

RESEARCH ARTICLES

Brain Electrical Activity Associated With Cognitive Processing During a Looking Version of the A-Not-B Task

Martha Ann Bell

*Department of Psychology
Virginia Polytechnic Institute and State University*

This work was designed to investigate individual differences in brain electrical activity during a looking version of the A-not-B task. It was proposed that this spatial task required the cognitive skills of working memory and inhibitory control, each associated with frontal lobe function. Electroencephalograms (EEGs) were recorded from 54 8-month-old infants during baseline and task. Only high performers on the looking task exhibited increases in 6- to 9-Hz EEG power from baseline to task. These task-related changes were evident at frontal and posterior scalp locations. High performers on the looking task exhibited lower EEG coherence values at right hemisphere frontal locations relative to the low performers. These lower coherence values were evident during baseline and task. All infants showed increased frontal–parietal coherence during the spatial working memory task relative to baseline values. These data confirm previous cognitive neuroscience work associating frontal lobe function with cognitive performance levels during infancy.

Recently there has been increasing focus on the development of the prefrontal cortex processes of working memory and inhibitory control during early and later childhood (e.g., Casey et al., 1995; Diamond, Prevor, Callender, & Druin, 1997; Luciana & Nelson, 1998; Nelson et al., 2000; Roberts & Pennington, 1996; Thomas et al., 1999). Nevertheless, neuroscience studies have shown that the frontal cortex

is active and maturing during infancy (e.g., Bell & Fox, 1992, 1996; Chugani, 1994; Chugani & Phelps, 1986; Goldman-Rakic, 1987; Huttenlocher, 1979, 1990). As such, the rudiments of these higher order cognitive processes of working memory and inhibitory control may be manifested during infancy and may be among the many skills involved in successful performance on the classic A-not-B reaching task (Diamond, 1990a, 1990b, 1991). The purpose of this study was to examine brain electrical activity associated with performance on a looking version of this classic infant task. The goal was to determine if changes in electroencephalogram (EEG) activity were evident from baseline to task and if individual differences in task performance were associated with differences in task-related EEG. It was assumed that the EEGs collected from the 8-month-old infants in this study were measuring part of the cortical activity associated with some cognitive processes involved in the A-not-B task.

The behavioral neuroscience work accomplished by Diamond and colleagues (Diamond & Goldman-Rakic, 1989; Diamond, Zola-Morgan, & Squire, 1989) provided the initial evidence that the maturation or integrity of the dorsolateral prefrontal cortex is involved at some level in successful performance of Piaget's A-not-B reaching task. In her work with human infants, Diamond has emphasized maturation and integrity of this brain area (Diamond, 1990a, 1990b, 1991; Diamond et al., 1997) as well as the wide range of individual differences among infants in A-not-B performance (Diamond, 1985). Likewise, Nelson (1995) agreed that the dorsolateral prefrontal cortex probably is involved with the memory requirement of the classic A-not-B reaching task. Citing evidence from behavioral neuroscience, neuroimaging, and morphological studies, he noted that this cortical area is likely mature enough by the last half of the first year of life to support memory functions. However, Nelson noted that the other skills required for successful performance probably rely on the coordination of dorsolateral and orbital prefrontal areas, the mediodorsal nucleus, and the anterodorsal caudate nucleus. Others (Haith & Benson, 1998; Johnson, 1998) also noted that the dorsolateral prefrontal cortex likely is involved in A-not-B reaching performance. Johnson (1998), however, questioned Diamond's emphasis on brain maturation in light of recent findings regarding infant success on looking tasks utilizing working memory and inhibitory skills at ages younger than infants are able to succeed on the A-not-B reaching task (e.g., Gilmore & Johnson, 1995). Haith and Benson (1998) questioned Diamond's emphasis on brain maturation and apparent neglect of experience for successful task performance (e.g., Munakata, McClelland, Johnson, & Siegler, 1997).

Nevertheless, there is electrophysiological evidence for some brain maturation influence on A-not-B reaching task performance. Using baseline EEG as a marker of brain development in a longitudinal study, Bell and Fox (1992) reported that changes in frontal EEG power values from 7 to 12 months of age were associated with changes in A-not-B reaching performance during that same age period. EEG power reflects the excitability of groups of neurons (Nunez, 1981). In the infant

EEG literature, increasing power values across age are considered a marker of brain maturation (see Bell, 1998; Bell & Fox, 1994, for reviews). In the Bell and Fox study, infants tolerating long delays between hiding of the object and actual search by 12 months of age showed changes across age from 7 to 12 months in frontal EEG power. Infants tolerating only short delays by 12 months of age did not. Also, infants tolerating longer delays by 12 months of age exhibited greater left occipital EEG power relative to right occipital power across the entire 6 months of the study. Thus, successful reaching performance in this longitudinal study was associated with age-related changes in frontal EEG power and consistent hemisphere asymmetry for occipital EEG power.

