The Epigenesis of Mind: Essays on Biology and Cognition

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3 Neuropsychological Insights into the Meaning of Object Concept Development

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I propose that infants know a good deal more about objects than Piaget gave them credit for knowing. For Piaget, many of the developments between 5 and 12 months of age concerned the elaboration of the concept of the object and the concept of space. The thesis of this chapter is (a) that what emerges between 5 and 12 months is, instead, the ability to *demonstrate* an understanding of these concepts, the understanding already having been present, and (b) that these behavioral developments between 5 and 12 months are intimately tied to maturation of frontal cortex.

If infants understand the object concept and spatial relationships, why can't they demonstrate this in their behavior? There appear to be two reasons. First, behavioral predispositions get in the way. Infants must be able to inhibit these action tendencies if they are to demonstrate what they know. Second, the demonstrations that Piaget required of infants often involve relating two actions together in a sequence or relating information over a separation in space or time. These inhibitory and relational abilities are not in place early in the first year. Frontal cortex and its network of neural interconnections must reach a certain level of maturity before these abilities begin to appear.

Inhibitory Control

Cognitive development can be conceived of, not only as the progressive *acquisition* of knowledge, but also as the enhanced *inhibition* of reactions that get in the way of demonstrating knowledge that is already present. Reflexes of the hand, which are invaluable aids during the first months of life, must be inhibited if more mature manipulatory behavior is to emerge. Over the period of *5–8 months of age* infants become able to inhibit their *reflexive reactions to contact,* such as the grasp reflex. Inhibition of these reflexes depends on maturation of the supplementary motor area (SMA) (see Fig. 3.1).

Between *8 and 12 months of age* infants first become able to inhibit *predominant response tendencies,* that is, they first become able to resist the strongest response of the moment. (A response tendency can be inherently predominant, such as reaching straight for a visible goal: If you see what you want, the tendency to go toward it does not have to be learned. Indeed, it requires effort and discipline to resist this tendency when a more circuitous route is appropriate. A predominant response can also be acquired or learned, e.g., on the basis of reinforcement experience.) Inhibition of the dominant or habitual response depends upon maturation of dorsolateral prefrontal cortex. Dorsolateral prefrontal cortex borders SMA and is immediately anterior to it (see Fig. 3.1).

Relational Abilities

Inhibition is only one of the abilities dependent on frontal cortex that appears to underlie behavioral changes between 5 and 12 months. Piaget correctly saw that many of the advances of this period are made possible by the increasing ability to "put into relation" (Piaget, 1952 [1936], pp. 237–239). Part of the task solved by infants between *5–8 months of age* is to *combine actions together into a behavioral sequence,* whether it be a means–end sequence or a reaching sequence consisting of two different movements. Relating two or more movements into a sequence in this way is dependent upon SMA.

Over the period of *8–12 months,* infants become able, for the first time, to relate two different movements together *simultaneously*. That is, they become able to do one action with one hand while at the same time doing something else with the other hand. This complementary use of the two hands is dependent upon maturation of the interhemispheric connections via the corpus callosum between the two SMAs on either side of the brain. Such bimanual coordination is an achievement of relational ability *and* inhibition, inasmuch as it requires not only coordinating the actions of the two hands but also inhibiting the tendency of both hands to do the same thing.

From *8–12 months* one also sees important advances in the ability to *relate information over temporal delays or spatial separations.* (Note that relating information over a temporal delay requires memory, or sustained attention, to keep something in mind in the absence of perceptual supports. This is seen here as part of a more general ability to relate information separated in space or time.) This ability is tied to dorsolateral prefrontal cortex. Whereas SMA

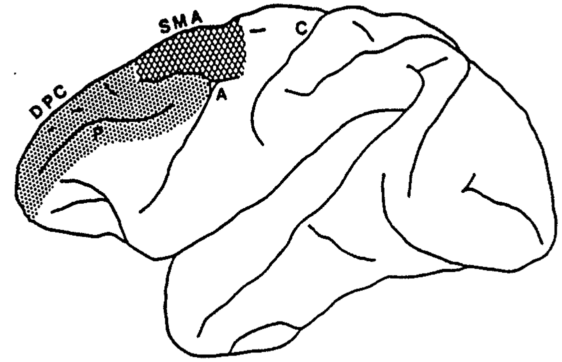


FIG. 3.1. A lateral view of the rhesus monkey (*macaca mulatta*) brain. The area covered by hatched lines just behind the arcuate sulcus represents the supplementary motor area (SMA), which extends further to the midline than can be shown in this diagram. SMA occupies the anterior medial surface of Brodmann's Area 6. In the terminology of other maps of the macaque brain, SMA corresponds to Area 6aβ of the Vogts and Areas FC and FB of von Bonin and Bailey (see Weisendanger, 1981).

The dotted area just in front of the arcuate sulcus represents dorsolateral prefrontal cortex (DPC). Dorsolateral prefrontal cortex centers around the principal sulcus and extends from the anterior bank of the arcuate sulcus to the frontal pole. It includes most of Brodmann's Area 9, Area 8, and some of Area 10. In the terminology of other maps of the macaque brain, it corresponds to Area 9, much of Area 8, and some of Area 10 of the Vogts, and corresponds most closely to Area 46 of Walker, including Walker's Areas 8 and 9 as well.

C = central sulcus. All cortex in front of the central sulcus is part of frontal cortex.

A = arcuate sulcus. This is the principal boundary between SMA and dorsolateral prefrontal cortex.

P = principal sulcus. This is the "heart" of dorsolateral prefrontal cortex.

is required for executing a sequence of actions, dorsolateral prefrontal cortex is required for remembering a sequence of actions (as in temporal order memory).

Frontal Cortex Maturation

Thus, I am proposing that some of the critical behavioral changes in the second half of the first year of life are made possible by maturational changes in frontal cortex and in its neural connections. More precisely, the hypothesis is that those maturational changes begin more posteriorally (involving the supplementary motor area [SMA]) and progress toward the frontal pole (dorsolateral prefrontal cortex) over these months, and include the emergence of interhemispheric communication between the frontal cortices on the two sides of the brain.

Plan of the Chapter

First, evidence is presented that an understanding of the object concept and of the spatial relations among objects, such as contiguity, are present early in the first year. Given that, the question of why infants make the striking mistakes Piaget so astutely observed is considered. (If infants are as smart as I claim, why do they act so "dumb"?) Finally, evidence is provided linking the behavioral advances during the first year, and the abilities that underlie them, to frontal cortex. Contiguous objects, hidden objects, and detour reaching are considered. The chapter is organized, not by problem or task, but by age. First, the changes between 5 and 9 months are considered, that is, tasks on which infants of 5–7 months fail but infants of 7½–9 months succeed. Second, the changes between 8 and 12 months are considered, that is, tasks on which infants of 7½–9 months fail but infants of 9½–12 months succeed.

CHANGES BETWEEN 5 AND 9 MONTHS OF AGE: RELATING ACTIONS TOGETHER IN A SEQUENCE AND INHIBITION OF THE REFLEXES OF THE HAND

Contiguous Objects

Piaget (1937/1954) concluded that infants do not understand the spatial concept of contiguity, that is, that an object continues to exist independently even when it shares a boundary with another object: "... [T]here is a general difficulty in conceiving of the relations of objects among themselves (in contrast to the relations of objects with the subject himself). It is this general difficulty which prevents the child from realizing that two objects can be independent of each other when the first is placed upon the second" (p. 177).

The behavioral observation on which this was based was that although infants can retrieve a small free-standing object, they fail to retrieve that same object if it is placed on top of a slightly larger object. This was confirmed by Bower (1974), who also demonstrated that infants fail to retrieve an object if it is placed directly behind a slightly larger object. For example, infants will retrieve a small object if it is several inches behind a screen but not if it is directly behind the screen. Bower's (1977) conclusion echoed that of Piaget: "It seems that what the baby doesn't understand is that two objects can be in a spatial relationship to one another, so that they share a common boundary. Evidently it is the common boundary that is critical" (pp. 116–117).

We have confirmed Bower's observations, using a plexiglass box open at the top rather than a screen. We found that infants could retrieve a building

block from the center of the plexiglass box (2 inches from the front wall of the box), but they failed to retrieve the building block when it was directly behind the front wall of the box (Diamond & Gilbert, 1989). However, we also found that infants succeeded in retrieving the building block when it was outside the box, bordering the front wall. Moreover, when a thinner building block was used, infants failed to retrieve that when it was a half-inch behind the front wall of the box (not touching the wall), although they successfully retrieved the thin block when it was in the center of the box (2 inches from the front wall). Here, infants succeeded in a condition of contiguity ("in front of") but failed in a condition where the wall and toy shared no common boundary (thin toy a half-inch from wall). These findings cannot be accounted for by a problem in understanding the concept of contiguity. Sharing a common boundary seems not to be the critical factor.

Infants did not fail because they did not try. All tried to retrieve the toy, and gave clear evidence that they were reaching for the toy and not the box. Their behavior indicated that they knew the toy was there even when it bordered the wall of the box. For example, infants showed little interest in reaching for the box alone, but when the toy was inside (even when it bordered the wall) they reached persistently. They showed great frustration at not being able to retrieve the toy. Although they typically made contact with the box rather than the toy, their reaches all appeared to be directed at the toy.

In studying the frame-by-frame record of the infants' performance, we noticed that unsuccessful reaches often ended with the infants grasping the edge of the box (grasp reflex) or grazing the edge of the box and then jerking their hand back (avoidance reflex). Grasping the edge or withdrawing their hand would then be followed by another attempt to reach, and another, and another, each ending with the same frustrating result.

In short, it seemed to us that the infants were trying to retrieve the toy, but were having difficulty in getting their hand to the toy. The problem seemed to be that (a) the infants could not guide their reaches accurately enough to avoid touching the edge of the box en route to the toy, and (b) once they touched the edge of the box they could not inhibit reflexive grasp or avoidance reactions. (A touch too slight to trigger a reflexive grasp is often sufficient to trigger the avoidance reaction, which consists of withdrawing or springing the hand back in response to contact [Twitchell, 1965, 1970].)[1]

Seven-month-old infants can accurately reach to a free-standing object

[1]According to Twitchell, the grasp reaction is not fully formed until after 4 months and then becomes less easily and reliably elicited by the last months of the first year. The avoidance reaction is fully formed by 24–40 weeks. Note that the experimental situation described here should be particularly well suited to elicit the grasp reaction because the infant is reaching out for the toy, primed to grasp, so that when the infant touches the box that which was primed gets released.

