The Relations between Frontal Brain Electrical Activity and Cognitive Development during Infancy

Martha Ann Bell and Nathan A. Fox
University of Maryland

BELL, MARTHA ANN, and FOX, NATHAN A. The Relations between Frontal Brain Electrical Activity and Cognitive Development during Infancy. CHILD DEVELOPMENT, 1992, 63, 1142–1163. The relations between changes in the scalp-recorded electroencephalogram (EEG) and the development of the ability to perform successfully 2 cognitive tasks attributed to frontal lobe functioning were examined in 13 infants from 7 to 12 months of age. Infants successful in performing the A-not-B task with increasingly longer delays across the second half of the first year of life showed changes in power in scalp-recorded brain electrical activity in the frontal region and an increase in anterior/posterior EEG coherence. Infants with rapid mastery of object retrieval did not differ in frontal EEG development from infants who exhibited the normal developmental progression in object retrieval performance. In a task examining inhibition of reaching to a novel toy, there were no differences in frontal EEG as a function of performance. Results from a cross-sectional sample revealed similar findings. These data confirm work with nonhuman primates on the importance of maturation of frontal cortex in the successful performance on certain tasks (A-not-B), but do not confirm nonhuman primate data on the importance of frontal cortex for other tasks (object retrieval). The data also suggest that the electroencephalogram may be useful as a noninvasive measure of central nervous system development during the first year of life.

There are few instances of known neuroanatomical substrates for human intelligent behavior during the first year of life. However, recent advances in behavioral neuroscience have permitted investigation of the relations between the emergence of object permanence skills and developing areas of the cerebral cortex (Goldman-Rakic, 1987a, 1987b; Goldman-Rakic, Isseroff, Schwartz, & Bugbee, 1983). A number of studies by Diamond and associates (Diamond & Goldman-Rakic, 1983, 1986, 1989; Diamond, Zola-Morgan, & Squire, 1989) have demonstrated that successful performance on a Stage IV object permanence task (the A-not-B task) depended upon maturation or integrity of dorsolateral prefrontal cortex.

Infant rhesus monkeys displayed a change in performance on the A-not-B task with delay across the first 5 months of life which corresponded to the developmental change in performance on the same task in human infants over the second half of the first year of life (Diamond & Goldman-Rakic, 1986). Infant monkeys who received bilateral lesions in dorsolateral prefrontal cortex (Broadmann’s areas 8, 9, and 10) at 4.5 months of age succeeded on the A-not-B task with 12-sec delay before surgery (Diamond & Goldman-Rakic, 1986). However, when testing resumed at 5.5 months and continued until 8 months of age, these infant monkeys were unable to succeed at the A-not-B task at any tested delay (e.g., 2, 5, and 10 sec; Diamond, 1990b; Diamond & Goldman-Rakic, 1986). Adult rhesus and cynomolgus monkeys with lesions in the prefrontal cortex were hampered, when compared to normal or hippocampal lesioned animals, on the A-not-B task with varying delay (Diamond & Goldman-Rakic, 1989; Diamond et al., 1989).

There is evidence, however, that the timing of bilateral lesions to the dorsolateral prefrontal cortex during infancy may affect the monkey’s performance on a similar task—delayed response. The A-not-B and the delayed response tasks differ only in the schedule for determining where the desired

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object is to be hidden. In the delayed response task, the object, or bait, is hidden randomly according to a predetermined pattern. Diamond (Diamond & Doar, 1989) has demonstrated that human infants and infant monkeys (Diamond & Goldman-Rakic, 1986) show a progressive increase in successful performance on the delayed response task similar to that shown for the A-not-B task.

The link between integrity of the dorsolateral prefrontal cortex and success on the delayed response task has been established by many researchers (e.g., Fuster, 1973; Goldman & Rosvold, 1972; Stamm & Rosen, 1969). However, Goldman (1971) has reported that infant monkeys with lesions to the dorsolateral prefrontal cortex did not show deficits on the delayed response task later in infancy. These monkeys did, however, demonstrate impairments on the task as adults. Thus, there is the possibility that other areas of the brain might mediate the infant monkeys' performance on the delayed response task when damage has occurred to the prefrontal cortex at an early age (Goldman, 1971).

Diamond has proposed that the skills essential for solving the A-not-B task include the ability to hold a representation in memory over time (i.e., recall memory) and the ability to inhibit a motor response (Diamond, 1985, 1988, 1990b). Diamond (1990b) has argued that the integration of these two skills (recall memory and inhibitory control) is a primary competency of dorsolateral prefrontal cortex. Tasks that utilize only one of these skills, such as the delayed non-match to sample task that makes use of recall memory but not response inhibition, can be successfully solved by monkeys with lesions of dorsolateral prefrontal cortex (Diamond, 1990b).

There are in the developmental literature many alternate explanations for a human infant's performance on the A-not-B task. Since Piaget's (1954) initial description of the task, researchers have proposed that confusion about the hidden object's identity (Harris, 1983) or egocentric conflicts (Butterworth, Jarrett, & Hicks, 1982) are key determinants of the A-not-B error. Recently, Wellman and colleagues (Wellman, Cross, & Bartsch, 1986) presented a critique of the major alternative explanations for the A-not-B error and proposed instead that there are different search modes that lead the infant to search at A and at B. Specifically, they argued that understanding object movement, not simply having object permanence, is a key to correct search at B during the A-not-B task. Thus, the infant must use an "inferred-location" approach to deduce an object's current location after observing its movements from one location to another over time (Wellman et al., 1986).

To investigate what she believes to be another representational competency associated with the frontal lobes, Diamond developed the object retrieval task (Diamond, 1990a, 1992; Diamond & Goldman-Rakic, 1986). This task was designed to tap the ability to relate information spanned over space, as well as the ability to inhibit motor responses. As with the A-not-B task, it is the integration of these two skills that requires frontal lobe involvement. In the object retrieval task, infants must inhibit reach toward a toy that is placed inside a clear Plexiglas box. According to Diamond, over the second half of the first year of life, infants develop strategies to find the opening to the box, relate the information about the opening to motor movements, and retrieve the toy.

Infant rhesus monkeys showed a developmental progression on object retrieval similar to that seen in human infants (Diamond & Goldman-Rakic, 1986). Adult rhesus monkeys with bilateral lesions of the dorsolateral prefrontal cortex (Brodmann's areas 8, 9, and 10) show impaired performance on object retrieval similar to human infants under 9 months of age (Diamond, 1990a, 1992; Diamond & Goldman-Rakic, 1985). Rhesus monkeys with lesions of parietal cortex or the hippocampus were not impaired on object retrieval performance (Diamond et al., 1989), although parietal lesions produced some misreaching errors. However, these errors were very different from errors made by infant rhesus monkeys and 7.5–9-month-old human infants.

These behavioral neuroscience studies of frontal lobe development have utilized nonhuman primates as subjects. Those studies of cognitive development in human infants (Diamond, 1990a, 1990b) have made inferences from the findings of lesion studies with monkeys regarding the role of dorsolateral frontal cortex. An additional source of evidence of regional maturation of the cortex in human infants may be found through measurement of the scalp-recorded electroencephalogram (EEG). Studies of EEG development have traditionally focused on descriptions of changes in frequency and
power. EEG power may be expressed as voltage squared (amplitude squared) in a particular frequency band.

Longitudinal studies over the first year of life (Hagne, 1968, 1972; Mizuno et al., 1970) have reported changes in both the amount of EEG power and the frequencies at which power is manifested. For example, Hagne (1968) reported that the amount of power between the left parietal and occipital regions decreased between 8 and 10 months of age and then increased between 10 and 12 months. She also noted that power between left central and common vertex steadily increased between 8 and 12 months of age. Similarly, Ohtahara (1981) reported data on a cross-sectional sample of infants over the first year of life in which there was a pattern of increases and decreases in occipital EEG power with a trend toward gradually increasing power values.