In a study with age held constant, Bell and Fox (1997) reported that individual differences in baseline frontal EEG among 8-month-old infants were related to differences in performance on the A-not-B reaching task. Specifically, higher levels of performance on an A-not-B reaching scale were associated with greater EEG power values at the frontal scalp locations. Higher performance was also associated with frontal asymmetry, as infants in the high-performance group exhibited greater right frontal EEG power values relative to their left frontal power values. As in their longitudinal study, Bell and Fox reported occipital EEG differences between performance groups, with higher levels of performance associated with greater occipital EEG power values. Thus, it appears that at least in baseline EEG recordings, frontal as well as occipital power values are associated with A-not-B reaching performance.

Although the neuropsychological perspective has been used to explain performance on the classic A-not-B reaching task, it may also be useful for explaining task performance under other response modalities. Recently, Bell and Adams (1999) argued that the cognitive skills essential for reaching performance on the A-not-B task (i.e., working memory and inhibitory control) are also essential for looking performance on the task. Using a within-subjects research design, Bell and Adams demonstrated comparable performance on reaching and looking A-not-B tasks among two different groups of 8-month-old infants. This finding supported the report of comparable reaching and looking A-not-B performance in a longitudinal study by Matthews, Ellis, and Nelson (1996). Neuropsychological evidence for frontal lobe involvement in the looking version of the A-not-B task could come from task-related EEG recordings.

Previous work by Bell and Fox (1992, 1997) associating individual differences in frontal EEG power values with performance on A-not-B object permanence scales utilized EEG recordings accomplished during baseline. The gross motor movements required by the classic reaching version of the A-not-B task negate the use of task-related EEG recordings. Typical adult protocols do not require gross motor movements during cognitive processing, however. Thus, in the adult psychophysiological literature EEG is recorded while research participants are engaged in cognitive problems (e.g., Crawford & Vasilescu, 1995; Davidson, Chapman, Chapman, & Henriques, 1990; Roberts & Bell, 2000; West & Bell, 1997),

and comparisons are made between baseline and task EEG. Change in the amount of electrical activity at a specific scalp location is considered indicative of the cortical areas involved in task performance. A looking version of the A-not-B task would allow task-related EEG recordings with infants, with EEG power values providing valuable information concerning frontal involvement in the looking version of the task.

Thus, the goal of this study was to determine if changes in EEG were evident from baseline to A-not-B looking task and if individual differences in task performance were associated with these changes. From Diamond's (1990a, 1990b, 1991) neuropsychological point of view, these changes should be evident only in the frontal scalp locations and, given Bell and Fox's (1997) baseline data, may be specific to the right hemisphere. However, given the EEG data reported by Bell and Fox (1992, 1997) and Nelson's (1995) admonitions that other brain areas subserved additional skills associated with A-not-B performance, the hypothesis was that there would likely be baseline to task EEG changes at other scalp locations as well, perhaps occipital. Wilson, O Scalaidhe, and Goldman-Rakic (1993) highlighted the interconnections of the occipital and frontal lobes in nonhuman primates. Ungerleider, Courtney, and Haxby (1998) reported frontal and occipital activation (as well as parietal) during spatial working memory tasks. Both regions of the cortex have areas utilized for object identity and object location.

Furthermore, I hypothesized that EEG power changes from baseline to task would be associated with individual differences in looking task performance. Thus, infants who perform at a high level on the task should show this task-related change, whereas infants who perform at a low level on the task should not show this task-related change. High and low performance is reflected in a brain that responds differently to baseline conditions and to the cognitive demands of the looking task.

The direction of these changes in EEG power values raises some intriguing possibilities. In the adult literature, cognitive processing is associated with decreases in EEG power at the alpha frequency band (8–13 Hz; e.g., Davidson et al., 1990) but increases in EEG power at the theta frequency band (4–7 Hz; e.g., Klimesch, Doppelmayr, Schimke, & Ripper, 1997). Infants have a noticeable peak in EEG power at 6 to 9 Hz (Bell, 1998), so this frequency band has been of interest in many recent developmental studies (e.g., Bell & Fox, 1992, 1996, 1997; Dawson et al., 1999; Schmidt, Fox, Schulkin, & Gold, 1999). This infant frequency band straddles the two adult bands, making it difficult to predict the direction of change with cognitive processing. However, because infants have more EEG power at the lower end of this frequency band (around 6–7 Hz) than at the upper end, I hypothesized that the direction of change would mimic the adult theta band and exhibit increases in EEG power between baseline and task.

It may be that EEG coherence values can provide even more important data concerning the functioning of the frontal lobe during cognitive processing. Coherence is the frequency-dependent squared cross-correlation between two scalp elec-

trode sites that reflects the degree of phase synchrony between them (Nunez, 1981; Thatcher, Krause, & Hrybyk, 1986). Coherence values range from 0 to 1, may be related to the strength and number of synaptic connections (Thatcher, 1994), and may reflect the level of connectivity between two EEG recording sites. Greater connectivity, however, does not indicate greater maturity. During early development high coherence values may indicate that two distant cortical regions are intricately linked and working together. With maturation there may be increased regional differentiation and a decrease in coherence. EEG coherence values cycle from high to low throughout infancy and childhood (Thatcher, 1994). EEG coherence, unlike EEG power, is not affected by arousal, opening or closing of the eyes, or state changes because coherence varies with the connectivity of two particular brain regions and not with arousal (Thatcher, 1994). Coherence may be a more informative measure of developing brain function than traditional power measures, which may be affected by arousal (Bell, 1998). Bell and Fox (1992) reported that the long-delay infants in their longitudinal study exhibited age-related changes in frontal–parietal and frontal–occipital coherence. The short-delay infants exhibited no changes in EEG coherence during the 6 months of the study.

