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CHAPTER 12

Toward Understanding Commonalities in the Development of Object Search, Detour Navigation, Categorization, and Speech Perception

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INTRODUCTION

During the latter half of the first year of life, infants show marked changes in their performance on a number of tasks. In this chapter we discuss changes on four of these tasks: the A \bar{B} object search task, the object retrieval task, the visual categorization task, and the cross-language speech perception task. A \bar{B} is a hiding task, in which a delay of a few seconds is imposed between when a reward is hidden in one of two identical locations and when the subject can reach to retrieve it. Object retrieval is a detour task, in which a reward is encased in a transparent box, only one side of which is open; the subject can always see the reward but must reach through the box opening to retrieve it. Visual categorization is assessed in a habituation-dishabituation looking task, in which three attributes of the stimuli covary while other attributes vary randomly; subjects' visual attention to violations of this covariation among correlated attributes is assessed. The cross-language speech perception task is a phoneme categorization task in which infants are conditioned to turn their heads when they detect a change from one syllable type to another. Subjects are tested on both native and non-native phonetic contrasts. Not only does performance on each of these tasks change over the same time period, but changes in performance on one task are highly correlated with changes in performance on the other tasks. For example, for individual infants, performance on one of these tasks

appears to be a better predictor of performance on the other tasks than is the infants' age.

In this chapter, we first briefly describe each task, outline the developmental changes in performance of each, and describe the intercorrelations between and among changes in performance across tasks. We then explore the possibility that common underlying abilities may be required in order to succeed on all of these diverse tasks, and finally suggest that maturational changes in prefrontal cortex may be related to changes in performance across these diverse tasks. Diamond has already found evidence that developmental changes in performance on the A \bar{B} and object retrieval tasks may be related to maturation of dorsolateral prefrontal cortex. The close relationship between developmental changes on all four of these tasks has led us to ask (1) whether changes in performance on the cross-language and visual categorization tasks may also be related to prefrontal maturation, and (2) whether improved performance on all four of these tasks may indicate the presence of common underlying cognitive capabilities. Since cross-language speech perception does not appear to require or be amenable to conscious control, if all four tasks require the same abilities, then perhaps conscious intentional control is less involved in the other tasks than has been traditionally believed. In addition, if all four tasks require the same abilities and similar neural bases, then developmental changes in cross-language speech perception not only may involve specialized linguistics mechanisms, but may also rely on general cognitive development.

DEVELOPMENTAL CHANGES IN PERFORMANCE ON THE TASKS

The A \bar{B} Task

In the A \bar{B} task (pronounced "A, not B"), an infant is seated in front of a table containing two identical wells, one to the left and one to the right. The infant watches as the experimenter hides a favorite toy in one of the wells. Care is taken to make sure the infant has clearly seen this. Then the wells are covered simultaneously by identical covers, and a delay is imposed of between 0 and 10 seconds (sec). Following the delay, the infant is allowed to reach. Trials are repeated at the same well until the infant is correct twice in a row; then the toy is hidden in the other well and the procedure is repeated.

Infants cannot be tested on A \bar{B} until they can uncover a hidden object (about 7½-8 months). At that age, when a brief delay of only 2-3 sec is introduced, infants typically reach correctly during trials 1 and 2 at the first well, but when side of hiding is reversed, they reach back to the first

well instead of searching at the new well. This is called the A \bar{B} error, because infants are correct at the first place (A), but wrong when the hiding switches to the second place (B); they reach back to A instead of going to B. This error has been seen in infants all over the world (e.g., Butterworth, 1977; Diamond, 1985; Gratch & Landers, 1971; Harris, 1973; Piaget, 1937/1954; Schubert, 1982; Wellman, Cross, & Bartsch, 1986; Wishart & Bower, 1985) since it was first described by Piaget (1936/1952). With age, infants can withstand longer and longer delays (see Figure 12.1), so that by 9 months of age, for example, delays of 5 sec are typically needed to produce the A \bar{B} error. By 12 months infants can withstand delays of about 10 sec on the task.

The imposition of a delay is critical to what makes this task difficult for infants. Throughout the age range of 7-12 months, if no delay is used or if the delay is decreased by 2-3 sec, infants reach correctly on all trials (Diamond, 1985). Similarly, if infants look at, reach toward, or strain their bodies toward the correct well throughout the delay, they perform

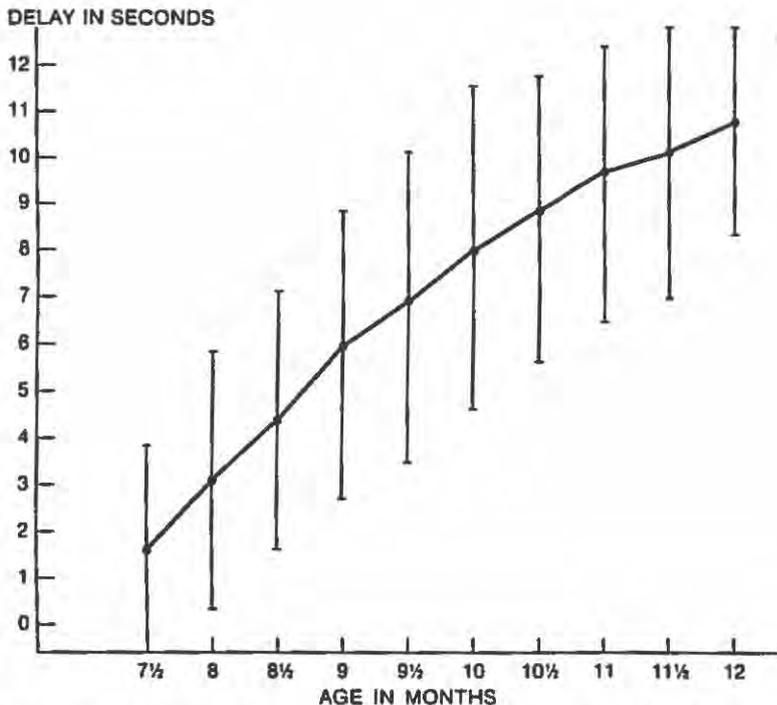


FIGURE 12.1. Developmental progression in the delay at which the A \bar{B} error occurs in infants. From Diamond (1985). Copyright 1985 by the Society for Research in Child Development. Reprinted by permission.

correctly. Thus, part of what makes this task difficult is the requirement that the subject maintain his or her attention where the reward was hidden on the last trial, despite distraction and delay.

The task can be made too difficult for infants by imposing too long a delay. When that happens, the systematic A \bar{B} error (of reaching back to the previously correct location on the first few trials at the new location) is no longer seen, and infants' behavior is severely disrupted (Diamond, 1985). Infants fuss and are very distressed, as if they know the task is now too difficult. They frequently fail to reach to either well, or else persistently reach to the incorrect well over a long series of trials, often without even bothering to check whether the toy is there or not. Affective signs of distress, and either failure to search at all or long, perseverative error strings, mark the point at which the A \bar{B} task has become too difficult for infants because of the imposition of too long a delay.

The Object Retrieval Task

In the object retrieval task, a toy is placed inside a small Plexiglas box open on one side. The infant's task is simply to figure out how to reach inside the box and retrieve the toy. Both transparent and opaque boxes are used. A box can be placed so that the top, front, left, or right side is open, and so that the infant can or cannot see through the opening of the box (by controlling the placement of the box on the table and placement of the toy inside the box).

At 6-7 months of age (phase I), infants focus only on the toy. When they see the toy through a closed side of the box they try doggedly to reach directly for the toy, but try no other route than straight through the side they are looking, despite feeling the solid surface of the box and often holding onto the opening. At 7½-8 months (phase IB), they actively try to change the side of the box they are looking through for the first time, by bending down to look in the front of the box or by raising the box so they can see in the front without bending down. But at this age, they are still locked into reaching at whatever side they happen to be looking. Thus, they appear to know that the box is there and look around for the opening, but they ignore the opening when they reach unless they are looking through it. In phase I or IB, if the toy is sticking partially out of the box and an infant accidentally pushes it back in the box in trying to retrieve it, the infant immediately removes his or her hand from the opening and reaches to the side of the box through which he or she now sees the toy. This always amazes adult observers, because the infant was right at the opening—only a fraction of an inch from the much-desired toy—but the sight of the toy through a closed side of the box seems to control the infant's behavior completely.

By 8½-9 months (phase 2), for the first time infants can look through the front of the box and then sit up, or let the box come back down after raising it, and reach through the open front while looking at the toy through the closed top. For the first time, they can coordinate reaching through one side and looking through another. However, they can only do this if they have looked through the opening on that trial. They cannot yet reach into the opening and retrieve the toy without first looking through the opening. Performance with the opening on the left or right side lags one phase behind performance with the opening at the front. Hence, at 8½-9 months infants actively lean and look for the side opening, but they must continue to look through that opening in order to succeed. When they are down in this position, leaning all the way over to see in the side, they reach with the hand contralateral to the opening (the "awkward reach"). This reach looks very awkward, almost comical, but it allows an infant to monitor his or her reach from start to finish, and it is easier to execute from the far leaning position than is a reach with the hand ipsilateral to the opening.

At phase 3 (9½-10½ months), infants succeed when the front of the box is open, without ever having looked in the opening at all. When the left or right side of the box is open, most infants lean and look in, but can then sit up, look through the closed top of the box, and reach through the side opening. The awkward reach is no longer seen; infants reach with the hand ipsilateral to the opening when they reach from an upright sitting position. At this age, a few infants are able to reach to the left or right opening without ever having looked through the opening; however, without the visual guidance of having looked along the route the hand will take, these infants typically mis-aim the hand so that one or more fingers get caught on the opening, or occasionally the hand misses the opening altogether. Finally, by 11-12 months (phase 4), infants have mastered the task. They can reach into any side without ever having looked through that side. They waste little time in determining which side of the box is open, and quickly reach in and retrieve the toy. Figure 12.2 summarizes the developmental progression on the task.

The Visual Categorization Task

"Categorization" is a ubiquitous ability that allows us to treat similar items as similar and to respond only to the commonalities that are critical in a particular situation. In the infancy literature, categorization is defined as the ability to treat two discriminably different stimuli as equivalent. As adults, we can freely and flexibly change our rules for categorization, such that at one instance we pay attention to differences

among kinds of chairs, and at another instance lump all chairs together and treat them as different from tables or benches. Very young infants, however, are only able to categorize stimuli on the basis of differences that are most salient to their perceptual systems.

By 2-3 months of age, infants can begin to modify their initial categories. For example, infants aged 3 months can categorize on the basis of line orientation (McGurk, 1972) or color (Bornstein, 1981). Infants can categorize male versus female voices by 4 months of age, and male versus female faces by 6 months of age (Miller & Younger, 1982). At about this same age they can also categorize simple patterns (Bomba & Siqueland, 1983). Infants 7 months of age can categorize line drawings of animals that vary in one or two attributes (Younger & Cohen, 1986). By 10 months of age, infants can categorize quite complex figures such as stuffed animals (Cohen & Caputo, 1978), and can categorize line drawings of animals on the basis of the correlational structure of three attributes while ignoring other attributes (Younger & Cohen, 1983).