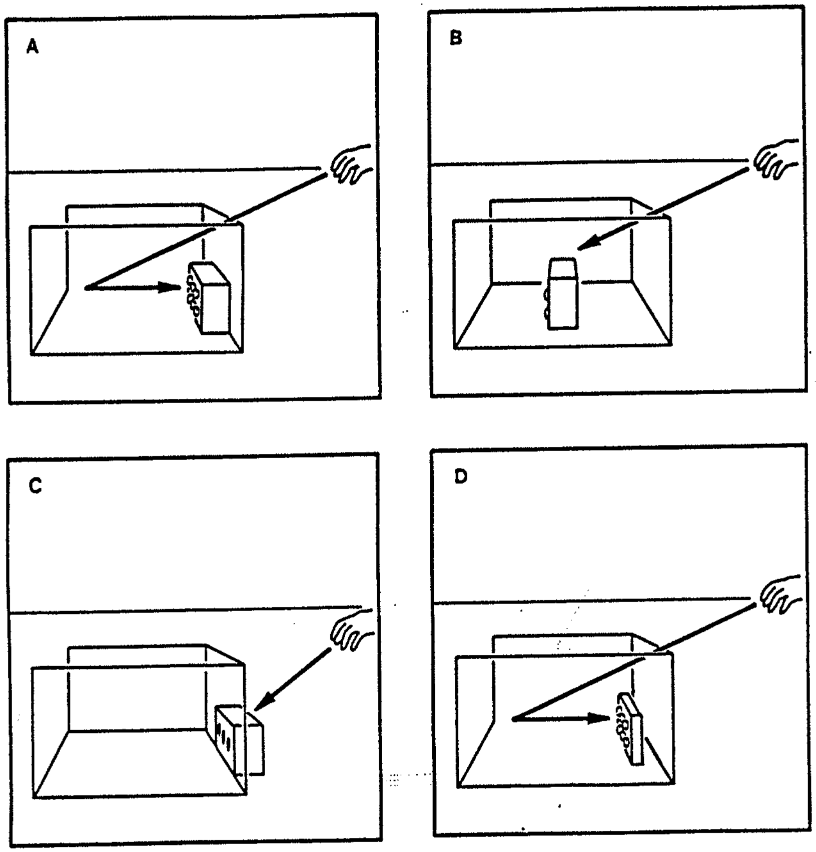


FIG. 3.2. Infants could reach on a straight line for the toy when (C) the toy was outside the box, bordering the front wall, and when (B) the toy was in the center of the box. However, when (A) the toy was inside the box, bordering the front wall, or when (D) a thinner toy was one-half inch behind the front wall, infants could not get to the toy by reaching on a straight line. They had to reach over the front wall of the box and then change direction to reach back for the toy. (Adapted from Diamond & Gilbert, 1989)

and can retrieve a toy from the center of the box. Why, then, should they have had difficulty aiming their hand to the toy when it was touching, or near, the front wall of the box? We reasoned that by 7 months infants could execute a straight reach with ease, but they had difficulty executing a reach that required changing direction (i.e., reaching away from the goal and then back toward it). When the toy was in front of the box touching the front wall, or in the center of the box, infants could reach for it on a straight line. However,

when the toy was directly behind the front wall of the box, infants had to first reach over the wall and then back for the toy. (See Fig. 3.2.)

To test this, we predicted that infants would perform better if the box were closer to them (so that they could reach straight down for the toy), if the walls of the box were lower, if the toy were placed vertically so that it was as tall as the box, or if the toy were placed perpendicular to the wall (so that although a side of the toy still bordered the wall, the toy extended into the middle of the box and could be reached on a straight line). In all of these conditions, a straight line of reach would be possible, even though the toy bordered the front wall in every case. All predictions were confirmed (Fig. 3.3). Infants succeeded even though the toy was directly behind the front wall; these same infants failed the baseline condition with the same toy in the horizontal position, directly behind the front wall. (See Fig. 3.3.)

Frame-by-frame analysis of the videotapes indicated that infants touched the edge of the front wall much more often in conditions requiring a two-directional reach than in conditions permitting a unidirectional reach for the toy. For example, when the toy was directly behind the front wall of the box, 7-month-old infants touched the edge of the box an average of 7.31 times per trial, whereas when the toy was in the center of the box they touched the edge of the box only an average of 1.53 times per trial (matched pairs t [15] = 4.74, p = .0005). By 10 months of age, infants touched the edge of the box significantly less often, even when a two-directional reach was required for success. For example, when the toy was directly behind the front wall of the box, 10-month-old infants touched the edge of the box only an average of 3.13 times per trial (vs. 7.31 for 7-month-olds: t [7] = 4.21, p = .01). Thus, when a direct line of reach was possible, infants of both 7 and 10 months of age reached accurately enough to avoid touching the box. When a two-directional reach was necessary, however, infants of 7 months had much more difficulty than infants of 10 months in accurately executing that sequence of movements and so touched the edge of the box significantly more often on their way to the toy.

Moreover, infants of 7 months typically reacted to touching the edge of the box by reflexively grasping the box (68% of the time) or reflexively withdrawing their hand (15% of the time). Infants of 7 months rarely continued a reach despite grazing the edge of box and rarely continued a reach after grasping the box. Instead, they recoiled their hand and began the reach again from the starting position. Infants of 10 months, on the other hand, were much less likely to react reflexively when they touched the box (grasping the edge only 25% of the time and almost never reflexively pulling their hand back) and were much more likely to continue their reach despite contacting the box (10-month-olds vs. 7-month-olds: t [7] = 14.18, p < .0001).

We interpret these findings to indicate that infants of 7 months do, indeed, know that an object that shares a boundary with another object is still there.

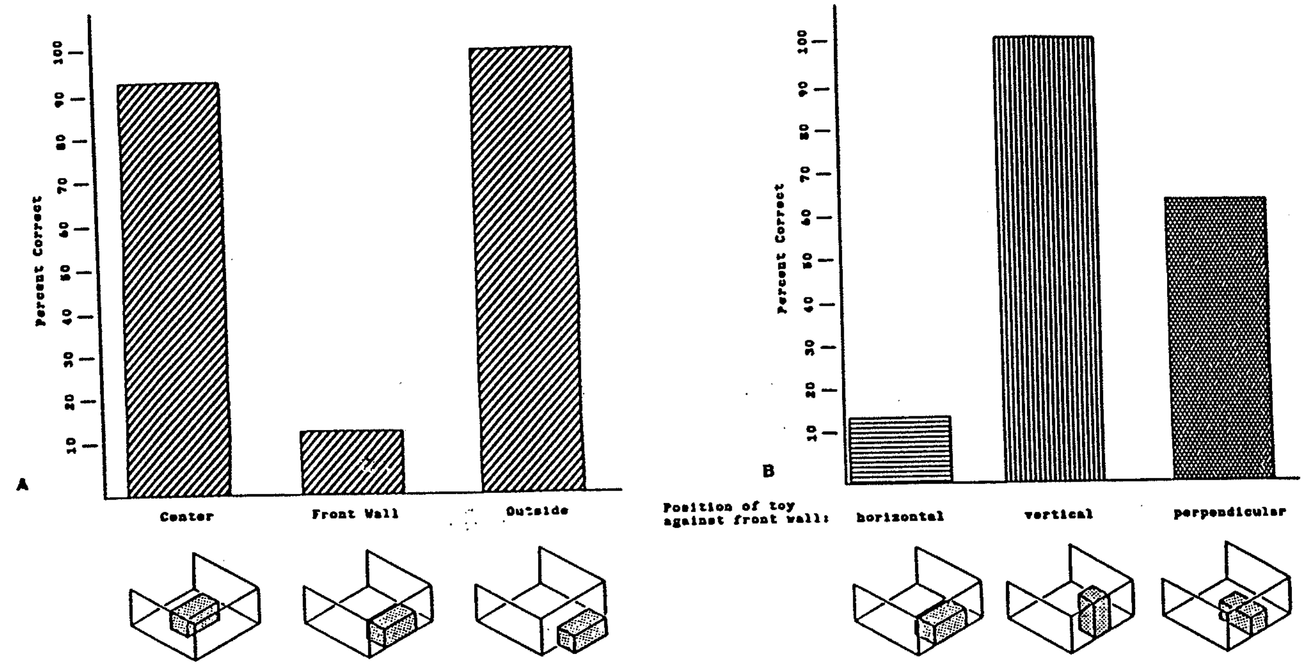
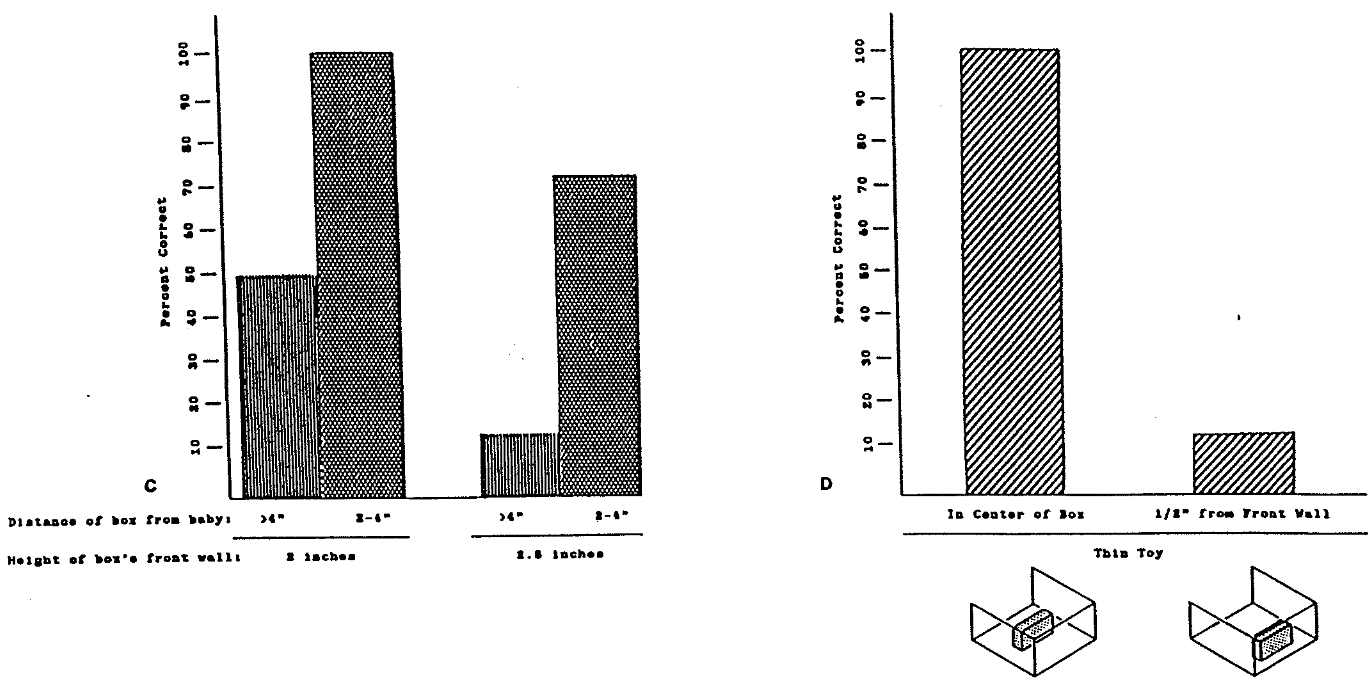


FIG. 3.3. (a) Percent correct with toy in the center of the box, directly behind front wall, and outside directly in front of the front wall.

(b) Percent correct with the toy horizontal, vertical, or perpendicular to the front wall. (In all instances, the toy bordered the front wall.)



(c) Percent correct by distance of box from the infant and height of the front wall of the box. Note that percent correct is lowest when the taller box was farther away, and highest when the shorter box was closer.

(d) Percent correct for thin toy with the toy in the center of the box and 0.5 inches from the front wall.

The box is drawn with the front of the box toward the right side of the page. Top and back of box are open. (From Diamond & Gilbert, 1989)

They give clear evidence of reaching specifically for that object, and under diverse conditions of a shared boundary they are able to successfully retrieve the object. They fail under certain conditions of contiguity (and, indeed, under other conditions where no common boundary is shared) because of difficulty in executing a reach which changes direction and difficulty inhibiting reflexive reactions of the hand.[2] We conclude that infants of 7 months (and even infants as young as 5 months, see Diamond, 1990b) understand the concept that an object continues to exist as a separate entity when it shares a boundary with another object. Their behavior often fails to reflect this understanding, however, because of their imperfect control of the movements of their hands. By at least 10 months of age, and perhaps earlier, infants have sufficient control of their actions to enable them to demonstrate in their behavior the conceptual understanding that was present much earlier.

Hidden Objects

Piaget was the first to observe that infants of 5–7 months will not reach for an object hidden under a cover or behind a screen, even if the experimenter rattles or squeaks the object, even if the object creates a large bulge under a cloth cover, and indeed even if the infant were in the process of reaching for the object when it was covered (e.g., Gratch, 1972; Piaget, 1936/1952; 1937/1954). Piaget concluded from this that infants below 8 months do not have the concept of object permanence; they do not know that an object continues to exist when it is out of sight.