Concerning EEG coherence values, I hypothesized that infants who perform at a high level on the task should show task-related changes in EEG coherence, whereas infants who perform at a low level on the task should not show this change. From a neuropsychological point of view, this should be evident only among the frontal scalp electrode pairs, but given the longitudinal data of Bell and Fox (1992), these task-related coherence changes may also occur between frontal–occipital electrode pairs.

Direction of change in EEG coherence values may be easier to predict than direction of change in the EEG power values. Lower coherence values are associated with a more efficient pattern of interconnectivity between cortical areas (Bell & Fox, 1996; Thatcher, 1994). Enhanced performance may be associated with lower coherence values during the task relative to baseline.

Thus, this work was designed to investigate individual differences in the brain electrical activity of 8-month-old infants during a looking version of the A-not-B task. I proposed that this oculomotor task required the cognitive skills of working memory and inhibitory control, each associated with frontal lobe functioning. Of major interest in this investigation was the relative change in EEG power and coherence values from baseline to cognitive task.

METHOD

Participants

Sixty-two healthy 8-month-old infants (33 boys, 29 girls; 53 White, 5 Black, 3 Asian, 1 Hispanic) were participants in this study and were recruited from birth an-

nouncements placed in the local newspaper. Infants were born to right-handed parents, each of whom had at least a high school diploma (highest level of education for mothers: 18% high school diploma, 68% bachelor's degree, 14% graduate degree; highest level of education for fathers: 27% high school diploma, 52% bachelor's degree, 21% graduate degree). All infants were born within 3 weeks of their calculated due dates and were healthy at the time of testing. Infants were seen when they were between 8.0 and 8.5 months of age, so that only 2 weeks separated the oldest and youngest infants in the study. All infants were given a small toy for their participation in the study. One additional infant was recruited for this study but cried and would not allow EEG electrode placement and would not perform the looking task.

Procedures

Immediately prior to the looking A-not-B task, EEG electrodes were applied and 1 min of baseline EEG was recorded. The electrodes remained on the infant's scalp during the looking A-not-B task so that task-related EEG could be recorded.

EEG recording. EEG recordings were accomplished during baseline and during the looking version of the A-not-B task. Recordings were made from 10 left and right scalp sites: frontal pole (Fp1, Fp2), medial frontal (F3, F4), lateral frontal (F7, F8), parietal (P3, P4), and occipital (O1, O2). All electrode sites were referenced to Cz. The baseline EEG was recorded for 1 min while the infant sat on the mother's lap. During the baseline recording, a research assistant manipulated a toy containing brightly colored balls on top of the testing table, 1.1 m in front of the infant. This procedure quieted the infant and yielded minimal eye movements and gross motor movements, allowing the infant to tolerate the EEG cap for the recording. Mothers were instructed not to talk to infants during the EEG recording. Immediately after baseline, the recording of EEG continued as the looking task was administered.

EEG was recorded using a stretch cap (Electro-Cap) with electrodes in the 10/20 system pattern (Jasper, 1958). After the cap was placed on the infant's head, recommended procedures regarding EEG data collection with infants were followed (Pivik et al., 1993). Specifically, a small amount of abrasive was placed into each recording site and the scalp gently rubbed. Following this, conductive gel provided by the cap manufacturer was placed in each site. Electrode impedances were measured and accepted if they were below 5K ohms. Electrooculogram (EOG), digitized along with the EEG channels and used for subsequent artifact editing, was recorded using Beckman miniature electrodes. Electrodes were placed on the external canthus and the supra orbit of the right eye.

The electrical activity from each lead was amplified using separate SA Instrumentation Bioamps and bandpassed from 1 to 100 Hz. Activity for each lead was displayed on the monitor of a 100-MHz acquisition computer. The EEG signal was

digitized online at 512 samples per second for each channel so that the data were not affected by aliasing. The raw data were stored for later analyses.

The EEG data were examined and analyzed using software developed by James Long Company. First, the data were rereferenced via software to an average reference configuration and then artifact scored for eye movements using a peak-to-peak criterion of 100 μV or greater. Artifact associated with gross motor movements over 200 μV peak-to-peak was also scored. These artifact-scored epochs were eliminated from all subsequent analyses. The data then were analyzed with a discrete Fourier transform (DFT) using a Hanning window of 1-sec width and 50% overlap. Power was computed for the 6- to 9-Hz frequency band. Infants 8 months of age have a dominant frequency between 6 and 9 Hz (Bell, 1998). The power was expressed as mean square microvolts and the data transformed using the natural log (\ln) to normalize the distribution.

Eight of the participants had incomplete EEG data (6 due to excessive gross motor artifact, either during baseline or task or both, and 2 due to EEG equipment failure), leaving complete behavioral data and EEG (baseline and task) data for 54 participants. All analyses were completed only on the 54 infants with complete EEG data.