To investigate infants' ability to use the correlational structure of a set of features, Younger and Cohen (1983) tested infants on a habituation-dishabituation task in which the featural elements could be combined in different ways. The basic logic of the experiment was as follows: During the habituation phase of the experiment, infants were shown a series of line drawings representing artificially created animals. The animals were made up of one of three body shapes, head types, tail types, head decorations, and numbers of legs. During the habituation phase, the infants were shown a series of animals in which there was a correlation among three of these attributes—for example, body, head, and tail were correlated (if they had body shape 1, they also had head and tail type 1, and if they had body shape 2, they also had head and tail type 2)—and the other two attributes were allowed to vary freely. During the dishabituation phase, infants were shown three figures: (1) The "correlated" stimulus maintained the correlation among the three criterial attributes, but had a novel combination of the two noncriterial attributes; (2) the "uncorrelated" stimulus violated the correlation among the three criterial attributes; (3) the "novel" stimulus was composed of entirely novel features (see Figure 12.3). Note that both the correlated and uncorrelated stimuli contained all familiar features, but only the uncorrelated stimulus violated the relation among the features that had been specified during the habituation phase.

The results of Younger and Cohen's (1983) research showed that 10-month-old infants could detect the correlational structure of the categories: They dishabituated to both the uncorrelated and novel stimuli. By contrast, 7-month-olds failed to appreciate the correlational structure, and only dishabituated to the novel display. Thus, the 7-month-old infants

A

VISUAL CONTROL OF REACHING

PHASES

	SIDE OF BOX THAT IS OPEN:	PHASES				
		1	1B	2	3	4
DOES NOT NEED TO LOOK AT TOY THRU OPENING AT ALL	SIDE					
	FRONT					
NEEDS TO LOOK AT TOY THRU OPENING AT BEGINNING, BUT NOT THROUGHOUT	SIDE					
	FRONT					
BEGINS TO LOOK FOR OPENING, BUT STILL REACHES EXCLUSIVELY ON DIRECT LINE OF SIGHT	SIDE					
	FRONT					
REACHES EXCLUSIVELY ON DIRECT LINE OF SIGHT	SIDE					
	FRONT					

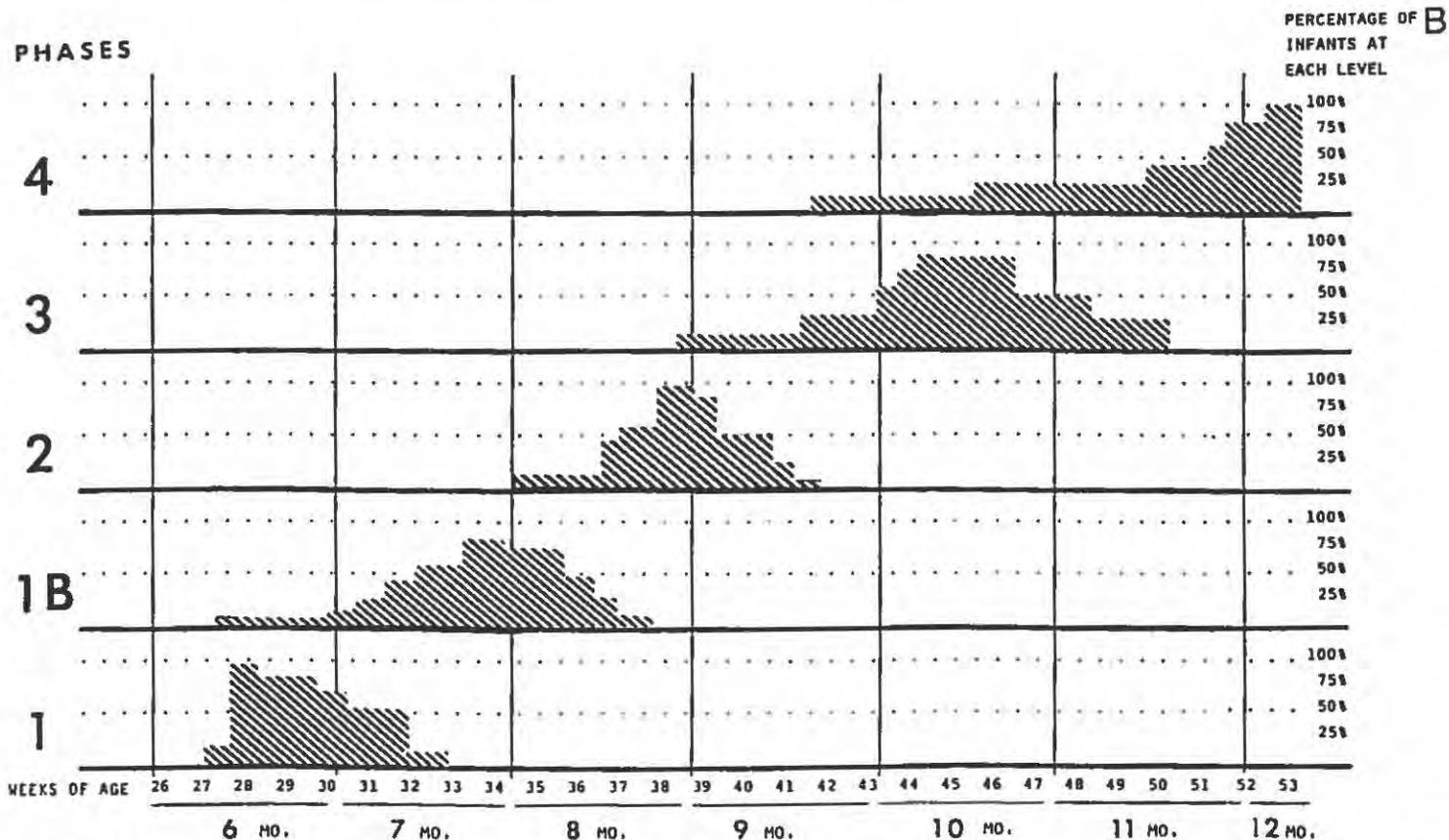
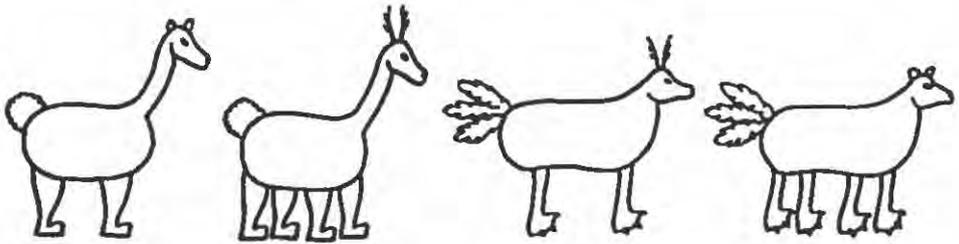


FIGURE 12.2. (A) Summary of the defining characteristics of the phases in performance of the object retrieval task. (B) Developmental progression in when the different phases in performance of the object retrieval task are reached by infants. From Diamond (1988). Copyright 1988 by Oxford University Press. Reprinted by permission.

HABITUATION STIMULI



TEST STIMULI

Correlated

Uncorrelated

Novel

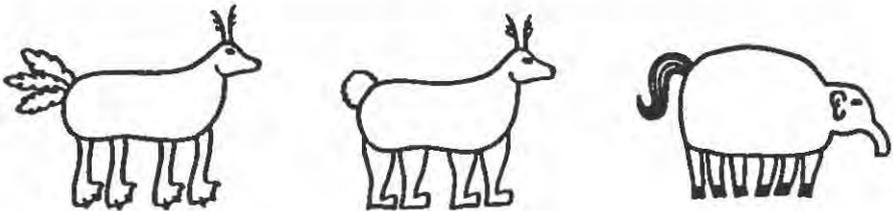


FIGURE 12.3. The visual categorization task stimuli. From Younger and Cohen (1983). Copyright 1983 by the Society for Research in Child Development. Reprinted by permission.

could remember the specific visual features shown to them during the habituation phase; what they failed to appreciate was the correlation among those features.

A similar experiment was conducted with infants 4 and 7 months of age (Younger & Cohen, 1986), using stimuli composed of only three attributes (rather than five), with two of the three attributes being perfectly correlated during the habituation phase. Results showed that the 7-month-olds could detect relations between two attributes. In this case, the 7-month-old infants dishabituated to both the novel and the uncorrelated stimulus, whereas the 4-month-olds only dishabituated to the novel stimulus. The infants of 7, but not 4, months of age could detect the overall similarity. Thus, Younger and Cohen's work with 4-, 7-, and 10-month-olds reveals a clear developmental progression in the amount of information infants can hold in mind, as well as in the complexity of

the rule they can use to relate that information. At 7 months, but not at 4 months, infants can detect the match between two pieces of information. At 10 months, but not at 7 months, infants can detect and respond to the correlation among three attributes.

Importantly, the matching of two features evident in the 7-month-olds could have been based on overall similarity, while the performance of the older infants could not. In subsequent research, Younger (1985) has shown that older infants respond on the basis of the rule specifying category membership over and above global similarity. In this work, Younger familiarized infants to stimuli, three attributes of which varied in five quantitative steps. The task was set up so that the "novel" stimulus was actually an average of the stimuli shown during the familiarization phase. Younger found that the infants treated the "novel" stimulus as different; this suggested that they had formed categories based on the correlation of the individual features, rather than on global similarity. They treated a new stimulus that maintained this correlation as similar.

The Cross-Language Speech Perception Task

Adults often have difficulty discriminating phonetic contrasts that are not used, or do not function to contrast meaning (are not phonemic), in their native language. Thus adult Japanese speakers have difficulty discriminating the English /ra/ versus /la/ contrast (Strange & Jenkins, 1978; Miyawaki et al., 1975; MacKain, Best, & Strange, 1981), and adult English speakers have difficulty discriminating two "t" phones, a dental /ta/ versus a retroflex /Ta/ as used in Hindi (Werker, Gilbert, Humphrey, & Tees, 1981). Unlike adults, young infants can easily discriminate both native and non-native phonetic contrasts (Aslin, Pisoni, Hennessy, & Perey, 1981; Lasky, Syrdal-Lasky, & Klein, 1975; Streeter, 1976; Trehub, 1976; Werker et al., 1981; Werker & Tees, 1984; Werker & Lalonde, 1988). Thus young infants seem to have an ability to discriminate speech contrasts from among any of the world's languages, whereas adults typically have more difficulty discriminating non-native speech contrasts.

Recent evidence suggests that this developmental change from broad-based to language-specific phonetic perception is apparent for consonants by the end of the first year of life. In tests with contrasts among several different consonants, it has now been demonstrated that although infants 6 months of age and younger seem to be able to discriminate native and non-native phonetic contrasts with equal ease, by the time they are 10-12 months of age they have difficulty discriminating at least some non-native contrasts. In the first demonstration of this age-related change across infancy in non-native speech perception, Werker and Tees (1984) compared infants aged 6-8, 8-10, and 10-12 months on their ability to discriminate two non-English speech contrasts (the Hindi

retroflex-dental /Ta/-/ta/ and the Nthlakampx glottalized velar-uvular /ki/-/qi/ distinctions). Infant subjects were tested in the head turn procedure, in which they were conditioned to turn their heads toward a visual reinforcer when they detected a change from one syllable type to another. The infants were first tested on the English /ba/-/da/ distinction to make sure they could (and would) perform in the procedure, and then on one of the non-native contrasts. If they failed to discriminate the non-native distinction within 25 trials, they were then retested on the native contrast to ensure they could perform the task. As shown in Figure 12.4, virtually all the infants aged 6-8 months were able to discriminate both the non-native contrasts, whereas among the infants aged 10-12 months, only 1 out of 10 was able to discriminate the Interior Salish Nthlakampx contrast and 2 out of the 10 the Hindi contrast.

