bait and opening widens, the age at which infants succeed progressively increases.

\overline{AB} and DR require the subject to relate two *temporally* separated events—cue and response. The subject watches as a bait is hidden in one of two identical wells, a brief delay follows, then the subject is allowed to reach. When there is no delay between hiding and retrieval even the youngest infants succeed. How-

ever, as the time interval between hiding and retrieval increases, the age at which infants succeed progressively increases.

It should be noted that the delays in AB and DR are very brief (e.g., 2–5 sec). Whereas the hippocampus appears to be required for information to be available beyond short-term memory, prefrontal cortex appears to be needed to use information effectively while it is within short-term memory, e.g., to keep information on-line for current use.

One challenge to the importance of the role of memory in the AB task has come from the fact that studies using multiple wells have typically found better performance on AB (especially on the trials at well B) than have studies using two wells (see, e.g., Wellman et al., 1987). We have recently demonstrated, however, that this is due to a difference in experimental procedure: *when two wells are used* both wells are uncovered, the reward is hidden, and then both wells are simultaneously covered; *when more than two wells are used*, on the other hand, only the correct well is uncovered, the reward is hidden, and then only the correct well is covered again. The latter procedure makes the task easier because it draws the subject's attention to the correct well. When multiple wells are used and all wells are covered simultaneously, infants perform worse with multiple wells than they do with only two wells (Diamond et al., 1989).

It might seem contradictory to argue that infants have difficulty remembering where the toy was hidden a few seconds ago, and yet can remember where they last found the toy on previous trials (which happened perhaps minutes ago). This is not contradictory because two different kinds of memory are involved, which rely on different neural systems. The kind of memory that shows up as a response bias is the kind of memory that has traditionally been assessed using conditioning paradigms. Studies that have used conditioning to assess memory in infants (the dependent measure being how long a response is retained) have typically found quite long memory in very young infants. For example, infants of only 2 months can remember a conditioned response for at least 3–5 days (Rovee-Collier, 1984). I would argue that this is the kind of memory called "implicit" or "procedural" (Cohen, 1984; Schacter, 1987; Squire and Cohen, 1984). It is the kind of memory that can be demonstrated in behavior without any conscious awareness of the "memory" on the part of the person. Adults with amnesia demonstrate similar robust memory on conditioning paradigms, even though they have no conscious recollection of having done the task and even though their conscious recall and recognition are very poor after a few minutes (Mishkin et al., 1984; Weiskrantz and Warrington, 1979). The areas of the brain required for implicit or procedural memory, i.e., required to show the effects of conditioning, are clearly subcortical and mature very early. For example, Thompson and colleagues (McCormick and Thompson, 1984; Thompson et al., 1984) have demonstrated the crucial involvement of the cerebellum in retention of the classically conditioned eyeblink response. AB and DR, on the other hand, require explicit recall of the hiding.

Conceiving of memory as one aspect of the ability to relate information over a separation, be it temporal or spatial, enables one to bring together literatures which are not usually discussed in the same breadth—conditioning in infants and the Piagetian AB task. Millar and Watson (1979) demonstrated that infants of 6–8 months could acquire a conditional response if the delay between response and reinforcement were 0 sec, but not if the delay were 3 sec. These results are quite comparable to those found for AB and DR. Infants of 8 months succeed on DR or AB when the delay between hiding and response is 0 sec, but not when the delay is 3 sec. The Millar and Watson task, like AB and DR, requires that memory be maintained on-line either to relate the response to the reward (Millar and Watson) or to relate the cue (site of hiding) to the response (site of retrieval) (AB and DR). These tasks all look at the ability to bridge a delay within a trial, the ability to integrate information over a temporal separation. Whereas, Millar and Watson looked at the effect of a temporal separation between cue and reward, Millar and Schaffer (1972; 1973) looked at the effect of a spatial separation between cue and reward. They trained infants to push a lever to produce a visual light display. As long as cue and reward were in the same visual field, infants of 6–8 months succeeded, but when required to look one place and reach another, only infants of 9 months or older succeeded. This is reminiscent of the results on Object Retrieval. Only by 9 months (Phase 2) could infants look one place (through a closed side) and reach another (through the opening). Having looked through the opening, a Phase 2 infant could sit up, look through a closed side and reach into the opening.

