Frontal Activation Asymmetry and Social Competence at Four Years of Age[1]

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Abstract:

The pattern of frontal activation as measured by the ongoing electroencephalogram (EEG) may be a marker for individual differences in infant and adult disposition to respond with either positive or negative affect. We studied 48 4-year-old children who were first observed in same-sex quartets during free-play sessions, while making speeches, and during a ticket-sorting task. Social and interactive behaviors were coded from these sessions. Each child was subsequently seen 2 weeks later when EEG was recorded while the child attended to a visual stimulus. The pattern of EEG activation computed from the session was significantly related to the child's behavior in the quartet session. Children who displayed social competence (high degree of social initiations and positive affect) exhibited greater relative left frontal activation, while children who displayed social withdrawal (isolated, onlooking, and unoccupied behavior) during the play session exhibited greater relative right frontal activation. Differences among children in frontal asymmetry were a function of power in the left frontal region. These EEG/behavior findings suggest that resting frontal asymmetry may be a marker for certain temperamental dispositions.

Article:

Data from several sources suggest that the pattern of electroencephalographic (EEG) activation recorded over the frontal region in humans may be a marker for certain temperamental dispositions. Specifically, individuals exhibiting resting right frontal asymmetry are more likely to exhibit signs of negative affect in response to mild stress, while individuals exhibiting resting left frontal asymmetry are likely to exhibit positive affect in response to similar novel elicitors. There are both developmental and adult data that support this position (Calkins, Fox, & Marshall, in press; Davidson & Fox, 1989; Fox, Bell, & Jones, 1992).

In a series of studies with infants, Fox and colleagues (Davidson & Fox, 1989; Fox et al., 1992) found that infants exhibiting right frontal EEG asymmetry were more likely to cry to maternal separation. In addition, infants who were likely to cry consistently to maternal separation across

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the second half of the first year of life displayed a stable pattern of right frontal asymmetry. Calkins et al. (in press) have also reported that infants selected at 4 months of age for a high frequency of motor arousal and negative affect were more likely to display right frontal asymmetry at 9 months of age compared to infants selected for displaying positive affect. In addition, infants preselected for displaying high motor/high negative affect who exhibited right frontal asymmetry at 9 months were more likely to display signs of fear and wariness at 14 months. Calkins et al. (in press) argue that right frontal asymmetry may be an important moderator variable reflecting an infant's disposition to respond with negative affect in response to novelty.

A number of independent laboratories have confirmed the relation between frontal asymmetry and emotional disposition. Dawson et al. (Dawson, Grofer-Klinger, Panagiotides, Spieker, & Frey, 1992) reported that 10-month-old infants exhibiting right frontal asymmetry were more likely to display signs of negative affect and distress to separation than those exhibiting left frontal asymmetry. In addition, Dawson et al. (1992) reported that infants of depressed mothers evidenced this particular right frontal pattern during a face-to-face interaction with their rnothers.

The asymmetry in EEG power that is reflected in the laterality index is a function of the dynamic changes in activity of both the left and right hemispheres. Traditionally, asymmetry has been indexed as the ratio of power in one hemisphere to another (R — L/R + L). The underlying assumption is that less power in one hemisphere compared to the other reflects greater relative activation in that hemisphere (Lindsley & Wicke, 1974). Thus, with the asymmetry metric, positive numbers reflect greater relative left hemisphere activation, while negative numbers reflect greater relative right hemisphere activation (Davidson, 1988). Obviously, there are a number of ways that individuals could differ in arriving at a right hemisphere asymmetry score (negative number). One individual could have more power in the left than power in the right hemisphere (an example of left hypoactivation), while one individual could have a right hemisphere asymmetry score as a result of less power in the right hemisphere (an example of right activation).

The process by which dynamic change occurs and hence whether the asymmetry index is a function of more power in one hemisphere or less power in the opposite hemisphere is of critical concern (Fox, 1994). A number of researchers have noted differences in the manner in which affective behavior is modulated as a function of either hyperactivation of one hemisphere or disinhibition of the contralateral side. One would expect behavioral differences as a function of these two different patterns of relative activation (Fox, 1994). For example, two groups of subjects may display a right frontal asymmetry score. One group's score may be the product of left frontal hypoactivation (more power in the left hemisphere), and these subjects may be expected to exhibit lack of positive affect and lack of approach (and possibly signs of depression; see Henriques & Davidson, 1991), while the scores of the second group of subjects may be the product of right frontal activation (less power in the right), and they may be expected to exhibit increased signs of negative affect and anxiety (see Calkins et al., in press; Finman, Davidson, Colton, Straus, & Kagan, 1989; Fox et al., 1992). One goal of the current study was to examine in detail differences in the dynamic nature of EEG asymmetry in relation to overt social behavior.

The notion that frontal activation may reflect an individual's disposition to respond with either positive or negative affect is derived in part from work on the relations among frontal lobe activity and the expression of emotions (see Davidson, 1983; Fox & Davidson, 1984). There is a diverse literature from cases of adults with unilateral brain damage or in response to unilateral administration of sodium amytal (WADA test) which suggests that the two hemispheres are differentially specialized for the production of different emotions. These studies have been reviewed in detail in numerous sources (Sackeim et al., 1982; Silberman & Weingartner, 1986).