This same pattern of results was found in a longitudinal design (Werker & Tees, 1984) and in a study using a voiced retroflex-dental contrast /da/-/Da/ (Werker & Lalonde, 1988). The result with respect to the /ki/-/qi/ contrast has been replicated in another laboratory using a habituation-dishabituation procedure (Best & McRoberts, 1989), and evidence for reorganization of the ability to perceive non-native contrasts is now evident for three Zulu contrasts (Best, 1993; but see Best, McRoberts, & Sithole, 1988, for a Zulu click contrast that does not show a similar developmental reorganization). Thus the finding of a decline between 6 and 12 months of age in performance on non-native consonant discrimination tasks has now been replicated many times.¹

Studies with adult subjects have made it clear that the decline in non-native speech perception does not involve an absolute loss of discriminatory capabilities. Indeed, adults can be trained to discriminate non-native contrasts (Logan, Lively, & Pisoni, 1991), can discriminate

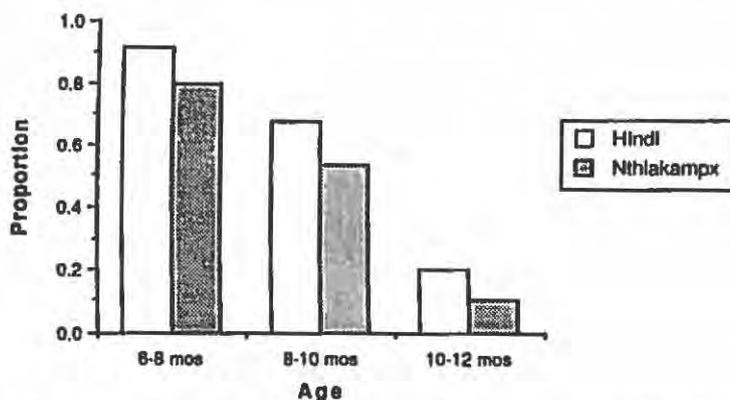


FIGURE 12.4. Proportion of infant subjects reaching criterion on Hindi and Nthlakampx contrasts by age.

many with no training at all (Best et al., 1988; Polka, 1991), and can show both language-universal and language-specific patterns of discrimination under different testing conditions (Werker & Logan, 1985). The difficulty shown in the ability to discriminate non-native contrasts should therefore be viewed as a reorganization rather than a loss, since the ability is clearly still there. This reorganization has been explained as a shift in attention away from some acoustic discriminations that the ear is still quite capable of making (Jusczyk, 1992), allowing an active process of recategorization to occur. The question, of course, is this: What kinds of experiences and/or abilities allow infants to ignore only some kinds of acoustic/phonetic variability?

RELATIONS BETWEEN PERFORMANCE ON THE TASKS

Performance on the A \bar{B} and Object Retrieval Tasks

Diamond (1988, 1991b) followed a group of 25 infants every 2 weeks from 6 to 12 months of age on both the A \bar{B} and object retrieval tasks. She found considerable individual variation in performance among infants of the same age on each of these tasks (see, e.g., the large error bars in Figure 12.1). However, despite this, and despite the marked differences between the two tasks, Diamond found that the age when infants could first uncover a hidden object closely matched the age when infants first showed phase 1B performance on object retrieval (see Table 12.1). For example, Brian first uncovered a hidden object at only 6½ months (28 weeks, 3 days), whereas Lyndsey was more typical in that she could not uncover a hidden object until 7½ months (33 weeks, 2 days). However, on the same day that Brian and Lyndsey first uncovered a hidden object, they also each took their first active steps to change the side of the transparent object retrieval box they were looking through (phase 1B performance—first seen in Brian at 28 weeks, 3 days, and first seen in Lyndsey at 33 weeks, 2 days). Progression through the phases of performance on the object retrieval task occurs over the same age period as progression on the delays infants can withstand on the A \bar{B} task. By 12 months, infants have mastered object retrieval and can succeed with delays up to 10 sec in length on the A \bar{B} task.

Performance on the A \bar{B} and Visual Categorization Tasks

Lalonde (1989) tested a group of 40 infants aged 8.25–10 months (mean = 9.0) on the A \bar{B} , cross-language, and visual categorization tasks. In the A \bar{B} task, a 3-sec delay was used. Infants' performance on the A \bar{B} task was

TABLE 12.1. Comparison of the Age of Onset of Phase 1B in Object Retrieval and the Age When Infants Could First Uncover a Hidden Object

	Onset of phase 1B, object retrieval	First able to uncover a totally hidden object
Brian	28 (3)	28 (3)
James	28 (5)	28 (5)
Erin	30 (3)	32 (4)
Nina	31 (0)	29 (0)
Jennine	31 (4)	31 (4)
Kate	31 (6)	33 (5)
Rachel	32 (4)	30 (6)
Isabel	32 (5)	32 (5)
Chrissy	32 (6)	32 (6)
Ryan	33 (1)	33 (1)
Bobby	33 (2)	33 (2)
Julia	33 (2)	33 (2)
Lyndsey	33 (2)	33 (2)
Jamie	34 (0)	34 (0)
Mariama	34 (0)	36 (3)
Michael	34 (0)	36 (3)
Emily	34 (2)	34 (2)
Graham	34 (2)	34 (2)
Jane	34 (5)	34 (5)
Sarah	34 (6)	34 (6)
Jack	35 (3)	35 (3)
Blair	35 (4)	35 (4)
Rusty	35 (6)	33 (5)
Tyler	36 (2)	38 (4)
Todd	39 (4)	35 (1)

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

classified according to essentially the same scoring criteria as Diamond (1985) had used. Performance that Diamond characterized as "accurate" was classified as "pass." Performance that Diamond characterized as the "AB error" was classified here as "error."² Performance that Diamond characterized as "deteriorated" was classified here as "fail." Subjects whose performance fell into this last category were unable to overcome the demands of the two-location object search task with a 3-sec delay. They showed signs of distress and often failed to reach at all, or failed repeatedly over trials. They did reach on some trials, however, and even succeeded on some, indicating that they could uncover a hidden object.

In the visual categorization task, three of five features of each stimulus were correlated. A comparison of subjects' looking times to the uncorrelated versus correlated stimuli in the visual categorization task

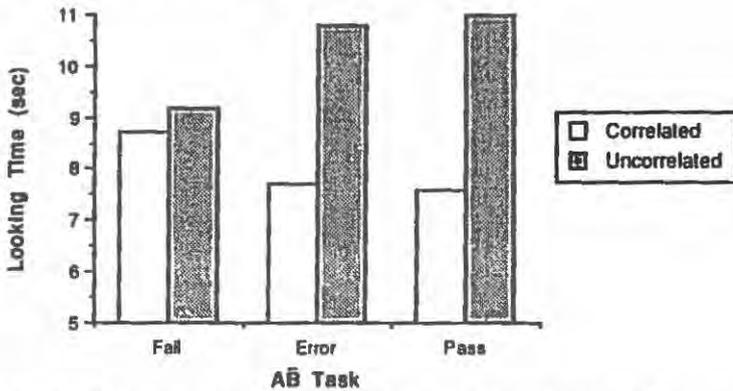


FIGURE 12.5. Looking time (in seconds) to the correlated and uncorrelated test stimuli by AB group.

with their performance on the AB task is shown in Figure 12.5. The results indicate a fairly strong developmental linkage between the tasks. Subjects in the AB pass group performed like Younger and Cohen's (1983) 10-month-old infants, looking longer to the uncorrelated than to the correlated stimulus. Subjects in the AB fail group performed like Younger and Cohen's 7-month-old infants, looking equally to the uncorrelated and correlated stimuli. Subjects in the AB error group performed almost as well as those in the AB pass group in this analysis. See Lalonde and Werker (1993) for a full description of scoring criteria and analysis.

Performance on the Visual Categorization and Cross-Language Tasks

Recall that failing to discriminate the non-native speech contrast is the more mature pattern of responding, which is generally evident by 10 but not 8 months of age. In Lalonde's (1989) study, performance on the cross-language task was thus coded as "immature" if infants could achieve a standard criterion of seven correct out of eight consecutive responses and "mature" if they could not achieve this criterion. To compare infants' performance on the cross-language and visual categorization, subjects' looking times in the visual categorization task to the uncorrelated versus correlated stimuli were compared to performance on the cross-language task. As the difference scores shown in Figure 12.6 indicate, infants who performed like older infants in the cross-language task also performed like Younger and Cohen's (1983) 10-month-old

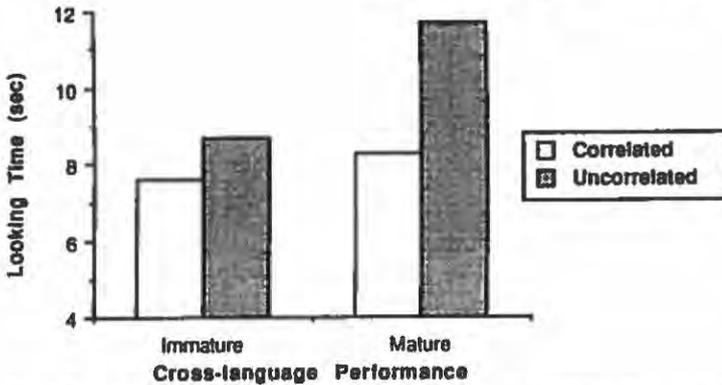


FIGURE 12.6. Looking time (in seconds) to the correlated and uncorrelated test stimuli by cross-language performance.

infants, looking longer to the uncorrelated than to the correlated stimulus. Thus infants who did not discriminate the non-native speech sounds were able to form visual categories on the basis of the correlations among the attributes. Subjects who showed more immature performance on the cross-language task performed like Younger and Cohen's 7-month-old infants. These infants showed both continued sensitivity to the non-native speech contrasts and an inability to use the correlations among the stimulus attributes in the categorization task.

Performance on the A \bar{B} and Cross-Language Tasks

A comparison of infants' performance on the A \bar{B} and cross-language tasks (Lalonde, 1989) revealed a linear relationship. (Recall, again, that failing to discriminate the non-native contrast constitutes more mature performance.) Percentage correct was highest for the A \bar{B} fail group, significantly lower for the A \bar{B} error group, and significantly lower still for the A \bar{B} pass group. Only the performance of the A \bar{B} fail group significantly exceeded a chance mean of 50% correct. A comparison of the number of infants per A \bar{B} group achieving the standard performance criterion of seven correct out of eight consecutive responses also revealed a linear trend: All of the A \bar{B} pass infants performed like 10-month-olds; half of the infants in the A \bar{B} error group performed like 10-month-olds and half like 7-month-olds; and only 3 of the 14 (21%) A \bar{B} fail infants performed like 10-month-olds, whereas the other 11 (79%) performed like 7-month-olds.