The development of the ability to relate or integrate two or more items is an ever-present theme in the age progression in Object Retrieval performance. It is seen in the development of (1) the ability to reach through one side of the box while looking through a different side, (2) the ability to attend to both visual and tactile information, and (3) the ability to do different things with the two hands. When infants reach through the side they are looking, they can almost always reach the toy by a straight route. When they look through one side and reach through another, their reach is almost always two-directional, as when an infant sits up and looks through the top and then reaches away from the midline to get to the left or right opening and then directs the reach back toward the midline to get the toy. Here one sees the development of the ability to integrate two movements in opposing directions.

Tasks that require the simultaneous use of multiple facts prove very difficult for adults with frontal cortex damage. For example, they can solve math problems such as "What is 30 divided by 2?" and "What is 15 times 5?" But they cannot solve "If the price of 2 packages is \$30, what is the price of 5 packages?" (Barbizet, 1970). Frontal patients also have unusually severe difficulty doing two things at once or attending to more than one thing at a time. When they are shown a pictorial scene suggesting a story, they typically fixate on one detail in the picture, missing the suggested story (Nichols and Hunt 1940).

Relating items in a sequence is also a problem. An expert cook, following frontal lobectomy, can still measure, pour, sift, and knead, but may not be able to put these together to bake a loaf of bread or to make a many course meal. Frontal patients have great difficulty keeping track of a temporal sequence. They can remember which of two pictures they saw before (unlike temporal lobe patients who cannot), but they cannot remember which of two pictures they saw most recently (Corsi, cited in Milner, 1974). When shown a page of words or pictures and instructed to touch all stimuli, one at a time, in any order, but without repeating a choice, frontal patients touch some stimuli more than once, never managing to touch them all (Petrides and Milner, 1982). They do not persevere; rather they simply fail to sample all stimuli systematically. This is reminiscent of the behavior of 8- to 9-month-old infants who fail to systematically check all sides of the box; they reach back repeatedly to sides they have tried and found closed.

Inhibiting Prepotent Responses

In Object Retrieval, the tendency to reach straight to a visible target must be inhibited. Infants must instead reach around to the opening. Results when the box is opaque provide particularly strong evidence here: infants perform better with the opaque box, where the toy cannot be seen through a closed side (Diamond, submitted). The counterintuitive finding that the task becomes easier when the goal is not visible supports the hypothesis that *seeing* the goal through a closed side makes the task harder because the tendency to reach straight to the goal must then be inhibited.

Inhibition of the predominant response is to be distinguished from perseveration. The predominant response is often the response a subject has been making, in which case lack of inhibitory control will be manifest as perseveration. However, when the prepotent response is different from the response just made, lack of inhibitory control is manifest by a failure to persevere (as seen in Object Retrieval). An example from work on the frontal lobe illustrating the distinction between inhibitory control and perseveration is as follows.

Jacobsen and colleagues (Jacobsen et al., 1935; Crawford et al., 1948) presented chimpanzees with a row of four pegs. The chimpanzees were taught to push on the first three pegs and pull the fourth to obtain a reward. Perseverative errors would have been to try to push peg 4, i.e., to repeat the response they had made at pegs 1, 2, and 3. The prepotent response, however, would be the one most closely associated with the reward. Since the reward was delivered after pulling the fourth peg, pulling would be prepotent here. Frontally lesioned chimpanzees did not try to push peg 4, instead they tried to pull pegs 2 and 3. These errors of "anticipation" were not overcome within the limits of testing.

Problems in the inhibitory control of behavior occur in all areas of life for frontal patients. Socially, they are "disinhibited," meaning that they lack the usual inhibitions about saying or doing inappropriate things (such as talking

about sex in public). Frontal patients are easily distracted by irrelevant, but firmly established, connections. They are pulled by this free association or that. This makes it extremely difficult to obtain even a simple personal history from such patients because of the many associations to that history.