Looking version of the A-not-B task. In this looking version of the classic A-not-B task, the infant searched for the hidden toy with eyes rather than hands. The testing apparatus was a table measuring 90 cm (L) \times 60 cm (W) \times 75 cm (H), and the hiding sites were bright orange and blue plastic tubs that measured 17 cm in diameter and 11 cm deep. The infant sat on the parent's lap 1.1 m from the edge of the testing table as the experimenter manipulated a mechanical toy and hid it under one (at midline) or two (17.5 cm on either side of midline) of the bright orange and blue plastic tubs.

The looking procedure is detailed in Bell and Adams (1999). Briefly, after the toy was hidden, the infant's gaze to the hiding site was broken and brought to midline by the experimenter calling the infant's name and asking, "Where's the toy?" The direction of the infant's first eye movement after being brought to midline was scored as either correct or incorrect. A video camera was placed behind and above the experimenter's head and focused to maintain a close-up view of the infant's face.

The following scale (Bell & Adams, 1999) was used to assess performance:

1. Object partially covered with one tub.
2. Object completely covered with one tub.
3. Object hidden under one of two identical tubs.
4. A-not-B with 0 delay.
5. A-not-B with 2-sec delay.
6. A-not-B with 4-sec delay.

Each infant was required to successfully make an eye movement toward the correct tub in two of three trials to be declared competent at scale Items 1 through

3. Because infants were not allowed to manipulate the toys, the visual experience they received from the moving, mechanical toy and the smiles and praise (e.g., “Good job! You found it!”) they received from the experimenter after an eye movement to the correct tub had to provide the impetus to continue to search for the toy. For an eye movement to the incorrect tub, the infants received a sigh and sad vocalizations (e.g., “Oh, no. It’s over here”) from the experimenter. For scale Items 4 through 6, two successful eye movements toward Side A resulted in the toy being hidden under the opposite Tub B. Infants who successfully made an eye movement toward the toy in two of three reversal trials at B (i.e., did not make the A-not-B error) were then tested with a 2-sec delay. Subsequent delays were initiated until the infant made the A-not-B error on two of three trials at any given delay. Delay was incremented in 2-sec intervals throughout the study. Under delay conditions, the experimenter clapped hands and counted out the delay period to keep the infant’s gaze from the well. It was unnecessary for the mother to restrain the infant because no infant leaned toward the tubs. After the delay period the experimenter asked, “Where’s the toy?” and the infant was permitted to search (i.e., make an eye movement toward a well).

An event marker was used in conjunction with the EEG recording so that it was possible to mark which portions of the EEG record were associated with the most cognitively demanding sections of the looking task. For this study, the task-related EEG used in data analyses included that associated with the simultaneous use of the cognitive skills of working memory and inhibition. The task-related EEG started with the covering of the hiding site(s) with the orange and blue tubs, continued through the distraction and delay periods, and stopped when the experimenter lifted a tub prior to giving the infant appropriate verbal feedback. EEG data not included in the analyses were those recorded when the experimenter was manipulating the toy prior to hiding it and those recorded when the experimenter was giving appropriate feedback to the infant after the infant’s eye movement to one of the hiding sites. The artifact-free EEG data from all trials, correct and incorrect, were used in the analyses.¹

Looking task performance. The data for performance on the object permanence scale are presented in Figure 1.² As can be seen, the distribution of these data

¹Analysis of these EEG data revealed no power or coherence differences between correct and incorrect trials.

²These infants were also assessed on the classic reaching version of the A-not-B task; that within-subjects comparison of looking and reaching performance can be found in Bell and Adams (1999, Experiment 1). In Bell and Adams, behavioral data for 62 infants were reported, and performance on looking and reaching versions of A-not-B was comparable. In this article, behavioral and electrophysiological data are reported for the 54 infants from Bell and Adams (1999, Experiment 1) who had complete EEG data. For these 54 infants, there was no difference in performance on the looking ($M = 2.94, SE = .14$) and reaching ($M = 3.16, SE = .13$) versions of the A-not-B task, $t(53) = 1.07, p = .29$.

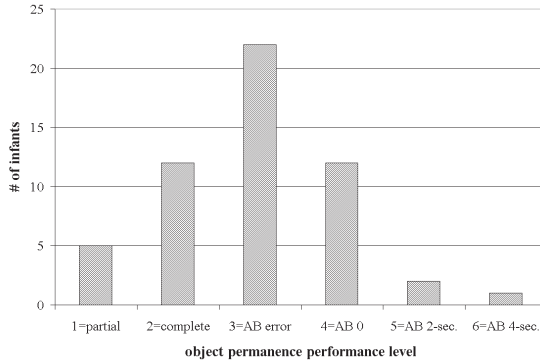


FIGURE 1 Individual infant performance on the looking A-not-B task.

had the mode at scale Item 3, the A-not-B error. These data are comparable to the looking data of Matthews et al. (1996), who reported that the delay needed to produce the A-not-B error at 36 weeks (8.5 months) was 1 to 2 sec (see Figure 3, Matthews et al., 1996, p. 2669).³ These authors noted that the 1- to 2-sec delay was the minimum delay possible with their methodology, which included closing and then opening a curtain across the hiding sites to break fixation to the correct location. The 0 delay in this study consisted of bringing the infant's gaze to midline, which in reality introduced a slight delay as well.