Performance on the A \bar{B} , Visual Categorization, and Cross-Language Tasks

A number of steps were taken to compare infants' performance on the A \bar{B} , visual categorization, and cross-language tasks (Lalonde, 1989). Cluster analyses were first performed to transform the cross-language and visual categorization data to the nominal categories of mature-immature and pass-fail, respectively. A profile of task performance was then generated for each subject, resulting in a table of cross-classifications (see Table 12.2). A prediction analysis of cross-classifications was then conducted to test the prediction that only subjects who fully passed the A \bar{B} task would show mature performance on the speech task and pass the visual categorization task; that those who failed the A \bar{B} task would fail the other two tasks; and that those who were classified as A \bar{B} error would show intermediate performance, with some failing and others passing. The results of this analysis strongly supported this model and, importantly, were not affected by the age of the subjects. Although there was a trend for older subjects to perform better on the A \bar{B} task than younger subjects, the relationship between passing the A \bar{B} task and passing the other two tasks remained when age was partialled out of the analysis.

COGNITIVE PREREQUISITES OF SUCCESSFUL PERFORMANCE ON THESE TASKS

The finding that more mature performance emerges at about the same time on all four tasks raises the possibility that success on these tasks depends on the presence of common underlying skills or abilities. We would like to suggest that there are two such abilities, and that both are

TABLE 12.2. Table of Cross-Classification Used in the Prediction Analysis

	Pass on A \bar{B} task	Error on A \bar{B} task	Fail on A \bar{B} task
Pass on categorization task			
Mature on speech task	9	6	1
Immature on speech task	0	2	4
Fail on categorization task			
Mature on speech task	5	0	2
Immature on speech task	0	4	7

required for successful performance on these tasks. The first is the ability to inhibit appropriate response tendencies. Such inhibition can be manifested, for example, as suppressing a previously rewarded response when a new response is needed, or as inhibiting distraction by extraneous or particularly salient stimulus features, enabling one to maintain one's focus on what is relevant. The ability to focus one's attention or to attend selectively (i.e., to inhibit distraction) is seen here as one instance of the more general ability to exercise inhibitory control over one's behavior. The second ability is the capacity to hold multiple pieces of information in mind so that they can be related to another, and the capacity to remember and manipulate those relations. Memory for temporal order (e.g., memory for the order in which things or events occurred) is seen here as one instance of the more general ability to relate information in one's mind, and to remember those relations. Below, we discuss the contributions made by these two abilities—inhibitory control and the ability to mentally relate separate pieces of information—to successful performance on each of the four tasks.

Role of Inhibitory Control in Successful Performance on the Tasks

Role of Inhibitory Control in the AB Task

The AB task requires that subjects not get distracted during the delay, despite the facts that visual fixation on the correct well is broken, bodily cueing is constrained, and the delay often lasts several seconds. Infants even as young as 8 months do not err on A if there is no delay, if they are not visually distracted during the delay, or if they are allowed to maintain a bodily orientation toward the correct well throughout the delay. The performance of younger infants falls behind that of older infants when subjects must maintain their attention on where the reward was last hidden, despite distraction and delay.

Memory of where the toy was hidden on earlier AB trials will not help a subject on the current trial, and indeed may interfere if the memory of earlier events is as strong as or stronger than memory of where the object was last hidden. On the AB task, subjects should ignore the history of past trials and instead maintain their attention on where they have seen the reward hidden on the current trial.

Subjects rarely err on the trials at the first hiding place. Errors begin when the reward is first hidden at the second location. One way to think about this is that on the initial trials at the first hiding location, there is no competing tendency to reach to the other hiding place. However, once subjects have been rewarded for reaching to the first place, a conditioned

tendency may be built up to reach back there. Now, if subjects "go on automatic" and just give the response their bodies are inclined to make, they will reach back to the first hiding place. When side of hiding changes, subjects must inhibit that tendency and must direct their reach instead to where the reward was last hidden. Evidence consistent with this interpretation is that when infants err on the A \bar{B} task, they often uncover the previously correct well, do not look in to see if the toy is there, and then immediately uncover the correct well and look there for the toy. It is as if they know the toy is not in the first well, but they reach there anyway. Occasionally, some infants will look squarely at the correct well as they reach back to the previously correct well (Diamond, 1988, 1990b, 1991b). Here, the infants appear to be telling us with their eyes that they know where the toy is, but they reach back to the other well anyway.

Role of Inhibitory Control in the Object Retrieval Task

The main problem posed by the object retrieval task appears to be that when infants can see a much-desired object, they seem unable to inhibit the tendency to reach straight for it. That tendency is maladaptive on this particular task because to succeed in retrieving the object they must first detour around the box opening. When the desired object is visible, infants seem so intent on that object that they appear to ignore the abundant tactile, and to a lesser extent visual, information specifying which sides of the box are open or closed. They perform much better, therefore, when the box is opaque (see Table 12.3). When the box is opaque, the desired object cannot be seen through any of the closed sides, so there is no pull to try to reach straight to the object through a closed side of the box. When the box is transparent, the object retrieval task thus requires

TABLE 12.3. Mean Trial Duration for Same-Size Transparent and Opaque Boxes on Left-Open Trials with Toy Deep in Box

Age in months	Transparent box	Opaque box
7½	28.6	15.7
8	29.4	16.5
8½	24.9	14.0
9	16.7	11.3
9½	15.4	10.4
10	13.8	10.3
10½	13.3	9.8
11	11.4	11.2
11½	5.2	6.8
12	4.7	3.3

(1) that the strong pull to reach directly for what you want be inhibited so that a circuitous detour reach can be executed; and (2) that attention to the desired object be inhibited, or dampened, long enough that attention can also be directed to the box and to where its opening is located.

Role of Inhibitory Control in the Visual Categorization Task

The visual categorization task requires infants to ignore irrelevant attributes (i.e., those that vary randomly across the stimuli), and instead to focus on the correlational structure of the attributes that are critical to category membership. In a study of infants' ability to categorize faces, it was found that infants 7-8 months of age were distracted by salient attributes such as "toothiness," whereas infants 10 months of age could ignore such salient features and categorize faces on the basis of overall configural information (Kestenbaum & Nelson, 1990). Here, the younger infants appeared unable to inhibit attending to salient but irrelevant attributes.

Role of Inhibitory Control in the Cross-Language Task

The more mature response in cross-language tasks is to ignore (indeed, not hear) linguistic contrasts that are irrelevant in one's own language. Young infants are able to discriminate native and non-native consonant contrasts, but by 10-12 months of age infants behave like adults and easily discriminate only those acoustic/phonetic changes that have functional significance in their language-learning environment. Infants thus come to restrict their attention to linguistic contrasts that are relevant in their own language. It is clear that this decline in performance does not represent a simple "loss" of the ability to discriminate the non-native contrasts, since adults do have a continuing or latent sensitivity to these same contrasts (though discrimination is difficult without training). This provides evidence that inhibition may indeed play an active role in the reorganization of phonetic sensitivity. This possibility is strengthened by our most recent data, which show that infants aged 10-12 months even have difficulty discriminating non-native vowel contrasts that adults find quite easy (Polka & Werker, 1991, in press; Werker & Polka, 1993a, 1993b). That infants fail to discriminate these non-native contrasts, even though they are acoustically quite salient, strengthens the suggestion that by this age infants attend selectively to acoustic/phonetic information that is relevant in their native language.

In short, all four of these tasks require selective attention (i.e., inhibition of attention to irrelevant, distracting information) and inhibition of the response the subject might be predisposed to make.

Role of Processing of Relational Information in Successful Performance on the Tasks

By "processing of relational information," we mean holding information in mind, so that multiple pieces of information can be compared and contrasted. The information held in mind can be recent perceptual information, information that was stored in memory, or both.

Processing of Relational Information in the AB Task

Errors on the AB task generally begin to appear when the reward is first hidden at the second location. During the initial trials at the first location, a correct answer to the question "Where have I ever seen this reward hidden?" will suffice to direct the response to the correct hiding place. However, once the reward has been hidden at the second place, an answer to this question alone will no longer suffice, because now subjects have seen the reward hidden at both locations. In this case, then, correct performance requires that the subjects be able to answer the question "Where have I seen the reward hidden last?" Thus, the task requires that infants be able to remember this minimal aspect of the temporal order in which the hidings occurred.

The information that specifies which hiding place is correct is also inherently relational, since the hiding places are identical, differing solely in their left-right location. Also, the AB task requires subjects to relate their knowledge of where the reward was hidden to the act of reaching. The larger the temporal gap (i.e., the longer the delay) over which hiding and retrieval must be related, the more difficult the task. Problems with memory for relative spatial location or problems in coordinating knowledge and action over a temporal gap should result in search failures even at the initial hiding place. However, infants perform well at the initial hiding location. Although the delay is constant across trials, errors are not randomly distributed; instead, errors occur predominantly when the hiding place is switched. Therefore, it would appear that problems with memory for relative spatial location cannot fully explain the AB error. It appears that the AB error is attributable to both (1) a failure to remember relational information and/or to relate information over a delay of seconds, and (2) a failure to inhibit the prepotent tendency to repeat a successful response.

Processing of Relational Information in the Object Retrieval Task

The object retrieval task requires that subjects relate the box and its opening to the toy, and also relate the visual information about the toy to the tactile information about the box and its opening. Younger infants

appear to be so gripped by the sight of the toy that they do not simultaneously attend to the box. They appear to ignore the abundant tactile information specifying which sides of the box are open or closed. The visual presence of the box is not particularly salient, as it is transparent, but infants feel its solid surfaces and often grasp the edges of the opening. If they attended to this tactile information, it would be a very good guide for their reach. The task requires that the subjects discover which side of the box is open, hold that information in memory, and coordinate the reach for the toy with that information.

The object retrieval task may also require temporal order memory in the sense of remembering which sides of the box the infants have already tried on this trial and found closed. Once infants begin to look for the opening, they try the same sides of the box over and over again (e.g., they may reach to the top, then the front, then the top again, front, top, front, top, left, front, top, left, front, top, left, etc.). If infants could remember that they had already tried the front of the box on this trial, for example, perhaps they would not keep returning to the front.

Processing of Relational Information in the Visual Categorization Task

The ability to notice the relation between two or more pieces of information is essential for successful performance on the visual categorization task. To detect the correlation that specifies category membership, subjects must remember what they have seen and relate that to what they subsequently see. Subjects must be able to remember the relation between two or more pieces of information.

To determine whether a given stimulus is an instance of a category, subjects must compare that stimulus with their memory of the critical relations defining category membership. This ability alone may not be sufficient if the infants are easily distracted by salient stimulus attributes. Thus, in order to succeed at this task, infants must be able to detect relations among attributes, to remember those relations, to compare the attributes of a new stimulus to their memory of how the attributes should be related, and to inhibit the tendency to attend to salient (but irrelevant) qualities of the stimuli.