In a series of papers, Fox and colleagues have demonstrated an association between left and right frontal asymmetry and emotion expression in infants (Fox & Davidson, 1986, 1987, 1988). In general, these studies indicate that infants exhibit greater right frontal asymmetry during the expression of negative emotions and greater left frontal asymmetry during the expression of positive emotions. Studies with human adults find parallel associations between facial expression of emotions and EEG asymmetry in the frontal region (Davidson, Ekman, Saron, Senulis, & Friesen, 1990).

Although the above referenced studies suggest that the two hemispheres may be differentially specialized for the production of behaviors associated with either positive or negative emotion, they do not address individual differences in the display of positive or negative affect. The conception that individual differences in the degree of frontal activation may be associated with disposition to emotional reactivity was first proposed by Davidson and Fox (1988) and is in part derived from work previously completed by Levy and colleagues (Levy, Heller, Banich, & Burton, 1983). Levy et al. (1983) were interested in understanding the variance among right-handed individuals in performance on either left or right hemisphere (verbal/spatial) tasks. They developed a set of chimeric face tests designed to measure the degree to which individuals exhibit resting left or right hemisphere arousal. Levy et al. (1983) hypothesized an interaction between hemisphere arousal and hemispheric specialization in the performance of verbal and spatial tasks performance. They found that subjects exhibiting right hemisphere arousal when performing a right hemisphere task were better than subjects exhibiting left hemisphere arousal, Davidson and Fox (1988) argued that a similar relation might exist for affective behavior. Specifically, individuals exhibiting tonic right frontal activation may be more likely to exhibit negative affect, while individuals exhibiting tonic left frontal activation would be more likely to exhibit positive affect.

There is reason to believe that resting frontal asymmetry may be a stable within- individual characteristic that is associated with an individual's tendency to express negative affect. For example, Tomarken, Davidson, and Henriques (1990) found that subjects with resting right frontal asymmetry were more likely to rate video film clips in a negative manner, while subjects with tonic left frontal asymmetry were more likely to rate these same clips in a positive manner. Jones and Fox (1992) report a similar relation between right frontal EEG asymmetry and negative rating bias for adults selected for high positive or negative affectivity. Davidson and colleagues have also found that undergraduates who score consistently high on the Beck Depression Inventory were more likely to exhibit resting right frontal asymmetry (Schaffer, Davidson, & Sawn, 1983). In a follow-up to this study, Henriques and Davidson (1990) found that adults with clinical depression exhibited greater right frontal asymmetry, and adults who had been depressed and were now in remission also exhibited this right frontal pattern. Also, Davidson and colleagues reported that children selected for characteristics of behavioral inhibition were more likely to exhibit right frontal asymmetry compared to children who were selected for extroverted behavior (Finman et al., 1989).

There is an interesting parallel between the research on social withdrawal and peer competence and the work on behavioral inhibition. Kagan and colleagues (Kagan & Snidman, 1991) have argued that wariness in the face of novel stimuli (behavioral inhibition) during the infant and toddler period is a stable characteristic that becomes associated with social wariness and solitude in the mid-years of childhood. Rubin and Lollis (1988) have suggested that among the developmental paths that might lead to social withdrawal is one in which an infant of irritable temperament who is involved in an insecure attachment relationship may evidence inhibited fearful behavior as a toddler. This fearful, anxious behavior may later be transformed to the peer setting and may be a factor in the child's inability to behave competently in social interactions.

If social withdrawal and inhibited behavior involve, in part, a disposition toward fearfulness and anxiety, it may be that children who evidence inhibited behavior in social settings also display a pattern of frontal brain electrical activity reflecting this disposition. That is, it is possible that frontal asymmetry is a marker for inhibited behavior among preschool children. The following study was designed to investigate this possibility. Forty-eight children who were part of an ongoing longitudinal study were seen at age 4 years in same-sex quartet play groups. The children's social behavior and interactive styles were observed and coded. Two weeks later, each child individually returned to the laboratory, at which time EEG was recorded while the child was presented with a computer generated stimulus. Relations among child social behaviors from the quartet session and measures of frontal asymmetry were investigated. It was predicted that children evidencing social withdrawal and inhibited behavior during the quartet session would exhibit right frontal EEG asymmetry. Similarly, it was predicted that children evidencing social competence and positive social interactive skills would exhibit left frontal EEC asymmetry. Confirmation of these predictions would suggest that frontal asymmetry may be a marker variable for affective disposition in children of preschool age.

METHOD

Subjects

The participants in this study were 48 preschool children (20 male, 28 female) between the ages of 49 and 62 months (mean age 54.63 months, SD 3.91 months). The children were primarily of middle-class background, living with their families in or near College Park, Maryland. Four of the children were African-American; the remaining 44 were Caucasian. The children were part of a larger unselected sample of 61 children who were participating in a longitudinal study (see Fox, 1989; Stifter & Fox, 1990, for details).

Procedure

At 24 months, infants came to the lab and were exposed to a series of conditions designed to elicit a range of positive and negative affects. These conditions included presentation of an unfamiliar adult, a novel toy, and a clown, and maternal separation. Infant behaviors, including latency to approach the stranger, robot, and clown, and duration proximity to mother during the stranger, robot, and clown episodes were coded, and a standardized index of behavioral inhibition was computed from these variables.