RESULTS

To examine relations between looking task performance and EEG power and coherence values, infants were divided into groups based on looking task performance (Bell & Fox, 1997). Infants whose greatest level of performance included scale Items 1 through 3 (i.e., infants who could do a partial cover or a complete cover or committed the A-not-B error) were grouped together and classified as low performers on the task ($n = 39$). Infants who succeeded on the A-not-B task, either at 0 delay or at a brief delay ($n = 15$), were classified as high performers on the task.

³Matthews et al. (1996) stated that they analyzed the "delays needed to produce the A-not-B error" (p. 2666) and the corresponding Figures 2 and 3 have this as the y-axis label. However, the captions for Figures 2 and 3 state that the data represent the "delays tolerated." If the data points represent the delays tolerated, rather than delays needed to produce the error, then the infants in the Matthews et al. study performed at a higher level than the infants in the study reported here.

Looking Task Performance Group and EEG Power

Prior to examination of group differences in EEG power values, it was important to verify that the two performance groups had equal amounts of artifact-free EEG (Pivik et al., 1993). The software program (James Long Company) for the Fourier analyses of the EEG used a window width of 1 sec, called a DFT window. A repeated-measures multivariate analysis of variance (MANOVA) was performed on the number of DFT windows available for analysis. The within-subjects factor was condition (i.e., baseline or task) and the between-subject factor was looking task performance group (i.e., low or high). There were no main effects or no interaction (all F 's < .51, all p 's > .48). There were comparable amounts of EEG data for baseline and task for each performance group.⁴

The hypothesis was that there would be changes in EEG power values from baseline to task and that these changes would be specific to the high-performance group. Specifically, this group should exhibit an increase in EEG power values from baseline to task. Furthermore, these changes should focus on frontal scalp locations. Bell and Fox (1992, 1997) reported effects at medial frontal (F3, F4) locations in their studies utilizing baseline EEG and noted asymmetries in frontal power values, with greater values at the right hemisphere (Bell & Fox, 1997). Changes in baseline to task EEG at occipital locations were also predicted. To test the hypotheses, a repeated-measures MANOVA was done on the ln EEG power values. The within-subjects factors were condition (i.e., baseline or task), region (i.e., frontal pole, medial frontal, lateral frontal, parietal, or occipital), and hemisphere (i.e., left or right). The between-subject grouping factor was looking task performance group (i.e., low or high).

There were main effects for condition, $F(1, 52) = 42.21, p < .001$, and region, Hotelling's $T^2 = .07$, approx $F(4, 49) = 175.71, p < .001$. There were two-way Group \times Condition interactions, $F(1, 52) = 13.25, p = .001$, and Region \times Hemisphere interactions, Hotelling's $T^2 = .82$, approx $F(4, 49) = 2.62, p = .046$. There was a three-way Group \times Condition \times Region interaction, Hotelling's $T^2 = .81$, approx $F(4, 49) = 2.95, p = .029$.

For ease in examining the three-way interaction among performance group, condition, and region, separate MANOVAs were performed on the EEG power values for each region (Keselman, 1998). This analysis also allowed for interpretation of the main effects for condition and region and for the interaction between group and condition as well as the interaction between region and hemisphere. For

⁴The two groups differed on the number of trials. The low performers had a mean of 13.5 trials ($SD = 4.09$) and the high performers had a mean of 19.6 trials ($SD = 4.46$), $F(1, 52) = 22.80, p < .001$. Because the two groups had the same number of artifact-free DFT windows of EEG for analysis, the high performers had more movement artifact in their EEG recordings. This finding may be a result of the longer testing period for the high performers.

these MANOVAs for each region, object permanence performance group was the between-subject factor; condition (i.e., baseline or task) and hemisphere (i.e., left or right) were the within-subjects factors.

Frontal pole (Fp1, Fp2). For the frontal pole data, there was a main effect for condition, $F(1, 52) = 12.95, p = .001$. The infants exhibited greater EEG power values during the task than during baseline. This effect was superceded by a Group \times Condition interaction, $F(1, 52) = 5.12, p = .028$. The high-performance group exhibited an increase in EEG power from baseline to task, Fp1: $t(14) = 3.24, p = .006$; Fp2: $t(14) = 4.05, p = .001$, although the low-performance group showed no change in EEG power values from baseline to task (both p 's $> .08$). See Figure 2.