Processing of Relational Information in the Cross-Language Speech Perception Task

The reorganization of phonetic sensitivities reflected in more mature performance in cross-language speech perception may also involve infants' newly emerging ability to categorize, coordinate, and compare complex stimuli. As noted above, the reorganization in cross-language speech perception does not appear to involve a loss of acoustic sensitivity, and

therefore involves some sort of selective redirection of attention. In order to attend to only the acoustic variability that is significant, the infant must have detected the rules specifying category membership for native language phones. For example, to an English-speaking adult, the retroflex and dental "t's" used in Hindi are both members of a single English phone category, alveolar /t/. Thus it seems reasonable that at the age at which an English-learning infant begins to "ignore" the difference between the retroflex and dental "t's," he or she has detected the rule specifying phone category membership in English, and related each of those "t" sounds to the single English (alveolar) phone category. This requires the ability to detect the rules specifying category membership, to hold a representation of the rules specifying native language phone categories in mind, and to relate any particular speech stimulus to those mental representations. However, it is important to note that there is no evidence that subjects have any conscious access to these processes.

POSSIBLE ROLE OF PREFRONTAL CORTEX IN THE EMERGENCE OF THESE ABILITIES

The two sets of abilities that appear to be required for the A \bar{B} , object retrieval, visual categorization, and cross-language tasks have been linked specifically to the region of the brain known as "prefrontal cortex." Prefrontal cortex is that portion of frontal cortex forward of motor cortex (i.e., forward of the precentral sulcus). In the monkey, these abilities have been linked specifically to the dorsolateral portion of prefrontal cortex. In the human, such precise localization has not yet been possible. When damage to frontal cortex occurs in humans, it is often more widespread, covering several regions within frontal cortex and sometimes subcortical areas as well.

The Role of Prefrontal Cortex in Inhibitory Control

Failure to Inhibit a Dominant Response; Dissociations between Conscious Intent and Action

The behavior of patients with damage to frontal cortex often appears to "go on automatic," so that the usual or predominant response is given even when it should be inhibited. For example, when presented with an object, a patient with damage to frontal cortex may automatically reach for it unthinkingly, even if instructed not to reach, and even if it is not an object the patient "wants": "Taking a pack of cigarettes, he hesitated a moment, then opened it and drew out a cigarette. He looked puzzled at

it, being a nonsmoker" (L'Hermitte, 1983, p. 246). Patients with frontal cortex damage perform very poorly on the Stroop task, in which color words are written in the ink of another color and subjects must call out the color of the ink; frontal patients tend to give the usual response when reading: They recite the word instead of the color of the ink (Perret, 1974; Pardo, Pardo, Janer, & Raichle, 1990). Frontal patients have no difficulty looking toward a visual cue. However, when instructed not to look at the cue, but instead to look in the opposite direction, frontal patients are severely impaired at inhibiting the natural tendency to look toward the cue (Guitton, Buchtel, & Douglas, 1985). The tendency of 7-month-old infants to attend to an irrelevant but salient visual cue, such as a "toothy" smile, could be seen as an instance of this type of behavior. Similarly, the ability of a 10-month-old infant to ignore an acoustically salient non-native vowel contrast may require the involvement of pre-frontal cortex. Luria (1973) gives many examples of similar failures on the part of patients with frontal cortex damage to inhibit the response most easily elicited when another response is, in fact, appropriate. Thus it appears that frontal patients have difficulty inhibiting predominant action tendencies, and/or inhibiting the tendency to direct their attention to a salient perceptual cue.

Patients with frontal cortex damage often say that their behavior does not "obey" them. For example, they may tell the experimenter the correct answer, even as their hands select the wrong answer trial after trial, in a manner very reminiscent of the AB error (Milner, 1964; Luria & Homskaya, 1964). Recall that on the AB task, infants occasionally reach to the incorrect location even while they are looking squarely at the correct location. When this happens one has the sense that the infants "know" where the toy is, although they reach back to the other well anyway. Similarly, patients with dorsolateral prefrontal cortex damage occasionally tell the experimenter the correct sorting criterion on the Wisconsin Card-Sorting Test even as their hands continue to sort the cards by the previously correct, but now incorrect, criterion. The patients know the response is wrong, but do it anyway.

In more extreme cases with larger or more medial damage to the frontal lobe, a patient's hand may seem to be acting as if it is no longer under the patient's conscious control, as in the "alien hand sign" seen after damage to the supplementary motor area (Goldberg, Mayer, & Togli, 1981):

A patient [with left hemisphere damage to the supplementary motor area] would reach out spontaneously with the right hand and then would be unable to release her grip voluntarily. She was unable consciously to inhibit this behavior although she was quite aware of it and was obviously frustrated by her inability to prevent it. . . . Motor perseveration was evident. The patient would begin to perform a task

with her right arm and would begin to persevere uncontrollably. The left arm would then interrupt by restraining the right arm and then complete the task. (Goldberg et al., 1981, pp. 683-684)

Selective or Focused Attention; Inhibiting Distraction

Patients with frontal cortex damage have great difficulty directing or limiting their attention. They have a notoriously difficult time staying on task. They are easily distracted. When talking, they often digress, and have to be frequently reminded to finish the line of thought they first began. When listening, they often shift their attention to whatever salient snippet of speech catches their attention (Luria, 1973). When doing a task, they often seem to lose track of what the instructions were (Konow & Pribram, 1970). Event-related potential (ERP) studies of brain electrical activity routinely find enhanced activity over frontal cortex during successful performance of selective attention tasks (e.g., Arnsten, Neville, Hillyard, Janowsky, & Segal, 1984; Knight, Hillyard, Woods, & Neville, 1981).

The Role of Prefrontal Cortex in Processing Relational Information

Dorsolateral prefrontal cortex is not required for the memory of single items of information; recognition memory is unimpaired after damage to dorsolateral prefrontal cortex. However, when two items must be related or compared in memory, then involvement of prefrontal cortex is often necessary. For example, patients with frontal cortex damage often do well on standard delayed-recall tests, but fail delayed-comparison tests where they must judge, for example, whether a color they saw earlier is the same shade as the color they see now, or whether a tone they just heard is the same pitch as the tone they hear now (Prisko, cited in Milner, 1964). This is precisely the kind of ability that is required for successful performance on the visual categorization and cross-language tasks. In each case, the infants must compare a stimulus (figure or sound) to one they have heard before, and judge whether it is the same or different.

Frontal patients are also notoriously poor at relating two pieces of information (e.g., Barbizet, 1970; Heilman & Valenstein, 1972). Grossman (1982) administered eight visual and auditory reversal tasks (i.e., tasks requiring that subjects appreciate the relation between original and transformed states) mediated by linguistic and nonlinguistic symbol systems to adults with localized brain damage. He found no domain-specific deficits; rather, patients with frontal cortex damage were impaired across the board on this type of task. Another example of the difficulty prefrontal cortex patients have in remembering the relation between bits of

information is provided by research showing that they are notoriously poor at remembering the context in which something occurred (e.g., Shimamura, Janowsky, & Squire, 1990).

Although patients with damage to frontal cortex can tell whether they have ever seen something before, if they are presented with two things (both of which they have seen before), they are unable to remember which one they saw more recently (Corsi, cited in Milner, 1971; Milner, Corsi, & Leonard, 1991). Recall that on the AB task, infants succeed at the first hiding location, when simply being able to answer the question "Where have I ever seen the reward hidden?" will suffice to guide performance correctly. However, younger infants fail after the toy has been hidden at both locations—that is, when one might conceive of the problem facing the infants as "Where have I seen the reward hidden most recently?" When asked about well-known events from the last several decades, patients with frontal cortex damage are impaired in recalling the order in which the events occurred, yet unimpaired in recognition and recall of the events (Shimamura et al., 1990). Memory of the order in which things have happened seems to require frontal cortex involvement.

Patients with dorsolateral prefrontal cortex damage fail at self-ordered pointing, in which they must remember which pictures they have already pointed to (Petrides & Milner, 1982). They do not persist in pointing to the same picture time after time; rather, they simply seem to lose track of which pictures they have already selected. Similarly, when infants begin looking for the box opening on the object retrieval task, they do not simply persist in reaching to the same side of the box; perhaps their behavior reflects that they have simply lost track of which sides they have already tried.

Patients with dorsolateral prefrontal cortex damage also fail the Wisconsin Card-Sorting Test. In part, this appears to be because they persist in sorting by the previously correct rule (i.e., they fail to switch or reverse—reminiscent of the performance of infants on the AB task). However, in part, it also appears that frontal patients lose track of which rule is currently correct (i.e., whether the current category is color, shape, or number). Both the visual categorization task and the cross-language speech perception task also appear to require that one remember the rule specifying category membership, so that one can determine whether the current stimulus is a member of the category or not.

Evidence that Successful Performance on the AB and Object Retrieval Tasks Requires Prefrontal Cortex Involvement

We have seen in this review that inhibitory control and processing of relational information have both been linked to prefrontal cortex. More-

over, the specific deficits in inhibitory control and processing of relational information manifested by adults with prefrontal damage appear, on the surface, to be similar to the kinds of errors made by infants on the four tasks described in this chapter. Almost all of the work thus far on the functions of discrete brain regions or systems in humans comes from adults. The tasks used with infants are too easy for adults, however, even adults with brain damage. Therefore, when comparing infants' performance with that of adults, we have had no choice but to rely on behavioral analogies. Surface similarities in behavior can be misleading, however. Seemingly similar behaviors can occur for very different reasons. It is important, therefore, to have evidence directly linking successful performance on these specific tasks to involvement of dorsolateral prefrontal cortex.

The A \bar{B} Task

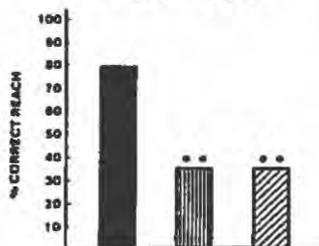
Infant and adult monkeys have been tested on the A \bar{B} task, using the same procedures as are used with human infants (Diamond & Goldman-Rakic, 1986, 1989; Diamond, Zola-Morgan, & Squire, 1989). Infant monkeys display the same developmental progression between 1½ and 4 months in the delays they can tolerate on the task as human infants display between 7½ and 12 months. By 4 months, infant monkeys can succeed on the task with delays of 12-20 sec. Adult monkeys can succeed with still longer delays.

Bilateral lesions of dorsolateral prefrontal cortex (see Figure 12.7), performed in adulthood or in infancy at 4½ months of age, result in monkeys' showing the same performance on the A \bar{B} task as do human infants between 7½ and 9 months (or infant monkeys between 1½ and 2½ months). That is, infant and adult monkeys with lesions of dorsolateral prefrontal cortex show the classic A \bar{B} error at delays of 2-5 sec, although they reach correctly if there is no delay or if they look at, reach toward, or sit in front of the correct well throughout the delay.

