Task-dependent changes in frontal brain asymmetry: Effects of incentive cues, outcome expectancies, and motor responses

ANITA MILLER[a] AND ANDREW J. TOMARKEN[b]

[a]Departments of Psychiatry and Psychology, University of Pittsburgh, USA
[b]Department of Psychology, Vanderbilt University, Nashville, USA

Abstract

The current study was designed to clarify the psychological functions most closely associated with frontal brain asymmetry. Electroencephalography (EEG) was recorded from 60 participants while they performed a delayed reaction time (RT) task that included manipulations of incentive, expectancy, and response. Significant alpha asymmetry effects were reflected in topographic differences across anterior EEG sites. Variations in monetary incentives resulted in parametric changes in anterior frontal alpha asymmetry. Manipulations of outcome expectancies were related to mid-frontal EEG changes that differed for men and women. Varied response requirements were related to central asymmetry patterns. Taken together, the findings suggest that regionally specific patterns of frontal asymmetry are functionally related to particular aspects of approach–withdrawal tendencies involved in the temporal guidance and regulation of goal-directed behavior.

Descriptors: Brain physiology, Electroencephalography, Frontal cortex, Emotion, Motivation, Approach–withdrawal.

A growing body of evidence suggests that patterns of anterior electroencephalographic (EEG) asymmetry, or differences in activation between the left and right anterior regions of the brain, are related to emotional and motivational behaviors that are elicited in a variety of related contexts. The primary framework proposed to account for such relations is the approach–withdrawal model of anterior brain asymmetry (for reviews of this empirical and theoretical work, see Davidson, 1995; Davidson & Tomarken, 1989; Fox, 1991; Tomarken & Keener, 1998). According to this model, the left anterior cortex of the brain is part of a neural system that promotes positive emotions and approach-directed motivation to attractive cues and appetitive goals. The right anterior brain region is hypothesized to be part of a neural system that facilitates negative emotions and withdrawal-directed responses to aversive or threatening stimuli.

Despite a growing literature, questions remain about the particular emotional and motivational processes that are primarily indexed by anterior EEG asymmetry. Specification of component processes is critical given the broad nature of the approach–withdrawal hypothesis. The current study was designed to begin to address such questions.

Conceptual Rationale

Approach and Withdrawal

The conceptual approach for the study involved two strategies. The first strategy was to identify behaviors that have traditionally been examined in research on approach and withdrawal and investigate their relation to anterior EEG asymmetry. Approach and withdrawal have been studied primarily in the context of a neurobehavioral systems theory of emotion (see Tomarken & Keener, 1998). From this perspective, emotions are viewed as action dispositions that are driven by appetitive and aversive motivational systems (see Lang, 1995). Such neurobehavioral–emotional systems serve to guide and regulate responses to critical stimuli (see Depue, 1996; Depue & Collins, 1999; Fowles, 1994). Based on early work by comparative psychologists and neurophysiologists (e.g., Konorski, 1967; Schneirla, 1959), researchers have argued that emotional responses are fundamentally associated with either an appetitive set favoring approach (e.g., smiling and reaching for a loved one, salivating in response to food, seeking pleasant experiences) or an aversive set disposing one to withdraw (e.g.,

grimacing and closing the eyes in response to loud noises, fleeing from life threatening situations, avoiding aversive events).

Neurobehavioral studies of emotion have frequently focused on rewards and punishments to examine approach–withdrawal tendencies (see Glickman & Schiff, 1967; Gray, 1987; Robbins & Everitt, 1996; Rolls, 1999; Stellar & Stellar, 1985). Organisms often approach reward-related cues (e.g., seeking food) and withdraw from punishment-related cues (e.g., escaping from painful stimulation). Thus, one goal of the current study was to examine whether frontal brain asymmetry changes with parametric changes in the value of incentive cues. Notably, however, other factors might moderate or interact with the effects of incentives. One such factor is outcome expectancy, defined here as the anticipated likelihood of actually receiving a reward or punishment. Studies of achievement motivation have shown that incentive values and outcome expectancies interact to influence emotional–motivational tendencies to approach success and withdraw from failure (for reviews of expectancy-value models, see Atkinson, 1983; Feather, 1982; Higgins, Roney, Crowe, & Hymes, 1994). Given such observations, a second goal of the current study was to investigate whether asymmetry changes are related to variations in outcome expectancy and whether incentive effects are influenced by such expectancies. Another factor that might moderate incentive effects is the requirement of a motor response. Some researchers have referred to approach–withdrawal tendencies as literal movements "toward" or "away" (see Dawson, 1994). However, it is currently unclear whether overt motor responses potentiate the effects of incentives, expectancies, or other factors on asymmetrical activation in anterior regions. Thus, examining the effects of response requirements was the third goal of this study.

The Frontal Cortex

The second strategy for examining the specific psychological functions related to anterior EEG asymmetry was to constrain hypotheses based on the functions of the frontal cortex (see Tomarken & Keener, 1998). This strategy was pursued because most previous findings concerning EEG asymmetry and emotion have been reported for midfrontal sites (i.e., F3-F4). Such sites are located on the scalp above the prefrontal cortex (see Lagerlund et al., 1993), and activity at such sites may largely reflect frontal cortical desynchronization (see Pfurtscheller, Stancak, & Neuper, 1996). Thus, the psychological processes that are most closely related to the known functions of the frontal cortex may be the ones that are most closely related to anterior EEG asymmetry.

The functions of the frontal cortex are complex, but neuroscientists generally agree that the frontal lobes include at least three major functional subdivisions. First, the orbital frontal areas appear essential for appropriately directing actions in relation to rewarding and socially meaningful cues and for extinguishing behavior when environmental cues are punished or no longer rewarded (see Bechara, Damasio, & Damasio, 2000; Price, Carmichael, & Drevets, 1996; Rolls, 2000). Second, dorsolateral frontal areas appear critical for guiding goal-directed behavior in the absence of direct environmental stimulation (see Goldman-Rakic, 1987; Roberts, Robbins, & Weiskrantz, 1998). In particular, this subdivision has been implicated in two complementary functions: working memory and preparatory set (see Fuster, 1985, 1989). Working or active memory serves a retrospective function of temporarily retaining sensory information in a sequence toward a goal. Preparatory set (including motor preparation and cognitive expectancies) serves a prospective function to facilitate action toward significant upcoming or anticipated events. Third, the most

posterior frontal areas have a primary role in voluntary motor activities, such as executing specific limb and facial movements (see Ghez, 1991; Kaas, 1990). Thus, frontal cortical functions can be viewed in relation to incentive motivation, expectancy–mnemonic processes, and motor responses. These processes function together to guide goal-directed behavior over time.