The assumption that scalp electrodes necessarily reflect brain activity from specific cortical regions immediately underlying the electrodes is not without problems. Likewise, there are concerns about the degree to which EEG measures reflect cortical versus subcortical brain activity, especially in infants. While issues of precise localization using the EEG remain, it is possible to examine corresponding changes in EEG power and frequency with cognitive performance (see Bell & Fox, in press, for a discussion of these issues). To date, there has been only one study which has examined the correspondence between changes in cognitive development below 12 months of age and the EEG. Hagne (1968, 1972) recorded EEG in 20 infants at 3 weeks, and at 2, 4, 6, 8, 10, and 12 months of age. Hagne administered the Griffiths Scale of Mental Development and reported two sets of correlations between the Griffiths Scale and the EEG. She computed a ratio score of two frequency bands (1.5–3.5 Hz/3.5–7.5 Hz) and found that infants with high Griffiths scores had a lower ratio (more power in the higher frequency band). In addition, infants with a higher peak frequency (i.e., the frequency bin exhibiting the greatest power value) at both 4 and 10 months of age scored higher on the Griffiths Scale at those ages.

Recent advances in understanding the physiological significance of certain parameters of the EEG have demonstrated that EEG may also be useful in reflecting the integrity of anatomical connections in the central nervous system. There are data, for example, which indicate that the coherence of the EEG recorded from electrode sites at different locations reflects the degree to which there are axonal connections between these regions (Nunez, 1981). Coherence (Thatcher, Krause, & Hrybky, 1986; Thatcher, Walker, & Guidice, 1987) has been related to the density of white matter axons and the short and long fiber networks of these axons. The strength and number of these axonal connections are reflected by coherence values. Coherence is defined mathematically as the absolute value of the cross-correlation function in the frequency domain. Values range between 0 and 1, with a value of 1 indicating a complete linear relation between two electrodes sites (Kuks, Vos, & O'Brien, 1988).

Thatcher reported that from birth to age 3 the coherence between pairs of electrode sites showed different patterns of development, with some pairs displaying an increase in coherence and others a decrease in coherence. After age 3, all pairs of leads simultaneously increase or decrease in coherence across age (Thatcher et al., 1987). Thatcher (Thatcher et al., 1986) also reported that the frontal region is strongly coupled to the posterior regions via long distance axonal connections. Thatcher has provided evidence that the periods of change in the magnitude of coherence between electrode sites across the first 12 years of life may correspond to the ages of major cognitive change as defined by Piaget (Thatcher et al., 1987).

One of the competencies of the frontal region, the sequencing of goal-directed behavior such as that involved in means-end tasks like A-not-B and object retrieval, may involve the synchronization of many specialized processes that are regulated by posterior regions (Pribram, 1973). Long distance connections (anterior to posterior) could be critical for successful performance of these complex behaviors. Connections between frontal cortex and the parietal cortex, for example, may be crucial for spatial cognitive competencies associated with the A-not-B and object retrieval tasks. Specifically, the posterior parietal cortex has been implicated in the generation and control of reaching in space (Georgopoulos, 1987; Jeannerod, 1988; Mountcastle, Lynch, Georgopoulos, Sakata, & Acuna, 1975).

Changes in spectral power of the EEG may reflect the mass organization and excitability of particular groups of neurons (Nu-
nez, 1981). Changes in spectral power in the frontal lobes across age could reflect maturation and organization within that brain region. To date, there have been no longitudinal studies of spectral power development of the frontal lobes during infancy. Hagne (1968, 1972) recorded EEG from the frontal region in her longitudinal study but failed to analyze the frontal data. Indeed, longitudinal research on the development of EEG during infancy has traditionally involved posterior scalp locations (e.g., Henry, 1944; Lindsley, 1939; Mizuno et al., 1970; Smith, 1938, 1941), the assumption being that the underdevelopment of the frontal lobes during infancy would yield no important EEG data. However, this assumption has recently been challenged by Chugani and Phelps (1986), who reported an increase in glucose metabolism in the frontal cortex of human infants between 8 and 12 months of age.

The purpose of this study was to examine the relations between regional changes in scalp-recorded brain electrical activity and the development of frontal lobe skills that Diamond proposed are manifested in successful performance of the A-not-B task with delay and the object retrieval task, namely, the integration of the abilities to hold a representation in memory over time and over space and the ability to inhibit a motor response (Diamond, 1990a, 1990b). Also included in the design was a third task that examines response inhibition but not representational memory. As with the delayed non-match to sample task, which utilizes only memory skills (but not response inhibition skills) and can be successfully solved by monkeys with lesions of the frontal cortex (Diamond, 1990b), the response inhibition to novelty task, utilizing response inhibition skills (but not memory skills), should not involve frontal lobe functioning.

The response inhibition to novelty task involved presenting different novel toys to the infants and observing latency to grasp the toy. Rothbart (1988) and Schaffer and Parry (1969) found a developmental change in this task such that infants nearing 12 months of age would inhibit their reach for a novel object. It is likely that wariness to novelty is a factor in the infant’s response inhibition in this novelty task, whereas search for an occluded and desirable object is a factor in the infant’s response inhibition in the A-not-B task. While these differences make comparison between the A-not-B and novelty tasks somewhat problematic, the resulting motoric behaviors from response inhibition in each task are similar. The actual motor behavior of “reaching,” either toward side A or toward the novel toy, is stopped. While it can be argued that the novelty task involves the ability to discriminate a new object from previously seen ones, it does not involve holding that memory trace during a period of delay, nor does it involve recall of the object’s position. Thus, the novelty task is a more elementary task which, nevertheless, shares one component skill with the more complex A-not-B and object retrieval tasks.

For the present study, three predictions were made: (1) There will be differences in frontal EEG development from 7 to 12 months of age between infants who display a greater tolerance of delay during the A-not-B task and infants who are unable to tolerate delay during the A-not-B task. Group differences in EEG will not be evident in the parietal or occipital regions. In addition, infants who display a greater tolerance of delay during the A-not-B task over the 6 months of the study will also display an increase in coherence between long distance, anterior to posterior sites. (2) There will be differences in frontal EEG development from 7 to 12 months of age between infants who display a rapid mastery of the object retrieval task and infants who display on-time mastery of the phases. Group differences in EEG development will not be evident in the parietal or occipital regions. Infants who display rapid mastery of the phases in the object retrieval task should also display an increase in coherence between long distance, anterior to posterior sites. (3) There will be no differences in frontal EEG maturation or in EEG coherence between those infants who display different patterns of development in latency to grasp a novel moving toy.

Method

SUBJECTS

Longitudinal Sample

Fourteen healthy, full-term Caucasian infants (eight girls, six boys) were recruited as the subjects for the longitudinal sample of this study. Infants were born to middle- and upper-middle-class parents (Hollingshead, 1975) and were recruited from a local support group for new mothers. Infants were selected according to the following criteria: born within 2 weeks of their calculated due dates, weighed at least 6 pounds at birth, and required no oxygen after delivery. In addition, none of the infants were diagnosed
as having neurological problems and none had ever sustained a head injury. Ten of the infants were born to two right-handed parents, three to one left-handed parent, and one to an ambidextrous parent, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). Infants were seen in the laboratory monthly from 7 until 12 months of age, for a total of six sessions. Infants were seen within 5 days of their month "birthday." Thirteen infants participated throughout the 6-month time period of the study. One female infant withdrew from the study after two laboratory visits. No data from that subject were included in the analyses.

Cross-sectional Sample

To control for effects of repeated testing, 36 healthy, full-term infants were the subjects for the cross-sectional sample of this study. Infants were recruited via local newspaper advertisements and new-parent mailing lists. There were six infants (three girls, three boys) at each of the six monthly testing ages (7, 8, 9, 10, 11, and 12 months). Infants were born to middle- and upper-middle-class parents (Hollingshead, 1975) and all were Caucasian, with the exception of one African-American male at 7 months of age. All infants were born to two right-handed parents. The criteria for subject selection employed with the cross-sectional sample were identical to the longitudinal sample. As with the longitudinal sample, cross-sectional infants were seen within 5 days of their month "birthday."

Procedures

Electrophysiological Recording

At each laboratory visit, EEG was recorded from six sites: left and right frontal, parietal, and occipital regions (F3, F4, P3, P4, O1, and O2). The electrical potential of each of the six sites was measured to the vertex (Cz) electrode. The EEG was recorded while the infant sat quietly on mother’s lap for a period of 2 min. During the EEG recording a research assistant seated 5 feet away from the infant blew soap bubbles into the air. This procedure quieted the infant and allowed each subject to tolerate the EEG recording.

Each infant’s emotional behavior during the EEG recording was coded from the videotape of the laboratory visit using the Hedonic Tone Scale (Easterbrooks & Emde, 1983). This scale has a four-point positive scale (+1 to +4) and a four-point negative scale (−1 to −4) that includes such behaviors as facial expressions, body movements, and vocalizations. Scored at 30-sec intervals and averaged across the 2 min of the EEG recording to get each infant’s individual score, the range of scores for all infants in the longitudinal and cross-sectional samples was very narrow (from +1.4 to +2.2), indicating that none of the infants displayed overt signs of behavioral distress during the recording. Interrater reliability for the Hedonic Tone Scale was assessed as .85.