Medial frontal (F3, F4). There were main effects for condition, $F(1, 52) = 20.94, p < .001$, again with infants exhibiting greater EEG power during the task than during baseline, and for hemisphere, $F(1, 52) = 7.72, p = .008$, with greater EEG power at right (F4) than at left (F3). These effects were superceded by a Group \times Condition interaction, $F(1, 52) = 9.16, p = .004$, and a trend toward a three-way Group \times Condition \times Hemisphere interaction, $F(1, 52) = 3.46, p = .068$. As shown in Figure 3, infants in the high-performance group displayed an increase in EEG power from baseline to task, F3: $t(14) = 5.09, p < .001$; F4: $t(14) = 3.58; p = .003$. Infants in the low-performance group showed no change in EEG from baseline to task (both p 's $> .10$). Further, the high-performance group showed an asymmetry in EEG during baseline, displaying greater power at right frontal, $t(14) = 2.79, p = .014$. During the task, the high-performance infants exhibited symmetry between left and right medial frontal, $t(14) = 1.50, p = .16$.

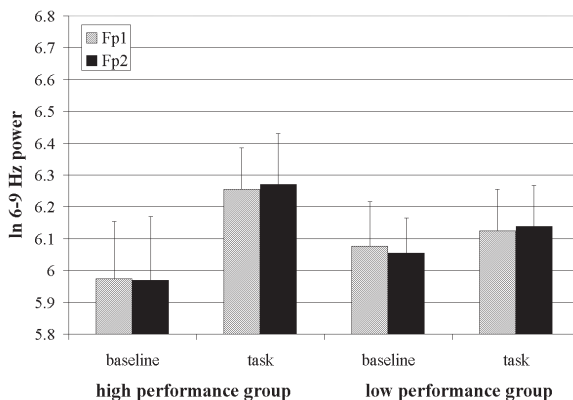


FIGURE 2 EEG power values (ln 6–9 Hz) from frontal pole (Fp1, Fp2) scalp locations for the two object permanence performance groups during baseline and task.

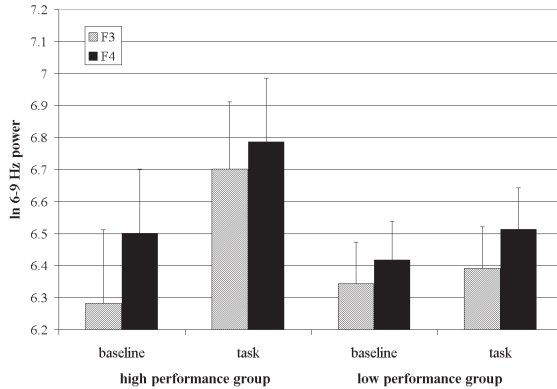


FIGURE 3 EEG power values (ln 6–9 Hz) from medial frontal (F3, F4) scalp locations for the two object permanence performance groups during baseline and task.

Lateral frontal (F7, F8). For the lateral frontal EEG, there was a main effect for condition, $F(1, 52) = 28.57, p < .001$. Infants exhibited greater EEG power during the task than during baseline.

Parietal (P3, P4). For the parietal EEG, there was a main effect for condition, $F(1, 52) = 32.76, p < .001$, and a Group \times Condition interaction, $F(1, 52) = 16.94, p < .001$. As in the other regions, the high-performance group showed an increase in EEG power from baseline to task, P3: $t(14) = 7.89, p < .001$; P4: $t(14) = 3.70, p = .002$. However, the low-performance group showed no change in EEG between conditions (both p 's $> .11$). See Figure 4.

Occipital (O1, O2). There was also a main effect for condition, $F(1, 52) = 25.70, p < .001$, and a Group \times Condition interaction, $F(1, 52) = 7.11, p = .01$. Again, the high-performance group showed an increase in EEG power from baseline to task, O1: $t(14) = 5.78, p < .001$; O2: $t(14) = 5.22, p < .001$, whereas the low-performance group showed no change in EEG between conditions. See Figure 5.

Summary. For all five scalp regions, there was a main effect for condition, with infants exhibiting greater power during the task than during baseline. For every region except lateral frontal (F7, F8), the effect of condition was superseded by an interaction between group and condition. The high-performance group showed increases in EEG power from baseline to task, whereas the low-performance group showed no change in EEG between the two conditions. Although the hypothesis was that this interaction would only be evident in the medial frontal and occipital

scalp leads, it was evident at four of the five regions (i.e., frontal pole, medial frontal, parietal, occipital).

In addition, for the medial frontal data (F3, F4), there was a main effect for hemisphere (higher right hemisphere, F4) and a trend ($p = .068$) toward a three-way interaction among group, condition, and hemisphere. The high-performance group showed greater right frontal power relative to their own left frontal power at baseline and then increased power to hemispheric symmetry during the task.

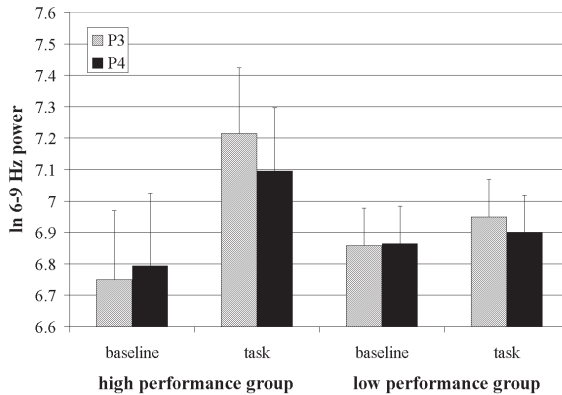


FIGURE 4 EEG power values (ln 6–9 Hz) from parietal (P3, P4) scalp locations for the two object permanence performance groups during baseline and task.