When looking rather than reaching is the dependent measure, however, infants of only 4–5 months demonstrate that they appear to know that an object they can no longer see does continue to exist (Baillargeon, 1987; Baillargeon, Spelke, & Wasserman, 1985). Baillargeon habituated infants to the movement of a screen back and forth through a 180° arc, like a drawbridge. A box was then placed behind the screen. In one test condition, infants were shown the screen moving along its arc until it reached the occluded box (movement of 112°; a possible event). In the other condition, the screen moved through its full 180° arc as though the box were no longer behind it (an impossible event). Infants of 4 and 5 months, and some infants of 3 months, looked significantly longer at the impossible, than at the possible, event,

[2]Note that if 7-month-old infants were able to execute two-directional reaches with precision *or* were able to inhibit reflexive reactions to touch, they would succeed in all conditions. It is only because they have problems both with executing the reach precisely and with reflex inhibition that they fail under certain conditions. If they could put the two parts of the reach together smoothly, they would never touch the edge of the box. Similarly, if they did not react to touching the box by grasping it or pulling their hand back, it would not matter if they touched the edge of the box. The slightest reorientation of the hand would suffice to give them access to the toy; but instead they halt the reach, back up, and try again.

TABLE 3.1
Looking Responses of 4–5-Month-Old Infants to the Movement of a Screen After They Had Habituated to the Screen Moving 180° by Whether or Not a Solid Object was Placed Behind the Screen After Habituation (Based on Baillargeon, 1987; Baillargeon, Spelke, & Wasserman, 1985)

	Infants' Responses to Movement of Screen 180°	*Infants' Responses to Movement of Screen 112°*
No object behind screen	looked little (bored)	looked long (surprised)
Solid object behind screen	looked long (surprised)	looked little (bored)

Note. Once the screen was raised 90° or more, the object was no longer visible.

suggesting that they knew the box hidden behind the screen was still there. When no box was placed behind the screen, all infants looked reliably longer when the screen stopped before completing its 180° arc (movement of 112°; same movement as in the possible condition above) than when the screen repeated the boring 180° arc to which they had habituated (see Table 3.1). Thus, the presence of an object which the infants could no longer see behind the screen significantly affected their looking time; the infants seemed to expect the screen to stop when it reached the object and were surprised (looked longer) when the screen continued beyond this point. The 4- and 5-month-old infants knew that an object they could no longer see was still there; they understood the concept of object permanence.

Why should there be this décalage between when infants' looking and reaching behaviors reveal their knowledge about objects? One possibility is that visual habituation requires only a simple response (looking at what one is interested in), whereas reaching measures have required a more complicated means–end response, such as removing a cover or detouring around a screen in order to then reach for the desired object. In visual habituation studies, the subject does not look at something in order to produce anything else. In reaching studies, however, subjects have had to act on one object in order to obtain another. The requirement that they execute a sequence of actions might account for why infants do not uncover a hidden object, or reach around an opaque screen to obtain a hidden object, until about 7½–8 months of age, although they know and remember that the hidden object is still there by at least 4–5 months of age. Note that infants begin to reach for hidden objects at about the same age as they first organize other actions into means–end sequences (e.g., pulling a cloth closer to retrieve a distant toy on the cloth) (Piaget, 1937/1954; Willatts, 1987). Note also that infants of 5 months appear to reach for objects in the dark (Wishart, Bower, & Dunkeld, 1978)—this might be because they can reach directly for the object there, without first acting on anything else.

To explore whether the crucial variable might be a simple response versus a means–end action sequence, we have tested infants on two versions of the same task. In one version the response is made by reaching; in the other version the response is made by looking; but in *both* versions the response is simple and direct (Diamond, 1990c). In both versions, infants are presented with a sample object until they habituate, a delay is imposed, and then the sample object is presented again paired with an object the infants have never been exposed to before.

This task has been widely used with infants with looking as the dependent measure, where it has been called the "visual paired comparison" task (e.g., Caron, Caron, Minichiello, Weiss, & Friedman, 1977; Fagan, 1970; Pancratz & Cohen, 1970; Rose, Gottfried, Melloy-Carminar, & Bridger, 1982; Werner & Perlmutter, 1979). By 4 months of age, infants show that they remember a sample object by looking preferentially at the novel object after delays of 10–15 sec (Albarran, in preparation; Pancratz & Cohen, 1970; Stinson, 1971). A similar task using reaching as the dependent measure, called the "delayed non-matching to sample" task, was originally devised to study brain function in monkeys (e.g., Gaffan, 1974; Mishkin & Delacour, 1975; Zola-Morgan & Squire, 1986; Zola-Morgan, Squire, & Amaral, 1989). Here, subjects must displace the object in order to retrieve the reward underneath (a means–end sequence). Children reach randomly on this task with a 5- or 10-sec delay until almost 2 years of age, when they begin to reach consistently to the new object (Diamond, 1990c; Overman, 1990)—compare this to their consistent looking to the new stimulus on the visual paired comparison task with delays of 10 sec at only 4–5 months of age. A similar décalage is seen in the performance of infant monkeys: They consistently prefer to look at the novel stimulus in the visual paired comparison task with delays of 10 sec as early as 15 *days* of age and perhaps earlier (Brickson & Bachevalier, 1984), but they fail to consistently reach to the novel stimulus in the delayed non-matching to sample task with delays of 10 sec until at least 4 months of age (Bachevalier & Mishkin, 1984).

We hypothesized that success on delayed non-matching to sample may appear much later than success on visual paired comparison because the former requires subjects to act on one object to retrieve another, whereas the latter requires only the simple act of looking. To test this, we modified the delayed non-matching to sample task so that it no longer required a means–end sequence, but only a simple reach. Instead of rewarding infants with something underneath the object, we allowed the infants to have the object they reached for as the reward. Because babies have a natural preference for novelty we reasoned that if we gave them enough time with the sample object to begin to get bored with it, they would want to reach for something new when later given the chance, rather than that old sample object again.

We now had a version of the task that required a simple looking response (the traditional visual paired comparison task) and a version of the task that

required a simple reaching response (the modified delayed non-matching to sample task). In both versions, the same 10 pairs of three-dimensional objects were used, and infants were tested for two trials each at delays of 10 sec, 15 sec, 1 min, 3 min, and 10 min. Half of the infants were shown an object to look at until they habituated to it and then, following a delay, were given the choice of looking at that same object or a new one. Half of the infants were shown an object to reach for and were allowed to keep the object until they habituated to it; then, following a delay, they were given the choice of reaching for the same object or a new one.

We replicated the finding from previous studies of visual paired comparison that infants of 4 months look preferentially at the novel stimulus after delays of 10 sec. Additionally, infants performed every bit as well on the modified delayed non-matching to sample task as they did on visual paired comparison, from roughly the earliest age infants can retrieve free-standing objects. That is, by 6 months of age, infants succeeded on the looking version of the task with delays of at least 1–3 min and succeeded on the reaching version with delays of at least 10 min. By 9 months of age, they succeeded on both versions with delays of at least 10 min (Diamond, 1990c; see Table 3.2).

Although our task did not involve reaching for a hidden object, we believe that the two versions of our task address the same conundrum as that posed by (a) Baillargeon's evidence that infants demonstrate knowledge of object

TABLE 3.2
Percent of Infants Choosing the Non-Matching (Novel) Object by Age, Task, and Delay

	4 Months Old		*6 Months Old*		*9 Months Old*		*12 Months Old*	
	VPC	*DNMS*	*VPC*	*DNMS*	*VPC*	*DNMS*	*VPC*	*DNMS*
Delays								
10 sec	70**		90**	85**	80**	85**		90**
15 sec	55		60	80**	80**	85**		85**
1 min	60		75**	70**	80**	90**		85**
3 min	50		70**	65*	65*	85**		90**
10 min	50		60	70**	70**	80**		85**

VPC = Visual Paired Comparison task.
DNMS = Delayed Non-Matching to Sample task (modified).
Choice of non-matching (novel) object in VPC = looked at novel object at least 67 percent of the time during 20-sec paired presentation.
Choice of non-matching (novel) object in DNMS = reached for novel object.
All *Ns* = 20. Each subject was tested on only one task and at only one age. All received two trials at each delay; these two scores are averaged for each subject.
Significance levels (binomial distribution): 90% = .0002, 85% = .0008, 80% = .004, 75% = .01, 70% = .03, 65% = .065, 60% = .10, 55% = .15.
* = significant at $p = .065$.
** = significant at $p < .05$.

permanence prior to 7½–8 months when judged by where they look, and (b) the wealth of evidence that infants cannot demonstrate this knowledge until after 7½–8 months when judged by where they reach. Baillargeon (Baillargeon, 1987; Baillargeon et al., 1985) demonstrated that the conceptual understanding appears to be present by at least 4–5 months. Why, then, do infants fail to demonstrate this understanding in their actions until 7½–8 months or later? Perhaps it is because infants cannot organize a means–end action sequence at 4–5 months, but they can at 7½–8 months, and the actions which infants have been required to make to demonstrate that they understand object permanence have always involved a sequence of actions (e.g., removing a cloth as the means to retrieving the toy underneath it). In another situation where a cognitive competence has been seen earlier when assessed by looking (visual paired comparison task) than by reaching (delayed non-matching to sample task), we have demonstrated that when a simple reaching act is required (instead of a means–end sequence) infants demonstrate acquisition of the cognitive competence as early in their reaching as they do through their looking, and much earlier than they do when required to demonstrate this by putting two actions together in a means–end sequence. Note that the ability to uncover a hidden object comes in at roughly the same age as the ability to retrieve one object directly behind another, which also requires linking two sequential actions together (reaching over the barrier and then reaching back for the toy).

In short, infants of 5–7 months appear to understand that an object continues to exist when it is out of sight or when it shares a boundary with another object. They have often failed to demonstrate this conceptual understanding in their behavior because the tasks we have used have required action skills that are beyond the ability of infants this age. Infants of 5–7 months cannot accurately put two actions together in a sequence and cannot inhibit reacting reflexively to touch. These shortcomings in the control of the movements of their hands, and not a failure to understand that contiguous objects, or hidden objects, are still there, have been the critical factor. By 7½–9 months, infants have these action skills and so succeed at the tasks that developmental psychologists have been using.

FUNCTIONS OF THE SUPPLEMENTARY MOTOR AREA (SMA): RELATING ACTIONS TOGETHER IN A SEQUENCE AND INHIBITION OF THE REFLEXES OF THE HAND

Reflexive grasping, which is present in earliest infancy and is thereafter inhibited, is released in adults by lesions in medial, anterior portions of Brodmann's Area 6 of frontal cortex (SMA). No other cortical area besides Area 6 has been implicated in the release of this reflexive behavior. The effect of Area 6 lesions on reflexive grasping was first noted in monkeys by Richter and Hines (1932) and has been confirmed by Fulton, Jacobsen, and Kennard (1932), Penfield and Welch (1951), Travis (1955), Denny-Brown (1966), and Goldberger (1972). Observations of this in human patients are abundant (Addie & Critchley, 1927; Davis & Currier, 1931; Freeman & Crosby, 1929; Goldberg, Mayer, & Toglia, 1981; Kennard, Viets, & Fulton, 1934; Luria, 1973; Penfield & Jasper, 1954; Walshe & Robertson, 1933). Kennard et al. (1934) offered this representative description of the behavior: "Forced grasping was also observed; very gentle contact with the skin of the palm did not in itself evoke grasping with the body in any position, but contact with the palm or skin at the base of the digits, especially when the patient's attention was diverted, caused a fairly prompt, involuntary grasp, which became more exaggerated as one pulled slightly on the flexor tendons" (p. 78).

Little has been written about the release, following brain damage in adults, of the avoidance reaction, the other reflexive reaction to contact seen in 5–7 month old infants. The only mention of it that I know of is by Denny-Brown (Denny-Brown, 1966; Denny-Brown & Chambers, 1958), who has linked it to lesions of parietal cortex.