EEG was recorded using a stretch lycra cap that contained electrodes in the 10/20 system pattern (Jasper, 1958). After the cap was placed on the infant’s head, a small amount of abrasive (Omni Prep) was placed into each recording site and the scalp was gently abraded with the blunt end of a Q-tip. Following this, a small amount of EEG gel supplied by the cap manufacturer (Electro Cap) was placed in each site. Electrode impedances were measured and were accepted if they were below 6K ohms. The electrical activity from each lead was amplified using separate Grass amplifiers (model 7P11) and were bandpassed from 1 to 100 Hz. Activity for each lead was displayed on separate channels of a Grass model 78 polygraph. The EEG signal was digitized on-line at 512 samples per second for each channel to ensure that the data were not affected by aliasing. The raw data were stored for later analysis. Prior to the recording of each subject, a 10 Hz .477 V rms sine wave was input through each amplifier of the polygraph. The amplifiers were set so that output of that signal represented 50 μV peak to peak, with a gain of 10,000.

The digitized EEG were first scored for eye movement and motor artifact. All pe-

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1 Examination of the data revealed no behavioral or EEG differences between the ten infants born to two right-handed parents and the three other longitudinal children.

2 For a subset of subjects, active sites Fp1 and Fp2 were recorded and their data used to score eye movements. The use of Fp1 and Fp2 to record eye movements has been noted in the EEG literature (e.g., Myslobodsky et al., 1989). We performed pilot work with a number of adult subjects who were asked to perform various eye movements (i.e., blinks, vertical movements, horizontal movements). This allowed us to determine how different EOG contaminants appeared in the EEG at Fp1, Fp2, F3, and F4. From these data it was possible to clearly see the presence
riods of artifact were underscored, and these data for all channels were eliminated from subsequent analyses. For the subjects in this study, an average of 24% of the 2-min EEG recording was rejected because of artifact. The EEG data were then re-referenced via software so that the data could be analyzed using an average reference configuration. This reference is considered optimal when computing coherence between spatially distinct electrodes (Fein, Raz, Brown, & Merrin, 1988; Lehmann, Ozaki, & Pal, 1986). The average reference data were analyzed with a discrete Fourier transform (DFT) using a Hanning window of 1 sec width and 50% overlap. Prior to computation of the DFT, the mean voltage was subtracted from each data point to eliminate any power results due to DC offset. Power in single Hz bands was computed for frequencies between 1 and 18 Hz. The power was expressed as mean square microvolts. Only the average reference data were used in subsequent statistical analyses.

Each session for each subject was analyzed in this manner. Subsequently, spectral power was plotted for each session for each longitudinal subject, and individual patterns were examined. These plots revealed a dominant frequency in all leads at all ages between 6 and 9 Hz. Because power values were positively skewed, subsequent analyses utilized a natural log transformation (ln) of the raw power values in this frequency band.

Measures of coherence for the 6–9 Hz band were computed using an algorithm published by Saltzberg, Burton, Burch, Fletcher, and Michaels (1986). Coherence uses the cross-spectrum of the frequency band from two spatially distinct electrode sites. Coherence for anterior to posterior (F3/P3 and F4/P4, F3/O1 and F4/O2) electrode sites was computed separately for each hemisphere. Following Thatcher (Thatcher et al., 1986), increases in coherence between electrode sites were interpreted as reflecting increased axonal connectivity between two topographically distinct brain regions.

Cognitive Tasks

After electrophysiological recording, the infants were tested on three tasks in the following order: the A-not-B task with delay, the object retrieval task, and response inhibition to novelty. Also included was one affect-eliciting task. Those data are reported elsewhere (Fox & Bell, 1990; Fox, Bell, & Jones, in press).

A-not-B task with delay.—The A-not-B task procedure was modeled after the standard two-location task commonly used in the developmental psychology literature; that is, there were identical covers and backgrounds, the same object was used throughout the task, the two hiding locations were horizontally oriented, and the object was hidden at the same location on all A trials and then hidden at the other location on the B trial (see Wellman et al., 1986). The A-not-B task apparatus was a cardboard box measuring 47.5 (L) × 22.5 (W) × 7.5 cm (D). It contained two wells 9.5 cm in diameter, 7.5 cm deep, and 29 cm apart from center to center. White fabric cloths used to cover the wells measured 20 cm square.

The A-not-B task apparatus was placed on the floor in front of the infant so that the center of the box was at midline and the cloths covering each well were within reach of the infant. The mother sat behind her infant. For the younger infant, the mother was needed to physically support the sitting posture of her infant. For the older infant, the mother was needed to hold the infant’s hands during implementation of the delay procedure. The experimenter was seated on the opposite side of the A-not-B task apparatus facing the infant and parent. A variety of toys, all of which fit in the apparatus wells

of synchronous potentials associated with eye movements and eye blinks in Fp1 and Fp2, as well as F3 and F4. Due to technical problems, Fp1 and Fp2 were recorded only with the last few longitudinal and cross-sectional subject visits. Thus, these leads were not included in subsequent data analysis.

3 The A-not-B task procedure used by Diamond (1985) utilized three hiding sites, while the procedure for this study utilized the standard two-location task described by Wellman and colleagues (Wellman et al., 1986). However, in her study Diamond never covered the third well. Indeed, Diamond reported that reaches to the uncovered well were “particularly rare” (Diamond, 1985, p. 870). Wellman and colleagues (Wellman et al., 1986) reported that number of wells was a main determinant of performance on the A-not-B task. Infants perform better in multilocation paradigms. Unlike Diamond’s method of leaving one well uncovered, however, it is standard practice to cover all of the wells in a multilocation procedure. Therefore, Diamond’s procedure appears to be more similar to the two-location task than the multilocation task.
(e.g., keys, plastic rattles, cloth rattles, etc.), were accessible to the experimenter.

The experimenter signaled the beginning of an A-not-B task trial by holding up a toy to attract the infant's attention. The experimenter then hid the toy in side A by lifting the cloth covering well A, slipping the toy in the well, and replacing the cloth over the well, completely hiding the toy. If the infant's attention was lost during the hiding process, the experimenter regained the attention and hid the toy again.

Successful retrieval was defined as the displacement of the cloth covering the hidden toy and recovery of that toy. After two successful retrievals at A, the object was then hidden in the opposite well B, with either a 0-sec or a timed delay before the infant was allowed to search for the toy. The use of delay during the A-not-B task was necessary in order to observe the A-not-B error in older infants.

Fox, Kagan, and Weiskopf (1979) reported that visual fixation to the well increased correct performance even after a delay period. Thus, a distractor was employed during the delay, similar to that used by Diamond (1985). Under delay conditions for this study, the mother was asked to hold the infant's hands while the experimenter snapped her fingers, smiled at the infant, and counted to divert the infant's gaze from the well. The use of distraction during the delay sets this work and that of Diamond apart from most A-not-B task research. The delay was timed by an observer with a stopwatch. After the delay period, the infant's hands were released and the infant was permitted to search. Each infant was required to successfully retrieve the toy from the B well in two out of three AAB trials to be declared competent at a given delay. The same toy was used throughout all three hidings (side A, side A, side B) of one A-not-B task trial. Toy changes only occurred between trials. If an infant's interest in a particular toy waned during the middle of an A-not-B trial, a new toy was chosen and the trial repeated.

Each infant was required to succeed at both left-to-right and right-to-left trials to rule out preferentially directed reaching. Therefore, after successfully retrieving a toy at side B in one AAB trial, the infant also had to correctly uncover well A in one BBa trial. If the infant could recover the toy in trial AAB, but could not recover the toy in trial BBa, trial BBa was repeated. Therefore, in order to show competence on two out of three A-not-B task trials, the infant had to succeed at both AAB and BBa. Initial side of hiding was randomized across infants.

Infants who successfully recovered the toy in two out of three trials with 0-sec delay at side B were then tested with a 2-sec delay at side B. Subsequent delays were initiated until the infant made the A-not-B error (or, at higher delays, displayed random performance) on two out of three trials at any given delay. Delays were incremented in 2-sec intervals throughout the study. For the infants in the longitudinal sample, the highest successful delay period in a given session was repeated at the next session 1 month later. Thus, if an infant successfully recovered a toy following a 4-sec delay at one session, but failed at 6 sec, the following session 1 month later began with the 4-sec delay.