One of the classic tests for frontal lobe function is the Stoop test. Here, the names of colors are printed in the ink of another color (e.g., the word "blue" is printed in red ink). Patients are instructed to report the color of the ink as they look through the list of words. The customary response when reading, however, is to ignore the ink and attend to the meaning of the word. Frontal patients fail the test; they recite the words and not the color of the ink (Perret, 1974).

In \overline{AB} and DR, a conditioned tendency or "habit" to reach to "A" (where the subject was rewarded) must be inhibited when the bait is hidden at "B." One would expect this tendency to be stronger, the greater the number of reinforced trials at A. Within a narrow range, more reinforced trials at A does *not* lead to more errors at B [one vs. three trials reinforced trials at A (Diamond, 1983), two vs. five trials (Evans, 1973), and three vs. five trials (Butterworth, 1977)], but when 2 vs. 8–10 consecutively correct reaches at A are compared, the expected result is found. Infants who reached correctly to A 8–10 times in a row made significantly longer strings of errors at B than infants who reached correctly at A only twice in a row before side of hiding was reversed (Landers, 1971).

If memory were the only requirement of \overline{AB} , errors should appear equally on all types of trials. The \overline{AB} error, however, consists of good performance when reward is hidden where the subject just reached correctly, and repeated errors when the side of hiding is reversed. When the side of hiding changes, \overline{AB} sets up a conflict between a subject's memory of where the reward was just hidden and the subject's tendency to repeat a rewarded response. To succeed on \overline{AB} , a subject must inhibit that tendency. Hippocampal monkeys, who have poor memory but can inhibit their response tendency, do not show the \overline{AB} error pattern. At short delays they perform well and at long delays, where their performance is poor, they are no more likely to err on reversal trials than when side of hiding is unchanged.

Infants and prefrontal monkeys may sometimes reach back to well A *even when they know the toy's location*, because of difficulty inhibiting the habitual response. Baillargeon (Baillargeon et al., 1985; Baillargeon, 1987; Baillargeon and Graber, 1988) has shown by visual fixation measures that infants appear to know where the hidden toy is, even though they err when allowed to reach. Certainly, infants sometimes reach back to A when the toy is visible at B, as when the covers are transparent, and occasionally when there is no cover at all (Butterworth, 1977; Harris, 1974). Often infants will uncover A, *not look in*, then reach immediately to B and retrieve the toy (Diamond, 1985). It is as if they know the toy is at B even though they reach first to A. Most telling, an infant occasionally looks directly at B before, and throughout, the reach, even as the infant's hand goes to A.¹⁰ If direction of gaze were the dependent measure, the infant would be scored as correct on such trials (see Figure 14).



Figure 14. Instance of an infant looking at B while reaching to A. Infant had successfully retrieved the toy at well A. Side of hiding is now reversed to B. Frame 1: Infant clearly sees the hiding at B. After a brief delay, infant was allowed to reach. Frames 2-4: Although infant is looking fixedly at B, his hand reaches back to A.

This interpretation gains support from observations with the Wisconsin Card Sort: After having been rewarded for sorting the cards by one criterion, patients with damage to the frontal lobe have difficulty sorting the cards by a new rule. However, these patients can sometimes tell you the new rule as they continue to sort the cards incorrectly. Indeed, they sometimes say as they are sorting the cards by the old criterion, "This is wrong, and this is wrong" (Luria and Homskaya, 1964; Milner, 1964; Nauta, 1971).¹¹ Infants cannot tell you the correct answer verbally, but looking at A even as they reach to B may be the nonverbal equivalent.

Thus improved performance here may mark the emergence of the ability for a memory-based intention to override habit: the emergence of the ability to exercise choice. In \overline{AB} , DR, and the Wisconsin Card Sort, an initial response is strengthened by reinforcement. This effect of reinforcement on a response is evident in infants soon after birth (e.g., Papousek, 1961) and in the simplest organisms (e.g., Castellucci and Kandel, 1976; Carew et al., 1984). It develops early (in both phylogeny and ontogeny) and is robust, capable of surviving considerable neurological insult. A more fragile and later developing ability is the capacity to resist a dominant action tendency, whether it is innately strong or has been strengthened by reinforcement. It is this ability that is required when the correct well changes in \overline{AB} or DR, the correct criterion changes in the Wisconsin Card Sort, or the subject sees the reward through one side of the Object Retrieval box but must reach through a different side. Although instinctual and habitual responses are very strong even in humans, we are capable, with effort, of breaking a habit, whereas organisms without frontal cortex may have no such option. This ability to resist the strongest response of the moment endows us with extraordinary flexibility and the freedom to choose and control our actions. Inhibitory control thus distinguishes us from lower organisms and is one of our highest accomplishments.