Much of the evidence that the frontal lobes serve temporal guidance functions comes from studies with delay tasks. This evidence informed our choices about the paradigm used in the current study. Classic delay tasks include a gap in time between a salient stimulus and a related action or goal. The prefrontal cortex is critical for bridging such time gaps (see Fuster, 1985, 1989). A variety of findings support this point. First, specific prefrontal neurons are active during delayed-match-to-sample tasks, in which laboratory animals must temporarily remember salient stimulus information and respond successfully to receive rewards (see Fuster, 1989, 1990a; Goldman-Rakic, 1987, 1990). Some neurons preferentially respond after the initial stimulus to serve retrospective–mnemonic functions, and other neurons preferentially respond prior to the response to serve prospective–anticipatory functions (Fuster, 1990b). Second, researchers have recorded readiness and expectancy potentials over frontal scalp areas during delayed reaction time (RT) tasks, in which a warning stimulus precedes a cue for a motor response (Brunia, 1993; Brunia, Damen, & Bocker, 1993; Walter, Cooper, Aldridge, McCallum, & Winter, 1964). Third, prefrontal lesions impair cognitive and motivational performance on various delay and problem-solving tasks (see Jacobsen, 1935; Petrides, 1997). Data from various delay tasks suggest that the frontal cortex is involved in the temporal guidance and regulation of goal-directed behaviors.

Guiding Hypothesis

Taken together, the literature on approach–withdrawal and the literature on the frontal cortex can be used to constrain hypotheses about the primary functions indexed by anterior EEG asymmetry. In fact, these two separate bodies of literature provide a convergent focus on incentives, expectancies, and motor responses. Thus, the current study was designed to examine the contributions of such processes to task-dependent changes in frontal brain asymmetry. The guiding hypothesis was that variations in frontal asymmetry may functionally be related to specific components or correlates of approach–withdrawal tendencies that are involved in the guidance of goal-directed behaviors over time.

Paradigm Rationale

The rationale for the current paradigm was based on previous psychophysiological research on anterior EEG asymmetry. In a previous investigation of the approach–withdrawal hypothesis of anterior asymmetry, Sobotka, Davidson, and Senulis (1992) presented 15 participants with a delayed RT task. Approach and withdrawal were manipulated with monetary incentives and motor responses. During individual trials of the task, a warning stimulus indicated the incentive value (i.e., whether one could win or lose 25¢). Following a 4-s delay, a second stimulus prompted the RT response (i.e., a press or release with the right index finger). Feedback about change in earnings was then given based on the speed of the response.

EEG signals were quantified during the 4-s-delay interval. Primary attention was given to the suppression of alpha-frequency activity, derived with Fourier transforms of the EEG waveform (see Davidson, 1988). The contingent negative variation (CNV)

was also quantified, based on the literature on negative slow waves in RT paradigms (see Tecce & Cattanach, 1987).

Several important observations were reported. First, using measures of alpha suppression, Sobotka found greater relative left activation specifically at midfrontal recording sites during reward/win than during punishment/lose conditions. This supported the relation between frontal asymmetry and incentives. Notably, however, they reported a *relative* asymmetry shift between reward and punishment conditions, and they observed greater left than right frontal activity throughout the task. Second, they found greater left temporal-parietal alpha suppression during the button press (the approach movement) relative to the button release (the withdrawal movement). The hypothesized relation between approach–withdrawal movements and *frontal* asymmetry was not empirically supported. Third, manipulations of Incentive and Response were not related to the magnitude of the CNV prior to the response prompt. In addition, spectral power in the theta and beta bands was not related to the experimental manipulations.

The experiment by Sobotka et al. (1992) provided a rationale for using a delayed RT task to study the effects of incentive cues on frontal alpha desynchronization. Although this task does not elicit working memory processes, per se (see Ruchkin, Canoune, Johnson, & Ritter, 1995), it has been used to study reward expectancy and the orbitofrontal cortex (see Hikosaka & Watanabe, 2000). Given previous work, a modified delayed RT task was ideal for testing our hypotheses about the primary functions associated with frontal brain asymmetry.

The Current Experiment: Overview and Predictions

In the current study, EEG was recorded continuously in normal young adults while they performed a delayed RT task. Experimental variables operationalized constructs that have been emphasized in the bodies of literature on approach–withdrawal and the frontal cortex. In particular, we examined the effects of incentive cues, outcome expectancies, and motor responses on frontal brain asymmetry. Each will be discussed in turn.

The Incentive Manipulation

Our first independent variable was incentive, or the amount of money one could win or lose on each trial. The goal was to examine how frontal asymmetry changed in relation to specific incentive stimuli. Notably, Sobotka and his colleagues (1992) included only reward and punishment conditions in their study, so it was unclear whether their asymmetry effects were due to reward, punishment, or both. Parametrically varied incentives with a neutral condition were needed to clarify such effects. Thus, the current study included five levels of incentive: large reward, small reward, no incentive, small punishment, and large punishment.

Specific hypotheses were tested about changes in anterior EEG asymmetry related to the incentive variable. In general, relative left frontal activation was expected during the reward conditions, and shifts toward right frontal activation were predicted during the punishment conditions. More specifically, variations in the degree of incentive were expected to result in parametric changes in frontal asymmetry. These predictions were based on the hypothesis that the relative balance of left and right frontal activation may be related to valence discriminations among emotionally relevant cues (see Aftanas, Koshkarov, Pokrovskaja, & Lotova, 1996).

The Expectancy Manipulation

Our second independent variable was expectancy, defined here as the probability or likelihood of achieving a successful outcome.

Such expectancies of success and failure appear to influence approach- and withdrawal-related processes such as task engagement, enjoyment, and effortful processing (see Atkinson, 1983). We included high, medium, and low expectancy conditions. On high expectancy trials, participants could easily respond correctly and had a high probability of success. On medium expectancy trials, participants had a moderate chance of succeeding. On low expectancy trials, the task was extremely difficult, and participants had a low likelihood of success. This was the first known study to examine anterior EEG asymmetry and outcome expectancy.

Two competing hypotheses were tested about EEG changes related to expectancy. One hypothesis was that relative left anterior activation would increase linearly as the expectancy for success increased, suggesting that anterior asymmetry is sensitive to the level of attainable success. An alternative hypothesis was for a curvilinear effect, such that the greatest left anterior activity would occur during the medium expectancy condition. Given that people often show maximal task engagement and effortful processing during medium relative to high or low expectancy conditions (e.g., Feather, 1982; Wright, Contrada, & Patane, 1986), such a finding would suggest that frontal asymmetry may be related to task engagement and effortful processing to achieve desired goals. To clarify such effects, self-report questions were included during the task to assess emotional experience and engagement.

The Response Manipulation

The third independent variable was response. The goal was to examine whether response requirements influence asymmetry shifts. Given Sobotka et al.'s (1992) findings that overt press–release movements are not related to frontal asymmetry, we did not include this manipulation. Instead, we focused on two other factors that could have influenced asymmetry.