For the cross-sectional sample, the experimenter began the 7–9-month-old infants with a 0-sec delay. The 10-month-old infants began with a 2-sec delay and the 11- and 12-month-old infants with a 4-sec delay. This strategy allowed the experimenter to determine the delay time needed by an older infant to make the A-not-B error without the infant losing interest in the task.

Object retrieval.—This task involved retrieval of an object from a clear Plexiglas box (Diamond, 1992). The apparatus measured $15 \times 15 \times 5$ cm and was constructed so that it had no bottom and one missing side. The infant had to determine the location of the missing side and retrieve the “hidden” toy from the box.

For task presentation, the infant was seated in a high chair with the clear Plexiglas box on the high chair tray.\(^4\) The parent
was seated in a chair beside and slightly behind the infant. The experimenter kneeled in front of the infant. A number of attractive toys were accessible to the experimenter. Toys were changed when the infant's interest in a particular toy appeared to wane. The box was centered on the high chair tray at the infant's midline and was approximately 12 cm from the infant, within easy reach. Within these bounds, the infant could vary proximity to the box by leaning forward to look at the toy through the Plexiglas or leaning back against the high chair. The infant could also push or pull the box to change its proximity. However, the infant was not allowed to pick up the box. Both experimenter and mother offered encouragement to the infant. The infant was allowed to take as long as needed to retrieve the toy.

The experimenter began each trial by holding up a toy to attract the infant's attention. The infant was first presented the box "upside-down" on the high chair tray so that the box had an open top side. This allowed the very young infants success on initial attempts to retrieve a toy. Infants were then presented the box with an opening on the front side. The experimenter placed a toy inside the clear box without showing the infant the opening to the box. Throughout the trial the experimenter kept the box in place on the high chair tray by holding the upper back corners of the box.

If an infant was unsuccessful in an attempt to touch the toy through the front opening, the experimenter provided clues as to the location of the opening by pulling the toy out of the box through the front opening or tilting the box by exerting downward pressure on the back corners of the box. The box had to be flat on the tray before the infant was permitted to retrieve the toy. The infant had to recover the toy in two out of three trials to successfully fulfill the criteria for a particular placement of the box.

When an infant was successful in retrieving the toy with the opening in front, the box was then placed so that the opening was on the infant's left or right. Again, a toy was placed in the box in a manner that did not allow the infant to determine the location of the open side.

If an infant could not determine the side opening location, the experimenter gave a clue to the infant by trailing the toy in and out of the opening and/or by sliding the box off and on the toy. The infant was considered successful at retrieval only if the toy was completely inside the box when retrieved. An infant was considered competent at left-side (or right-side) opening if the object was retrieved on two out of three trials.

Strategies used by the infant to retrieve the toy determined an individual infant's developmental level in the object retrieval task. Interrater agreement for phase assignment on the object retrieval task was assessed as 92%. According to Diamond (1992), a Phase 1 infant (6 or 7 months of age) reached exclusively on direct line of sight. Thus, the infant succeeded in retrieving the toy from the opening if line of sight is through the opening and if this line of sight can be maintained throughout the reach. A Phase 1 infant did not search for the opening to the box, but persistently hit and scratched the closed side through which the toy is seen, thus acting only on one side of the box. Success at retrieval with the box directly in front of the infant was achieved in the front-open trials only if the infant could utilize line of sight into the front opening.

The Phase 1B infant took active steps to change the side through which the toy was seen by shifting body position or moving the box but still reached exclusively on direct line of sight. The infant in Phase 1B acted on both the top and the front of the box during a single trial. As with the Phase 1 infant, the Phase 1B infant was not successful at side opening trials because of the inability to locate the side openings.

A Phase 2 infant needed to bend and look at the toy through the front opening before sitting up and retrieving the toy while looking through the closed top of the box.
An infant in this phase also began to look for side openings, but still reached exclusively on direct line of sight. A Phase 2 infant retrieved the toy from side openings by manipulating the box so that the opening could be seen, leaning sideways, and retrieving the toy from the side opening with the "awkward" hand (e.g., using the right hand to get the toy from the left side opening). Diamond (1992) reported that an infant in this phase must be able to continuously see the toy being retrieved. This "awkward" position allowed reaching into the side openings while maintaining direct line of sight.

A Phase 3 infant did not need to look at the toy through the front opening to retrieve it. For the side openings, the infant leaned over and looked in the open side, straightened up, and then used the same-side hand to retrieve the toy (e.g., the left hand for the left side opening). The infant no longer needed to look at the toy while retrieving it from the box. The initial look at the opening preceded successful retrieval.

The infant at the highest developmental level, Phase 4, determined the location of the opening by feeling all sides of the box and then inserting the hand in the open side to grab the toy from the box. This infant retrieved the object without viewing it through the opening.

Response inhibition to novelty.—The infant, seated in the high chair, was first presented with a novel plastic toy and allowed to play with the toy for 30 sec. This toy was then removed and the infant was presented with a moving novel toy. This procedure was modeled after Schaffer and Parry (1969) and Rothbart (1988). Toy selection was made randomly from a pool of five novel, stationary, plastic toys and five moving toys.

After gaining the infant’s attention, the experimenter placed the toy on the high chair tray at the infant’s midline and near the back edge of the tray, approximately 26 cm from the infant. Thus, the infant had to purposefully reach to grasp the toy. Latency to grasp the toy was timed. The assistant began timing with a stopwatch when the experimenter placed the toy on the high chair tray and stopped timing when the infant’s fingers curved around the toy in a grasp. Batting at the toy, touching the toy with the palm with the fingers stiff, and touching the toy with one finger were not coded as grasps.

The novel, moving toy trial was 15 sec in length. The infant received no encourage-

ment from the experimenter, who looked at the toy with a blank face. The mother was instructed to remain silent during the trial. If the infant did not grasp the toy within 15 sec, the experimenter touched the toy and talked with the infant about the toy. If an infant became distressed by the moving novel toy and began to cry, the experimenter immediately removed the toy from the high chair tray and the child received a latency to grasp score of 15 sec.

Results

A 2 (sample: longitudinal vs. cross-sectional) × 6 (age) ANOVA was computed for each of the three cognitive tasks to determine the effects of repeated testing on the longitudinal sample. Results of the ANOVA computed on the A-not-B task data revealed no main effect for sample and no sample × age interaction (all F's ≤ .80, p’s ≥ .55). As expected, there was a main effect for age, F(5,99) = 9.44, p ≤ .001, with the delay tolerated in seconds increasing with age. Likewise for the object retrieval task data, results of the ANOVA revealed no main effect for sample and no sample × age interaction (all F's ≤ .83, p’s ≥ .36). There was a main effect for age, F(5,99) = 41.81, p ≤ .001, with the assigned phase level increasing with age.

For the response inhibition task, there were no main effects for sample or for age (all F’s ≤ .73, p’s ≥ .60). However, there was a sample × age interaction, F(5,98) = 3.03, p = .01. Inspection of the means at each age using one-way ANOVAs revealed that at 10 months the two samples differed in latency to grasp the moving novel toy. The longitudinal subjects had a longer latency to grasp (M = 10.5 sec) than did the cross-sectional subjects (M = 4.3 sec), F(1,17) = 7.52, p = .01. However, there were no differences between the two samples at any other age (all other F's ≤ 3.44, p’s ≥ .08). There were no differences in any of the EEG power and coherence measures between the longitudinal and cross-sectional samples (all F’s ≤ 2.13, p’s ≥ .16).

Three of the longitudinal subjects did not complete one of the six scheduled laboratory visits. Two subjects were unable to attend the 8-month assessment, and the other subject was unable to attend the 9-month testing. To avoid having these three subjects dropped from all the multivariate analyses utilizing the EEG data because of their missing data, EEG power and coherence values for the missed session for each
of the three infants were interpolated from data collected at the two sessions adjacent to the missed session. The interpolation procedure was chosen, as opposed to substituting the mean EEG power of all subjects at the age of the missing data, because the interpolation procedure yielded a substituted value that more closely resembles the individual infant’s EEG power values.

Data from one cross-sectional subject at 10 months (a boy) were excluded from all analyses due to technical problems that occurred during the electrophysiological recording.