It is as much a developmental achievement to be able to inhibit unadaptive reactions as to acquire new behaviors and knowledge. Development proceeds both by the progressive acquisition of concepts and by the progressive inhibition of reactions that get in the way of expressing knowledge that is already present. To some extent, infants appear to know more than they can demonstrate in their behavior, as when they seem to know the location of a hidden toy, but are unable to demonstrate this in their reaching behavior (see also, Diamond and Gilbert, 1989).

In conclusion, I would like to suggest that a maturational change in frontal cortex underlies improved performance on \overline{AB} , DR, and Object Retrieval between 7½ and 12 months in human infants and 1½-2½ months in infant monkeys, and that the cognitive abilities subserved by frontal cortex and required for success on these tasks are (1) the ability to integrate information over a temporal or spatial interval, and (2) inhibitory control (the ability to resist a bias to make the prepotent response). These tasks are dependent on frontal cortex

function because they require *both* of these abilities. If either ability is taxed alone some errors occur (e.g., a few errors occur at well A in the AB task when a delay is used, taxing only memory; a few errors occur at well B when transparent covers are used, taxing only inhibitory control), however, the vast majority of errors occur when both abilities are taxed (when the reward is hidden at well B with opaque covers and a delay).

This leads to the prediction that infants of 7½–9 months of age would succeed at Delayed Match to Sample [we already know that monkeys with lesions of dorsolateral prefrontal cortex perform well on this task (Passingham, 1975; Mishkin and Manning, 1978)], *but* that both these infants and monkeys would fail Delayed *Nonmatch* to Sample. Delayed Match to Sample and Delayed *Nonmatch* to Sample are formally similar. On both tasks the subject is shown a sample object, and then after a brief delay the subject is given the choice of reaching to the object that matches the sample or to a novel object. The crucial difference between the tasks comes from the fact that infants (e.g., Fantz, 1964; Fagan, 1970) and monkeys (e.g., Brush et al., 1961; Harlow, 1950) have a natural tendency to prefer novel stimuli over familiar ones. Thus, Delayed Match requires only memory (which object have I seen before?), whereas Delayed *Nonmatch* requires both memory and inhibition of the tendency to reach to the new stimulus.¹² It is this combination of requirements that I believe is the hallmark of tasks dependent on prefrontal cortex.

Coda: Principles of Development as They Are Illustrated by A \bar{B} , Delayed Response, and Object Retrieval

It is of interest to consider the developmental progressions outlined here in light of the principles outlined by Gilbert Gottlieb at the meeting and summarized in his 1983 paper.

Invariant Sequence

Despite significant individual differences in the quantitative aspects of development, the *sequence* in which behavioral stages follow each other in any given species is remarkably constant when typical developmental conditions prevail. (Gottlieb, 1983, p. 8)

All infants progressed through the same series of phases in the same order on Object Retrieval. So consistent was this developmental sequence across infants that it fit a Guttman scale with a coefficient of reproducibility of 0.93. Although no infant of 7½ months had yet reached Phase 2, by 9 months no infant was still in Phase 1, and by 12 months *all* infants had reached Phase 4. No infant ever reached a later phase without having gone through the earlier phases.

On A \bar{B} , all infants showed an increase in the delay they were able to tolerate between hiding and retrieval. No 7-month-old infant was ready for A \bar{B} testing

with a delay even as long as 5 sec. Indeed, at 8 months most infants were still making the A \bar{B} error at delays under 5 sec. By 12 months of age, however, only one infant was still making the A \bar{B} error at a delay of 5 sec, and only three infants were still making the A \bar{B} error at delays under 10 sec.