First, our response manipulation included a between-subjects comparison of active and passive responses. Response demands are notable given that the frontal cortex bridges sensory–motor systems and guides response sequences (see Roberts et al., 1998). Thus, some participants made active RT presses, and others made no overt responses. We tested two competing hypotheses about response. If directed motor responses are necessary to elicit changes in frontal EEG asymmetry, then incentive and expectancy effects should be maximized during the active relative to passive conditions. In contrast, if actual motor responses are not necessary to elicit changes in asymmetry, then effects for the other variables might be similar across the active and passive conditions. The latter would suggest that frontal EEG asymmetry may be related less to motor responses, per se, and perhaps linked more to complex emotional–cognitive processes.

Second, the response manipulation included a between-subjects comparison of left- and right-hand conditions. In addition to the passive response group, a second group made active RT presses with the right index finger, and a third group made active presses with the left index finger. This manipulation was designed to specify the active response demands and to examine the potential confound between lateralized motor control and the effects of other variables. Given the contralateral cortical control of voluntary hand movement (see Ghez, 1991; Kim et al., 1993), we predicted left frontal-central activation during the right-hand condition and right frontal-central activation during the left-hand condition. In addition, we examined whether frontal asymmetry effects for incentive are influenced by left-right responses. A significant Response × Incentive interaction would help to explain why Sobotka et al. (1992) found that relative asymmetry shifts between reward

and punishment were superimposed on absolute left frontal asymmetry during both conditions. It may be the case that such absolute left frontal asymmetry occurs only during right-handed responses (as in the Sobotka et al. study), but not during left-handed responses. However, if we did not observe such a pattern, then frontal EEG asymmetry may be related less to overt movements than to other factors.

Summary

This study examined EEG asymmetry effects of incentive, expectancy, and response during a delayed RT task. Predictions were generated in the context of the guiding hypothesis that frontal brain asymmetry may be related to specific approach–withdrawal tendencies involved in the temporal guidance and regulation of goal-directed behavior.

Methods

Participants

Sixty-three college students were recruited from the Introductory Psychology Pool at Vanderbilt University. Three participants did not complete the study due to excessive fatigue, inattention, or anxiety, and their data were excluded from analyses. The final sample consisted of 30 men and 30 women. Ten men and 10 women were randomly assigned to the (1) right-response condition, (2) left-response condition, or (3) passive condition. The sample was 75% Caucasian, 10% Asian, 8% American Indian, 3% Arabic, 2% African American, and 2% Hispanic. The mean age was 19 years. The sample was restricted to right-handed participants (Oldfield, 1971). Individuals with a neurological disorder were excluded from the study.

Procedures

Overview. Each participant came to the laboratory for two experimental sessions. The two sessions lasted 3 h each and were separated by 1 week. Informed consent was obtained at the beginning of the first session. The task was introduced as follows:

The Money Game

The object of the game you are about to play is to make as much money as you can. First, you will be given $5. On specific problems, you can either lose this money or win more money. The money you earn will be yours to keep. In addition, one participant will win $200. Your ID number will be entered into a lottery, and the entry will be weighted based on your performance on this task. The better you do on the task, the higher the probability of winning the $200. The money will be awarded at the end of the year, after the study is completed.

Following the introduction, we presented specific instructions about the details of the task. Participants then completed 20 practice problems to ensure that they understood the task.

Each of the two sessions included six experimental blocks of 40 trials each. Thus, the task consisted of 240 experimental trials per session and 480 total trials across the two sessions. The incentives (i.e., how much money one could win or lose) were varied within sessions on a trial-by-trial basis. Expectancy conditions (i.e., how likely one was to actually win or lose money) were blocked, such that each block of 40 trials had a high, medium, or low chance of success. Twenty-four different block orders (e.g., high-med-low-high-med-low) were created and counterbalanced in the experiment. Response conditions were varied among three groups of participants. Thus, each participant made only right, left, or pas-

sive responses throughout the task. Given the length of the task, 5-min breaks were given after every block (i.e., after every 40 trials). During the breaks, participants rested and made emotion ratings. The breaks facilitated participants' focus, minimized movement artifacts, and maximized data quality.

Apparatus. Participants were seated in a chair in front of a small table. The head was stabilized with a chin rest from Richmond Products, Inc. This apparatus helped participants to remain still during the task, thus minimizing movement artifacts in the physiological recordings. Stimuli were presented 35 cm in front of the participants on a 21-in. Nokia computer monitor. A PC presented the task and sent a synchronization signal to the physiology acquisition computer.

EEG and electrooculographic (EOG) data were collected continuously during each block of trials. The data were amplified and filtered with a bioamplifier from the James Long Company, set for bandpass filtering with half power cutoff frequencies of 0.01 and 100 Hz (12 dB/octave rolloff). The gain was 5000 for EEG channels and 2500 for EOG channels. Data were digitized at 512 Hz, using the signal acquisition package Snapstream.

Task presentation. The individual trial sequence consisted of three cues and three delay periods. First, a warning stimulus was presented for 500 ms to designate the incentive value. Large-reward, small-reward, no-incentive, small-punishment, and large-punishment incentive conditions were signified by: "+$1," "+10¢," "$0," "−10¢," and "−$1," respectively. This stimulus cued participants to "get ready" for the upcoming response prompt.

Following a 6-s delay period, a 3-cm square appeared for 500 ms in the middle of the screen. This square prompted participants in the right condition to press the button with the right index finger, participants in the left condition to press the button with the left index finger, and participants in the passive condition to think the word *now*. Information about the specific responses was given during the instructions. The task stimuli were the same for all participants. Everyone was told that the goal of the task was to respond as quickly as possible to the square.

Following a 5-s delay from the offset of the square, the feedback stimulus, a five-tier box, appeared for 500 ms. It indicated the outcome for that trial. The outcome represented the change in monetary earnings based on the speed of the response. A dot in the first, second, third, fourth, or fifth tier indicated a win of $1, a win of 10¢, no monetary change, a loss of 10¢, or a loss of $1, respectively. Finally, a 6-s postfeedback and intertrial interval occurred between trials. An asterisk was presented as a fixation point during the delays and the intertrial intervals to minimize eye movements.

At the beginning of each trial block, participants were shown a stimulus designating the current expectancy level (i.e., "Chance of Success: High," "Chance of Success: Medium," "Chance of Success: Low"). The chance of success was controlled by changing the RT criteria. For the active response conditions, the criteria were based on the participant's own RTs. On high expectancy trials, the criterion time was equal to the fifth percentile RT latency from the 20 previous trials. On these trials, they could easily succeed (mean success rate = 91.20%). On medium expectancy trials, the criterion was set to the RT that fell at the fiftieth percentile. These trials were moderately difficult (mean success rate = 49.67%). On low expectancy trials, the criterion was the RT that fell at the ninety-fifth percentile. On these trials, it was relatively improbable that participants would respond correctly on any given trial (mean

success rate = 5.47%). For participants in the passive response condition, success rates were set by the computer at 95%, 50%, and 5% for high, medium, and low expectancy blocks, respectively. No participants were told details about how we controlled the probability of success.