A-not-B Task Performance

Longitudinal Sample

Table 1 presents the data for the 13 subjects in the longitudinal sample for the successful performance of the A-not-B task at each age. As can be seen, there was a clear change across age in the mean delay tolerated without making the A-not-B error. Examination of A-not-B task data revealed a positive relation between delay tolerated and age (r = +.54, p = .001). The mean delay tolerated at 8 months was 1.1 sec, while the mean delay tolerated at 12 months was 7.5 sec.

These data are comparable to those reported by Diamond (1985), although the format for their presentation is different. Diamond reported the average delay in seconds needed for the infants to commit the A-not-B error, while the data for this study are reported as the highest delay tolerated without making the A-not-B error. In general, infants successful in retrieving the toy from side B during a 2-, 4-, 6-, 8-, or 10-sec delay, and who were unsuccessful at an incremented 2-sec delay, committed the A-not-B error. However, those infants who were capable of successfully retrieving the toy from side B at rather long delays of 12 or 14 sec by 12 months of age sometimes showed random performance or failure to search at the incremented 2-sec delay.

Although in this study there were clear changes across age in mean performance on the A-not-B task, there was wide variability in individual infant performance across age. Cluster analysis (K-means) was used to group the infants into two A-not-B task performance groups based on their pattern of performance across the 6 months of the study. As shown in Table 1, one A-not-B task performance group (n = 6, three girls and three boys) tolerated a 13-sec delay at 12 months of age. The other group (n = 7, four

<table>
<thead>
<tr>
<th>TABLE 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MEAN A-NOT-B DELAY Tolerated by Performance Group at Each Age</strong></td>
</tr>
<tr>
<td><strong>Age</strong></td>
</tr>
<tr>
<td>Longitudinal sample</td>
</tr>
<tr>
<td>(n = 13):</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
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<td>11</td>
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<td>12</td>
</tr>
</tbody>
</table>

*Note.*—In order to maintain the continuous-variable nature of the A-not-B task performance data, failure to perform the A-not-B task at 0-sec delay was coded as −1.

*Longitudinal: n = 6 for long delay and n = 7 for short delay.*

*Cross-sectional: n = 14 for long delay and n = 21 for short delay.*
girls and three boys) tolerated about a 3-sec delay at 12 months. A repeated-measures MANOVA, with A-not-B task performance at each age as the within-subjects factor and A-not-B group assignment as the between-subjects factor, was used to confirm that this grouping method produced two A-not-B task performance groups that indeed differed on A-not-B task performance. MANOVA results revealed a main effect for group, $F(1,11) = 15.29, p = .002$, a main effect for age, multivariate $F(5,7) = 53.35, p < .001$, and a group $\times$ age interaction, multivariate $F(5,7) = 26.60, p < .001$. Examination of the group means at each age showed that the two A-not-B task groups differed on object permanence performance at 10, 11, and 12 months (all $t's \geq 3.05, p's \leq .01$).

**Cross-sectional Sample**

Table 1 also presents the data for the 35 subjects in the cross-sectional sample for the successful performance of the A-not-B task at each age. As with the longitudinal sample, there was a clear change across age in the mean delay tolerated without making the A-not-B error. Examination of A-not-B task data revealed a positive relation between delay tolerated and age, $r = +.58, p = .001$. The mean delay tolerated at 8 months was 1.3 sec, while the mean delay tolerated at 12 months was 4.7 sec.

Within each cross-sectional age group, there was variation in the delay tolerated. For example, at 10 months of age two infants were successfully performing the A-not-B task with 12-sec delay, while the other four were successfully performing at 4-sec delay. As with the longitudinal analyses, infants were divided into two groups. Infants tolerating the higher delays at each age ($n = 14$, five girls and nine boys) were contrasted with those unable to tolerate the high delays at each age ($n = 21$, 13 girls and eight boys), as seen in Table 1. A two-way ANOVA (group $\times$ age) was used to determine if this grouping method produced two A-not-B task performance groups that were indeed different on A-not-B task performance. ANOVA results revealed a main effect for group, $F(1,24) = 59.92, p < .001$, and a main effect for age, $F(5,24) = 15.49, p < .001$, for A-not-B task performance. There was also a group $\times$ age interaction for A-not-B task performance, $F(5,24) = 3.32, p = .02$. Simple effects testing revealed that the two A-not-B task groups differed on object permanence performance at 8, 9, 10, 11, and 12 months (all $t's \geq 2.67, p's \leq .05$).

**EEG and A-not-B Task Performance**

**Longitudinal Sample**

The prediction was that there would be differences in frontal EEG development from 7 to 12 months of age between the infants in the longitudinal sample who displayed a greater tolerance of delay during the A-not-B task and the infants in the longitudinal sample who displayed little tolerance of delay during the A-not-B task. We predicted that these group differences in frontal EEG would be manifested as changes in spectral power, leading to gradually increasing power values across age, for the long delay group. Further, we predicted that group differences in EEG development would not be evident in the parietal or occipital regions.

This prediction was tested with repeated-measures MANOVA performed on the EEG (ln 6–9 Hz) power values separately for each region. Hemisphere (left/right) and age (7, 8, 9, 10, 11, 12 months) were the within-subjects factors. A-not-B task performance group, determined by cluster analysis, was the between-subjects factor.

As previously noted, EEG power values were correlated across age. The repeated-measures MANOVA procedure was chosen to analyze the EEG data because it does not require the sphericity assumption of the univariate repeated-measures approach. Current psychophysiological literature suggests use of the multivariate approach in analyzing repeated-measures data (Cohen, 1987; Fridlund, 1987; Vasey & Thayer, 1987).

For the long delay group, 22.4% of the baseline EEG data was rejected due to artifact. For the short delay group, 24.6% of the data was rejected. There were no significant differences in the amount of rejected EEG data between the two groups.

**Frontal EEG activity.**—Results of a repeated-measures MANOVA on the frontal EEG power revealed a group $\times$ hemisphere $\times$ age interaction for frontal EEG, multivariate $F(5,7) = 4.89, p = .03$. The group tolerating long delays at 12 months exhibited changes in frontal EEG development not apparent in the group tolerating short delays at 12 months. Examination of the means showed that the long delay group displayed a decrease in right frontal EEG power between 7 and 8 months of age, $t(5) = 2.65, p = .05$. This group also displayed the greatest monthly increase in frontal EEG power be-
between 9 and 10 months of age (see Fig. 1, top). This trend was apparent in both hemispheres, F3: $t(5) = -1.63, p = .16$; F4: $t(5) = -1.74, p = .14$. The group tolerating short delays at 12 months only showed a change in right frontal power between 10 and 11 months of age, $t(6) = -2.41, p = .05$ (see Fig. 1, bottom). There were no other interactions and no main effects for frontal EEG activity (all $F's \leq 2.13$, $p's \geq .17$).

Parietal EEG activity.—There were no main effects for group or age or hemisphere, nor were there any interactions, for parietal [In 6–9 Hz] power (all $F's \leq 1.12$, $p's \geq .24$).

Occipital EEG activity.—Due to technical problems with the electrophysiological recording at the onset of longitudinal data collection, there were complete occipital EEG data on 9 of the 13 longitudinal subjects. Of the four infants without complete occipital data, three were in the A-not-B task performance group tolerating long delays. The following analyses are reported with the caution that group membership was three for the long delay group and six for the short delay group.

Results of the repeated-measures MANOVA revealed a group × hemisphere interaction for occipital [In 6–9 Hz] power, $F(1,7) = 8.92, p = .02$. The A-not-B task performance group tolerating long delays had greater power in the left occipital lead (O1) relative to the right occipital lead (O2) across the 6 months of the study. There were no other interactions, and there were no main effects for group, hemisphere, or age (all $F's \leq 3.02$, $p's \geq .20$).

Coherence.—The prediction was that infants who display an increasing tolerance of delay during the A-not-B task over the 6
months of the study will also display an increase in 6–9 Hz coherence between long distance, anterior to posterior sites. As with the results from the occipital EEG power analyses, the following coherence analyses are reported with the caution that group membership was three for the long delay group and six for the short delay group.

The coherence prediction was tested with a repeated-measures MANOVA examining coherence values separately for each hemisphere. The within-subjects factors were length (frontal/parietal vs. frontal/occipital) and age (7, 8, 9, 10, 11, 12 months). A-not-B task performance group, determined by previous cluster analysis, was the between-subjects factor.