The quartets were formed on the basis of their score on the standardized index of inhibition at 24 months. Quartets were same sex. An attempt was made to compose each same-sex quartet with one child who at 24 months was found to be inhibited, one child who at 24 months was found to be uninhibited, and two children who at 24 months were around the mean on the inhibition index. In addition, the child's age was taken into account, and an attempt was made to have children in any one quartet who were within 6 months of each other in age. Seventy-five percent of the quartets (9 of 12 quartets) met the above criteria. The remaining three quartets consisted of children whose 24-month standardized inhibition scores were more toward the mean.

The four children and their mothers came to the laboratory. Children and mothers waited in an area of the lab until all four children had arrived and all parents had been briefed and consent granted. The four children were then led into a playroom that had in it a set of attractive toys. The children were told that they were to play in this room for a while and that afterward they would participate in a set of games. The children in each quartet had never met each other. Their main point in common was that all had been born at the same local hospital and all were participants in the larger longitudinal study.

Children were given name tags, which were pinned onto their backs so that their names would be visible to the video camera. The sessions were video- and audiotaped for future coding and analysis.

The quartet session consisted of four parts. Part I was free play and lasted for 15 min. During this period of time the four children were in the room by themselves. Parents were in a waiting area and were asked, during this time, to fill out a series of questionnaires. Part II was a cleanup session that lasted up to 5 min. An experimenter entered the room and told the children that the free- play session had ended and that they were going to play a series of games. The experimenter asked the children to clean up the toys, placing them in a large cardboard box that had been placed in the center of the playroom.

Part III of the session consisted of speeches. The experimenter asked the four children to sit in a semicircle facing her (the children were facing the one-way mirror and their faces could be easily videotaped). The experimenter then told the children that they were going to play a brief game of show-and-tell during which each child would stand up and tell the rest something about their recent birthday party. The experimenter then asked for volunteers and allowed each child to stand and talk for up to 2 min. Following the speeches, the experimenter brought out to the center of the room a small table and four chairs and asked the children to sit around the table. A basket with colored cards was on the table and the experimenter asked the children to take one card of each color and make up five sets of cards (Part IV). Following this, the final 15- min free-play session began. The experimenter reentered the room, brought the box with toys, and allowed the children to play in the room by themselves for an additional 15 min.

During this visit to the laboratory., arrangements were made with each mother for an individual follow-up visit. These visits were usually within 2 weeks of the quartet session. Mothers were told that at the follow-up visit there would be a psychophysiological assessment and additional testing.

Behavioral Coding
The videotapes of the quartet sessions were sent to the second author (KHR) for coding. Coders were blind to the assignment of the individual children and to the hypotheses of the study.

Free-play sessions.—Behaviors in the first and second play sessions were coded with Rubin's (1989) Play Observation Scale. Ten-second intervals were coded for social participation (unoccupied, onlooking, solitary play, parallel play, conversation, group play) and the cognitive quality of play (functional, dramatic, and constructive play; exploration; games with rules). This resulted in approximately 90 coding intervals per child in each of the two free-play sessions.

Additional variables coded during the free-play sessions included (1) the proportion of observational intervals that included the display of anxious behaviors (e.g., automanipulatives, digit sucking, crying); (2) the latency to the child's first spontaneous utterance (first play session only); (3) the frequency of child-initiated social interactions; and (4) the frequency of social initiations from peers.

Cleanup and ticket-sorting sessions.— During the cleanup and ticket-sorting sessions, the proportion of time each child spent off task-unoccupied was recorded. Behaviors were considered off-task during the cleanup if they did not involve such actions as picking up toys, or placing toys in the toy box. Off-task behaviors during the ticket- sorting session included not sorting tickets or not talking about the task at hand. Unoccupied behavior was defined similarly to the behavioral variable of the same name used during the free-play sessions. Time spent off-task but engaged in any other type of alternative activity (e.g., goofing off, continuing to play with toys, disrupting others who were trying to clean up/sort tickets) was coded as off-task-goofing off.

Speeches.—The speeches were coded for (a) the duration of the entire speech episode, and (b) the percentage of time each child actually spent speaking. The duration of the episode was defined as the amount of time that each child "held the floor," from the moment he or she was asked to speak, until the researcher asked the next child to speak. The percentage of time spent talking was calculated by dividing the amount of "real time" during which each child verbally described their birthday party by the duration of their speech episode.

Reliability.—The Play Observation Scale (Rubin, 1989) and additional observational variables were coded by four independent observers.. Interrater reliability on a randomly selected group of children totaling 30% of the sample (four quartets; 16 children) was calculated between pairs of observers using Cohen's kappa. For a full variable matrix, including social and cognitive play categories, and additional observational variables, computed kappas between pairs of raters ranged between K = 0.71 and K 0.86. Intercoder disagreements were resolved by review and discussion.

Aggregate Variables
Two theoretically driven and empirically substantiated aggregate variables were computed from the variables assessed during the free-play, cleanup, ticket-sorting, and speech episodes (see also Coplan, Rubin, Fox, Calkins, & Stewart, 1994).

Social reticence-inhibition.--The first aggregate variable was thought to represent social reticence and inhibition and was computed as the sum of the following standardized variables: (1) proportion of anxious behaviors during free play; (2) latency to first spontaneous utterance during free play; (3) proportion of reticent behavior (unoccupied and onlooking behavior) during free play; (4) proportion of unoccupied behavior during cleanup; (5) proportion of unoccupied behavior during ticket sorting; (6) the inverse of the duration of the speech episode; and (7) the inverse of total time talking during the speech episode. Intercorrelations among these indices ranged from .16 to – .47 and from .24 to .49. All but one of the intercorrelations were statistically significant ($p < .05$).