Infants of 5–7 months might still succeed in retrieving contiguous objects, despite their inability to inhibit the grasp and avoidance reactions, if they could correctly aim their reach so they did not touch the neighboring object (the front wall of the box in our situation). However, the precision of the reach appears to suffer when infants must first aim to clear the front wall of the box and then change direction to retrieve the object inside. Errors in aiming a reach are often observed after lesions to parietal cortex (e.g., *monkeys*: Lamotte & Acuna, 1977; Stein, 1976, 1978; *humans*: Allison, Hurwitz, Graham White, & Wilmot, 1969; Bender & Teuber, 1947; Cole, Scutta, & Warrington, 1962; Damasio & Benton, 1979). An example of such misreaching errors would be to try to reach inside a box, but instead reach to the box's side. Often the reach is too high, too low, too far to the right, or too far to the left. Infants sometimes make mistakes reminiscent of this (Diamond, 1981), but their errors in reaching for contiguous objects do not seem to be of this type. The reaching errors seen after lesions of frontal cortex, on the other hand, are errors in putting two different movements together, such as are seen in 7-month-old children. For example, instead of reaching over a barrier and then back for the goal object, a monkey with a lesion to frontal cortex may keep on reaching in the initial direction and go well past the goal object. Here, the problem seems to be inhibiting the first movement. The animal continues the first movement instead of switching to the second. Errors in switching are common after lesions in various areas of frontal cortex, but errors at this level of concreteness are most common following lesions of medial, anterior Area 6 (see, e.g., Luria, 1973).

Another typical problem following lesions to Area 6, especially SMA, is in linking two or more movements together in the proper order. For example, having been taught to execute a sequence of three movements (push, turn, lift), monkeys with bilateral lesions to SMA were severely impaired in relearning the sequence, although they were unimpaired in executing the individual movements (Halsband, 1982). (In humans see: Orgogozo & Larsen, 1979, and Roland, Larsen, Larsen, & Skinhoj, 1980.) This is reminiscent of the inability of 5–7-month-old infants to string together two actions into a means–end sequence, even though they are perfectly capable of executing the two actions individually.

In short, I propose that maturational changes in SMA may contribute to the ability of infants older than 7 months to successfully retrieve contiguous objects and hidden objects. By 5–7 months of age, and probably much earlier, infants understand that an object contiguous with another, or an object obscured by another, is still there. Thereafter, their developmental task is not so much to elaborate these concepts, but to gain control of their behavior so that it accurately reflects what they know.

CHANGES BETWEEN 8–12 MONTHS OF AGE: RELATING ACTIONS TOGETHER SIMULTANEOUSLY, RELATING INFORMATION OVER A TEMPORAL OR SPATIAL SEPARATION, AND INHIBITION OF PREPOTENT RESPONSE TENDENCIES

Hidden Objects

The characteristic error with hidden objects seen in Sensorimotor Stage IV ($7^1/_2$–9 months of age) is called the $A\bar{B}$ ("A, not B") error. By Stage IV, infants are able to find a hidden object. However, having found an object at one place (A), if the object is then hidden at another place (B), infants often search at A, even though they have watched the object being hidden at B only moments before. Piaget believed that infants make this mistake because they still do not understand that objects are permanent, enduring things, independent of the child's actions. Infants somehow believe that no matter where an object is hidden, it can be found where the infant first found it. As Piaget (1937/1954) put it, "[The child] seems to reason as if the place where the object was found the first time remains where he will find it when he wants to do so" (pp. 44–45). ". . . [T]he child looks for and conceives of the object only in a special position, the first place where it was hidden and found. . . . [T]he original screen seems to him to constitute the special place where the action of finding is successful" (p. 50).

Infants continue to make the $A\bar{B}$ error from about $7^1/_2$ to 12 months of age, as long as the delay between hiding and retrieval is incremented as the infants get older (Diamond, 1985). The testing procedure has become quite standard

by now. Typically, the hiding places consist of two wells embedded in a tabletop, identical except for their left–right position. The infant watches as a toy is hidden in one of the wells. Both wells are covered simultaneously by identical covers and a brief delay is imposed (0–10 sec). We prevent infants from staring, or straining, toward the correct well during the delay. Then the infant is allowed to reach. The youngest infants often make the $A\bar{B}$ error with almost no delay at all. If anything interrupts their visual fixation on the correct well, or their bodily orientation in that direction, they fail, no matter how brief the interruption. Their plan or intention to reach to B seems extremely fragile. Indeed, infants of $6^1/_2$–$7^1/_2$ months sometimes start reaching to the correct well and then stop in mid-reach, as if they have forgotten why they started reaching. Often they reach to a hiding well, but then in removing the cover get distracted by it, and lose the train of what they were doing. It is difficult to tell at this age, but it appears as if the infants are reaching for the toy, not for the cloth. Once they get the cloth in their hand, however, they attend to that instead of continuing to retrieve the toy. Unlike older infants, infants who can uncover a hidden object at $6^1/_2$–$7^1/_2$ months of age rarely correct themselves if they reach to the wrong hiding well on the $A\bar{B}$ task (Diamond, 1983). Older infants spontaneously try to reach to the correct well straightaway if their first reach is wrong (i.e., they try to "self-correct"). The failure of the younger infants to self-correct suggests that they forget why they were reaching if their first reach does not produce the toy.

The fragility of the plan of action indicated here, with the infants easily distracted, easily diverted from their course of action, is very similar to the behavior of patients with frontal cortex damage. They are very easily distracted and have great difficulty sustaining a train of thought. It is remarkably difficult, for example, to obtain a simple personal history from a frontal patient because the patient gets distracted by associations to the history and goes off on tangents. Frontal patients will start to respond to a question or instruction but then get sidetracked so that one must continually remind them what they were doing. As Luria (1973) noted: "Usually these patients begin to perform the task set, but as soon as a stranger enters the ward, or the person in the next bed whispers to the nurse, the patient ceases to perform the task and transfers his gaze to the newcomer or joins in conversation with his neighbor (p. 275).

At $7^1/_2$–8 months of age, the average delay between hiding and retrieval required for the $A\bar{B}$ error is 2 sec. By 9 months it is 5 sec, and by 12 months infants perform well on the $A\bar{B}$ task at delays as long as 10 sec or more (Diamond, 1985).[3] At all ages, infants perform well if allowed to look at or strain toward the correct well throughout the delay (Cornell, 1979; Fox,

[3]Once delays are introduced, I wonder if $A\bar{B}$ does not properly become a Stage V task. Piaget used no delay when he administered it to his children.

Kagan, & Weiskopf, 1979; Diamond, 1985). At each age, if the delay is reduced 2–3 sec below the level at which the $A\bar{B}$ error is found, infants reach correctly whether the toy is hidden at A or at B. If the delay is increased 2–3 sec above the level at which the $A\bar{B}$ error is found, infants err even on the trials at A and they become very distressed (Diamond, 1985). They cry or fuss and refuse to reach at all or perseverate excessively in reaching to the wrong well.[4] All of this suggests that memory ability is crucially important for infants' success on $A\bar{B}$. If delays are brief, infants succeed; if delays are longer, they fail. If allowed to circumvent the memory requirements of the task by orienting themselves toward the correct well throughout the delay, infants succeed.[5] Older infants only continue to err if increasingly long delays are imposed. Because infants can succeed with short delays or with uninterrupted attention to where the toy was hidden, it is unlikely that their problem is that they think A is the special place where they can find the toy regardless of where it is hidden, as Piaget believed. If this were true, errors should occur regardless of delay or memory load.

Inadequate memory cannot account for all of the findings with the $A\bar{B}$ task, however. First, because the basic procedures, including delay, are the same on all trials, the memory requirements of all trials should be the same. Hence, errors should be no more likely on one trial than another; errors should be randomly distributed over trials—but they are not. Infants perform very well on "repeat following correct" trials (roughly equivalent to trials at A) but perform poorly on reversal trials (e.g., when the location of hiding changes to well B) and on "repeat following error" trials (roughly equivalent to the subsequent trials at B), even though the delay is the same on all trials

[4]The progression from accurate performance at short delays, to the $A\bar{B}$ error, to deteriorated performance at long delays, marks a linear decrement in performance, not a curvilinear trend, as Wellman, Cross, and Bartsch (1987: p. 36) seemed to think. At short delays, infants are correct at both A and B. At slightly longer delays, infants are still correct at A, but they err at B (hence, performance is significantly worse at B than at A). At long delays, infants err at both A and B (so that there is again no significant difference between performance at A and B, not because performance at B has improved, but because performance at A has worsened).

[5]The role of memory in $A\bar{B}$ performance has recently been questioned because infants have performed better when multiple hiding wells are used (where one would think the memory requirements are more severe) than they do when only two hiding wells are used. However, this performance difference may be an artifact of a difference in hiding procedures. When two wells are used, the experimenter typically covers both wells simultaneously. When multiple wells are used, the experimenters have changed the procedure to accomodate to the fact that we only have two hands: They have uncovered only the correct well, hidden the toy, and then re-covered that well alone (the other wells remaining covered the entire time). Harris (1973, experiment III) demonstrated that infants perform better with two wells if A is covered and then B, as the last action by the experimenter draws the infant's attention to B. Diamond, Cruttenden, and Neiderman (1989) demonstrated that when multiple wells are used and all wells are covered simultaneously, performance is significantly worse than when only the correct well is uncovered and covered, and it is much worse than performance typically found in experiments with only two wells (see Diamond, 1990a).

TABLE 3.3
Types of Trials

Performance on Previous Trial	*Side of Hiding* — *Same as on Previous Trial*	*Side of Hiding* — *Changed*
Correct	Repeat-Following-Correct Trials	Reversal-Following-Correct Trials
Wrong	Repeat-Following-Error Trials	Reversal-Following-Error Trials

Note: Type 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 only administered in $A\bar{B}$ following a correct reach. Thus, when discussing $A\bar{B}$, the term "reversal trials" always refers to Reversal-After-Correct trials.

(Diamond, 1985). (See Table 3.3 for a description of these three types of trials.)

Second, infants show a similar error pattern on the $A\bar{B}$ task even with transparent covers, although they err less often (Butterworth, 1977). Memory should not be taxed at all when the toy remains visible under a transparent cover. Third, infants, beyond the age of about $7^1/_2$ months typically reach immediately to the correct well if their initial reach is incorrect. Indeed, often when they reach incorrectly to A, they do *not* look in to see if the toy is there, but reach immediately to B, and then look in for the toy. It is as if they know the toy is at B, even though their first reach was to A. Occasionally, an infant will look fixedly at B even as he or she reaches to A (see Fig. 3.4). Although this behavior is not common, it has been observed by many researchers in many laboratories; it is very striking when it does occur because at this age infants almost always look where they are reaching. Here, infants appear to be showing with their eyes that they know where the toy is hidden, even though they reach back to A anyway. This is another instance where infants appear to know more than they can demonstrate in their reaching behavior. They seem to understand the concept of object permanence; their problem is demonstrating this understanding through their behavior.