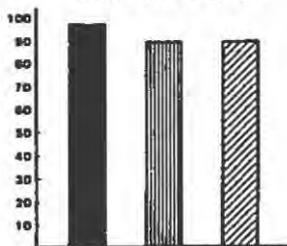
Monkeys with bilateral lesions of inferior parietal cortex (Brodmann's area 7; Diamond & Goldman-Rakic, 1989) or of the hippocampus (including the dentate gyrus, subiculum, and much of the entorhinal cortex and parahippocampal gyrus; Diamond et al., 1989) do not show this pattern of behavior. They show excellent performance on the A \bar{B} task at delays of 2-5 sec, and even at delays of 10-15 sec (see Table 12.4). Monkeys with hippocampal lesions have impaired memory, and at delays of 30 sec their percentage of correct reaches on the task is finally comparable to that found in infants of 7½-9 months or monkeys with lesions of dorsolateral prefrontal cortex. However, neither at shorter delays nor at the 30-sec delay do monkeys with lesions of the hippocampus show the A \bar{B} error pattern. That is, they do not show a disproportionate tendency to err when the side of hiding changes. They do tend to

HUMAN INFANTS

7½-9
MONTHS OLD

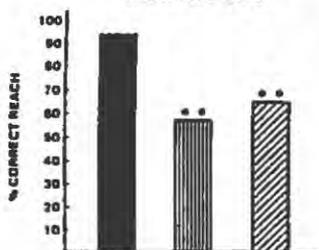


12 MONTHS OLD

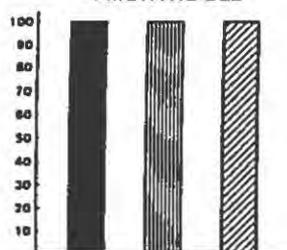


INFANT RHESUS MONKEYS

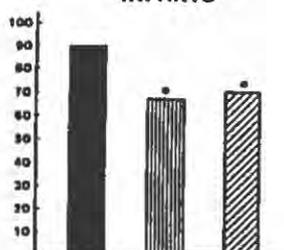
1½-2½
MONTHS OLD



4 MONTHS OLD

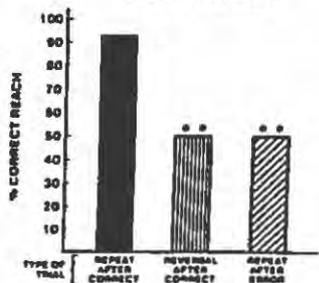


PREFRONTAL
INFANTS

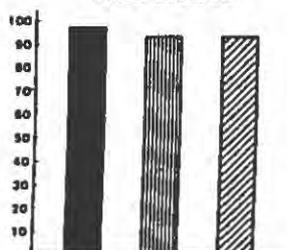


ADULT RHESUS MONKEYS

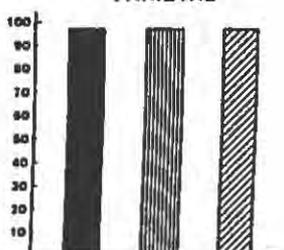
PREFRONTAL



UNOPERATED

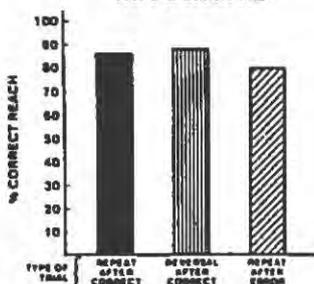


PARIETAL



ADULT CYNOMOLGUS MONKEYS

HIPPOCAMPAL



UNOPERATED

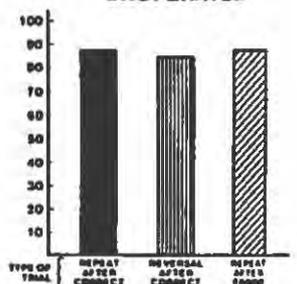


TABLE 12.4. Mean Percentage Correct on the A \bar{B} Task by Delay and by Experimental Group

	Delay (in sec)		
	2	5	10
Adult rhesus monkeys with lesions of dorsolateral prefrontal cortex	63*	64*	60*
Adult rhesus monkeys with lesions of parietal cortex	98	98	96
Unoperated adult rhesus monkeys	98	97	97
Adult cynomolgus monkeys with lesions of the hippocampal formation	98	92	84
Unoperated adult cynomolgus monkeys	98	92	90
Infant rhesus monkeys with lesions of the dorsolateral prefrontal cortex	78	74*	68*
Unoperated infant rhesus monkeys	97	97	97

*, significantly impaired, $p < .001$.

repeat an error once they make one, but where these strings of errors begin is randomly scattered throughout a session (Diamond et al., 1989).

Thus, here is a specific link between damage to one region of the brain (dorsolateral prefrontal cortex) and impaired performance on the A \bar{B} task. Damage to other areas of the brain does not have this effect. Damage to dorsolateral prefrontal cortex does not impair performance on other tasks, such as remembering that the reward is always hidden under a particular cover or on a particular side (visual discrimination tasks) (e.g., Mishkin, Prockop, & Rosvold, 1962; Pohl, 1973). Moreover, the performance of animals with lesions of dorsolateral prefrontal cortex closely matches the performance of 7½- to 9-month-old human infants on the task. They err at the same delays and in the same ways, showing the same patterns of performance and reacting in the same ways to parametric variations in the task (Diamond, 1988, 1991b; Diamond & Goldman-Rakic, 1989).

The Object Retrieval Task

Infant and adult monkeys have also been tested on object retrieval, using the same procedures as are used with human infants (Diamond &

FIGURE 12.7. Percentage correct at delays of 2-5 sec on the A \bar{B} task by type of trial in human infants, unoperated infant monkeys, infant monkeys with lesions of dorsolateral prefrontal cortex, unoperated adult monkeys, adult monkeys with lesions of dorsolateral prefrontal cortex, adult monkeys with lesions of parietal cortex, and adult monkeys with lesions of the hippocampal formation. * $p < .01$, ** $p < .0001$. From Diamond (1991c). Copyright 1991 by Oxford University Press. Reprinted by permission.

Goldman-Rakic, 1985, 1986; Diamond et al., 1989). Infant monkeys start out performing at the phase 1B level. From the outset, they actively move around to try to look through different sides of the box. Between 1½ and 2½ months, they show the behaviors characteristic of phases 1B and 2. That is, if monkeys aged 1½-2 months accidentally push the reward back inside the box, but then do not look into the opening, the infant monkeys are unable to retrieve the reward, even though they pushed it in the box themselves. Infant monkeys of 2-2½ months will lean and look in the opening at the left or right side of the box, but then must continue to look in the opening in order to succeed. When down in that position, they reach with the hand contralateral to the opening (showing the "awkward reach"). By 3½-4 months infant monkeys are in phase 4, having mastered the task. Adult monkeys find the task quite easy and succeed from the first day or two of testing.

Bilateral lesions of dorsolateral prefrontal cortex result in monkeys' showing the same performance on the object retrieval task as do human infants between 7½ and 9 months (or infant monkeys between 1½ and 2½ months). That is, they show the behaviors characteristic of phases 1B and 2. If they accidentally push the reward back inside the box, they desert the opening and reach only at the side of the box they happen to be looking through, even though they pushed the reward inside the box themselves. They actively look for the opening, though, never showing phase 1 performance. When the left or right side of the box is open, they lean all the way over to see in through the opening, and when reaching from that position show the "awkward reach" (see Figure 12.8).

Monkeys with bilateral lesions of parietal cortex (Diamond & Goldman-Rakic, 1985) or of the hippocampus (Diamond et al., 1989) do not persist in trying to reach for the reward through closed sides of the box. Monkeys with lesions of the hippocampus succeed easily on the task. Monkeys with lesions of parietal cortex show some errors in aiming the hand so that it accurately enters the box opening; they often reach too high, too far, or too short. However, they do not persist at closed sides of the box and do not need to look into the opening in order to reach there.

Thus, again, we have a specific link between damage to one region of the brain (dorsolateral prefrontal cortex) and impaired performance; this time on the object retrieval task. Damage to other areas of the brain does not have this effect. Moreover, the performance of animals with lesions of dorsolateral prefrontal cortex closely matches the performance of 7½- to 9-month-old human infants on the task. They err under the same conditions and in the same ways. They not only show similar rates of success and failure, but they show the same behaviors; they approach the task in the same ways.

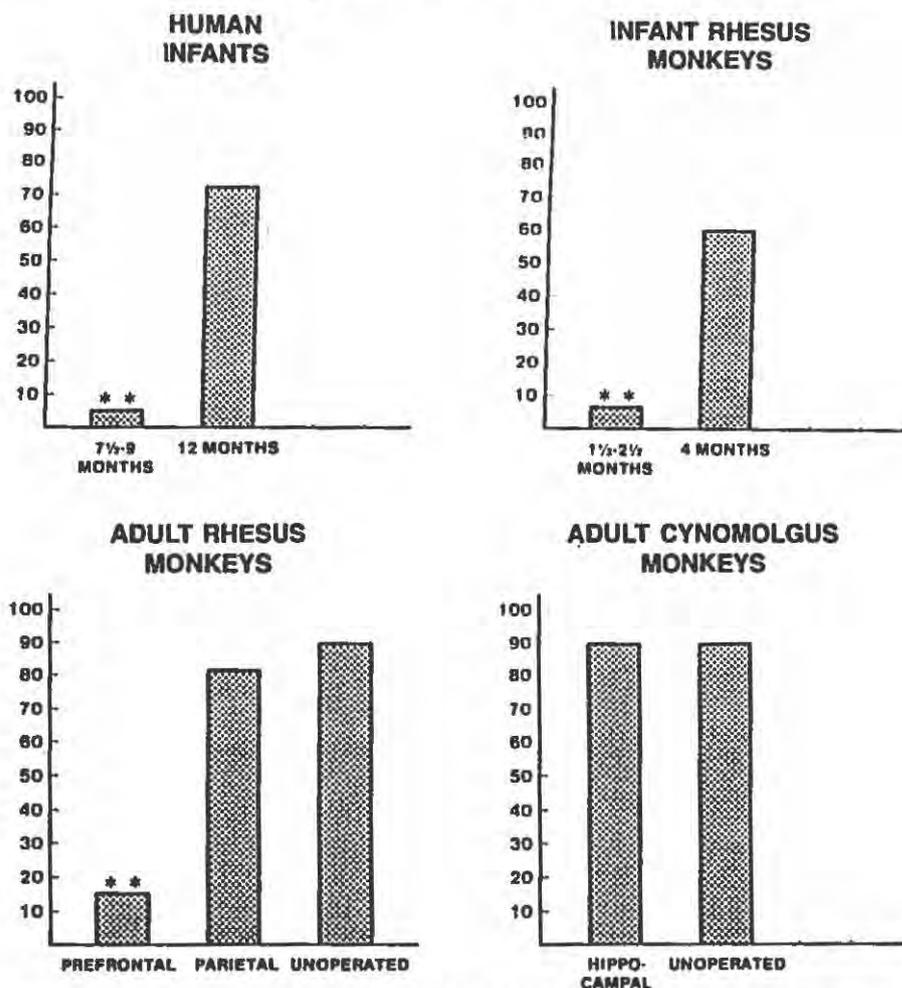


FIGURE 12.8. Percentage of trials in the object retrieval task on which subjects reached to the box opening without having looked in the opening on that trial for human infants, infant monkeys, unoperated adult monkeys, and adult monkeys with lesions of dorsolateral prefrontal cortex, parietal cortex, and the hippocampal formation. **, significantly different from other group(s), $p < .001$. From Diamond (1991a). Copyright 1991 by Lawrence Erlbaum Associates, Inc. Reprinted by permission.