Sociability-social competence .—The second aggregate variable was thought to represent sociability and social competence and was computed as the sum of the following standardized free-play variables: (1) the frequency of child-initiated social interactions; (2) the frequency of initiations received from peers; and (3) the proportion of time engaged in sociodramatic play (a marker of social competence in preschoolers; Howes, 1987; Rubin, Fein, & Vandenberg, 1983). Intercorrelations among these indices ranged from .38 to .60. All of these intercorrelations were statistically significant ($p < .01$).

Maternal Ratings

Mothers completed the Colorado Temperament Inventory (Buss & Plomin, 1984; Rowe & Plomin, 1977). This measure is composed of factors that assess maternal perceptions of various child characteristics (e.g., emotionality, activity level, shyness, soothability, sociability). Of specific interest to us were the factors assessing shyness and emotionality.

Psychophysiological Assessment

When the child and mother returned to the lab, the child was shown the testing room, which had been decorated and designed to resemble a space shuttle. There were pictures of planets on the wall and ceiling, and a chair had been decorated as the command chair for the spaceship. In addition, a computer had been placed in the room and cardboard around the computer was set and painted to illustrate the controls of a space ship. A Lycra stretch cap was placed on the child's head for EEG recording. The cap contained the electrodes for EEG recording placed in an arrangement in accordance with the 10-20 system (Jasper, 1958). A small amount of omni-prep abrasive was put into each site and the scalp gently abraded with the blunt end of a Q-tip. A small amount of electrolyte was then placed in the site and impedances were checked. Impedances were accepted if they were 5 K ohms or below.

The EEG was recorded from six sites (F3, F4, P3, P4, 01, 02, referenced to vertex, Cz). In addition, separate channels for Al and A2 each referenced to Cz were recorded. Finally, Beckman mini-electrodes were placed on the outer canthus and supra orbit of one eye in order to record EOG. All nine channels were amplified by individual 7p511 Grass AC amplifiers with the high pass setting at 1 Hz and the low pass at 100 Hz. The data from all nine channels were digitized at 512 Hz on an IBM AT using HEM acquisition software. The digitized data were stored for later artifact editing and analysis.

After the cap was in place and impedances were checked, a computer program was started. The program consisted of a colorful building taurus and a star. The taurus and star were separate segments and each lasted for 15 to 30 sec. Each child was presented with a minimum of six taurus and star segments with the goal of collecting at least 3 min of EEG data during each condition. The child was instructed to hold still and attend to the screen when the star came on. The child was told that if he or she could attend to the star they would win a prize at the end of the session. EEG was recorded continuously during the computer session, and a separate channel indicated the onset and offset of the star section. A camera placed unobtrusively recorded the child's behavior, including visual attention to the computer monitor, during the EEG recording.

After the recording session, which lasted 10 min, the cap was removed, any excess gel was removed from the child's hair, and the child was taken to a second room for additional assessments.

The digitized EEG was transformed via software to an average reference configuration. The average reference configuration was used, as this is the preferred configuration when coherence is computed between different electrode sites (Fein, Raz, Brown, & Merrin, 1988; Lehmann, Ozaki, & Pal, 1986). The data were then scored manually for eye movement and gross motor movement artifact using software designed by James Long, Inc. The software allowed the display of all channels graphically on the computer screen. Using a cursor, the operator could underline those sections of the EEG that were contaminated by motor movement or that contained eye movements as indicated by activity in the EOG. Two coders, previously trained and tested to reliability, artifact scored the EEG data. One coder was responsible for scoring all subjects, while a second coder overlapped on 12 subjects. Cohen's kappa was computed to examine reliabilities among the coders. Kappa values ranged from 0.60 to 0.80. The artifact scored EEG was then analyzed using the same software system with a discrete fourier transform, with a hanning window of 1 sec in length and 50% overlap. Power in single Hz bins from 1 through 20 Hz was computed for each segment of the taurus and star.

Quantification of laterality indices.— Most previous research on laterality has utilized laterality scores based on activity within each hemisphere without acknowledging the possibility of correlated activity reflecting interhemispheric communication (Wheeler, Davidson, & Tomarken, 1993). Alternatively, laterality scores could incorporate a measure of statistical dependence reflecting interhemispheric communication. One method commonly available to evaluate interhemispheric communication is to use cross-spectral analysis to generate a coherence spectrum. The coherence statistic indicates the degree that the activity (i.e., power densities) at a specific frequency or frequency band within each hemisphere is shared with the other, Coherence is independent of the amplitude of the signal (i.e., variance or power density), but is dependent upon phase. If the phase between two signals at a common frequency (or frequency band) is constant, the coherence will approach LO. In contrast, if the phase between two signals at a common frequency (or frequency band) is a white noise process, the coherence will approach 0. Coherence reflects the percent of shared variance between two signals at a specific frequency (or frequency band). Thus, knowledge of the coherence would enable the determination of the activity within each hemisphere that is shared with, or unique to, the activity in the other hemisphere.