Adults with damage to dorsolateral prefrontal cortex also indicate, on occasion, that they know the correct answer, despite the fact that they cannot indicate this in their reaching behavior. The classic test for frontal cortex function in adult patients is the Wisconsin Card Sort. The patient is presented with a deck of cards that can be sorted by color, shape, or number. Frontal patients are able to deduce the first criterion by which to sort the cards as well as anyone else. However, after being rewarded for sorting by the first criterion, when the experimenter changes the criterion, patients with frontal cortex damage are impaired in switching to the new criterion. They continue to sort the cards by the first criterion. These patients can sometimes tell you, however, what the new criterion is. Indeed, a patient will sometimes say, as he or she is sorting the cards by the old criterion, "This is wrong, and this is

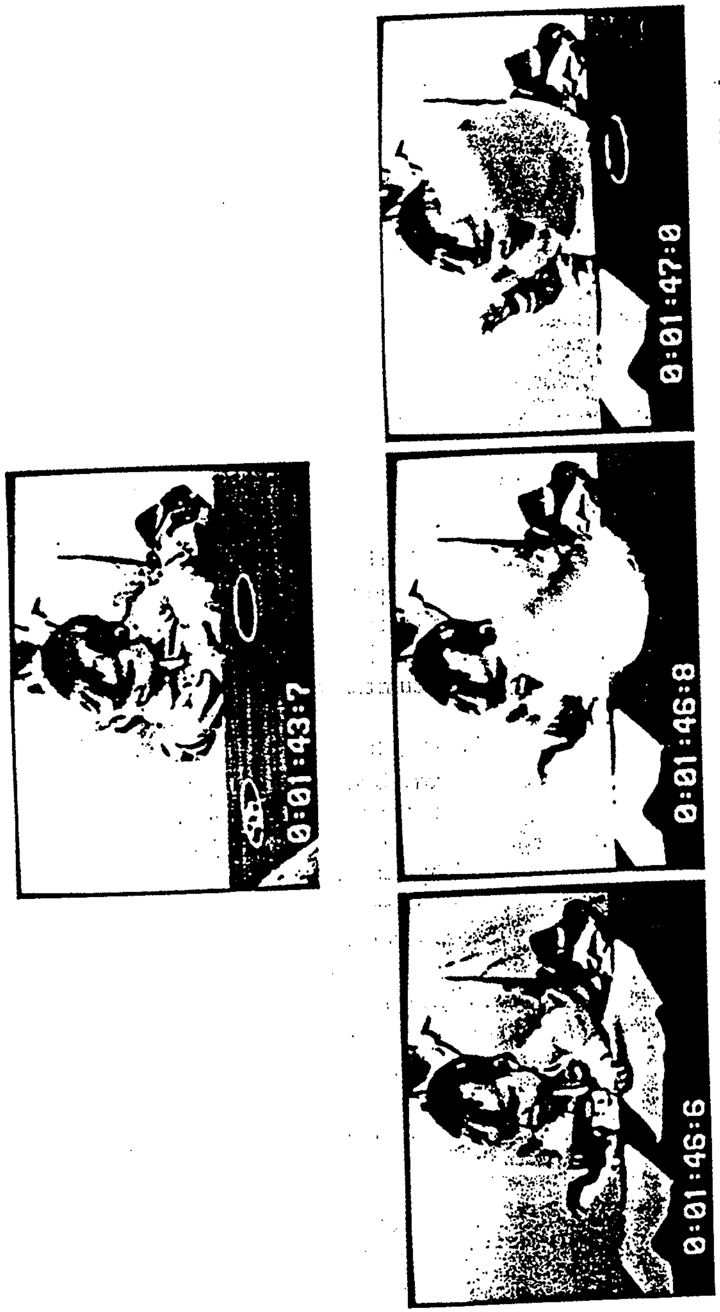


FIG. 3.4. Instance of an infant looking at B while reaching to A. Infant had successfully retrieved the toy at A. Side of hiding is now reversed to B. Infant clearly sees the hiding (top row). Following a brief delay, infant was allowed to reach. Although infant was looking fixedly at B, his hand went back to A (bottom row).

wrong, . . ." (Luria & Homskaya, 1964; Milner, 1964). Here, as when infants look at B while reaching to A, patients appear to know the correct answer but cannot gain control of their behavior to reflect what they know.[6] (This might be considered, in some sense, the inverse of what is seen in amnesia. Amnesic patients often fail to consciously remember information, but they show evidence of "memory" of this information in their behavior. Patients with frontal cortex damage appear to consciously remember the information, but they are often unable to show evidence of this in their reaching behavior.)

In summary, there are two abilities required by the AB̄ task: One is memory, and the other is the ability to inhibit the tendency to repeat the rewarded reach at A. When the initial reaches to A are reinforced, the tendency to reach to A is thereby strengthened; it is that response tendency that must be inhibited.[7] This explains the pattern of errors (poor performance at B, excellent performance at A). It also explains why some errors still occur at B (although far fewer) even when there is no memory load (as when transparent covers are used)—here, inhibitory control is taxed (hence some errors) but memory is not (hence fewer errors than when both abilities are required). The pull to reach back toward A can be seen even with multiple wells when the hiding places are arranged so that infants can reach to wells on the side of B away from A or to wells on the side of B toward A. Here, errors are not randomly distributed around B (as a memory interpretation might predict) but are found disproportionately on the side of B toward A (Diamond, Cruttenden, & Neiderman, 1989). Finally, the present interpretation can also account for why some errors (although only a few) are found at well A when a delay is used (e.g., Sophian & Wellman, 1983)—here, memory is taxed (hence some errors) but inhibitory control is not (hence, fewer errors than when both abilities are required).

There appear to be several characteristics of the type of memory ability required for AB̄:

1. It is very brief (2–5 sec).
2. It must be maintained on-line to link together the various components

[6]Patients with acute damage to SMA also show a dissociation between consciousness and action. The phenomenon is called the "alien hand" (Goldberg, 1985; Goldberg et al., 1981) where "the limb performs normally organized acts directed toward goals linked to objects in extrapersonal space in which the patient does not perceive himself as a causal agent. . . . The alien hand sign can be interpreted as a disorder of intention because the patient reports that the behavior of the limb is dissociated from the patients' own volition" (Goldberg, 1985, p. 605). This behavior usually disappears within a few months after the injury to SMA.

[7]One successful reach to A is sufficient to produce a pull to reach to A, and within the range of 1–5, the number of successful reaches to A does not seem to matter (Butterworth, 1977; Diamond, 1983; Evans, 1973). However, infants repeat the error of reaching back to A over significantly more trials after 8–10 successful reaches to A than after only 2 successful reaches to A (Landers, 1971).

of a trial to guide behavior. That is, the delay is imposed within a trial (between hiding and response), as opposed to between trials or between testing sessions. When a delay is imposed between trials or between sessions, one is typically studying whether subjects can remember an association they have already learned; in $A\bar{B}$, subjects must bridge a temporal gap in order to establish the association.

3. Infants must pay attention to the hiding on each trial and continually update their mental record of where the reward has been hidden. Once the toy has been hidden at well A on at least one trial and at well B on at least one trial, one might consider the task to be one of temporal order memory ("Where was the toy hidden most recently?")

4. Because the hiding wells typically differ only in location, one might consider the task to be one of memory for spatial position ("Was the toy hidden on the left or the right?")

5. The information that infants must remember is presented briefly and only once in $A\bar{B}$—on any given trial, infants see the toy hidden only once and then the well is quickly covered. The subject "is not trained to the correct response by making it . . . but instead must respond on the basis of a single unrewarded and unpunished presentation" (Jacobsen & Nissen, 1937, p. 132).

The type of memory required for $A\bar{B}$ can be contrasted with memory abilities seen in infants much younger than 7½–9 months. Once they have learned an association between a cue and response, they can remember it for long periods (hours, days, and even weeks [e.g., Rovee-Collier, 1984]). Here, they are typically given repeated presentations and long exposure times to learn the association, and once it is learned they never need to update it. As long as they remember it, that single rule leads to correct performance across all trials and all testing sessions.

Indeed, within the $A\bar{B}$ situation, infants can learn to associate the hidden toy with a landmark, and to use the landmark's location to guide their reaching (Diamond, 1983). Memory is required here, for the infant must remember the association between the landmark and the reward. However, once this single association is learned, the infant can use that to guide performance on all trials; memory does not need to be updated on each trial.

Visual paired comparison and delayed non-matching to sample require that memory be updated on each trial, and they require that memory of the sample be maintained on-line during the delay period within a trial. Yet infants show evidence of memory on visual paired comparison and on our modified version of delayed non-matching to sample at delays of at least 1 minute at 6 months and delays of at least 10 minutes at 9 months—delays far longer than the 2–5 sec at which they fail $A\bar{B}$ at the ages of 7½–9 months. The differences in the memory requirements are that visual paired comparison

and delayed non-matching to sample do not pose problems of temporal order memory, as unique stimuli are used on each trial, and they do not require memory of spatial information. Moreover, if an infant remembers which stimulus was the sample, the infant need only do what comes naturally (i.e., choose the new stimulus); whereas on $A\bar{B}$ the infant must not only remember where the object was hidden, but must also resist a strong response tendency to reach to the previously correct location.

Detour Reaching

Over the same ages that infants' ability to find hidden objects improves, infants also improve in their ability to detour around a barrier to retrieve objects. The detour task I have studied, called "object retrieval," involves a small, clear box. The box can be placed so that the front, top, left, or right side is open. The infant's task is to retrieve a toy from inside the open box; the toy being clearly visible through the transparent walls of the box (Diamond, 1981).

Infants of 6½–7 months reach only at the side of the box through which they see the toy. If they see the toy through the opening, they reach in and retrieve it, but if they see the toy through a closed side, they reach repeatedly to that side, trying no other approach to the toy. This is typical of Sensorimotor Stage III behavior: Alternative approaches are not generated, behavior is not varied; rather, the same way of attempting to retrieve the toy is tried over and over again.[8]

The tendency to reach straight through the side at which they are looking is remarkably strong. Even when an infant has successfully retrieved the toy from the front of the box on three trials in a row, if the box is moved so that the infant now sees the toy through the top of the box, he or she will not reach to the open front but will reach only to the top of the box. Here, the infant's failure to inhibit the strong urge to reach straight to the toy results not in perseveration, as it does on $A\bar{B}$, but in a change in where the reach is directed. If the infant repeated the previous response (i.e., if the infant continued to reach to the front of the box), the infant would succeed, but infants fail by not perseverating.

When the left or right side of the box is open, they can retrieve the toy if it extends partially outside the box opening, but not if it is totally inside the box. This is because they reach only at the sides through which they see the toy, which are the top and front sides of the box.

At 7½–8 months of age, infants take active steps for the first time to change

[8]Frontal patients are also poor at generating alternative solutions, such as generating abstract drawings using only four lines or generating all the words they can think of beginning with the letters "F", "A", or "S" (FAS test) (e.g., Benton, 1968).

the side of the box through which they see the toy. They bend down to look in the front of the box, or raise the box so they can see in through the front. They are no longer restricted to acting on only one side of the box. On their own initiative, they reach to both the top and the front of the box on the same trial. This is the kind of change from a reactive, passive approach to a more active orientation that marks Piaget's Sensorimotor Stage IV. Indeed, the same infants tested on object retrieval and on object permanence first show this active orientation on object retrieval at the same age at which they can first find a hidden object (Diamond, 1988). A similar change occurs in attachment behavior at this time: Infants progress from just reacting to the overtures of their caregivers (Phase 2 Attachment) to actively initiating overtures to their caregivers on their own (Phase 3 Attachment) (Bowlby, 1969).

Infants of $7^1/_2$–8 months still reach only to the side of the box through which they are looking, however. When they see the toy through the top, they reach to the top; when they see the toy through the front, they reach to the front. Moreover, their efforts to raise the box are of little help to infants at $7^1/_2$–8 months. They cannot raise the box *and* reach for the toy at the same time, and after the box comes back down and they see the toy again through the top of the box, they reach only there. (See Fig. 3.5.)

Often, infants of $7^1/_2$–8 months raise the box with both hands, but with both hands thus occupied, there is no free hand with which to retrieve the toy. The infants lean forward, their head just inches from the toy, but the toy remains inaccessible. Often, too, an infant will raise the front of the box with both hands, remove one hand from the box and attempt to reach for the toy, but

FIG. 3.5. Frame 1: Front of box is open. Nina raises box, establishing a direct line of sight to the toy through the opening. (Experimenter is holding back of box, exerting downward pressure on it.)

Frame 2: Nina starts to reach for the toy through the opening, but when one hand comes down to reach, the hand left holding onto the box comes down, too. Note that Nina's hand is now inside the box, perhaps a half inch from the toy, but her line of sight to the toy is now through the top.

Frame 3: Nina withdraws her hand from inside the box and tries to reach for the toy through the top, i.e., she tries to reach through the side she is looking. (From Diamond, 1981)

the box comes down, halting the reach. The box comes down because when one hand is lowered to reach for the toy, infants have great difficulty *not* lowering the other hand. They try repeatedly to reach while the box is raised, but the hand left to hold up the box keeps failing at its task. Bruner, Lyons, and Watkins (1968) noted similar behaviors with a slightly different task. Their apparatus was a box with a transparent lid. The lid was 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. Bruner et al. (1968) observed that infants of seven months have "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" (p. 222).