There were also marked individual differences on A \bar{B} , however, as can be seen by the size of error bars in Figure 3. Children of the same age differed widely in the delay at which they made the A \bar{B} error, so much so that age accounted for only 46% of the variance. For example, at 8 months, the range of delay at which the A \bar{B} error occurred was 0–8 sec and at 11 months it was 2–12 sec. Some infants progressed gradually and continuously on A \bar{B} , others showed early precocious performance but then no further advance for months, and still others progressed in spurts where no change was seen for weeks and then suddenly there was a dramatic improvement.

There was less variability across infants in the age of attainment of the Object Retrieval phases. This was particularly true for the younger ages. With the later phases (Phases 3 and 4), however, individual differences in rates of attainment became more noticeable. Thus, the age range for Phase 3 was 9–11½ months and the age range for Phase 4 was 9½–12 months.

Although infants progressed through an invariant sequence of phases on Object Retrieval, there was still room for alternative developmental routes to successful performance in that the character of the phases did not always look the same for all infants. In particular, when 4 of the 25 infants followed longitudinally reached Phase 3, they did not conform to the pattern of Phase 3 behavior described above. When the left or right side of the box was open, most Phase 3 infants did not reach to the opening unless they had already looked into the opening, although this line of sight did not need to be maintained. However, four Phase 3 infants did not need to look in the left or right side of the box to reach there. They reached to a side opening without ever having looked into it. This was not yet Phase 4 performance, however, because these four infants never succeeded in getting inside the opening and retrieving the toy on these trials. Each of these infants failed because of an “aim problem” (e.g., reaching too high and getting their thumb caught on top edge of opening, or reaching too far back and reaching behind the box instead of into the opening). While most infants appeared to attend to visual information only, ignoring information available through touch, these four infants appeared to attend to tactile information only, ignoring information available through vision. These infants seemed to tactily search for the opening by feeling for an edge. It was striking to see an infant feel the back wall of the opening then reach behind the box as if it were the opening. The two infants who kept getting their thumb caught did so even when the box was tipped, greatly increasing the size of the opening, because they kept adjusting their reach upward so that their thumb kept hitting the top edge of the opening. Thus, no infant at Phase 3 was yet fully integrating visual and tactile information. However, while most infants attended to vision, a few directed their attention to touch. This latter strategy may have been superior because all 4

infants who chose this route reached Phase 4 at an earlier age than did the other 21 infants.

Critical Periods

There are prenatal and postnatal periods or stages in development when the organism is dependent on certain forms of stimulation for subsequent normal (typical) development. Other ways of viewing these stages are that they are ones in which the organism is maximally susceptible to certain kinds of stimulation, or when ease of mastering certain behavioral tasks is much higher than at other times in the life cycle. These stages are sometimes referred to as critical periods of development. . . . On its weakest interpretation, the concept of an optimum or critical stage implies that the development of particular abilities or endpoints is not equipotential over the lifespan; on its strongest interpretation, the critical period concept means that certain experiences must occur during a delimited period early in development if subsequent development is to be normal (species typical). (Gottlieb, 1983, p. 7)

There is no evidence that there is a critical period for attainment of $\overline{A\overline{B}}$ or Object Retrieval. There is no evidence that if some critical experience does not occur by a certain stage, infants will be impaired on $\overline{A\overline{B}}$ or Object Retrieval. On the other hand, there *is* evidence that infants cannot benefit from certain experiences *before* certain ages. Although the term "optimum" or "critical" stage is usually meant to imply that it is best if some experience occurs before a certain age, it is suggested here that a point of development might also be "optimum" or "critical" in that a given experience will have little or no effect if it occurs before that point. On Object Retrieval, the critical points were transitions between phases. Experience with the opaque box often aided an infant in moving to the next higher phase with the transparent box when that infant was at the border of moving to that next higher phase. However, if an infant had just entered a particular phase, experience with the opaque box did not improve performance with the transparent box. Having looked through the opening did not aid a Phase 1 or 1B child if this line of sight was broken, however, it greatly aided older infants. The results on Object Retrieval yield countless examples of experiences or information that did not aid performance until infants reached a certain age.