Emotion ratings. During the task, participants completed two brief emotion questionnaires following each experimental block (i.e., six times per session). The first questionnaire was the Positive and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988), which included ratings of various affective words (e.g., interested, determined, distressed, irritable). The PANAS is a factor analytically developed instrument that consists of two primary scales. The Positive Affect Scale assesses active engagement and positive emotional responses. The Negative Affect Scale assesses unpleasant engagement and negative emotional responses. A second set of questions was used to inquire about several specific responses to the task. For example, participants were asked to use a 7-point scale to rate their feelings of happiness and unhappiness during specific reward and punishment trials.

EEG recording. EEG recording followed standard guidelines (see Pivik et al., 1993). Continuous recordings during task blocks were made from 32 tin scalp electrodes sewn into a Lycra stretchable cap from Electro-Cap International, Inc. (see Blom & Anneveldt, 1982). The cap was positioned on the head using an expanded 10-20 International System (American Electroencephalographic Society, 1994; Jasper, 1958). Based on precedents from previous research, primary attention was given to middle frontal (F3-F4), central (C3-C4), and middle-parietal (P3-P4) sites. In addition, anterior frontal (AF3-AF4) leads were also included in the group of primary electrodes. These sites were chosen because they are the electrodes closest to the middle-frontal leads and gave better representation to target frontal areas. In addition, tin drop electrodes from the cap were used to record from the left and right earlobes (A1-A2). All scalp sites were recorded referenced to vertex (Cz). The frontal midline site (Fz) was used as the isocommon ground. Nine millimeter tin cup electrodes were placed above and below the eyes to record blinks and vertical eye movements and on the outer canthi to record horizontal eye movements. The EOG was recorded using a bipolar reference. All electrode impedances were under 5 kΩ, and impedances for homologous sites were within 500 Ω of each other. Impedances were documented to change minimally during the course of the experiment.

Data Reduction

Multiple methods were used to minimize artifacts and noise in the data. To maintain the integrity of original data, we asked participants to place the head in a chin rest and fixate the eyes on a central point. In addition, extensive manual postsession reviews with EEGEDIT software (James Long Company) were performed to edit the EEG signals. This procedure eliminated epochs that were confounded by artifacts such as movement, extensive muscle tension, and saccades. Eighteen percent of the 1-s data chunks were rejected due to artifacts in this study. Furthermore, prior to this artifact excision process, a correction was used to remove the effects of blinks from the EEG data to maximize the amount of data available for analyses.

The blink correction routines were developed for this study, based on methods described in the literature (e.g., Lins, Picton, Berg, & Scherg, 1993a, 1993b). Given that the EOG signal propagates by volume conduction across the skull, we computed prop-

agation factors to scale the EOG signal for blink correction. First, we used a three-point algorithm with the vertical EOG channel to quantify the rate of change of the slope. This identified portions of the data containing blink exemplars. Second, to prepare a temporary data file for computing propagation factors, all channels in the physiology record were low-pass filtered at 7 Hz. This decreased the amount of EEG and muscle activity that contaminated the EOG signal and the blink propagation factors (see Lins et al., 1993a). Thus, we maximized the focus on blink activity in EOG and EEG recordings and minimized biases from brain activity recorded at both eye and scalp sites. Third, using the filtered data file of blink epochs, the vertical EOG signal was regressed on each unique EEG site to estimate propagation factors (i.e., beta weights) that characterized the linear relation between the vertical EOG site and the blink artifact at each EEG site. Next, the temporary filtered data file was discarded. The actual blink correction was then applied to the entire *original unfiltered* data. This approach ensured that the data remained continuous and continuously differentiable, which is a prerequisite for performing discrete Fourier transforms. The correction was implemented by using the propagation factors as coefficients in linear transformations to residualize the EEG from the blink-contaminated signal by computing [EEG-βEOG] for each EEG sample.

We tested the blink correction procedures before they were used for this study. First, we compared different least squares regression models, one with vertical EOG as the sole predictor and the other with both vertical and horizontal EOG as predictors. Results showed that the horizontal EOG did not account for sufficient variance to be included in the algorithms for this study. Next, after implementing and testing the integrity of the linear regression methods, we investigated whether we were biasing spectral power as a result of applying the correction to the continuous data set. In particular, we compared the residualized data against the raw data for epochs that were clearly free of any artifacts. Results showed that we were not introducing biases in the continuous data set because we found correlations in the .98 to .99 range between alpha power from the "corrected" and "uncorrected" artifact-free epochs. In addition, we examined the impact of lateralized vertical EOG placement. We found no significant differences in EEG power or asymmetry when left versus right vertical EOG placements were used.

Following the artifact-reduction procedures, data were rereferenced off-line using James Long Company EEG Analysis System software. In particular, we performed linear transformations of the digitized EEG to derive a computer-averaged ears reference (see Davidson, 1988; Senulis & Davidson, 1989). This ears-based referencing scheme is consistent with the analytic approach often adopted in the literature (e.g., Sobotka et al., 1992).

The EEG Analysis System software was then used to execute discrete Fourier transforms of the digitized EEG during specific stimulus-labeled delay epochs. The software used a Hanning window to identify 1-s periods of artifact-free data within each target delay epoch. The windows were overlapped by 50%. The resulting estimates of spectral power from 1-Hz bins were clustered together into broad bands. The frequency band of primary interest was alpha (7.5–12.5 Hz) because empirical evidence has indicated that alpha power varies inversely with cortical activation in adults (e.g., Davidson, 1988; Pfurtscheller, 1986; Pfurtscheller & Klimesch, 1991). In addition, the clear majority of previous frontal EEG and emotion findings pertain to the alpha band (see Davidson & Tomarken, 1989). Power values were converted to power density scores and were averaged within blocks for each delay interval and

experimental condition. The condition-specific power density scores were transformed to natural logarithms to normalize the distribution of scores to be used in statistical analyses (Gasser, Bacher, & Mocks, 1982).

Based on previous research, our a priori hypotheses focused on alpha suppression during the warning stimulus interval. Consistent with this, preliminary results from theta and beta bands did not show meaningful task-related patterns. In addition, clear effects were specific to the warning-stimulus interval and were not found for the postresponse interval nor the intertrial interval. Furthermore, we did not include CNV data, because results from Sobotka et al. (1992) did not show a relation between CNV amplitude and incentive or response manipulations.