There are several problems with generating a summary measure of shared and unique hemispheric EEG variance. First, coherences may not be constant across all the frequencies within the frequency band of interest (in our case, 6-8 Hz). To solve this problem, we applied the Porges method (Rohrer & Porges, 1982; Porges & Bohrer, 1990; Porges et al., 1980) to calculate a weighted coherence. The weighted coherence is determined by arithmetically weighting the coherence at each frequency within the 6-8 Hz band by its power. This method produces a ratio indicating the percent of shared variance between the two signals. Second, coherences may not be constant across time. To deal with this problem, we generalized the weighted coherence method to accumulate values across all 1-sec windows.

Although the Porges method was developed to describe the shared rhythmicity of two systems across a band of frequencies with the weighted coherence statistic, it also provides information on shared variance. Statistically, the weighted coherence is derived by the ratio of shared variance to total variance. Thus, the weighted coherence methodology provides us with a way to quantify shared variance and to use the shared variances in evaluating laterality.

As evident in Formula 1 {see the Appendix), the weighted coherence is equivalent to the sum of the products of coherence x power at each frequency within the alpha band divided by the total power within the same frequency band. The numerator of this formula provides a measure of shared power and is presented in Formula 2 (Appendix). The difference between the numerator and denominator provides a measure of unique power and is provided in Formula 3 (Appendix). These formulas were used to calculate shared and unique variances within each 1- see window and were accumulated (i.e., added) across all available 1-sec windows to provide a measure the total shared and unique variances for each hemisphere.

Since the weighted coherence is equivalent to the percent of shared variance, multiplication of the weighted coherence by the sum of the power within the frequency band will quantify the variance shared between the two systems. Moreover, when this quantity is subtracted from the sum of the power, a measure of unshared or unique variance associated with one hemisphere is quantified. Thus, the weighted coherence methodology provides us with a method to partition power in the 6-8 Hz frequency band within each 1-sec window into shared and unique variances. To generate an estimate for shared and unique power across time, we accumulated the shared power and total power for each 1-sec window across available 1-sec windows. By subtracting the shared variance from the total power, we obtained a measure of unique variance. These procedures were calculated for each hemisphere to provide a left and right measure of shared and unique variance. The new measures of asymmetry were calculated by subtracting the natural logarithms of these variances.

In sum, the EEG analyses were computed on the standard metric of power for each electrode site, as well as on shared and unshared EEG power for each site. Laterality difference scores (Ln R — Ln L) were computed using both the traditional estimate of power and the shared and unshared power estimates.

RESULT

The data to be presented in this article deal specifically with relations between measures of EEG asymmetry and power and behaviors observed in the quartet session as well as relations with maternal report. The analyses that were performed were completed on the EEG data that were recorded during the "still star" conditions. There were two reasons for choosing the "still star" EEG data for subsequent analyses. First, inspection of the visual attention data revealed that subjects paid significantly more attention to the monitor during the star versus during the taurus segment. This is not surprising given that subjects were instructed that they may move around during the taurus segment but were to be still and pay attention during the star segment. Second, there were significantly more EEG data available from the star versus the taurus segment. Because subjects were allowed to move more during the taurus segment, there was more movement artifact that was edited out of the records. The greater amount of data provided a more stable estimate of individual EEG patterns. Third, preliminary analyses were completed examining relations between EEG recorded during the "taurus" phase and child social behavior. No significant relations were found. We believe this is due to the lack of subject engagement during these segments and the small amount of EEG data available for analyses. Therefore, subsequent analyses were computed on the EEG data from the "star" period.

EEG asymmetry and social behavior.—As a first step, Pearson product correlations were computed between the two summary behavioral measures, the two CCTI factors, and the three EEG laterality measures (the traditional laterality score based on power derived from the spectral analysis, the laterality score based on shared power, and the laterality score based on unshared or unique power). As can be seen from Table 1, there were significant relations between the frontal asymmetry scores and the two behavioral summary measures as well as for one of the temperament factors. Inhibited behavior was associated with greater relative right frontal activation; the greater the inhibition score, the more negative the asymmetry score. As noted earlier, negative values on the asymmetry index reflect greater relative right activation. Social competence was associated with greater relative left frontal activation; the higher the score on social competence, the more positive the asymmetry index—positive values reflect greater relative left frontal activation. Finally, there was a trend for maternal rating of social fear/shyness to be associated with the asymmetry index. Children whose mothers rated them high on social fear had more negative asymmetry scores. This relation for social fear was the only significant finding among the correlations between the temperament factors and the asymmetry scores. The asymmetry scores based upon unshared or unique power were better at predicting social behavior than the traditional asymmetry measures of EEG power. None of the asymmetry measures from either the parietal or occipital regions were significantly related to any of the behavioral or maternal report measures.

Although the asymmetry index reflects relative differences in activation between the left and right hemispheres, it does not indicate the locus of within-subject differences in power. In order to examine this issue, a second set of Pearson correlations was computed between the absolute power values for each frontal lead, shared and un- shared power values for the frontal leads, and the two summary behavior scores as well as the two maternal report factors. As can be seen in Table 2, there were significant associations between left frontal un- shared power and the social competence and inhibition aggregate scores. Social competence was associated with less left frontal power, while inhibition was associated with more left frontal power. There were no significant associations between any of behavioral or maternal report variables and measures of right frontal power.