Limits to the Role of the Environment

It is the developmental geneticist Waddington's (1942) notion that early normal or species-typical physiological and anatomical development can withstand great assaults or perturbations and still return to (or remain on) its usual developmental pathway, thus producing the normal phenotype. Waddington's concept of canalization is one that says that usual developmental pathways are buffered and thus normal (typical) development can be only temporarily derailed. (Gottlieb, 1983, p. 9)

The abilities required for Object Retrieval and $\overline{A\overline{B}}$ appear to be well canalized (to use Waddington's terminology) or characterized by a narrow range of modifiability (to use the terminology of Lorenz, 1965), at least over the ranges of experience thus far investigated. Infants tested longitudinally do perform better than infants tested only once. But the differences are small and are as easily attributed to familiarity with the tester and laboratory as to practice. The same developmental progression on $\overline{A\overline{B}}$ is found in lower and upper middle class children (lower middle class: Gratch and Landers, 1971; upper middle class: Diamond, 1985), although preliminary results suggest that very poor children may be more significantly behind their attainment of milestones on the task. On Object Retrieval, exposure to the opaque box aided performance with the transparent box if an infant was almost ready to move on to the next phase. However, experience with the opaque box never aided infants who had just entered a phase and it never enabled infants to move up more than one phase. Thus, its effects were limited both in terms of when they could occur and in magnitude.

Facilitation Versus Induction

Facilitation acts as a temporal regulator of achievements which will nonetheless eventually be reached even if the organism is deprived of the normally occurring experience. *Induction* represents experience that is essential if the species typical endpoint is to be fully achieved. (Gottlieb, 1983, p. 15)

Performance on Object Retrieval and $\overline{A\overline{B}}$ can be facilitated by experience to a small extent, but success on both is achieved regardless of the infant's experience, at least within the range of experience thus far investigated. Repeated testing and exposure to the opaque box are two experiences that appear to have salutary effects. However, infants of 1 year who were tested only once and who were never exposed to the opaque box performed perfectly on $\overline{A\overline{B}}$ even at delays as long as 10 sec and succeeded on all Object Retrieval trials, displaying sophisticated Phase 4 behavior. Thus, $\overline{A\overline{B}}$ and Object Retrieval would appear to be dependent on abilities so fundamental to the human organism that given the normal range of experience these abilities will be acquired by all infants.

Acknowledgements

The work summarized here was carried out at: (a) Harvard University, in the laboratory of Jerome Kagan, with funding from NSF (Doctoral Dissertation Grant BNS-8013-447) and NICHD (HD-10094), and support to the author from NSF and Danforth Graduate Fellowships, (b) Yale University School of Medicine, in the laboratory of Patricia Goldman-Rakic, with funding from NIMH (MH-00298 & MH-38456), and support to the author from a Sloan Foundation

award and NIMH Postdoctoral Fellowship (MH-09007), (c) University of California, San Diego, in the laboratory of Stuart Zola-Morgan, with funding from the Medical Research Service of the Veterans Administration, NIH, and the Office of Naval Research, and support to the author from a grant from Washington University, and (d) Washington University, St. Louis, and the University of Pennsylvania, in the laboratories of the author, with funding from the McDonnell Center for Studies of Higher Brain Function at Washington University School of Medicine, NIMH (MH-41842), & BRS (RR07054 & RR07083).

Notes

1. "Frontal lobe" is used in this paper to refer to that portion of frontal cortex rostral to the precentral gyrus. It includes association cortex (prefrontal, supplementary motor, and premotor), but not primary motor cortex. The frontal lobe is the largest and most prominent functional subdivision of cortex in the human brain. It is also the area that has undergone the most dramatic increase in size over the course of human evolution. Thus, for example, not only is the human brain larger than the cat brain, but the frontal lobe occupies 25% of this larger human brain whereas it occupies only 3% of the cat brain.

2. Infants do not reach for hidden objects until about 7½ months of age. Since the AB task requires the subject to uncover a hidden object, infants younger than 7½ months cannot be tested on the task.

3. The lesion used by Moll and Kuypers was unusually large, extending from the posterior two-thirds of the principal sulcus to the rostral portion of the precentral gyrus. Thus, it included the posterior portion of dorsolateral prefrontal cortex, the entire periacuate region, the supplementary motor area (SMA), and premotor cortex.