The repeated-measures MANOVA for the left hemisphere coherence values revealed a group × age interaction, multivariate $F(5,3) = 9.76, p = .05$. When averaging across frontal/parietal and frontal/occipital data, follow-up analyses revealed that the A-not-B task performance group tolerating long delays showed an increase in coherence from 10 to 12 months of age, $t(2) = -6.40, p = .02$, after an initial decrease in coherence between 8 and 9 months, $t(2) = 6.31, p = .02$ (see Fig. 2). Coherence values between 9 and 10 months of age did not change. Values for the group tolerating short delays showed a trend toward an increase in coherence between 11 and 12 months of age, $t(5) = -2.00, p = .10$. There were no other changes in coherence for the short delay group (all $t's \leq 1.47, p’s \geq .20$).

Results of a repeated-measures MANOVA for the left hemisphere coherence values also revealed a length × age interaction, multivariate $F(5,3) = 12.24, p = .03$, where the F3/P3 connection displayed a U-shaped function in coherence across age, while the F3/O1 connection remained stable (see Fig. 2). There was also a main effect for length, $F(1,7) = 78.67, p \leq .001$, and a main effect for age, multivariate $F(5,3) = 23.25, p = .01$, that denoted the U-shaped function manifested by the F3/P3 connection.

Results of a repeated-measures MANOVA for right hemisphere coherence revealed a main effect for length, $F(1,7) = 73.52, p < .001$. As in the left hemisphere, the F4/O2 connection had greater coherence across age than did the F4/P4 connection. There were no other main effects and no interactions (all $F’s \leq 3.36, p’s \geq .17$).

Additional research questions.—(1) Were there changes in EEG spectral power for infants between the ages at which they could not successfully solve the A-not-B task and the age at which they could?

Results of pairwise $t$ tests for each frontal and parietal EEG lead (comparing EEG at the age prior to success on the A-not-B task and EEG at the age where the A-not-B task was solved) revealed no differences in EEG spectral power in any of the frontal or parietal leads between the time the infants could not solve the A-not-B task and the time they could (all $t’s \leq .39, p’s \geq .70$).

(2) Were there differences in EEG spectral power depending upon the age at which the A-not-B task was first passed with 0-sec delay?

Infants in the longitudinal sample were placed in one category if they solved the A-not-B task with 0-sec delay “early” at 7 or 8 months of age ($n = 8$, four girls and four boys), or in a second category ($n = 5$, three girls and two boys) if they solved the A-not-B task with 0-sec delay “late” at 9 months of age. Differences in EEG spectral power between infants who solved the A-not-B task “early” versus “late” were analyzed using 8-month EEG values in order to compare the EEG of infants who can already solve the A-not-B task with infants who are not yet able to do so. MANOVAs were calculated separately for frontal and parietal EEG. Hemisphere was the within-subjects factor and early/late group was the grouping variable. Results from the frontal EEG analysis revealed a group × hemisphere interaction, $F(1,11) = 5.87, p = .03$. Post hoc analyses revealed that the infants who passed the A-not-B task “early” had greater power at 8 months in the right frontal lead compared to the left frontal, $t(7) = -2.33, p = .05$. There was no main effect for group, $F(1,11) = 2.07, p = .18$. Results for the parietal EEG data revealed no main effects for group or hemisphere and no group × hemisphere interaction (all $F’s \leq 3.09, p’s \geq .15$).

Cross-sectional Sample

The cross-sectional EEG power and coherence data were analyzed similarly to the longitudinal, except that age and A-not-B task performance group, based on performance split within each age group, were both between-subjects factors. There was no within-subjects factor. The dependent variable for the two-way ANOVA design was (In 6–9 Hz) power.

The EEG activity for the cross-sectional sample was analyzed separately for each lead. Analyzing the EEG leads by region, as
was done in the longitudinal sample, would have yielded a 2 (group) × 2 (hemisphere) × 6 (age) design of 24 cells, unsuitable for a sample size of 35. Because multiple two-way ANOVAs were employed, the acceptable significance level was adjusted to .01.

Frontal EEG activity.—Results of two-way ANOVAs (group × age) performed separately for each frontal lead showed a trend toward main effects for group for each lead: F3—left frontal, $F(1,23) = 6.381, p = .019$; F4—right frontal, $F(1,17) = 6.322, p = .022$. Due to technical problems during the physiological recordings, there were no right frontal (F4) EEG data for six infants in the cross-sectional sample. The cross-sectional group tolerating higher delays on the A-not-B task at each age showed a trend toward greater (ln 6–9 Hz) power at each age. There was neither an age main effect nor a group × age interaction for frontal EEG activity (all $F$'s ≤ 1.85, $p \geq .14$).

Parietal EEG activity.—Results of two-way ANOVAs performed separately on each parietal lead showed a main effect for group for the left parietal (P3) EEG lead, $F(1,23) = 8.66, p = .007$. The cross-sectional group tolerating higher delays on the A-not-B task at each age had greater (ln 6–9 Hz) power. There were no other effects or interactions for the parietal EEG (all $F$'s ≤ 4.32, $p \geq .05$).

Occipital EEG activity.—Results of two-way ANOVAs performed separately on each occipital lead showed no main effects for group or age and no group × age interaction for occipital EEG (all $F$'s ≤ 3.64, $p \geq .07$).

Coherence.—Separate two-way ANOVAs were conducted for each intrahemispheric connection for the cross-sectional sample (e.g., F3/P3, F3/O1, F4/P4, F4/O2). Results showed a group × age interaction for the right hemisphere F4/P4 connection, $F(5,17) = 6.38, p = .002$. Post hoc analyses showed that the A-not-B task performance group tolerating long delays had greater F4/P4 coherence at 8 months than the A-not-B task performance group tolerating short delays: long
TABLE 2
MEAN OBJECT RETRIEVAL PHASE LEVEL BY PERFORMANCE GROUP AT EACH AGE

<table>
<thead>
<tr>
<th>Age</th>
<th>Total Sample</th>
<th>Early Group</th>
<th>On-Time Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Longitudinal sample (n = 13): a</td>
<td>1.15</td>
<td>1.20</td>
</tr>
<tr>
<td>7</td>
<td>1.62</td>
<td>2.10</td>
<td>1.31</td>
</tr>
<tr>
<td>8</td>
<td>2.73</td>
<td>3.80</td>
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<td>9</td>
<td>3.12</td>
<td>4.00</td>
<td>2.56</td>
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<td>10</td>
<td>3.31</td>
<td>4.00</td>
<td>2.88</td>
</tr>
<tr>
<td>11</td>
<td>3.92</td>
<td>4.00</td>
<td>3.88</td>
</tr>
<tr>
<td>Cross-sectional sample (n = 35): b</td>
<td>1.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>3.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note.—The values represent the highest phase level attained.

a Longitudinal: n = 5 for early and n = 8 for on-time Phase 4.
b Cross-sectional: Infants were not grouped because of lack of within-age variability in performance.

delay $M = .37$, short delay $M = .14$; $t(4) = 4.09, p = .02$. However, the opposite effect was found at 11 months of age. The A-not-B task performance group tolerating short delays had greater F4/P4 coherence at 11 months than the A-not-B task performance group tolerating long delays: long delay $M = .16$, short delay $M = .40$; $t(3) = -3.34, p = .04$. There were no main effects for group or age and no group $\times$ age interactions for any of the other coherence values (all $F$'s $\leq 1.85, p \geq .14$).

OBJECT RETRIEVAL PERFORMANCE

Longitudinal Sample

Table 2 presents the data for infant performance on the object retrieval task. Infants performing at Phase 1 received a score of 1 for the task, infants at Phase 1B received a score of 1.5, at Phase 2 a score of 2, etc. Infant performance improved across the 6-month period, with all but one infant in the longitudinal sample performing at Phase 4 by 12 months of age. Each infant in the longitudinal sample progressed through the phases in sequence, although some infants skipped either Phase 2 or Phase 3. Diamond (1992) tested infants twice a month, while the infants for this study were tested once a month. It could be that more frequent testing is necessary to observe performance at each phase of development.

Changes in infant retrieval strategy paralleled performance on the A-not-B task such that as infants were able to tolerate longer delay, they were also able to retrieve the object with more efficient strategies, $r = .55, p = .001$.