By $8^1/_2$–9 months of age, infants can bend down to look in the front of the box, then sit up, look through the top, and reach into the front. For the first time, one sees a separation of line of sight from line of reach: Infants can look through one side of the box while reaching through another. Similarly, they can raise the box, let the box come back down, and reach into the front while looking through the top. Although they are still not able to hold the box up with one hand and reach in with the other, they are able to do this sequentially, first raising the box and then reaching in.

Millar and Schaffer (1972, 1973) also found that the ability to look one place and reach another emerged at around 9 months of age. Using an operant conditioning paradigm, they trained infants to depress a lever in order to see a colored light display. Even infants of 6 months could learn this when the lights and lever were in the same visual field. When the lights and lever were not in the same visual field, however, 6-month-olds failed to acquire the response, although 9-month-olds succeeded. Nine-month-olds succeeded by looking one place (at the lights) while simultaneously acting at another (the lever). This strategy was not in evidence at 6 months.

Infants of $8^1/_2$–9 months still need to have seen the toy through the opening on each trial to succeed, but success no longer depends on maintaining that line of sight. For the first time, the memory of having seen the toy through the opening is enough. Raising the box aids performance now, not because infants are able to reach in for the toy with one hand while raising the box with the other, but because once the box is back down on the table, they can reach in while looking through the top, having looked into the opening while the box was raised.

When the top of the box is open and the box is far from the infant, infants of $8^1/_2$–9 months begin to raise one hand to reach for the toy as they extend the other to pull the box closer to themselves. As the pull begins, the other hand is raised in readiness, and the reach is timed to meet the toy as the box draws near. For the first time, the action sequence gives the clear appearance of having been planned from the start. By 9 months this is very smooth and skillful.

When the right or left side of the box is open, infants of $8^1/_2$–9 months reach with the hand contralateral to the opening. That is, they reach to the right side of the box with their left hand and to the left side with their right hand (Bruner, Kaye, & Lyons, 1969; Diamond, 1981; Gaiter, 1973; Schonen & Bresson, 1984). Reaching with the hand farthest from the opening makes the action maximally contorted and awkward, and is therefore called an "awkward reach." This reach may occur because infants need to look into the opening *and maintain that line of sight* in order to succeed. Infants need to lean over quite far to look into the opening. In that leaning position, the hand ipsilateral to the opening is almost trapped under the body, and there is a tendency to want to leave it available to break one's fall if the pull of gravity becomes too strong. Hence, the awkward reach may be a consequence of the need to match up the infant's line of sight and line of reach to the toy. On the other hand, from an upright position, the only way to retrieve the toy through the left or right side of the box is to reach away from the toy at the midline (toward the opening), and then reach back to the toy (midline)—a two-directional reach. When an infant is leaning over and the hand is coiled to reach, the hand can shoot in for the toy on a straight line. Hence, the awkward reach may be consequence of the need to make a direct, straight movement rather than a sequence of two movements.[9] Finally, if the box is the visual world of the infant for the moment, and the toy is all the way over in the far corner of the box, the image of the toy may fall on the visual field of only one hemisphere, in which case infants reaching with the "awkward hand" would be reaching with the hand controlled by the same hemisphere as the one receiving the visual image of the toy.

By $9^1/_2$–10 months, infants can coordinate looking through the top of the box while reaching through the front, without ever having looked in the front opening. They can also coordinate raising the box with one hand and simultaneously reaching in for the toy with the other. Note, however, that there is less need to raise the box at this age because infants have less need to see in the front opening. When the left or right side of the box is open, most infants need to have leaned and looked in the opening before they reach to the opening. However, they can now lean and look, then sit up straight, and reach through the side opening while looking through the top of the box. The awkward reach no longer is seen.

[9]Performance with the opening of the box at the side always lagged behind performance with the opening at the top or front of the box. For a discussion of possible reasons for this, see Diamond (1981).

Finally, by 11–12 months, infants are perfect on the object retrieval task. They can retrieve the toy from any side of the box efficiently, speedily, and without ever having looked in the opening.

One of the major problems posed by object retrieval is the need to inhibit the pull to reach directly to the visible goal. Indeed, infants perform much better when the box is opaque (Diamond, 1981, 1990b; see Bruner et al., 1969; Church, 1971; Lockman, 1984; Schonen & Bresson, 1984, for similar results with transparent and opaque barriers).

Most infants early in the second half of the first year attend to the sight of the toy, ignoring abundant tactile information about the closed and open surfaces of the box. For example, if they see the toy through the top of the box, they reach only at the box's top, even if they happen to be touching or grasping the opening of the box. A minority of infants at $9^1/_2$–10 months appear to attend only to tactile information. For example, one child kept getting her thumb caught on the top edge of the opening when the left or right side of the box was open. To help her, the experimenter tipped the box to enlarge the size of the opening, but then the child reached yet higher and still got her thumb stuck on the top edge of the opening! She seemed to search for the opening the way a blind person would, by feeling for the edge. When the opening was made very large, she still went for the edge. Other infants, upon feeling the back edge of the opening, bent their hand around the back of the box as if they thought they had touched the front edge of the opening and were entering the box. No infants, however, until close to 1 year of age, give evidence of attending to both visual and tactile information.

The developmental progression in the use of visual and tactile information nicely illustrates Piaget's point that differentiation and intercoordination are part and parcel of the same development. As infants become better able to intercoordinate vision and touch, attending to both, they also become better able to dissociate them so that they can look one place and reach another.

For Piaget, many of the advances during the second half of the first year of life reflect infants' newly acquired ability to "put into relation": relating one action to another in a means–end sequence, relating two objects to one another in a spatial relation, and so forth. In this, Piaget was most certainly correct. For example, infants progress from straight line reaches to reaches that require relating a movement in one direction to another movement in a different direction; infants become able to relate the movements of their two hands so that what each hand does complements the other. In particular, infants become able to do different things simultaneously—for example, they can look one place, or along one route, while reaching at another place, or along another route; they can reach simultaneously for two different objects (Diamond, 1988); they can simultaneously concentrate on both visual and tactile information. They also become able to relate information over increasingly large temporal separations (increasingly long delays in $A\bar{B}$) and increasingly large spatial separations (increasing distances between the toy and box opening in object retrieval).

Advances of the second half-year also reflect (more than Piaget appreciated) infants' emerging ability to resist or inhibit the reflexes of the hand and later to resist or inhibit response tendencies strengthened by reinforcement (as in $A\bar{B}$) or innately strong (such as the response tendency to reach straight to one's goal seen in object retrieval). Instead of reacting automatically with the strongest response of the moment, infants begin to gain more control over their behavior and begin to demonstrate intentionality, which Piaget saw as the crowning achievement of the Sensorimotor Period.[10] The execution of intentional behavior requires not only planning and "putting into relationship," as Piaget so clearly saw, but also resisting more automatic action tendencies that lead the behavior astray.

INTERHEMISPHERIC COMMUNICATION BETWEEN THE SUPPLEMENTARY MOTOR AREAS (SMAs) ON THE LEFT AND RIGHT SIDES OF THE BRAIN: RELATING ACTIONS TOGETHER SIMULTANEOUSLY

Human adults, and monkeys, with lesions of SMA have difficulty with the complementary use of the two hands. Their hands tend to do the same thing, making bimanual coordination difficult. Brinkman (1984) provides an excellent example of this in the monkey following an SMA lesion. Removal of SMA in human adults results in similar lasting deficits when simultaneous, but different, movements of the two hands are required (Laplane, Talairach, Meininger, Bancaud, & Orgogozo, 1977; Luria, 1973). For example, these patients have great difficulty making a fist with one hand while simultaneously turning their other hand palm-up. They either do the same thing with both hands or execute the movements sequentially. This is very similar to the behavior seen in 7½–9-month-old infants. In their reaching, for example, infants of 7 months move both hands in the same direction, instead of in opposite (complementary) directions, as do infants by 11 months (Goldfield & Michel, 1986). When infants of 7½–9 months raise the object retrieval box with both hands, they have great difficulty not lowering the second hand when one hand goes down to reach in the box. By 8½–9 months, infants can solve this sequentially by first raising the box and then reaching in, but it is still

[10]Here, the presence of intentionality is distinguished from the ability to provide evidence of it in behavior. The intention may be there early, but the ability to demonstrate it may depend on frontal cortex maturation.

beyond their ability to simultaneously raise the box and reach inside. Simultaneous integration of the movements of the two hands requires not only involvement of SMA, but inhibitory projections via the corpus callosum so that the tendency of one hand to do the same thing as the other hand can be suppressed.

Integrating movements, whether sequentially or simultaneously, is dependent on SMA. Sequential integration is seen earlier, however, because simultaneous integration requires interhemispheric communication through the corpus callosum between the left and right SMA, whereas sequential integration does not require callosal connections. Involvement of the corpus callosum in the changes occurring around 9½–10 months can also be seen in the disappearance of the "awkward reach." One explanation for the awkward reach is that the sight of the toy may fall on the visual field of only one hemisphere, and, lacking, callosal connections to communicate this information to the other hemisphere, infants reach with the hand controlled by the same hemisphere as that receiving the image of the toy (i.e., the hand contralateral to the opening, the "awkward hand"). This explanation has gained support from the finding of Lamantia, Simmons, and Goldman-Rakic (personal communication) that monkeys in whom the corpus callosum has been prenatally removed continue to show the awkward reach long after the age when monkeys normally cease showing this behavior and, indeed, may continue to show this behavior indefinitely.

Adults who were born without a corpus callosum (congenital acallosals) have difficulty suppressing "associated movements"; that is, they have difficulty inhibiting one hand from doing what the other is doing (Dennis, 1976). Indeed, inhibitory control of callosal fibers on movement has been well documented (e.g., Asanuma & Okamoto, 1959).

FUNCTIONS OF DORSOLATERAL PREFRONTAL CORTEX: RELATING INFORMATION OVER A TEMPORAL OR SPATIAL SEPARATION AND INHIBITION OF PREPOTENT RESPONSE TENDENCIES

Adult monkeys are able to succeed easily on the $A\bar{B}$ and object retrieval tasks. Lesions of dorsolateral prefrontal cortex in the monkey disrupt performance, producing exactly the same sorts of errors, on both tasks, as seen in human infants at the age of 7½–9 months (Diamond & Goldman-Rakic, 1985, 1989).

For example, adult monkeys with lesions of dorsolateral prefrontal cortex show the $A\bar{B}$ error at delays of 2–5 sec (Diamond & Goldman-Rakic, 1989) just as do human infants of 7½–9 months. Prefrontal monkeys, like human infants, perform well when the hiding is at A, but they err when the reward is then hidden at B. They perform well if there is no delay, or if they are allowed to stare at, or orient their body, toward the correct well throughout the delay. They immediately try to self-correct after an error. They can learn to associate a landmark with the correct well and can use the landmark to help them reach correctly on every trial (Diamond, 1990a). In all respects, their performance is comparable to that of 7½–9-month-old human infants. Lesions to no other area of the brain produce this pattern of results. Monkeys with lesions to parietal cortex (Diamond & Goldman-Rakic, 1989) or the hippocampal formation (Diamond, Zola-Morgan, & Squire, 1989) perform perfectly on the AB̄ task at delays of 2–5 sec, and even at longer delays never show the AB̄ error pattern.

Indeed, AB̄ is almost identical to the task that has been most strongly linked to dorsolateral prefrontal cortex (the delayed response task) (Fuster, 1989; Jacobsen, 1936; Nauta, 1971; Rosenkilde, 1979). In delayed response, as in AB̄, the subject watches as the experimenter hides a reward in one of two identical wells, a delay of 0–10 sec is imposed, and then the subject is allowed to uncover one of the wells. Over decades of research, using a wide array of physiological, pharmacological and anatomical procedures, performance on delayed response has been consistently shown to depend specifically on the functioning of dorsolateral prefrontal cortex (see e.g., Diamond, in press, for review). Further evidence of the close association between these two tasks is that infants show the same developmental progression on delayed response between 7½–12 months as they show on AB̄ (Diamond, 1990a; Diamond & Doar, 1989).