4. As there has been some misunderstanding about the characteristics of "deteriorated performance," some clarification is in order. Deteriorated performance is seen when the task has become so difficult that the subject becomes distressed and does not want to remain in the situation. Sometimes subjects react by reaching randomly; other times they exhibit exceedingly long error strings. Always they show overt signs of distress, such as crying or fussing (or, in the case of monkeys, agitated circling); and often they fail to self-correct. This is the only time that performance on repeat-following-correct trials (roughly equivalent to trials at well A) is as poor as performance on reversal trials (roughly equivalent to trials at well B) and as performance on repeat-following-error trials.

The progression from accurate performance, to the the AB error, to deteriorated performance is not curvilinear, as Wellman et al. (1987) thought I was saying. As illustrated in Figure 6, during accurate performance subjects are correct at both wells A and B. The defining characteristic of the AB error is significantly worse performance at B than at A. Empirically, subjects perform at roughly chance on the trials at B, and significantly better than chance on trials at A. During deteriorated performance subjects perform poorly on trials on both A and B; there is no longer any differential pattern of performance by type of trial.

5. A similar observation was made by Bruner (1970). Here the task consisted of a box with a transparent lid mounted on sliding ball bushings. To retrieve the toy, the child had to slide the lid up its track, which was tilted 30° from the horizontal and would fall back down if not held. "A seven month old has great difficulty holding the panel with one hand while reaching underneath with the other. Indeed, the first compromise solutions to the problem consist of pushing the panel up with both hands, then attempting to free one

hand in order to slip it under the panel. One notes how often the infant fails because the two hands operate in concert" (Bruner, 1970, p. 71).

6. It is important to note that although developments in Object Retrieval performance have been discussed here in terms of no longer needing to look through the opening, it is equally accurate to describe these developments in terms of being able to relate two movements to one another. When infants could see the toy through the opening they could reach straight for the toy. When infants were looking through a closed side of the box, they usually needed to reach in one direction to clear the opening and then change direction to retrieve the toy.

Younger infants almost always reached on a straight line. Two-directional reaches were seen in older infants and emerged as infants began to reach into the opening without simultaneously looking into the opening. In part, progress on Object Retrieval over age appears to be progress in executing reaches that change direction, i.e., reaches with two vector components.

7. Infant monkeys do not reach for hidden objects until about 1½ months of age. Since the AB task requires the subject to uncover a hidden object, monkeys younger than 1½ months cannot be tested on the task.

8. After the covering of the wells, a curtain was quickly lowered and raised between the wells and the subject. Thus, the "0" sec delay was probably at least 1–2 sec long.

9. Note how different the results are if a conditioning paradigm is used to determine how long a delay between response and reward the subject can withstand within a trial (as done by Millar and Watson) as opposed to how long the subject can retain a response once it is learned.

10. It should be emphasized that such dissociation of looking and reaching is uncommon in infants; infants, especially at 7½–9 months, almost always look where they are reaching. However, laboratories all over the country who have studied AB have seen this behavior, and it is particularly dramatic because it goes counter to the strong tendency of infants to direct their eyes and their hands to the same place.

11. Such dissociations between frontal patients' verbal and motor behavior are common. One such example is provided by Teuber: The patient "has in many ways what people call a classical frontal lobe syndrome. . . . He was put to work in the garden where he was assigned to another man who was digging ditches; our patient had a big pair of shears with which to cut roots. . . . And while a ditch was opened, a huge thing appeared: four black strands lying side by side. The patient was standing there, and the subsequent episode was described by both the patient and his companion. He said, "Ha, ha, it's not a root. It looks like a root (going through the motions of cutting). It looks like a root. It's not a root. Why are the fire alarms ringing?" By cutting the strands he had sorted out all the cables that led to the alarms all over the camp." (Teuber, in discussion of Konorski and Lawicka, 1964, pp. 287–288).

12. Neither monkeys with lesions of dorsolateral prefrontal cortex nor human infants have been tested on Delayed Nonmatch to Sample with the modern procedure of trial-unique stimuli. This procedure is critical because if the same stimuli are used repeatedly over trials, then no stimulus is new, and the tendency to reach to the new stimulus does not need to be inhibited.

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