Data Analysis

A multivariate repeated measures approach was chosen to test experimental hypotheses (see Keselman, 1998). The Pillai's Trace statistic was selected to evaluate predictions (see Olson, 1976). All a priori hypotheses were tested with an alpha level of .05. To control the experiment-wise error rate, initial EEG analyses focused on four primary pairs of scalp electrodes: anterior frontal (AF3-AF4), middle frontal (F3-F4), central (C3-C4), and middle parietal (P3-P4). These sites were selected based on previous research. Consistent with the a priori strategy, results at these sites were more robust and interpretable than later exploratory analyses that included all recording sites. Session was not included as a factor because preliminary analyses did not reveal significant effects for this factor. A Bonferroni correction procedure was adopted for familywise error control of post hoc comparisons. Results from questionnaire, behavioral, and physiological data will each be discussed in turn.

Results

Task-Related Emotion Questionnaires

A repeated measures analysis of variance was conducted with the PANAS data from each expectancy block. Between-subjects factors included Response (left hand, right hand, passive response) and Sex (male, female). Within-subjects factors were Expectancy (high, medium, low) and Emotion Scale (PA, NA). Incentive was not included as a factor because it was intermixed within blocks. The omnibus analysis revealed a main effect for Emotion Scale, $F(1,54) = 83.38, p < .0001$; a main effect for Expectancy, $F(2,53) = 10.82, p < .001$; and an interaction for Emotion Scale $\times$ Expectancy, $F(2,53) = 35.41, p < .001$. No sex differences were found. The Emotion Scale $\times$ Expectancy interaction is shown in Figure 1. The affect intensity scores for Positive Affect (PA) and Negative Affect (NA) Scales are shown for each of the expectancy conditions. The figure documents that there were linear decreases in PA and increases in NA across the high, medium, and low expectancy conditions. The results of post hoc linear trend contrasts were significant for both PA, $F(1,59) = 60.21, p < .0001$, and NA, $F(1,59) = 38.04, p < .0001$.

Additional questions assessed emotional responses to reward and punishment incentive conditions. Specifically, participants completed 7-point rating scales indicating the degree to which they felt happy and unhappy during reward and punishment trials. A repeated measures test revealed a Reported Emotion (happy, unhappy) $\times$ Incentive (reward, punishment) interaction, $F(1,54) = 52.74, p < .0001$. The results of post hoc contrasts showed that participants reported greater happiness during the reward than punishment conditions, $F(1,59) = 6.43, p < .02$, and greater unhappiness during the punishment than reward conditions, $F(1,59) = 43.21, p < .0001$.

Reaction Time Responses

A repeated measures analysis of variance was conducted with the RT data. Factors included Response (left hand, right hand) $\times$ Sex (male, female) $\times$ Incentive (large reward, small reward, no incentive, small punishment, large punishment) $\times$ Expectancy (high, medium, low). This analysis showed main effects for Incentive, $F(4,29) = 50.45, p < .0001$, and Expectancy, $F(2,31) = 5.24, p < .01$. No sex differences were found. A significant quadratic contrast was observed for Incentive, $F(1,32) = 171.57, p < .0001$, suggesting that the fastest responses occurred in the large incentive conditions (mean RTs: LR = 234 ms, LP = 240 ms) and the
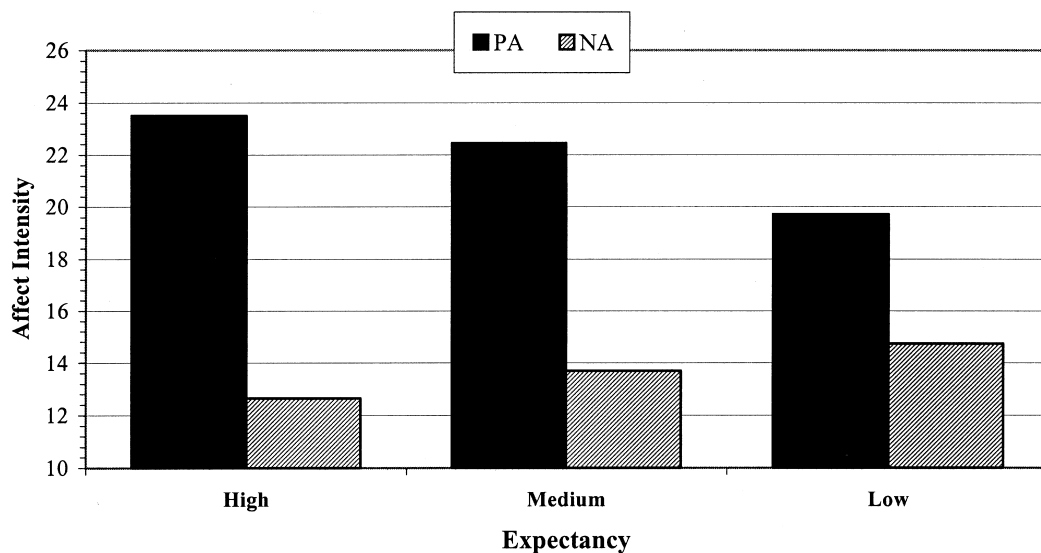

Figure 1. Self-reported positive and negative affect related to expectancy.

slowest responses occurred in the no incentive condition (mean RT: NI = 288 ms). RTs for the small incentive conditions fell between these values (mean RTs: SR = 251 ms, SP = 250 ms). Post hoc contrasts showed that the omnibus effect for expectancy was related primarily to faster reactions in the medium (mean RT: 238 ms) relative to high (mean RT: 244 ms) expectancy conditions, $F(1, 32) = 10.44, p < .003$.

Electroencephalography

Repeated measures analyses of variance for the EEG data included six factors. Response (left hand, right hand, passive response) and Sex (male, female) were included as between-subjects factors. Within-subject factors were: Incentive (large reward, small reward, no incentive, small punishment, large punishment), Expectancy (high, medium, low), Epoch (first-half, second-half of the warning-stimulus interval), and Hemisphere (left, right).
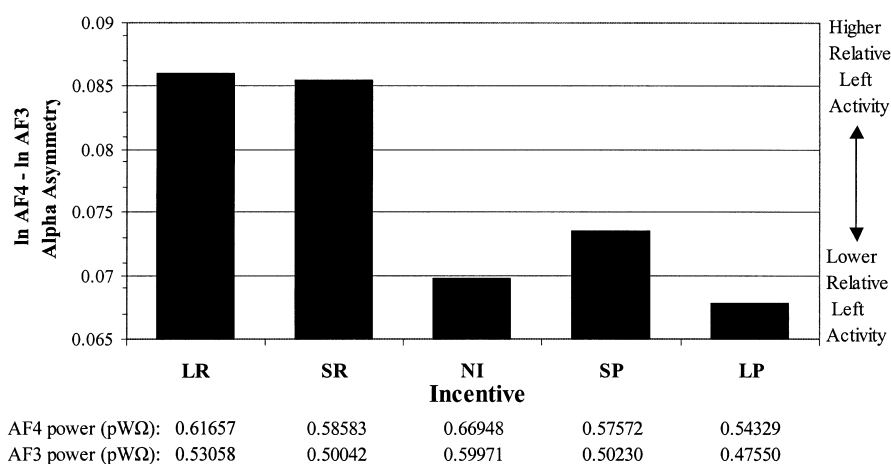
Omnibus Effects. An initial multivariate repeated measures analysis of variance included Region (anterior frontal, middle frontal, central, parietal) with the above variables. Overall results included several main effects. In particular, we observed main effects for Region, $F(3, 51) = 148.23, p < .0001$; Hemisphere, $F(1, 53) = 14.28, p < .0004$; Interval $F(1, 53) = 26.93, p < .0001$; and Incentive, $F(4, 50) = 8.38, p < .0001$. In addition, we found several interactions of Incentive, Expectancy, and Response with Region and Hemisphere. First, there was a Region × Hemisphere × Incentive interaction, $F(12, 42) = 2.23, p < .03$. Second, interactions relevant to Expectancy included a Region × Hemisphere × Expectancy × Sex effect, $F(6, 48) = 2.37, p < .05$; a Region × Hemisphere × Expectancy × Interval effect, $F(6, 48) = 2.94, p < .02$; and a Region × Expectancy effect, $F(6, 48) = 2.74, p < .02$. Third, we found a Region × Hemisphere × Response interaction, $F(8, 102) = 3.86, p < .002$. Site-specific analyses to clarify the region effects related to incentive, expectancy, and response were used to test a priori predictions.