As with the A-not-B task data, there were individual differences in object retrieval performance among the 13 infants in the longitudinal sample. Cluster analysis (K-means) was used to group the infants into two object retrieval performance groups based on the pattern of performance across the 6 months of the study (see Table 2). The results of the cluster analysis showed that one group of infants reached Phase 4 level of performance at the expected age, around 11 or 12 months ($n = 8$, four girls and four boys). However, the other group began performing at Phase 4 at a very early age, between 9 and 10 months ($n = 5$, three girls and two boys).

Although there was a positive correlation between the length of delay tolerated on the A-not-B task and the phase reached on object retrieval, membership in the two object retrieval performance groups was not related to membership in the two A-not-B performance groups (Fisher's exact probability test = .59, two-tailed test; see Table 3).

Cross-sectional Sample

Table 2 also presents the data for the 35 subjects for the object retrieval task. There was a change across age in the mean performance of the 35 subjects. As with the longitudinal sample, changes in infant retrieval strategy paralleled performance on the A-not-B task such that the infants who were

TABLE 3
COMPARISON OF LONGITUDINAL SAMPLE A-not-B TASK PERFORMANCE GROUPS AND OBJECT RETRIEVAL PERFORMANCE GROUPS

<table>
<thead>
<tr>
<th>A-not-B Task Performance Group</th>
<th>Object Retrieval Group</th>
<th>Early</th>
<th>On-Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long delay</td>
<td></td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Short delay</td>
<td></td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

Note.—Fisher's exact = .59 (two-tailed test).
able to tolerate longer delay were also able to retrieve the object with more efficient strategies, \( r = +.54, p = .001 \).

Within each cross-sectional age group there was little variation in the phase level attained. For example, at 10 months of age all infants were performing at Phase 3 and at 12 months of age five infants were performing at Phase 4 and one infant at Phase 3.

**EEG AND OBJECT RETRIEVAL PERFORMANCE**

**Longitudinal Sample**

The prediction was that there would be differences in frontal EEG development from 7 to 12 months of age between the infants in the longitudinal sample who displayed a rapid mastery of the phases in the object retrieval task and those infants in the longitudinal sample who displayed on-time mastery of the phases. We predicted that these group differences in frontal EEG would be manifested as changes in spectral power, leading to gradually increasing power values across age, for the long delay group. Further, we predicted that group differences in EEG development would not be evident in the parietal or occipital regions.

These predictions were tested with repeated-measures MANOVA performed on the EEG (ln 6–9 Hz) power values separately for each region. Hemisphere (left/right) and age (7, 8, 9, 10, 11, 12 months) were the within-subjects factors. Object retrieval performance group, determined by cluster analysis, was the between-subjects factor.

Results of repeated-measures MANOVA analyses revealed no main effects and no interactions for frontal EEG power (all \( F's \leq 1.34, p's \geq .35 \)), parietal EEG power (all \( F's \leq 1.27, p's \geq .37 \)), occipital EEG power (all \( F's \leq 3.86, p's \geq .15 \)), or coherence (all \( F's \leq .74, p's \geq .64 \)).

**Cross-sectional Sample**

Because of little variation within each age group in object retrieval performance, the cross-sectional sample was not divided into two object retrieval performance groups for EEG analyses.

**RESPONSE INHIBITION TO NOVELTY**

**Longitudinal Sample**

Subject performance on the novel toy task did not result in clear longitudinal changes in inhibition. Rather, across age, infants exhibited inhibition to moving novel toys (see Table 4). Again, there was wide variation in latency to grasp the novel toy at each age.

Cluster analysis (K-means) was used to group the infants in the longitudinal sample into two performance groups based on the pattern of latency to grasp the novel moving toy from 7 to 12 months of age. Results of the cluster analysis revealed two distinct patterns in response inhibition (see Table 4).

### Table 4

**Mean Response Inhibition to Novelty Latency to Grasp by Performance Group at Each Age**

<table>
<thead>
<tr>
<th>Age</th>
<th>Total Sample</th>
<th>Long Latency Group</th>
<th>Short Latency Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>7.02</td>
<td>6.74</td>
<td>7.20</td>
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<td>8</td>
<td>9.89</td>
<td>11.28</td>
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<td>13.36</td>
<td>8.69</td>
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<td>9.68</td>
</tr>
<tr>
<td>12</td>
<td>7.22</td>
<td>13.68</td>
<td>3.19</td>
</tr>
<tr>
<td>Cross-sectional sample ((n = 35):^b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>11.65</td>
<td>15.00</td>
<td>4.94</td>
</tr>
<tr>
<td>8</td>
<td>11.64</td>
<td>14.73</td>
<td>5.45</td>
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<tr>
<td>9</td>
<td>10.93</td>
<td>14.26</td>
<td>4.29</td>
</tr>
<tr>
<td>10</td>
<td>4.30</td>
<td>7.44</td>
<td>2.81</td>
</tr>
<tr>
<td>11</td>
<td>5.35</td>
<td>14.59</td>
<td>3.50</td>
</tr>
<tr>
<td>12</td>
<td>10.56</td>
<td>13.49</td>
<td>4.72</td>
</tr>
</tbody>
</table>

**Note.**—Values represent the latency in seconds. Maximum = 15.

^a Longitudinal: \( n = 5 \) for long latency and \( n = 8 \) for short.

^b Cross-sectional: \( n = 19 \) for long latency and \( n = 16 \) for short.
4). One group of infants (n = 5, three girls and two boys) increased their latency to grasp across the 6 months of the study from a mean latency to grasp of 6.7 sec at 7 months to a latency of 13.7 sec at 12 months. The other group of infants (n = 8, four girls and four boys) decreased their latency to grasp from 7.2 sec at 7 months to 3.2 sec at 12 months. Membership in the two response inhibition performance groups was not related to membership in the two A-not-B task performance groups (Fisher’s exact probability test = .27, two-tailed test) or the two object retrieval performance groups (Fisher’s exact probability test = .56, two-tailed test).

CROSS-SECTIONAL SAMPLE

Unlike the longitudinal sample, there were across-age changes in response inhibition to the novel moving toy that resulted in a U-shaped data curve for the cross-sectional sample of infants (see Table 4). However, within each age group there was great variation in latency to grasp.

Infants in the cross-sectional sample were divided into two groups, as noted in Table 4. Infants exhibiting the higher latencies to grasp the novel toy at each age (n = 19, 10 girls and nine boys) were contrasted with those exhibiting lower latencies (n = 16, eight girls and eight boys). A two-way ANOVA (group × age) was used to determine if this grouping method produced two response inhibition performance groups that were indeed different on latency to grasp a novel toy. ANOVA results revealed a main effect for group, $F(1,23) = 150.79$, $p < .001$, and a main effect for age, $F(5,23) = 3.86$, $p = .01$, for latency to grasp. There was no group × age interaction. For infants in the cross-sectional sample, membership in the two response inhibition performance groups was not related to membership in the two A-not-B task performance groups (chi-square = .07, $p > .79$).

EEG AND RESPONSE INHIBITION PERFORMANCE

LONGITUDINAL SAMPLE

The prediction was that there would be no differences in frontal EEG development between infants who displayed different patterns of development in latency to grasp a novel moving toy. Results of repeated-measures MANOVA analyses, with group as the between-subjects factor and hemisphere and age as the repeated factors, revealed no main effects or interactions for frontal EEG power (all $F$’s ≤ .97, $p ≥ .34$), parietal EEG power (all $F$’s ≤ 2.11, $p$’s ≥ .18), occipital EEG power (all $F$’s ≤ .76, $p$’s ≥ .51), or coherence (all $F$’s ≤ 1.85, $p$’s ≥ .33) for the longitudinal sample.

CROSS-SECTIONAL SAMPLE

As with the analyses for A-not-B task performance, the EEG activity for the longitudinal sample was analyzed separately for each lead. Because multiple two-way ANOVAs were employed, the acceptable significance level was adjusted to .01.

Results of the two-way ANOVAs showed no main effects for group or age and no group × age interaction for frontal, parietal, or occipital EEG activity or for coherence for the cross-sectional sample (all $F$’s ≤ 1.92, $p$’s ≥ .13).

DISCUSSION

The data presented in this paper indicate that there is a relation between frontal brain electrical activity and performance on the A-not-B task with delay. Infants who, from 7 to 12 months of age, exhibited an increasing ability to tolerate delay on the A-not-B task also displayed changes in frontal EEG power. Infants unable to tolerate long delays on the A-not-B task showed little change in frontal EEG power from 7 to 12 months of age. In addition, the age at which the two groups of infants first differed on A-not-B task performance (10 months) was the age at which the group tolerating longer delays showed a trend toward the greatest monthly increase in frontal EEG power. It was also at this age that the group tolerating longer delays on the A-not-B task began to display an increase in anterior to posterior coherence.