As a second step to investigate the locus of effects of power, we divided children based on their standardized (z transform) score of social competence and inhibition. Three groups were made from each aggregate score: high (z scores .5 or greater), mid-

TABLE 1

CORRELATION BETWEEN FRONTAL ASYMMETRY SCORES AND 4-YEAR BEHAVIOR AND MATERNAL REPORT OF TEMPERAMENT

	Traditional Frontal Asymmetry Score Ln (R) − Ln (L)	Unshared Power Asymmetry Score	Shared Power Asymmetry Score
Social competence (sociability)	.47***	.59***	.15
Inhibition (social reticence)	−.16	−.35**	−.23
Social fear (CCTI Scale)	−.19	−.24*	.01
Emotionality (CCTI Scale)	−.13	−.03	−.16

NOTE.—$N = 42$.
* $p = .06$.
** $p = .01$.
*** $p = .001$.

TABLE 2

CORRELATION BETWEEN LEFT AND RIGHT FRONTAL POWER VALUES (6–8 Hz) AND 4-YEAR BEHAVIOR AND MATERNAL REPORT OF TEMPERAMENT

	Power in Left Frontal	Power in Right Frontal	Unshared Power in F3	Unshared Power in F4
Social competence (sociability)	−.15	−.13	−.27*	−.12
Inhibition (social reticence)	.15	.07	.32**	.17
Social fear (CCTI Scale)	.03	−.02	.32**	.15
Emotionality (CCTI Scale)	.04	.10	.12	.16

NOTE.—$N = 42$.
* $p = .05$.
** $p = .01$.

dle (z scores greater than – .5 and less than .5), and low (z scores below – .5). Separate multivariate analyses of variance for each score were computed with group (three levels: high/middle/low), region (three levels: frontal/parietal/occipital), and hemisphere (two levels: left/right). The dependent measures were standard EEG power in each lead, shared power, and unshared power. Across all three analyses, the only significant factor to emerge was that of region: multivariate Wilks for standard power = .255, approximate $F(2, 38) = 57.37$, p .000; multivariate Wilks for shared power = .122, approximate $F(2, 38) = 136.66$, $p = .000$; multivariate Wilks for unshared power = .609, approximate $F(2, 38) = 12.16$, $p = .000$.

In order to understand the effects as a function of region, we repeated the analyses on each of the behavior groups (the high, mid, and low sociability children and the high, mid, and low social reticence children) separately for each region (frontal, parietal, occipital). This was a group (three levels) x hemisphere (left/right) ANOVA for each of the three dependent measures (traditional power, shared power, and unshared power).

Sociability-social competence.—There were no significant main or interaction effects for those analyses using either traditional power or shared power as the dependent variable for any region. For the analysis using unshared power, the two-way ANOVA for the frontal region revealed a significant two-way interaction (group x hemisphere), $F(2, 39) = 4.06$, $p = .03$. Post-hoc

Newman Keuls tests comparing the level of unshared power in each lead between the three groups revealed that children exhibiting high social competence exhibited less left frontal unshared power compared to children in the low social competence group { $p < .05$) (see Fig. 1). There were no significant main or interaction effects for the parietal or occipital data.

Social reticence-inhibition.—There were no significant main or interaction effects for the analyses using the traditional measure of EEG power or the measure of shared power.

For the analyses using unshared power, the two-way ANOVA for the frontal region revealed a significant two-way interaction for group x hemisphere, $F(2, 39) = 4.19$, p = Post-hoc Newman-Keuls tests revealed that the group of children exhibiting high social reticence displayed more left un- shared power compared to the group of children exhibiting low social reticence ($p < .05$) (see Fig. 2). There were no significant main or interaction effects for the parietal or occipital data.

DISCUSSION

The data from the current study suggest that individual differences in frontal asymmetry exhibited by children may reflect, in part, their pattern of affective responsivity and consequent social competence. Children exhibiting right frontal asymmetry were less socially competent and exhibited more inhibited behaviors during a peer interaction session. Children exhibiting left frontal asymmetry were more sociable and displayed more socially competent behaviors.

Individual differences among children in EEG asymmetry were localized to the frontal region. There were no group differences among children for either the parietal or occipital scalp regions. In addition, there were no significant associations between parietal or occipital asymmetry scores and child behavior. This pattern of findings is

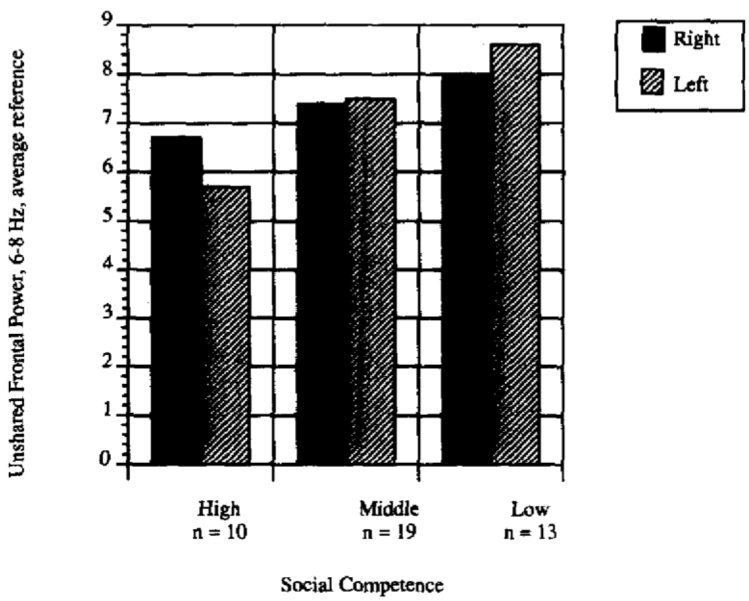

FIG. 1.—Unshared frontal power scores of children exhibiting high, medium, and low social competence at 4 years of age.

similar to those of Fox et al. (1992), Davidson (Henriques & Davidson, 1991), and Dawson (Dawson et al., 1992), who have consistently found the locus of asymmetry/ affect effects to be localized to the frontal scalp leads. The pattern across studies reinforces the argument that the differences among children are not a function of generalized hemispheric arousal but rather are specific to functions of the frontal region.