Incentive. We predicted an Incentive × Hemisphere interaction at anterior EEG sites. In particular, we hypothesized that the greatest relative left frontal activation would occur during the large reward condition and the greatest relative right frontal activation would occur during the large punishment condition. Overall, we predicted a linear trend indicating progressive decreases in left frontal activity across the large reward, small reward, no incentive, small punishment, and large punishment conditions. This pattern was expected to be most evident for anterior sites that lie over the frontal cortex (i.e., AF3-AF4 and F3-F4 but not C3-C4 and P3-P4).

Asymmetry differences related to the incentive manipulation occurred at the more anterior pair of frontal sites. In particular, the Incentive × Hemisphere interaction was significant specifically at anterior frontal (AF3-AF4) sites, $F(4, 50) = 4.89, p < .002$. Figure 2 illustrates the means for this effect. Given that an interaction involving hemisphere is equivalent to a main effect for asymmetry, the data are presented simply as asymmetry metrics in this figure. Power at specific sites is given below each condition label. In keeping with the general hypotheses, greater relative left alpha suppression occurred during reward than during punishment conditions. In addition, the results supported the general hypothesis that manipulations of reward and punishment are related to parametric changes in frontal asymmetry, but greater relative left anterior frontal activation was not observed in the neutral condition relative to the small punishment condition. A linear trend was found for the Incentive × Hemisphere interaction, $t(1, 53) = 12.81, p < .0007$. As shown in Figure 2, progressive declines in left anterior frontal activation were observed as we moved from large reward to small reward and from small punishment to large punishment.

Incentive × Hemisphere interactions were not statistically significant at the other target frontal sites. Thus, our hypotheses about incentive were not supported for F3-F4 sites. Notably, significant main effects for incentive were found at all sites, including F3-F4, $F(4, 50) = 10.05, p < .0001$. An alpha-adjusted, post hoc contrast demonstrated a quadratic pattern to these effects, $F(1, 53) = 25.15, p < .0001$. The greater alpha suppression during the large incentive conditions appeared to parallel the faster RTs that occurred in these conditions (see above results).

Figure 2. Anterior-frontal alpha asymmetry effect for incentive. Data are presented as right:left asymmetry ratios for alpha power density (i.e., the electrical activity in the 7.5–12.5 Hz band). Scores are computed as the natural logarithm of alpha power density at the right anterior-frontal recording site minus the logarithm of alpha power density at the left anterior-frontal recording site (i.e., lnAF4 − lnAF3). Given that alpha power density varies inversely with cortical activation, higher values represent greater relative left anterior activation. The X axis identifies the five incentive conditions: LR = large reward, SR = small reward, NI = no incentive, SP = small punishment, LP = large punishment.

Despite the overall pattern of effects, more limited analyses revealed results similar to those reported by Sobotka et al. (1992). Our midfrontal data for the right-hand, medium expectancy, small reward, and punishment conditions were most similar to this previous study (see the introduction). Thus, data from these conditions provided the best test of replicability. A simple effects analysis showed greater relative left midfrontal asymmetry during small reward than during small punishment conditions, $F(1, 18) = 4.44$, $p < .05$. This finding replicates the previous midfrontal incentive effect. In addition, the mean asymmetry differences found in these conditions were almost identical to the asymmetry differences reported previously. Yet, the fact remains that results across all levels of incentive in our study were not significant at midfrontal sites. Our incentive effects were stronger at anterior frontal sites.
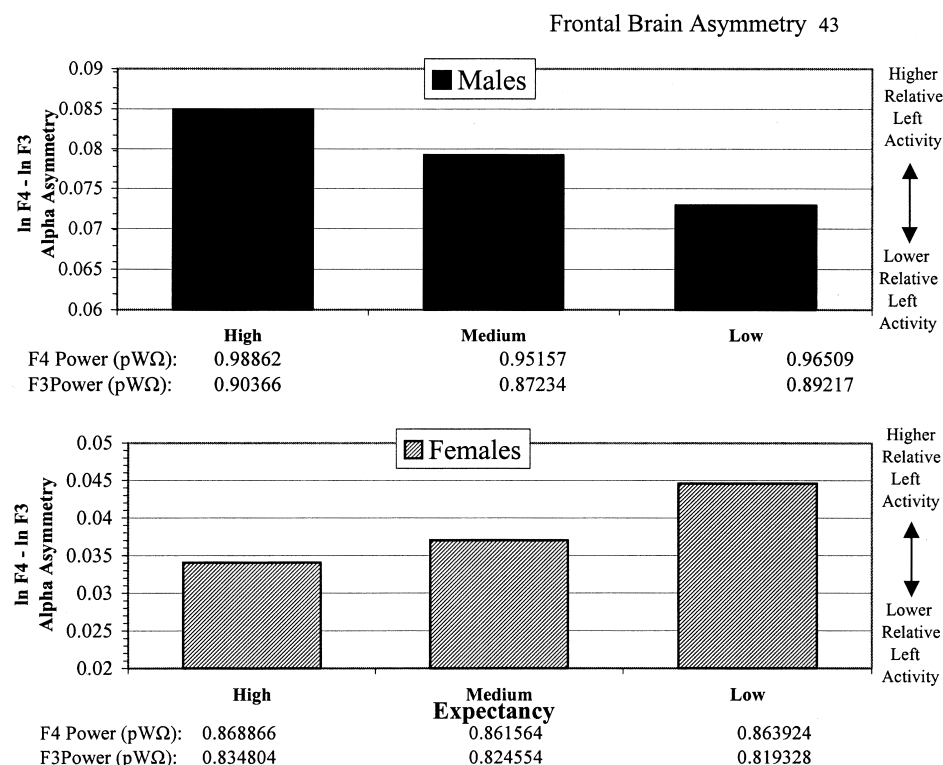
Expectancy. Although we predicted significant Expectancy × Hemisphere interactions, such effects were not found. However, we did find a Hemisphere × Expectancy × Sex interaction specifically at middle frontal sites (F3-F4), $F(2, 52) = 4.24$, $p < .02$. The asymmetry scores are illustrated in Figure 3. Males showed the greatest relative left midfrontal activation during the easy, high expectancy condition and linear decreases in left midfrontal activation during the medium and low expectancy conditions. However, females showed the greatest relative left midfrontal activation during the difficult, low expectancy condition and linear decreases in left midfrontal activation during the other two conditions. An alpha-adjusted post hoc linear trend was found for the Hemi-