There is as yet no direct evidence on the neural systems involved in mature performance of visual categorization or cross-language tasks. Moreover, there is as yet only preliminary evidence linking A \bar{B} or object retrieval to dorsolateral prefrontal cortex in *human* infants or indicating that *maturational* changes in the prefrontal neural system are related to improved performance on A \bar{B} or object retrieval. The preliminary evi-

dence linking AB and object retrieval to dorsolateral prefrontal cortex comes from Diamond's continuing work with infants and young children with localized damage to the brain as a result of hemorrhage. The results are preliminary because of the small number of such infants meeting the strict localization criteria, but thus far infants with prefrontal cortex damage have shown impaired performance on AB and object retrieval, while infants with parietal cortex damage have not.

The preliminary evidence linking maturational changes in the prefrontal neural system to improved performance on the tasks comes from the laboratories of Fox and Chugani. In a longitudinal study of AB and object retrieval performance, Fox and Bell (1990) found increased frontal EEG activity in individual infants at the time when each infant was improving on the tasks. The relation between increased frontal cortex activity and improved performance was significant for each task. Using 2-deoxy-2-[¹⁸F]fluoro-D-glucose and PET, Chugani, Phelps, and Mazziotta (1987) have been able to measure metabolic rates for glucose uptake in localized regions of the brain in healthy, awake infants at rest, as young as 5 days of age. The more active a neural region, the more glucose it will need to use. Chugani et al. (1987) found that beginning at about 8 months of age, glucose utilization increases specifically in frontal cortex (i.e., activity in frontal cortex appears to increase just before and during the period when infants are improving on the AB, object retrieval, and visual categorization tasks, and beginning to show the more mature pattern of performance in cross-language speech perception).

In addition, it is clear that destruction of dorsolateral prefrontal cortex in monkeys, even infant monkeys, severely disturbs performance on the AB and object retrieval tasks, and that this disturbed performance closely mirrors the performance seen in human and monkey infants who cannot yet succeed at these tasks. Damage to other areas of the brain, such as parietal cortex or the hippocampus, does not produce these patterns of impairments; impairments are seen, but they look quite different from those shown by human infants or infant monkeys on these tasks.

Do These Findings Challenge Our Understanding of the Four Tasks?

Piaget (1936/1952) considered an infant's emerging ability to uncover a hidden object and then succeed on the task as the critical evidence indicating the emergence of intentionality and conscious control of behavior. For when the object is hidden, it cannot be that the infant sees an object and then is pulled to reach for it. Here, the toy cannot be seen at the outset of the action, and in order to obtain the toy the infant must first act on another object (e.g., displace the cloth). As Piaget saw it, this clearly

indicates forethought and planning. In addition, in the A \bar{B} task the infant must choose between two possible hiding locations, further demonstrating that the infant's action is willful and purposeful. The object retrieval task also requires acting in relation to one object (the box) in order to retrieve another (the toy inside of it). Object retrieval, too, appears on the surface to require forethought and planning.

It is not obvious, however, that the visual categorization task, which assesses only preferential looking, involves conscious choice. In the cross-language task, in fact, there is strong reason to believe that the subject's behavior is not under conscious control. Indeed, it is notoriously difficult to gain conscious access to phonetic detail. Even such abilities as noting the similarity among words beginning with the same letter and being able to report the number of individual sounds in a word are often not mastered without reading (or prereading) instruction, and are absent (or greatly diminished) in illiterate adults (Bertelson & deGelder, 1991). Adults can learn to strategically direct their attention to acoustic/phonetic detail in training studies (e.g., Werker & Logan, 1985), but there is little evidence that infants or young children share this flexibility (Werker & Tees, 1983).

Moreover, the pattern of performance shown by infants 10-12 months of age on the non-native speech perception task provides no indication that they are actively choosing to *ignore* an acoustic difference that is readily apparent to them. Instead, their performance indicates that they cannot even *hear* the non-native distinction. On logical grounds, it would seem that their auditory systems must be sensitive to these distinctions at some level, since younger infants hear them quite easily, and adults can hear them if sufficiently sensitive testing procedures are used. Nevertheless, when presented with a non-native contrast in the head turn procedure, infants 10-12 months of age become very agitated. Some completely lose interest in the procedure (only to regain interest when retested with a contrast they can discriminate); others start turning their heads toward the visual reinforcer almost constantly; and still others simply become frustrated and cry. In all cases, however, they initially appear to be trying very hard to figure out when to turn their heads in order to "turn on" the toy animals. Observations of infants' behavior in the head turn cross-language task make it hard to argue that they are intentionally ignoring what, for them, is an obvious distinction.

We are thus left with a quandary. Performance on all four of these tasks seems to require inhibition and processing of relational information, but these abilities seem to be under more conscious control when recruited for the A \bar{B} , object retrieval, and possibly even the visual categorization tasks than they are when utilized in the cross-language task. This raises a number of new questions. Either (1) all of these changes are related, all rely on maturation of prefrontal cortex, and none require con-

scious control; (2) prefrontal cortex serves as a member of multiple systems, at least one of which operates at the unconscious level (as in speech perception), and some of which are amenable to conscious control (as on the other tasks); or (3) the decrease in perceptibility of consonant contrasts from other languages (an ability that is present in younger infants and then diminishes) is an unrelated phenomenon that happens, by chance, to occur at the same time as changes on the other three tasks. There is some evidence that perhaps some maturational changes may occur synchronously throughout the brain—for example, the work of Rakic, Bourgeois, Zecevic, Eckenhoff, and Goldman-Rakic (1986) on changes in synaptic density across diverse neocortical areas, and the work of Marcus, Nolen, Rankin, Stopfer, and Carew (1988) showing a widespread synchronous increase in the number of neurons throughout the central nervous system of *Aplysia* toward the end of its juvenile period. The current data do not allow us to fully disambiguate these possibilities. However, the strength of the association among the A \bar{B} , visual categorization, and cross-language tasks leads us tentatively to reject the third possibility. Infants do not improve uniformly on all cognitive tasks during this period. For example, infants succeed on the visual paired-comparison task (e.g., Fagan, 1990), a reaching version of the visual paired-comparison task similar to delayed nonmatching to sample (Diamond, 1990c, 1992), and conjugately reinforced foot kicking (Rovee-Collier, 1990) at long delays many months earlier than improvement appears on the few tasks that we focus on in this chapter. In terms of the memory requirements of the task, there appears to be no further improvement on the visual paired-comparison task or its reaching version after 9 months of age (Diamond, 1990c, 1992), in contrast to the marked improvement seen on the A \bar{B} , object retrieval, and visual categorization tasks between 9 and 12 months.

The implications arising from the first possibility are perhaps the most radical, both for the traditional understanding of the capacities needed for successful performance on the A \bar{B} and object retrieval tasks and for the traditional understanding of speech perception. It leads us to question the role of intentionality in the A \bar{B} and object retrieval tasks. It also leads us to question whether developmental changes in speech perception represent localized changes within the specialized domain of linguistic skills, or whether these changes may be part and parcel of general cognitive developmental changes.

Perhaps the traditional view of A \bar{B} and other "means-end" tasks, such as object retrieval (with its detour requirement), as quintessentially intentional behavior is wrong? It may be that these tasks can be successfully performed without intentional planning or conscious control. We now know that people can do much more without awareness than had previously been thought. They can keep track of the number of times a

stimulus has appeared (e.g., Hasher & Zacks, 1984). They can learn skills such as mirror reading without any conscious memory of previous practice sessions (e.g., Cohen & Squire, 1980). They can acquire conditioned associations without ever being aware of it and without even consciously having noticed the association (e.g., Daum, Channon, & Canavan, 1989). They can more easily access previously presented words than words not presented earlier on word fragment completion or perceptual identification tests, without any conscious memory that the words were previously presented (e.g., Schacter, 1985, 1990). They can navigate a complicated route while sleepwalking or while their minds are on other things (Abe & Miyako, 1984; Karacan, 1988). (See also Langer's work—e.g., Langer, Blank, & Chanowitz, 1978; Langer & Weinman, 1981.)

Speech perception has often been viewed as requiring special-purpose, modular capabilities (Fodor, 1983; Liberman & Mattingly, 1985). Within a modular approach, age-related changes in the perceptibility of non-native consonant contrasts result from a direct "resetting" of the parameters by which phonetic information is analyzed in the input module (Liberman & Mattingly, 1991; Werker, 1991). The data reviewed in this chapter would suggest, however, that more general cognitive capabilities may underlie age-related changes in discrimination of non-native consonant contrasts. If this is correct, it would suggest either that speech is not analyzed via specialized input modules (at least after 10-12 months of age), or that the outputs from specialized input modules become accessible to more general cognitive processes at this developmental juncture. We think it worth considering that at some point in development the products of a perceptual analysis of phonetic information may become accessible to general cognitive operations, facilitating children's use of that information for other purposes—for example, to map onto real words, to engage in rhyming games, and to map onto the alphabet. The data presented in this chapter raise the possibility that this information may be available for more general-purpose analysis by 9-10 months of age.

Although there have been no attempts as yet to directly link prefrontal cortex functioning to mature performance on the cross-language task, there is considerable evidence that prefrontal cortex is involved in speech processing. Damage to any of several areas within prefrontal cortex can lead to linguistic impairments. Perhaps the area of prefrontal cortex that is best known for its role in language is Broca's area, located within the third (inferior) frontal gyrus, in the ventral portion of frontal cortex in the left hemisphere (Broca, 1861; Lichtheim, 1885; Ojemann & Whitaker, 1978; Kertesz, 1979). However, other areas of prefrontal cortex also appear to play a role in language processing, including dorsolateral prefrontal cortex (Kaczmarek, 1987), the supplementary motor area (Foerster, 1936; Penfield & Roberts, 1959; Goldberg et al., 1981; Jonas,

1987), the anterior cingulate (Posner, Peterson, Fox, & Raichle, 1988), and orbitofrontal cortex (Kaczmarek, 1987).

Prefrontal cortex appears to be important for generating verbal output on the basis of meaning. For example, a person with prefrontal cortex damage (especially in the supplementary motor area) often has no trouble repeating what someone else says, but has great difficulty generating meaningful speech (Luria, 1969; Goldberg et al., 1981; Damasio & Van Hoesen, 1980). Prefrontal cortex (especially the anterior cingulate) is also important for attending to stimuli or detecting targets in semantic tasks, although not in sensory detection tasks, even when no motor output is required (Posner et al., 1988). It may therefore be that prefrontal cortex enhances sensitivity to contrasts that carry meaning in one's own language, and screens out contrasts that carry no meaning.

On the other hand, the possibility also exists, as noted above, that prefrontal cortex may be involved in multiple systems—some of which influence performance of the AB and object retrieval tasks, another the visual categorization task, and still another the cross-language task. In this way, more mature performance on each of these tasks may rely on maturation of prefrontal cortex, but may not necessarily require precisely the same set of underlying skills. Thus consciousness and intentionality may be involved in object retrieval and AB but not in the other tasks, whereas the ability to inhibit prepotent or automatic response tendencies may be involved in all four, as may the ability to process relational information. In the next section, we discuss this possibility by examining some of the multiple connections between prefrontal cortex and other areas of the brain.