A number of researchers (Wheeler et al., 1993) have speculated that the pattern of asymmetry in the frontal region reflects im-

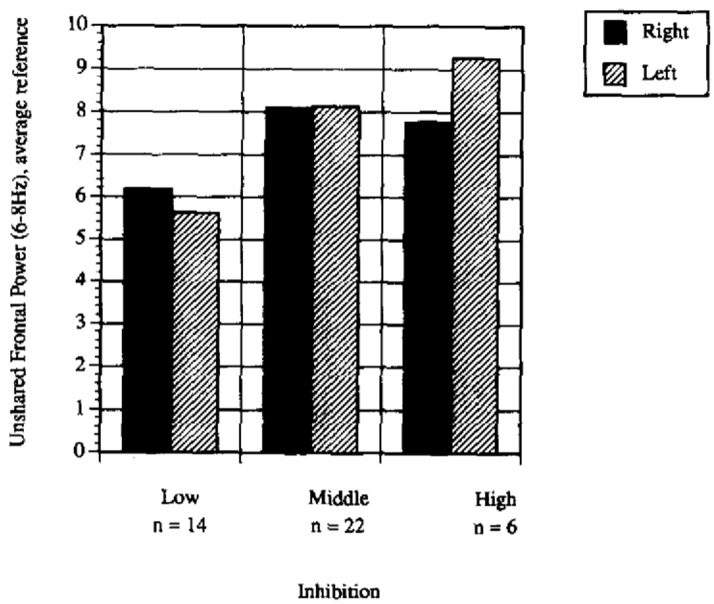

FIG. 2.—Unshared frontal power scores of children exhibiting high, medium, and low inhibition–social reticence at 4 years of age.

portant individual differences in affective responsivity. Davidson (Davidson, 1992), for example, has argued that the pattern of resting anterior activation (he has labeled it RAA) reflects the threshold with which individuals are likely to respond with either positive or negative affect to novelty or mild stress. He argues that these differences represent a stress diathesis. Individuals with resting greater relative right anterior activation are more likely under certain circumstances to respond with negative affect. Davidson and colleagues have found that depressed subjects or subjects in remission who had been clinically depressed were more likely to exhibit right frontal activation (Henriques & Davidson, 1991). Interestingly, they found that depression was specifically associated with reduced left frontal activation (more left frontal power or left frontal hypoactivation). There were no differences in right frontal activation between depressed and nondepressed subjects.

The current data extend these findings, suggesting that among a nonselected population of children, individual differences in their social behavior during a peer session are related to their pattern of frontal asymmetry. The current data, in addition, indicate that high degrees of sociability and social competence are also associated with frontal asymmetry.

In the studies with depressed adults, Henriques and Davidson (1991) reported that differences between depressed and control subjects were localized to the left hemisphere. That is, the pattern of right frontal asymmetry was a function of greater power in the left frontal scalp lead as opposed to less power in the right frontal lead. Henriques and Davidson (1990) suggested that higher power in the left frontal lead reflected the absence of approach behavior or absence of positive affect in these individuals. However, in these studies, differences among groups were in absolute EEG power. Since this measure is the sum of multiple sources of variance, it provides only an indirect estimate of the specific contribution of that region to the asymmetry effect. The current data, however, support these findings using a more sensitive measure of site- specific power. Right frontal asymmetry in the current study was a function of greater site-specific power in the left frontal scalp lead (left frontal hypoactivation).

Previously it had been suggested that the functional distinction between the two frontal regions in the expression of affect may involve the individual's tendency to either approach or withdraw from a novel stimulus. Fox and Davidson (1984) had suggested that the left frontal region was differentially specialized for the organization of behaviors involved in approach, while the right frontal region was specialized for the organization of behaviors involved in withdrawal. Activation of the right frontal region, therefore, would be accompanied by an increased tendency to exhibit behaviors associated with withdrawal (anxiety, negative affect). Hypoactivation of the left frontal region may be associated with the absence of approach behavior and lack of positive affect. The manner in which the two frontal regions interact, therefore, is of some importance in understanding frontal/affect behavior relations. For example, two individuals exhibiting right frontal asymmetry may in fact present with different pictures with regard to the activation of either the left or right hemispheres. One may display the asymmetry as a function of decreased right activation, while the second may display the asymmetry as a function of increased left power (decreased left activation). The asymmetry metric does not provide adequate insight into these differences, and it is therefore important to identify the specific differences between hemispheres in increase or decrease of activation.

A number of researchers have attempted to understand these changes in EEG power. One common approach has been to examine absolute power in each lead. To the extent that groups differ in the magnitude of power in one hemisphere versus another, one can infer differences in hemispheric activation. However, power in any single scalp lead is a function of multiple sources. It has thus been important to identify methods that might partial out the different sources of variance in the power measure in order to understand the unique contribution reflected at each scalp location. A number of workers have attempted regression approaches, although these methods present important statistical problems (Wheeler et al., 1993).