Nunez (1981) has proposed that spectral power of the EEG reflects the mass organization and excitability of particular groups of neurons. Thus, the changes in spectral power found in the EEG of infants tolerating long delays in the A-not-B task may reflect increased organization and excitability in the frontal region. Results from two other longitudinal studies with infants have shown that changes in spectral power in the 6–9 Hz range in other brain regions are related to cognitive ability or motor milestones. Hagne (1968) found that spectral power in the 3.5–9.5 Hz frequency range in the central, temporal, parietal, and occipital regions was associated with better performance on the Griffiths Scale (Hagne, 1972). Mizuno (Mizuno et al., 1970) reported that
spectral power in the 7.17–10.30 frequency band in the occipital region was correlated with motor milestones (holding up head, sitting, standing, walking).

In this study, the A-not-B task performance group tolerating long delays displayed greater power in the left occipital lead relative to the right occipital lead across age. This group difference was not predicted and is in need of replication. The long delay group also showed an increase in left hemisphere coherence between 10 and 12 months of age. There were no group effects for right hemisphere coherence. For the long delay group in this study, left hemisphere maturation may be occurring at a more rapid rate, as evidenced by greater power in the left occipital lead and increasing left hemisphere coherence between anterior and posterior sites.

Results from the cross-sectional sample confirmed the longitudinal findings by showing group differences in EEG for the A-not-B task performance groups. Infants within each cross-sectional age group who could tolerate the longer delays at the A-not-B task revealed a tendency toward greater EEG power in the frontal region compared to infants in the short delay group. In contrast to the longitudinal sample, where there were no group differences in parietal EEG power, infants in the cross-sectional sample who tolerated long delays evidenced greater power in the left parietal region than did the short delay infants.

The two object retrieval performance groups showed no differences in frontal EEG power or in coherence. Likewise, membership in the two object retrieval performance groups was not related to membership in the two A-not-B performance groups. However, there remains the possibility of a task by task interaction in the data. For example, it may be that infants who tolerated greater delays on the A-not-B task by 12 months of age and who reached Phase 4 on object retrieval at an early age display frontal EEG development that is different from those infants who were unable to tolerate high delays on A-not-B and who attained Phase 4 object retrieval at the expected age. The small number of subjects in the current study does not allow inspection of this possibility.

Diamond has noted that tasks most sensitive to dorsolateral prefrontal cortex function are ones that require both representational memory over time and space and inhibitory control (Diamond, 1990a). It is possible that the A-not-B task and object retrieval tap the integration of different skills. While each task involves the ability to inhibit a motor response, the object retrieval task may not involve the type of representational component attributed to it by Diamond (1985, 1988, 1990b). In the A-not-B task, the hiding and retrieval of a toy are separated in time by an imposed delay. The infant must ignore the distraction during the delay to successfully search. The infant must also ignore the mother's attempts to restrain the child's reach toward the correct well. For some infants in this study, these distractions overwhelm the infant's ability to relate information over time and remember the location of the toy in well B.

During object retrieval, the distraction in retrieving the toy is the clear Plexiglas box itself. However, the infant still has the toy in full view while seeking the opening of the box. The infant has less opportunity to become distracted by other diversions because the nature of the task calls for continuous search for the opening through which the toy might be obtained. It does appear that the different phases of object retrieval performance are defined by the development of visually guided reaching. Once that reaching skill is mastered, the infants are able to perform object retrieval without first seeing the object through an opening (Phase 4).

De Schonen and Bresson (1984) independently reported the same "phases" of reaching behavior during a transparent barrier task as Diamond reported concerning the object retrieval task. More importantly, de Schonen and Bresson (1984) proposed that difficulties in obtaining an object around a transparent barrier do not stem from problems with memory or the inability
to relate spatial information. Rather, they concluded that difficulties in reaching for a toy within a transparent box are related to the inability to "program" a reaching gesture with a detour on the basis of available spatial references. While one cannot ignore Diamond's data on the performance of frontal lesioned monkeys on the object retrieval task, there was no correlation between object retrieval performance and frontal EEG in the current study. It is, of course, possible that the lack of relation is due to differences in task administration (see footnote 3). Future research that involves exact replication of task demands may shed further light on the current pattern of data.

Both the object retrieval task and the A-not-B task with delay require the infant to sequence a number of complex actions. Object retrieval requires the infant to find the opening of the clear box and maneuver the hand around the clear barrier toward the toy. The A-not-B task requires the infant to remove the cloth and reach for the toy in the well. However, only the A-not-B task with delay requires a memory component. It may be the memory skill that accounts for the wide range of A-not-B task performance found in the longitudinal sample. Examination of the developmental progression of the object retrieval task showed a narrow range of individual differences in performance. By 12 months of age, all but one of the longitudinal infants were at the highest level of performance (Phase 4). On the other hand, performance on the A-not-B task showed great variability in performance for the longitudinal sample. For these infants, the range of performance even at 12 months was from 0-sec delay to 14-sec delay. It is also worthy to note that the relations between frontal EEG and A-not-B task performance did not concern differences in EEG between the ages before and after the task could first be solved with no delay. Rather, the relation between frontal EEG and task performance concerned differences between subjects who could or could not tolerate greater time delays.

EEG from the frontal region correlated with the ability to tolerate delay on the A-not-B task, not with the ability to succeed on the A-not-B task initially at 0-sec delay. During the delay period, the infant must, in effect, "ignore" the distraction in order to successfully use memory to inhibit reaching for A and to retrieve the toy at B. The EEG from the scalp recordings over the frontal region may indeed be sensitive to the integration of three skills: memory over a delay, response inhibition, and the ability to ignore distraction during the delay. Diamond has discussed only recall memory and response inhibition as possible abilities integrated by the dorsolateral prefrontal cortex (Diamond, 1988, 1990b). It is possible, however, with regard to the A-not-B task that maturation of dorsolateral frontal cortex underlies the integration of these three skills for successful performance.

It is also possible that infants are utilizing a type of memory, other than recall memory, in successful performance of the A-not-B task. Goldman-Rakic (1987a) has demonstrated that the dorsolateral prefrontal cortex is specialized for the encoding of specific locations for brief time periods. Memory for spatial information or location may be crucial for successful A-not-B task performance. The anatomical connections between prefrontal cortex and parietal cortex are numerous (Schwartz & Goldman-Rakic, 1984). Data from this study corroborate the importance of these connections. Infants who tolerated greater delays on the A-not-B task at 12 months of age displayed a pattern of increasing coherence between frontal and parietal EEG leads between 10 and 12 months of age.

The two longitudinal response inhibition to novelty groups showed no differences in any of the EEG power or coherence measures. Indeed, no differences in frontal EEG development were expected because this task tapped response inhibition, but was not a frontal lobe task. While the longitudinal sample showed no developmental changes in latency to grasp, the cross-sectional sample did display a U-shaped curve in latency to grasp.

The electrophysiological and behavioral data presented here provide new information on the maturation of frontal brain electrical activity during the first year of life. They suggest that there is meaningful scalp-recorded brain electrical activity (EEG) recorded over the frontal region. These data also indicate that there are differences in frontal EEG that are associated with variation in performance on a well-known cognitive task during infancy, Piaget's A-not-B task. They corroborate the nonhuman primate data that have implicated maturation of the dorsolateral frontal cortex in successful performance on this specific task (Diamond & Goldman-Rakic, 1983, 1986, 1989; Diamond et al., 1989). However, they do not cor-
robaborate the nonhuman primate data that have implicated this same area of the cortex as essential for successful performance on the object retrieval task (Diamond, 1992; Diamond & Goldman-Rakic, 1985; Diamond et al., 1989). Thus, as evidenced by these data on the A-not-B and object retrieval tasks, there appears to be a relation in human infants between frontal region changes in scalp-recorded brain electrical activity and the ability to tolerate greater delay on the A-not-B task.

References

Bell, M. A., & Fox, N. A. (in press). Brain development over the first year of life: Relations between EEG frequency and coherence and cognitive and affective behaviors. In G. Dawson & K. Fischer (Eds.), Human behavior and the developing brain. New York: Guilford.


Schwartz, M. L., & Goldman-Rakic, P. S. (1984). Callosal and intrahemispheric connectivity of the prefrontal association cortex in rhesus...