Involvement of Prefrontal Connections with Other Areas of the Brain in Successful Performance on These Tasks

Prefrontal Projections to the Superior Colliculus

No area of the brain acts in isolation. Prefrontal cortex makes certain cognitive abilities possible through its role as a member of a network of neural connections. Prefrontal cortex (the dorsolateral portion and premotor cortex) projects to the superior colliculus directly (e.g., Goldman & Nauta, 1976; Kunzle, 1978), as well as indirectly via the substantia nigra (e.g., Rinvik, 1966; Bunney & Aghajanian, 1976; Kunzle, 1978). It may be that the inhibitory modulation of the superior colliculus by prefrontal cortex is important for success on the object retrieval task. Maturation of this projection may underlie improved performance on the object retrieval task during development. The superior colliculus is an early-developing midbrain structure that is especially important in the

processing of visual information, but that receives auditory and tactile input as well. David Ingle (personal communication) has shown that the interruption of inhibition of the colliculus results in animals' trying to go straight through a transparent barrier to a visible reward, rather than detouring around. This appears to be very similar to the deficit on the object retrieval task shown by infants, and by monkeys with lesions to dorsolateral prefrontal cortex.

Best, Weldon, and Stokes (1990) have shown that although lesions of the superior colliculus do not impair *detection* of visual stimuli or attentiveness to *tactile* stimuli, they do make animals relatively less attentive to visual input. It may be that inhibition of the superior colliculus has a similar effect. It may be that in the absence of inhibition to the superior colliculus, the organism is overly attentive to visual input, attending to what is seen and largely ignoring information from other senses if that information conflicts with the information to the eyes. If this is so, it could account for why younger infants fail the object retrieval task, attending as they do only to the sight of the toy, ignoring abundant tactile information that specifies which sides of the box are open or closed. For example, feeling the edge of the opening appears to tell them nothing, as long as they are looking at the toy through a closed side of the box. Tactile information is a better guide on this particular task; a developmental change that made infants less dominated by vision and more attentive to touch would, therefore, be likely to aid performance on the task.

Prefrontal Interconnections with Visual Cortex

Fox and Bell (1990; Bell & Fox, 1992) have conducted a longitudinal study of infants' performance on the A \bar{B} and object retrieval tasks³ and their patterns of brain electrical activity as indicated by EEG recordings. Fox and Bell found that infants who improved the best on A \bar{B} between 6 and 12 months showed an increase in coherence between left-hemisphere recordings over frontal cortex and visual cortex (which is located in the occipital lobe at the back of the brain). Infants who were not able to tolerate increasing delays on A \bar{B} did not show an increase in fronto-occipital coherence. It makes sense that communication between frontal cortex and visual cortex would be very important for success on the A \bar{B} task, as the only source of information a subject has on where the reward is hidden is the visual information provided by watching the hiding. Prefrontal cortex is important for keeping that visual information in mind and in using it to generate the appropriate behavioral response. Communication between prefrontal cortex and visual cortex may well be important for the visual categorization task as well.

Dopaminergic Innervation of Prefrontal Cortex

Much more research is needed for a better understanding of the neural circuits in which prefrontal cortex participates, as well as the ways in which these circuits subserve the various functions in which prefrontal cortex participates. What are the critical elements? How do they work together? How is this function modulated by neurotransmitters? One piece of the puzzle that appears to be emerging is the importance of the dopaminergic innervation of prefrontal cortex even during infancy for the proper functioning of prefrontal cortex. Levels of dopamine appear to be increasing in the brain during the period when performance on the tasks we have been discussing improves (see Goldman-Rakic & Brown, 1982, for developmental increases in dopamine concentrations in the rhesus monkey brain; see Diamond & Goldman-Rakic, 1986, and Diamond, 1990a, 1990b, for developmental improvements in infant rhesus monkeys' performance on the AB and object retrieval tasks).

Evidence of the importance of dopamine for prefrontal cortex cognitive functions was perhaps first demonstrated by Brozoski, Brown, Rosvold, and Goldman (1979). They demonstrated that if prefrontal cortex was selectively depleted of dopamine through administration of 6-hydroxydopamine, rhesus monkeys showed impairments on cognitive tasks requiring prefrontal function as severe as those found after removal of prefrontal cortex. Sawaguchi and Goldman-Rakic (1991) have since demonstrated that local injection of dopamine antagonists into prefrontal cortex impairs the performance of rhesus monkeys in a precise, dose-dependent manner.

Diamond and her colleagues began studying infants and young children treated early and continuously for phenylketonuria (PKU) because of the possibility that these children might have a selective deficit in dopamine metabolism in prefrontal cortex if their phenylalanine (Phe) levels were mildly elevated. The work of Diamond, Ciaramitaro, Donner, Djali, and Robinson (in press) with an animal model has confirmed that there is indeed a decrease in dopamine metabolism in prefrontal cortex when Phe levels are mildly elevated, and the work of Diamond, Hurwitz, Lee, Grover, and Minarcik (1993) has demonstrated that even with early and continuous treatment, infants and young children with PKU have a profound deficit in the cognitive functions dependent on prefrontal cortex if their Phe levels are mildly elevated.

PKU is a disorder in the metabolism of Phe to tyrosine most commonly caused by mutations of the gene in chromosome 12 that codes for phenylalanine hydroxylase (Woo, Lidsky, Güttler, Chandra, & Robson, 1983). Phenylalanine hydroxylase is the essential enzyme for the conversion of Phe to tyrosine. This deficit in the metabolism of Phe results in a

buildup of Phe in the bloodstream and often lower blood levels of tyrosine. If untreated, PKU results in widespread brain damage and severe mental retardation. Treatment consists of restricting the dietary intake of Phe. Phe cannot be removed from the diet altogether, however, because to do so would require removing too much protein from the diet. Thus, children placed on this special diet since shortly after birth (i.e., children "early-treated" for PKU) do not have the grossly elevated Phe levels associated with untreated PKU (≥ 20 mg/dl [≥ 1200 μ mol/liter]), but they do not have normal levels either (the normal level of Phe in the bloodstream is roughly 2 mg/dl). Children with early-treated PKU have phenylalanine levels of 4-10 mg/dl.

Phe and tyrosine compete for the same transporter proteins to cross into the brain (Pardridge, 1977). Therefore, moderate increases in Phe relative to tyrosine in the bloodstream result in moderately less tyrosine reaching the brain. Tyrosine is an essential precursor of dopamine. Most dopaminergic systems in the brain are insensitive to mild changes in the level of tyrosine, but not the prefrontal dopaminergic system, whose neurons fire faster, turn over dopamine faster, and are acutely sensitive to even mild reductions in the level of tyrosine (Thierry et al., 1977; Bannon, Bunney, & Roth, 1981; Chiodo, Bannon, Grace, Roth, & Bunney, 1984; Roth, 1984; Bradberry, Karasic, Deutch, & Roth, 1989; Tam, Elsworth, Bradberry, & Roth, 1991). Dopamine metabolism in prefrontal cortex is profoundly affected by reductions in available tyrosine when dopamine metabolism in most other areas of the brain remains unaffected. This is consistent with Diamond and colleagues' finding of a decrease in dopamine metabolism specifically in prefrontal cortex in animals with mild elevations in Phe.

Infants and children (ages 6 months through 7 years) treated early and continuously for PKU, whose Phe levels are in the range of 6-10 mg/dl (360-600 μ mol/liter), perform poorly across the board on tests of prefrontal function, although they perform normally on control tasks (Diamond et al., 1993).⁴ This is consistent with the marked sensitivity of the cognitive functions subserved by prefrontal cortex to any reduction in dopamine. Diamond et al. further found that the prefrontal deficits are already evident in early infancy. Moreover, even within the narrow range of variation in phenylalanine found in children with early-treated PKU, those infants and children with higher phenylalanine levels (6-10 mg/dl) perform more poorly on prefrontal tests than do children with lower phenylalanine levels.

The role of neurotransmitters in prefrontal function and the role of the other areas of the brain to which prefrontal cortex is interconnected are two of the important questions on which further research is much needed.

NOTES

1. The story is a bit more complicated with respect to cross-language vowel perception. In previous work, Kuhl (1991) has found a "perceptual magnet effect" for the prototypes of speech categories. Both adult and infant subjects are better able to discriminate a peripheral versus central exemplar from within a single vowel category if they are first presented with the peripheral one, and then asked to indicate whether the central ("prototypical") stimulus is different, if the stimuli are presented in the reverse order. In more recent work, Kuhl and colleagues have shown this prototype magnet effect to be language-specific by 6 months of age (Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992). Importantly, this work shows that the internal structure of vocalic categories is influenced by native language experience by 6 months of age, but does not address the question of whether young infants can discriminate *between* two vocalic categories that are not distinguished in the native language.

In ongoing work, Polka and Werker have begun to address the question of whether the reorganization in non-native vowel perception follows the same developmental course as has been shown for consonant perception, and the further question of whether the language-specific influence evident by 6 months of age on the internal structure of vocalic categories is related to subsequent changes in between-category discrimination. This work has confirmed that infants 4 months old can discriminate native and non-native vocalic categories (Werker & Polka, 1993a, 1993b; see also Trehub, 1973). Furthermore, this work has replicated Kuhl et al.'s finding of language-specific influences on within-category vocalic perception by 6 months of age, but also shows that performance on tasks requiring infants to discriminate between vocalic categories does not conform to native language categories until 10-12 months of age (Polka & Werker, 1991, in press; Werker & Polka, 1993a, 1993b). Thus it appears that although there are important language-specific influences on vowel perception by 6 months of age, the full reorganization in the ability to discriminate non-native vocalic contrasts mirrors that seen for consonants, and is not evident until 10-12 months of age.

2. The AB error consists of a pattern of error whereby subjects reach incorrectly when the reward is hidden at a new location, often repeating that error over the next one, two, or three trials at the new location; however, the same subjects reach correctly at the first hiding location and, once they are correct at a new hiding location, continue to reach correctly on succeeding trials until side of hiding again changes. Thus, errors are confined to reversal trials and trials immediately after the reversal, and are not randomly distributed over all trials. A subject who errs on more than one "repeat following correct" trial (where side of hiding is unchanged and the subject was correct on the previous trial) is considered to be lacking the specificity in performance characteristic of the AB error.

3. Unfortunately, Fox and Bell modified the object retrieval task, making it substantially easier for infants and less clearly dependent on prefrontal cortex. They are now in the process of replicating this work using a procedure for object retrieval very close to that used by Diamond in devising the task. Their behavioral results with this latter procedure are now in agreement with Diamond's earlier findings; their EEG results are still being analyzed.

4. The control tasks for infants were spatial discrimination (in which an infant has to deduce that the toy is always hidden on the right or the left on each trial, although the hiding is done out of sight) and a reaching version of the visual paired-comparison task, which has been linked to structures in the medial temporal lobe such as the hippocampal formation (Brickson & Bachevalier, 1984; Bachevalier, 1990; McKee & Squire, 1993). The infant tests of prefrontal function were the AB and object retrieval tasks. For toddlers and young children, a wider variety of tests were used with each child, including several tests requiring prefrontal cortex involvement, control versions of those tasks, and control tasks requiring either parietal cortex involvement (including a test of global-local spatial processing) or medial temporal lobe involvement (such as tests of recognition memory).

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