Adult monkeys with lesions of dorsolateral prefrontal cortex also fail the object retrieval task, showing the same behaviors as do human infants of 7½–9 months (Diamond, 1990b; Diamond & Goldman-Rakic, 1985). They have great difficulty inhibiting the urge to reach straight to their goal, and so persist in trying to reach directly through the side of the box through which they are looking. When the opening of the box is on the left or right side, they lean and look, and then reach with the "awkward hand," just as do human infants. Lesions of the hippocampus have no effect on performance of the task (Diamond, Zola-Morgan, & Squire, 1989). Parietal cortex lesions produce misreaching errors (reminiscent of the few 9½–10-month-old infants who appeared to ignore available visual information) but produce no other deficit on the task (Diamond & Goldman-Rakic, 1985).

Importantly, lesions of dorsolateral prefrontal cortex produce the same effects on performance of these tasks in infant monkeys as they do in adult monkeys. Infant monkeys show the same developmental progression on the AB̄ and object retrieval tasks between 1½ and 4 months of age as do human infants between 7½ and 12 months (Diamond, 1990a, 1990b, 1990c, in press; Diamond & Goldman-Rakic, 1986). On AB̄, they show the same pattern of performance over trials as do human infants and as do monkeys with lesions of dorsolateral prefrontal cortex: Their errors are confined to only certain types of trials, rather than being randomly distributed; they reach correctly if they orient themselves toward the correct well throughout the delay; and they try to correct themselves immediately if they reach to the wrong well. At 1½–2½ months, they make the AB̄ error at delays of 2–5 sec (just as do human infants of 7½–9 months and prefrontally operated adult monkeys), and by 4 months they are perfect at delays of at least 10 sec (like human infants of 12 months) (see Figs. 3.6 and 3.7). If infant monkeys then receive lesions of dorsolateral prefrontal cortex at 4 months, their performance on AB̄ at 5 months is once again as it was at 1½–2½ months of age (i.e., they make the AB̄ error at delays of 2–5 sec, although prior to surgery they were performing perfectly at delays of 15 sec or longer) (Diamond, 1990a; Diamond & Goldman-Rakic, 1986).

On the object retrieval task, infant monkeys of 1½ months perform much like human infants of 7½–8 months (i.e., they reach only at the side of the box through which they are looking), and at 2 months of age infant monkeys show the "awkward reach" (seen in human infants at 8½–9 months). That is, on object retrieval, as on AB̄, infant monkeys of 1½–2½ months perform as do human infants aged 7½–9 months and as do monkeys with lesions of dorsolateral prefrontal cortex (see Figs. 3.8 and 3.9). By 4 months, infant monkeys are perfect on the object retrieval task, as are human infants of 12 months (Diamond, 1990a, in press; Diamond & Goldman-Rakic, 1986; see Table 3.4.)

This body of evidence suggests that the improved performance of human infants on these tasks from 7½–12 months of age may reflect maturational changes in dorsolateral prefrontal cortex. Infants of 7½–9 months may fail these tests because dorsolateral prefrontal cortex is too immature to support the abilities that the tasks require. Dorsolateral prefrontal cortex is not fully mature at 12 months; indeed, it will not be fully mature until many years later; but by 12 months it appears to have reached the level where it can support certain critical cognitive functions.

Dorsolateral prefrontal cortex is required for those tasks, such as AB̄, delayed response, and object retrieval, where subjects must integrate information that is separated in space or time *and* must inhibit a predominant response. If only one of these abilities is required, involvement of dorsolateral prefrontal cortex is not necessary. Tasks that require only inhibitory control or only memory do not depend on dorsolateral prefrontal cortex.

The object retrieval task requires the subject to relate the opening of the box 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, and even monkeys without prefrontal cortex,

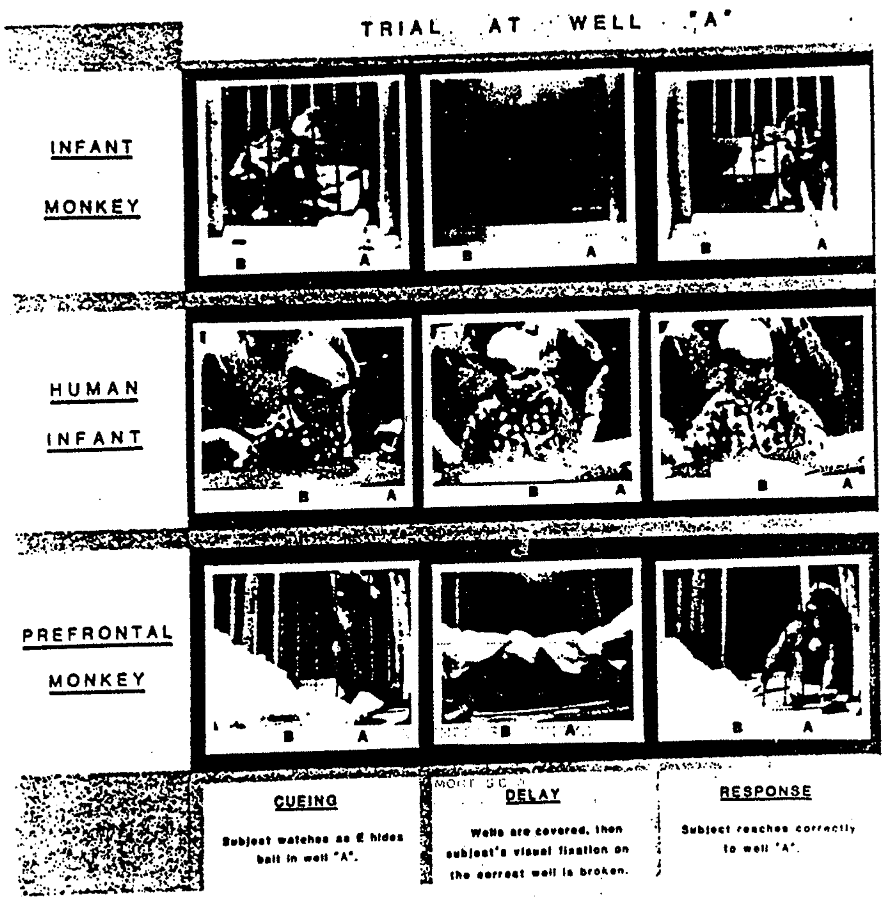
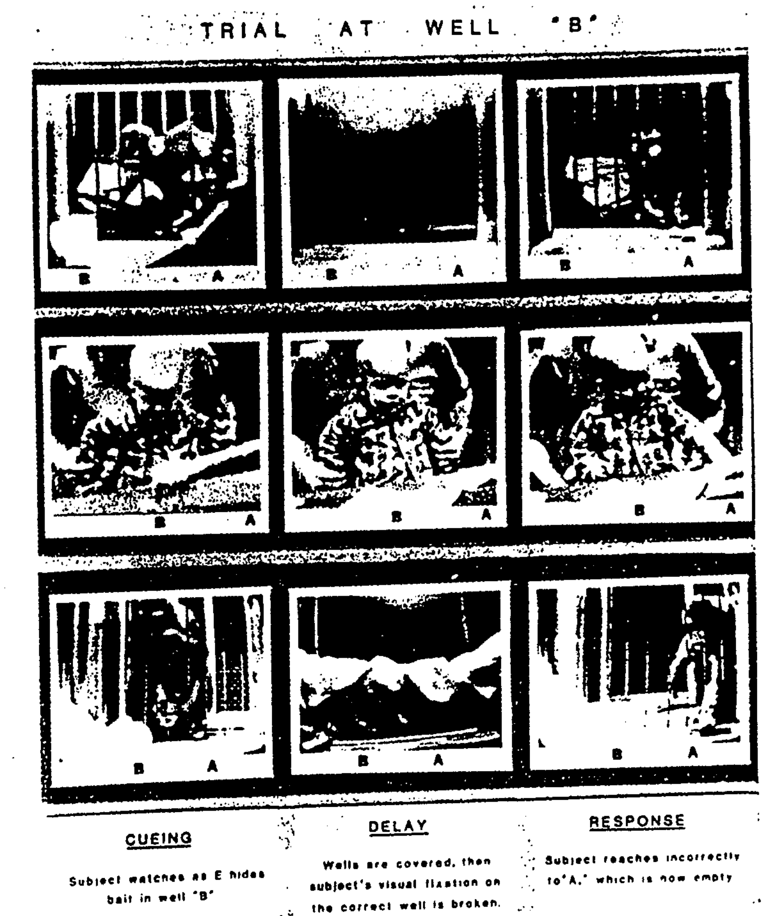


FIG. 3.6. Example of the AB̄ error in an infant monkey, human infant, and an adult monkey with bilateral lesions of dorsolateral prefrontal cortex.

(a) Illustration of performance on trials at the initial hiding place (A).

(b) Illustration of performance when side of hiding changes, i.e. trials at B.

AB̄ testing procedures for monkeys and human infants were virtually identical. The AB̄ performance of 1½–2½-month-old infant monkeys, 7½–9-month-old human infants, and adult monkeys with lesions of dorsolateral prefrontal cortex is fully comparable in all respects.



succeed. However, as the spatial separation between bait and opening widens (i.e., as the bait is placed deeper inside the box), the age at which infants succeed progressively increases.

The AB task requires the subject to relate two temporally separated events—cue and response. When there is no delay between hiding and retrieval, even the youngest infants, and even monkeys without prefrontal cortex, succeed. However, as the time interval between hiding and retrieval increases, the age at which infants succeed progressively increases.

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

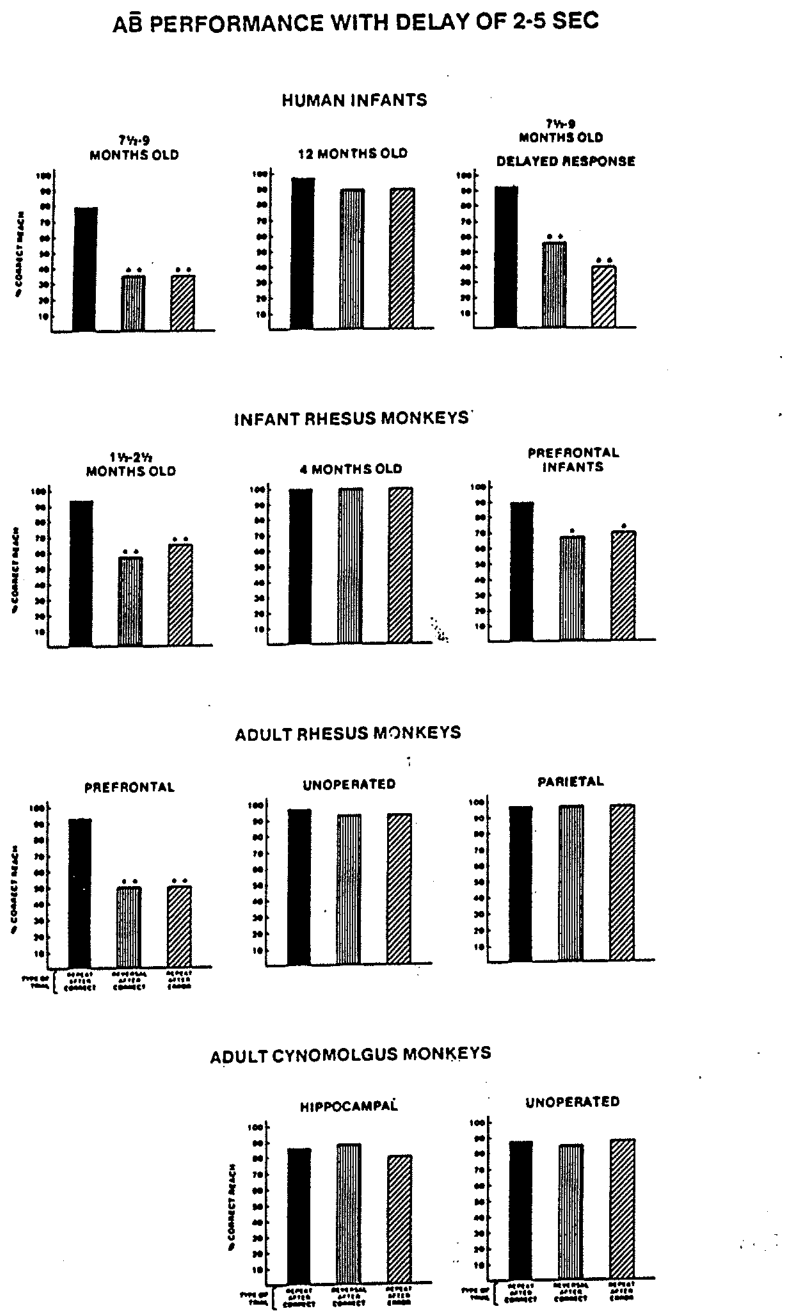


FIG. 3.7. The AB̄ error is characterized by a particular pattern of performance by type of trial. The subject performs very well on repeat-following-correct-trials, but errs on reversal trials and repeat-following-error trials. With delays of 2–5 sec, the AB̄ error pattern is seen in 7½–9 month old human infants, adult monkeys with dorsolateral prefrontal cortex lesions, infant monkeys of 1½–2½ months, and 5 month old infant monkeys who received lesions of dorsolateral prefrontal cortex at 4 months. On the other hand, infants of 12 months, infant monkeys of 4 months, unoperated adult monkeys, and adult monkeys with lesions of parietal cortex or the hippocampus all perform

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, 1981). The counterintuitive finding that the task is 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.