sphere × Expectancy × Sex interaction, $F(1, 53) = 8.60$, $p < .005$. Linear trends were found for both males, $F(1, 29) = 4.32$, $p < .05$, and females, $F(1, 29) = 4.26$, $p < .05$.

Response. The response variable was included in the current study in order to assess (1) the degree to which alpha suppression is influenced by right- and left-handed responses, and (2) to clarify whether asymmetry changes depend on participants making active motor responses.
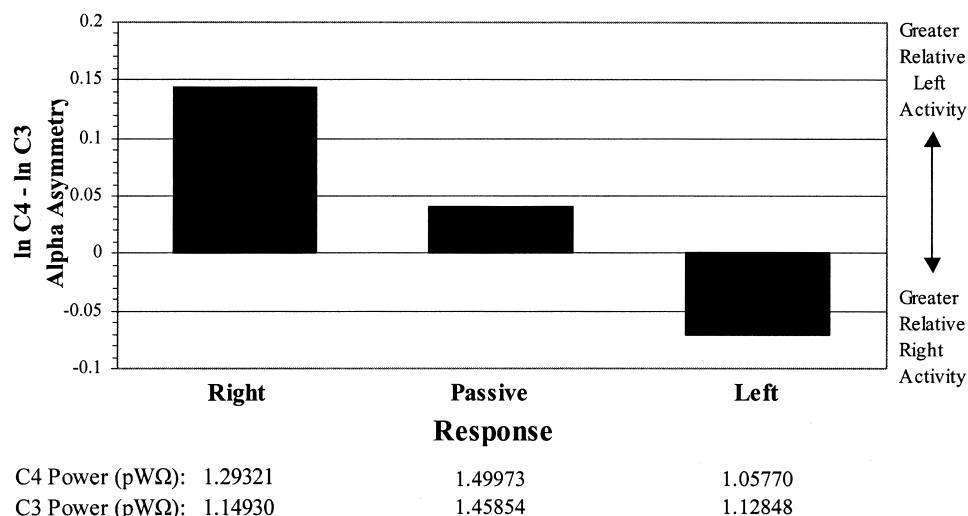
First, the results were consistent with the well-established contralateral cortical control of voluntary motor function. In particular, the Response × Hemisphere interaction was significant at central sites (C3-C4), $F(2, 53) = 8.17$, $p < .0008$, and parietal sites (P3-P4), $F(2, 53) = 6.98$, $p < .002$. The asymmetry effect for central sites is shown in Figure 4. This figure shows greater left central activity during the right-hand response condition and increased right central activity during the left-hand condition. The asymmetry value for the passive condition fell between these values.

Second, we tested competing hypotheses about whether the effects of incentive and/or expectancy were conditional upon response requirements. Results showed no significant interactions between response and hemisphere at frontal leads (all $ps > .05$). In addition, we did not find that response differentially interacted with incentive or expectancy. In the region where we observed the strongest incentive effects (AF3-AF4), we did not find interactions involving response. Motor response requirements did not moderate the effects of frontal asymmetry.

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	High	**Medium**	**Low**
F4 Power (pWΩ):	0.98862	0.95157	0.96509
F3 Power (pWΩ):	0.90366	0.87234	0.89217

	High	**Medium**	**Low**
F4 Power (pWΩ):	0.868866	0.861564	0.863924
F3 Power (pWΩ):	0.834804	0.824554	0.819328

Figure 3. Midfrontal alpha asymmetry Expectancy × Sex interaction. The data are presented as asymmetry scores, and higher values reflect greater relative left midfrontal activation.

Figure 4. Central alpha asymmetry effect for response. The data are shown as asymmetry scores. Higher scores reflect greater left central activation.

Discussion

The current study was part of a program of research to clarify the psychological functions most closely associated with frontal brain asymmetry (see Tomarken & Keener, 1998). We generated predictions based on the approach–withdrawal model of frontal brain asymmetry and a temporal guidance model of frontal lobe functions. Our guiding hypothesis was that variations in frontal brain asymmetry may be linked to specific emotion-related functions involved in the guidance of goal-directed behavior over time. The results reported here were of interest both for what was found and for what was not found.

The overall results showed regionally specific changes in EEG asymmetry related to manipulations of incentive cues, outcome expectancies, and motor responses. Significant asymmetry effects for incentive, expectancy, and response occurred at anterior frontal, midfrontal, and central recording sites, respectively. The effects of these variables were not reflected in interactions at the midfrontal sites. Rather, effects were observed as topographic differences across anterior EEG sites. Issues related to each manipulation will be discussed in turn.

Incentive

Our results clarified the relation between frontal brain asymmetry and reward–punishment contingencies. The relative balance of left and right anterior frontal brain activity changed with parametric variations in incentive values within a goal-directed task. This effect was notable given basic neuroscience research. Such work has shown that orbital frontal areas are involved in responding to reward-related cues (for reviews, see Robbins & Everitt, 1996; Rolls, 1999, 2000). For example, Tremblay and Schultz (1999) showed that orbitofrontal neuronal activity in monkeys increased in response to rewards and reward-predicting signals. The neurons discriminated different rewards, primarily based on the relative preference among available rewards rather than physical reward properties. Hikosaka and Watanabe (2000) reported similar results using a delayed RT task with monkeys. This suggests that orbitofrontal neurons discriminate among incentives related to the motivational control of goal-directed behavior.

The current results were also notable in relation to the study by Sobotka et al. (1992). As described in the introduction, these researchers varied the possibility of winning 25¢ versus losing 25¢ in a delayed RT task while they recorded EEG. They found significantly greater relative left alpha suppression at midfrontal recording sites during the reward/win condition than during punishment/lose condition. We replicated these findings with a subset of our data from the conditions most similar to those used in the Sobotka et al. study. In particular, we found greater relative left midfrontal activity in response to small rewards versus small punishments when analyses focused on the medium expectancy, right-hand response conditions.