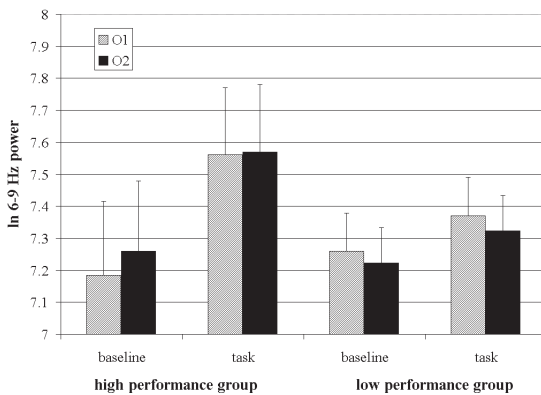


FIGURE 5 EEG power values (ln 6–9 Hz) from occipital (O1, O2) scalp locations for the two object permanence performance groups during baseline and task.

Looking Task Performance Group and EEG Coherence

The coherence hypothesis was that infants who perform at a high level on the task should show task-related changes in EEG coherence, whereas infants who perform at a low level on the task should not show this change. This should be evident among the frontal scalp electrode pairs, as well as between frontal–occipital electrode pairs. Specifically, the high-performance group should display lower power values during task than during baseline. To test this hypothesis, a repeated-measures MANOVA was done on the EEG coherence values. The within-subjects factors were condition (i.e., baseline or task), electrode pair (i.e., frontal pole–medial frontal, medial frontal–lateral frontal, medial frontal–parietal, or medial frontal–occipital), and hemisphere (i.e., left or right). The between-subject grouping factor was looking task performance group (i.e., low or high).

There was a main effect for pair, Hotelling's $T^2 = 4.13$, approx $F(3, 50) = 68.87$, $p < .001$. There was a two-way Group \times Hemisphere interaction, $F(1, 52) = 4.38$, $p = .041$, and a trend toward a three-way Group \times Hemisphere \times Pair interaction, Hotelling's $T^2 = .16$, approx $F(3, 50) = 2.59$, $p = .063$.

For ease in examining the three-way interaction among performance group, hemisphere, and electrode pair, separate MANOVAs were performed on the EEG power values for each electrode pair (Keselman, 1998). These analyses also allowed for interpretation of the main effect for pair and for the two-way interaction involving group and hemisphere. For these MANOVAs done for each electrode pair, object permanence performance group was the between-subject factor; condition (i.e., baseline or task) and hemisphere (i.e., left or right) were the within-subjects factors.

Frontal pole–medial frontal (Fp1–F3 & Fp2–F4). For the frontal pole–medial frontal coherence pairs, there was a Group \times Hemisphere interaction, $F(1, 52) = 4.34$, $p = .042$. The high-performance group exhibited lower coherence in the right hemisphere than in the left hemisphere, $t(14) = 2.09$, $p = .05$. The low-performance group showed no hemispheric differences in frontal medial–frontal pole coherence, $t(38) = 1.61$, $p = .12$. See Figure 6 (top).

Medial frontal–lateral frontal (F3–F7 & F4–F8). There was a main effect for hemisphere, with the right hemisphere exhibiting lower coherence than the left hemisphere, $F(1, 52) = 4.34$, $p = .042$. There was a trend toward a Group \times Hemisphere interaction, $F(1, 52) = 3.30$, $p = .075$, with the high-performance group exhibiting lower coherence in the right hemisphere than in the left hemisphere, $t(14) = 2.45$, $p = .028$. The low-performance group showed comparable coherence in the hemispheres, $t(38) = .25$, $p = .81$. See Figure 6 (bottom).

Medial frontal–parietal (F3–P3 & F4–P4). There was a main effect for condition, with greater coherence between medial frontal and parietal electrode

sites during the looking task ($M = .39$, $SE = .03$) than during baseline ($M = .28$, $SE = .02$), $F(1, 52) = 4.05$, $p = .049$.

Medial frontal–occipital (F3–O1 & F4–O2). There were no main effects or interactions, all $ps > .10$.

Summary. For both sets of frontal pairs (frontal pole–medial frontal and medial frontal–lateral frontal) there was an interaction between group and hemisphere. The high-performance group showed lower right hemisphere coherence relative to left hemisphere coherence, whereas the low-performance group showed symmetry. For the medial frontal–parietal pairs, all infants exhibited greater coherence during the task than during the baseline. There was no interaction between group and condition for the medial frontal–parietal coherence data.