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 perseverate. This is seen in object retrieval as when, after three successful reaches into the front opening, the box is moved an inch closer to the infant and the toy a half-inch deeper in the box, so that the infant now sees the toy through the top of the box—instead of perseverating the infant deserts the front opening and reaches to the top of the box.

In AB̄, a conditioned tendency or "habit" to reach to "A" (where the infant was rewarded) must be inhibited when the toy is hidden at "B." When such inhibition is not required, as on the initial trials at A, infants perform quite well.

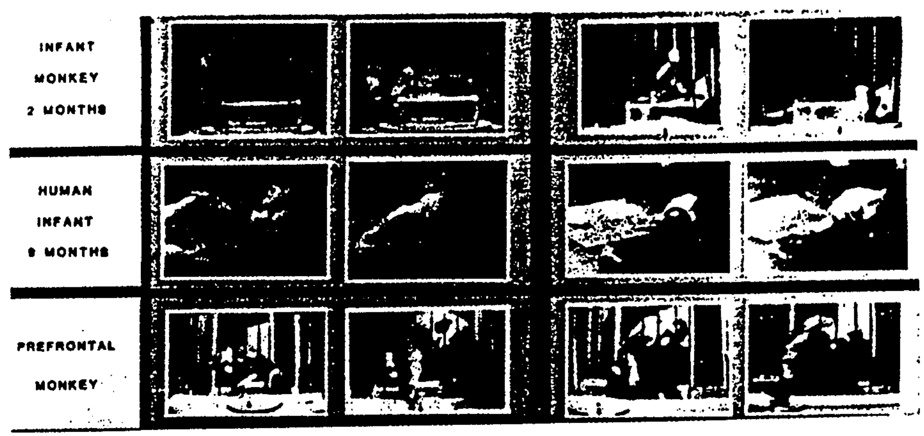


FIG. 3.8. The Awkward Reach in a 2-month-old infant monkey, a 9-month-old human infant, and an adult monkey with a bilateral lesion of dorsolateral prefrontal cortex.

Frame 1: Subject leans and looks at bait through opening of box.

Frame 2: Subject reaches in awkwardly with the far hand.

Frame 3: Opening is on the other side of the box. Performance is the same. Subject leans and looks into the opening.

Frame 4: Subject reaches in awkwardly with the far hand.

(From Diamond 1981, 1990b; and Diamond & Goldman-Rakic, 1985; 1986)

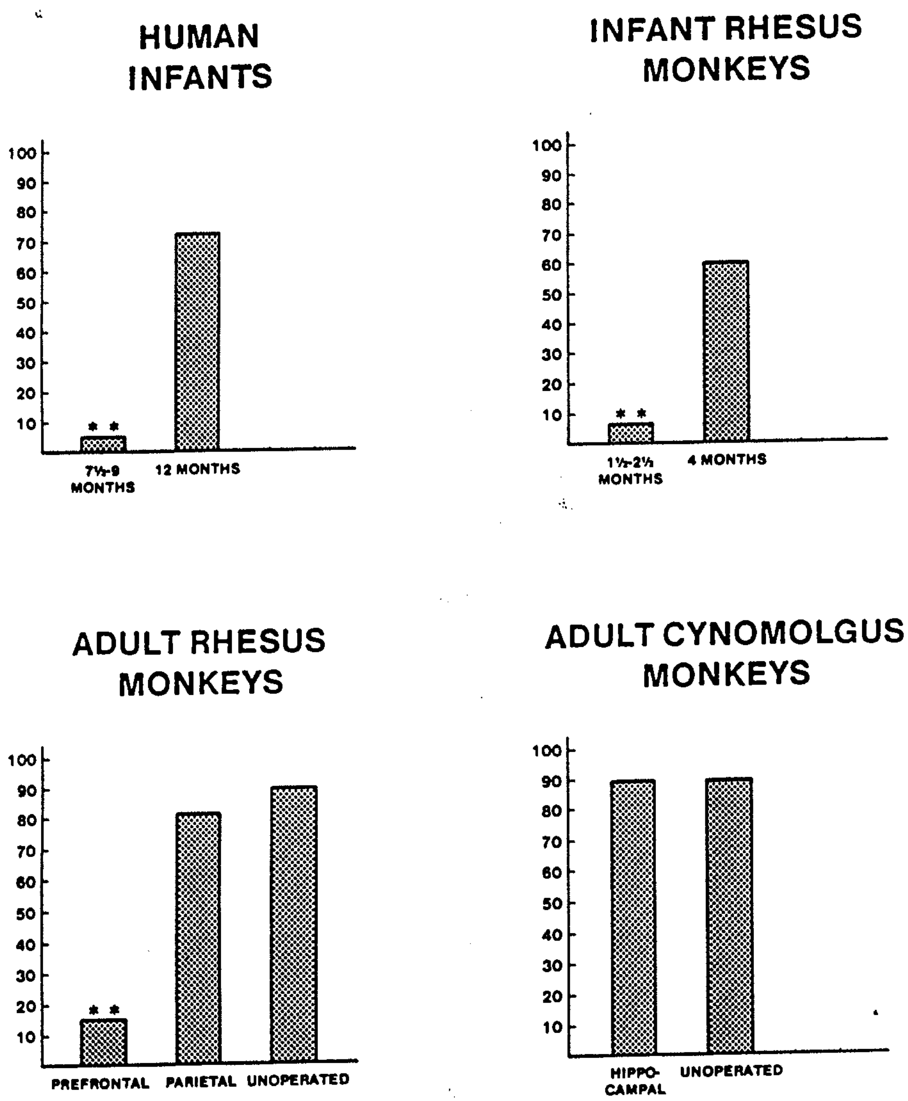


FIG. 3.9. Percent of trials during object retrieval testing where subjects reached to the box opening without ever having looked into the opening on that trial. Human infants of 7½–9 months, adult monkeys with lesions of dorsolateral prefrontal cortex, and infant monkeys of 1½–2½ months, almost never reach to the opening unless they have looked into the opening on that trial. On the other hand, 12-month-old human infants, 4-month-old infant monkeys, unoperated adult monkeys, and adult monkeys with lesions of parietal cortex or the hippocampus often reach to the opening without ever having looked into the opening on that trial. This figure summarizes work from Diamond 1981; Diamond & Goldman-Rakic, 1985; 1986; and Diamond, Zola-Morgan, & Squire, 1989.

TABLE 3.4
Performance of Human Infants, Infant Monkeys, and Monkeys with Selective Lesions of the Brain on the $A\overline{B}$, Delayed Response, and Object Retrieval Tasks

	$A\overline{B}$	*Delayed Response*	*Object Retrieval*
Human infants show a clear developmental progression from 7½–12 months.	Diamond, 1985	Diamond & Doar, 1989	Diamond, 1981
Adult monkeys with lesions of frontal cortex fail.	Diamond & Goldman-Rakic, 1989	Diamond & Goldman-Rakic, 1989	Diamond & Goldman-Rakic, 1985
Adult monkeys with lesions of parietal cortex succeed.	Diamond & Goldman-Rakic, 1989	Diamond & Goldman-Rakic, 1989	Diamond & Goldman-Rakic, 1985
Adult monkeys with lesions of the hippocampus succeed.	Diamond, Zola-Morgan, & Squire, 1989	Squire & Zola-Morgan, 1983	Diamond, Zola-Morgan, & Squire, 1989
Infant monkeys show a clear developmental progression from 1½–4 months.	Diamond & Goldman-Rakic, 1986	Diamond & Goldman-Rakic, 1986	Diamond & Goldman, Rakic, 1986
5-month-old infant monkeys, who received lesions of frontal cortex at 4 mo, fail.	Diamond & Goldman-Rakic, 1986	Diamond & Goldman-Rakic, 1986	

SUMMARY

Evidence that by at least 5–7 months of age infants understand that a hidden object remains where it was last seen and that an object contiguous with another continues to exist as an independent entity has been reviewed. An explanation has been offered for why infants at this age often fail to demonstrate these understandings in their behavior. Infants of 5–7 months have great difficulty inhibiting reflexive reactions to objects they touch and they have great difficulty combining two actions together in a behavior sequence, whether it be a means–end sequence or a reaching sequence consisting of two different movements. I have suggested that it is for these reasons that infants at this age cannot retrieve a contiguous object, uncover a hidden object, or detour around a barrier. The problem for the infants is not to acquire an understanding that objects continue to exist when they share a boundary or are no longer visible; by at least 5–7 months infants understand this. The problem for the infants is to gain control of their actions so they can demonstrate this understanding. By $7\frac{1}{2}$–9 months, infants begin to be able to retrieve contiguous objects, uncover hidden objects, and detour around barriers. It is suggested that these advances may be due in part to maturation in the SMA neural system.

Infants of $7\frac{1}{2}$–9 months can find a hidden object, but they fail the $A\overline{B}$ hiding task if a delay is introduced. Indeed, even with no delay or with transparent covers, they still have some difficulty *not* repeating the previously reinforced response of reaching to A. They also have difficulty inhibiting the pull to reach straight to their goal in the object retrieval task and inhibiting the tendency to do the same action with both hands. They can link two actions together in a sequence, but they still have great difficulty doing, or attending to, two things simultaneously, whether it be bimanual coordination or the coordination of vision and reaching or vision and touch. They know where to reach for a hidden toy if allowed to reach immediately and can retrieve a toy from the object retrieval box if the toy is sitting in the box opening; however, they run into difficulty if a temporal gap is imposed between when the toy is hidden and when they are allowed to reach (as in $A\overline{B}$) or if a spatial gap is imposed between the toy and the box opening by placing the toy deep inside the box (in object retrieval). By 12 months, infants begin to be able to do all of these things skillfully. It is suggested that these advances are made possible partly through maturational changes in the dorsolateral prefrontal cortex neural system and in callosal connections between the supplementary motor areas (SMAs) of the left and right hemispheres.

It may be that inhibitory control makes possible infants' emerging ability to construct relations. To relate two stimuli to one another, one must fight the tendency to attend only to the more salient stimulus. To relate two movements in a two-directional reach, one must stop the first movement so that the second one can begin. Reasoning and planning require that one inhibit focusing exclusively on one stimulus or idea so that more than one thing can be taken into account and interrelated.

The ability to inhibit making the predominant response frees us to exercise choice and control over what we do. That is, it makes possible the emergence of intentionality. All organisms have prepotent response tendencies, innate and conditioned. It is not clear, however, that all organisms have the capacity to *resist* the strongest response of the moment or an engrained habit. That seems to depend upon the highest levels of cortical control, and may not be possible for organisms without frontal cortex.

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