Despite the replication, our overall results demonstrated the relative weakness of the aforementioned midfrontal EEG effect. In particular, we did not observe a Hemisphere × Incentive interaction at middle frontal recording sites (i.e., F3-F4) when all conditions were included in the analysis. Rather, parametric asymmetry changes across the large reward, small reward, no incentive, small punishment, and large punishment conditions occurred specifically at anterior frontal recording sites (i.e., AF3-AF4). Our interpretation of this effect was that anterior frontal asymmetry changes were related to discriminating the relative preference of salient reward and penalty cues. Such effects are not likely due to artifacts such as eye movements, given the careful artifact scoring of the present data. For reasons that are not clear, the effects found by Sobotka may be limited to specific combinations of task parameters, such as moderate rewards. Stronger effects for incentive appear to be linked to anterior frontal sites.

Several questions remain about the details of our anterior frontal incentive effect. First, as illustrated in Figure 2, we did not observe greater left anterior frontal asymmetry during the neutral relative to the small punishment conditions. It is unclear why this was the case, but it may reflect differences in general task engagement. It is possible that participants were less engaged during the neutral condition (in which they could neither win nor lose money) than in the small punishment condition (in which they could avoid losing money). The slower RTs in the neutral condition are consistent with this, assuming that slower RTs reflect less engagement. Such generalized task engagement may be another type of ap-

proach motivation that is superimposed on the appetitive anticipation of rewarding outcomes (see Tomarken, Davidson, Wheeler, & Doss, 1992).

Second, as seen in Figure 2, we observed overall left greater than right anterior frontal activity during all incentive conditions. This was also true in the Sobotka et al. (1992) study. Given such findings, we examined whether the left frontal asymmetry reflected a confound with right-handed responses, given the known contralateral hemispheric control of voluntary movements. However, we found greater left than right hemisphere activation during both reward and punishment conditions regardless of whether participants made right- or left-handed responses. Alpha suppression at central, not frontal, sites varied in relation to the hand of response. Given such results, questions remain about how to interpret the overall pattern of left frontal asymmetry. On the one hand, asymmetry patterns could possibly be influenced by the nature of the experimental task manipulations. For example, greater right frontal activity might be observed in response to more aversive conditions than losing money. From another perspective, the overall pattern of relative left frontal asymmetry may be related to tonic resting patterns of brain activity. Further work is needed to examine interactions between phasic, task-dependent changes and tonic, individual differences in asymmetry (see Davidson & Tomarken, 1989).

Expectancy

A second set of issues was related to expectancy, or the anticipated likelihood of actually receiving a reward or punishment. We examined whether outcome expectancy was related to changes in frontal asymmetry and whether it interacted with incentive manipulations. The primary observation was a Hemisphere × Expectancy × Sex effect at midfrontal regions. Males displayed linear changes in relative left frontal asymmetry, with the greatest left asymmetry for the high expectancy condition and lowest for the low expectancy condition. This pattern was consistent with the hypothesized linear relation between expectancy and asymmetry. However, females showed linear changes in relative left frontal asymmetry that were highest for the low expectancy condition and lowest for the high expectancy condition. Thus, variations in outcome expectancies resulted in opposite linear changes in midfrontal asymmetry for men and women.

Questions remain about how to interpret the finding that men and women showed opposite asymmetry changes related to the expectancy manipulation. Most literally, our data suggested that increases in relative left midfrontal asymmetry indexed increases in the likelihood of success in males but that decreases in relative left midfrontal asymmetry were related to greater chances of successful outcomes in females. Understanding the nature of this difference requires more research. However, several hypotheses can be raised.

One possibility is that sex differences in frontal EEG may reflect differences in basic physiological processes elicited by delay tasks. Notably, positron emission tomography (PET) studies have shown greater frontal cerebral blood flow in women than men during delayed alternation, spatial delayed response, and Wisconsin card sorting tasks, but not during sensorimotor control tasks (Esposito, VanHorn, Weinberger, & Berman, 1996). Using similar tasks with pharmacological hormone challenges, these researchers also demonstrated that administration of a gonadotropin-releasing hormone agonist (Lupron) markedly attenuated task-related frontal cerebral blood flow in women and that hormone replacement with estradiol or progesterone normalized the pattern of brain activation (Berman et al., 1997). It is currently unclear whether natural hormone-related factors contributed to sex differences in our study.

From another perspective, sex differences may reflect a divergence in the psychological processes or strategies elicited by the different expectancy conditions. For example, one could argue that perhaps men and women experienced different patterns of positive and negative emotions during the high, medium, and low chance of success conditions (see George, Ketter, Parekh, Herscovitch, & Post, 1996; Kring & Gordon, 1998; Tomarken et al., 1992). This notion would be supported by differences between men and women in self-reported emotions during the task, but we found no such sex differences. Further work is needed to examine other psychological factors. For example, previous research has documented important sex differences in emotional rumination and causal attributions (see Nolen-Hoeksema, 1990) and coping styles related to general personality traits (see Finkel & McGue, 1997). The current study highlights the importance of examining sex differences in future work on brain asymmetry and emotion.

Response

The third set of issues was related to the response manipulation. Some researchers have described approach and withdrawal as movements "toward" or "away" (see Dawson, 1994). However, Sobotka et al. (1992) showed that frontal asymmetry did not vary with pressing and releasing movements. This response manipulation was related to changes at central-parietal recording sites and not frontal sites. Likewise, the effects of our left hand–right hand manipulation resulted in asymmetry effects at central and not frontal recording sites. We observed greater left central brain activity during the right-hand condition and greater right central activity during the left-hand condition. Furthermore, anterior frontal asymmetry changes related to incentive cues were observed even when participants made no overt motor response on the delayed RT task.

Our response findings were consistent with the known contralateral cortical control of voluntary motor control (e.g., Ghez, 1991). Notably, though, the asymmetry effect we reported was during a time period that included preparation for a motor response and not the actual motor response itself. Thus, activity at central recording sites appeared to index a preparatory motor process. Such findings are generally consistent with work on event-related desynchronization related to motor preparation (see Pfurtscheller, Pregenzer, & Neuper, 1994; Pfurtscheller et al., 1996). Yet, despite the implications for motor preparation, neither main effects for response nor interactions with incentive and expectancy were observed for anterior or middle frontal asymmetry. Taken together, current and previous data suggest that frontal brain asymmetry is not literally linked to a motor response component of approach and withdrawal, per se, but rather to more complex emotional–cognitive processes that may or may not include overt movements.

Summary and Conclusions

In the context of a delayed RT task, we observed significant changes in EEG asymmetry related to manipulations of incentive cues, outcome expectancies, and motor responses. These primary effects occurred at anterior frontal, midfrontal, and central recording sites, respectively. The results can be used to inform the approach–withdrawal model of frontal brain asymmetry and a temporal guidance model of frontal lobe functions. Our results can serve to constrain hypotheses in future research about the relation between scalp-recorded EEG asymmetries and specific emotion-related functions involved in the guidance of goal-directed behavior over time.

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