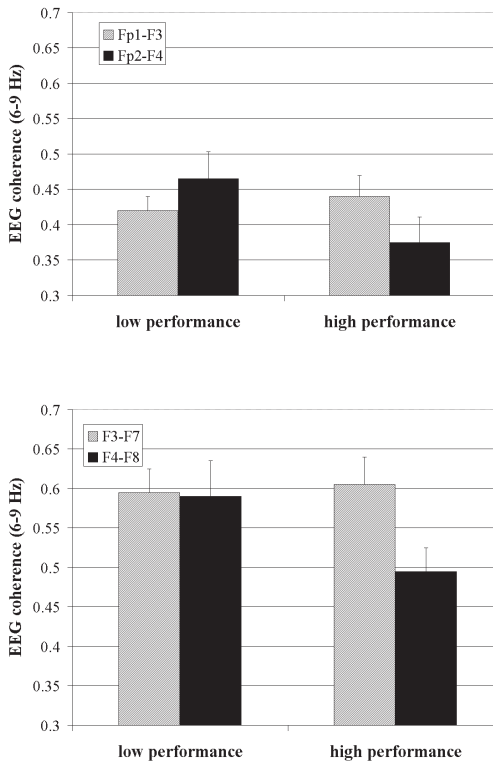


FIGURE 6 EEG coherence values (6–9 Hz) at frontal electrode pairs for the two object permanence performance groups. Top: Frontal pole–medial frontal pairs (Fp1–F3, Fp2–F4). Bottom: Medial frontal–lateral frontal pairs (F3–F7, F4–F8).

DISCUSSION

These data provide further evidence for a relation between frontal brain electrical activity and performance on the A-not-B task. Both EEG coherence and EEG power values were associated with task performance. The coherence data yielded a Group \times Hemisphere interaction among the frontal pairs, whereas the power data yielded a Group \times Condition interaction at both anterior and posterior sites, with a three-way Group \times Condition \times Hemisphere interaction specifically for the medial frontal location. This pattern of results (i.e., Group \times Hemisphere interaction for coherence and Group \times Condition interaction for power) suggests that these two measures may be tapping different aspects of brain development and that each of these aspects informs about individual differences in cognitive performance.

EEG coherence measures may be tapping brain organization. Infants in the high-performance group exhibited lower coherence among right frontal scalp locations than did infants in the low-performance group. This was true for both baseline and task-related EEG recordings. The hypothesis was that infants in the high-performance group would show lower coherence during task, relative to baseline, and that the low-performance group would show no task-related change in coherence. In other words, a Group \times Condition interaction was hypothesized, but a Group \times Hemisphere interaction was the result. Thatcher (1994) proposed that the coherence measure reflects the strength and number of synaptic connections. Thatcher et al. (1986) predicted that with development, coherence should decrease between sites that are topographically close. This decrease should reflect greater differentiation within a particular area. For the infants performing this task, it appears that these EEG coherence values were more reflective of brain organization than of brain functioning because the group difference in coherence was not modified by condition.

The coherence data showed a main effect for condition for the medial frontal–parietal electrode pairs indicative of brain functioning. Specifically, there was greater coherence during task than during baseline. This means that the medial frontal–parietal areas of the cortex were working together during this working memory looking task. Researchers working with monkeys and adult humans have reported prefrontal and parietal activation during positron emission tomography and functional magnetic resonance imaging (fMRI) studies using a spatial working memory task (Quintana & Fuster, 1999; Sarnthein, Petsche, Rappelsberger, Shaw, & vonStein, 1998; Ungerleider et al., 1998). Other researchers doing fMRI work with human children have reported right dorsolateral prefrontal and right parietal activation during spatial working memory tasks (Nelson et al., 2000; Thomas et al., 1999). The EEG coherence findings in this study with human infants replicate recent fMRI work with children.

Whereas the group differences in coherence appear to be associated with brain structure because they were not modified by condition, the group differences in

EEG power appear to tap brain function. A Group \times Condition interaction was hypothesized for the EEG power data, and that interaction was the result. The high-performance group showed task-related increases in EEG power relative to baseline, although the low-performance group did not. The hypothesis was that this interaction would be specific to the frontal scalp locations and perhaps the occipital locations; however, it was associated with other scalp locations as well. At medial frontal specifically, the high-performance group displayed higher right hemisphere power values, a finding that replicates previous work by Bell and Fox (1997) using baseline EEG measures and the classic reaching A-not-B task. Changes in EEG power may reflect the mass association and excitability of particular groups of neurons (Nunez, 1981). For infants performing this task, EEG power values appear to be reflective of brain functioning. From these power data it also appears that many cortical areas, not just frontal ones, were associated with looking task performance.

These EEG power and coherence looking task data replicate previous Bell and Fox (1997) work highlighting right hemisphere associations with high levels of performance on the A-not-B reaching task. Bell and Fox acknowledged the right frontal asymmetry but offered no explanations. Recently, however, Bell and Adams (1999) proposed that in addition to working memory and inhibition, the A-not-B task also requires the cognitive skill of attention. This additional skill may explain the right frontal findings noted here and previously by Bell and Fox.

The data from this study allow for examination of dynamic brain electrical activity associated with working memory during infancy. In the developmental neuropsychological literature there is a great deal of information concerning the development of recognition memory during infancy and the association of this behavior with maturation of the temporal areas of the cortex (e.g., Nelson, 1995; Nelson & Dukette, 1998). Correspondingly, we know relatively little about the development of the frontal lobe during infancy. The type of working memory associated with infant frontal lobe function during the looking A-not-B task may be the precursor of higher order cognitive functioning during childhood and beyond. The data presented here are a valuable first step toward understanding infant frontal lobe function.

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