The approach taken in the current article (computing both shared and unshared or unique power) is an attempt at dealing with these complex issues. By computing the weighted coherence between interhemispheric electrode sites and then calculating the degree of both shared and unshared power, we can examine the degree to which asymmetry is a function of both unique and shared properties of the two sides of the brain. And we can determine with a certain degree of precision the role of each hemisphere in contributing to important behavioral differences.

It is therefore interesting to examine the relations between these different measures of EEG activation and behavior. As the data suggest, unshared power is the best discriminator of individual differences in social behavior. The magnitude of associations between asymmetry scores and behavior was greatest when this metric was used. And it best discriminated differences among high, middle, and low socially competent and socially reticent children.

Importantly, differences in frontal asymmetry between children high or low in social competence or high or low in social reticence were a function of left-hemisphere power. Children who were sociable, were frequent in their initiations of social interaction, and were judged to be socially competent exhibited less left frontal unshared power (hyperfrontal activation) than children exhibiting fewer of these behaviors. Children who displayed social withdrawal and anxious and onlooking behaviors exhibited greater left frontal unshared power (hypofrontal activation) compared to children who exhibited fewer of these behaviors. The pattern of these data, particularly those for the socially reticent children, is similar to that reported by Davidson and colleagues for both behaviorally inhibited children (Finman et al., 1989) and for individuals with depressive symptomatology (Henriques & Davidson, 1991). They suggest that the pattern of frontal activation recorded in these 4-year-old children reflects an important individual difference in their disposition to respond affectively to novel and mildly stressful situations.

Children exhibiting this pattern of behavior, when confronted with novel events such as interaction with unfamiliar peers in an unfamiliar environment, are likely to respond with onlooking behavior (lack of approach) and a relative absence of social interaction (tack of positive affect).

The associations found in this study between social behavior in the quartet session and left frontal power are in contrast to previous findings from Fox's laboratory, which reported an association between right frontal power and negative affect. In two studies (Davidson & Fox, 1989; Fox et al., 1992), right frontal asymmetry, a function of less right frontal power, was associated with the tendency to display distress to maternal separation. And, in a third study (Calkins et al., in press), right frontal asymmetry, again a function of less right frontal power, was associated with infants selected for a high motor/ high negative affect temperamental pattern. Infants selected for this temperament display more behavioral inhibition at 14 and 24 months of age (Kagan & Snidman, 1991). There are a number of possible reasons for the apparent differences in the locus of effects between previous studies and the current data.

Previously, researchers who found a relation between right frontal asymmetry and emotional behavior indicated that the right frontal pattern was associated with the expression or disposition to express negative affect. For example, infants who cried to maternal separation or infants who cried frequently to novel stimuli were found to display less right frontal power compared to those infants who were not prone to display negative emotions in these situations. The children in the current study who exhibited a pattern of left frontal hypoactivation displayed a pattern of socially reticent behavior, including more onlooking behavior and less time talking. But there was little evidence of overt display of negative affect. It is possible that their behavior reflected one of approach/withdrawal conflict, and that this combination of both approach and withdrawal motivations is the source of the left frontal hypoactivation. Alternatively, the pattern of onlooking, unoccupied behavior and absence of overt signs of negative affect may reflect a lack of approach rather than overt withdrawal. Thus, the pattern of left frontal hypoactivation may reflect absence of approach rather than overt withdrawal.

A second possible explanation for differences in the pattern of EEG power between the current study and previous work with infants may be that there are developmental changes in the reactivity of the two hemispheres. There are data which indicate that the right hemisphere matures earlier than the left (see Bell & Fox, 1994). Differences in the locus of power may thus be a function of developmental changes in hemispheric responsivity. The right hemisphere may be more reactive at an earlier age prior to the maturation of the left hemisphere and left hemisphere functions.

Another possible explanation for the different pattern of findings may involve understanding the different pathways by which infant or toddler behavioral inhibition is expressed during early and middle childhood. Previously, researchers have indicated that social withdrawal in early childhood is a risk factor for both anxiety-related disorders and depression. While the common behavioral pattern seen in infancy for these different outcomes may be behavioral inhibition, various environmental factors may influence the development (or lack of development) of different patterns of behavioral problems. It is possible that the pattern of EEG activity may change with the expression of different outcomes. At present, there are no longitudinal data that directly address this important issue. Whether the pattern of frontal EEG activity changes with the differential expression of certain behavioral styles or whether early patterns of EEG asymmetry remain stable across different paths that individuals take across development is an important question for future research.

Appendix

$$C_W = \frac{\sum_{\theta 1}^{\theta 2} \mathrm{Coh}\,(\theta)\,\hat{f}(\theta)}{\sum_{\theta 1}^{\theta 2} \hat{f}(\theta)}, \qquad (1)$$

where Coh is the coherence and $\hat{f}$ is the power at each frequency (Θ). In this example, (Θ) includes frequency 6 Hz, 7 Hz, and 8 Hz to define the alpha band in this age group.

$$\sum_{\theta 1}^{\theta 2} \mathrm{Coh}\,(\theta)\,\hat{f}(\theta), \qquad (2)$$

$$\sum_{\theta 1}^{\theta 2} \hat{f}(\theta) - \sum_{\theta 1}^{\theta 2} \mathrm{Coh}\,(\theta)\,\hat{f}(\theta). \qquad (3)$$

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