

# Regulating action: alternating activation of midline frontal and motor cortical networks

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## Abstract

**Objectives:** Focal electrical fields recorded over the midline prefrontal cortex have been found to index rapid evaluative decisions, including the recognition of having made an error in a speeded response task. The nature of these electrical fields and how they are related to cortical areas involved in response execution remains to be clarified.

**Methods:** As subjects performed a speeded response task the EEG was recorded with a 128-channel sensor array. By filtering out the large slow waves of the event-related potential, we found that the error-related negativity (Ne/ERN) arises from a midline frontal oscillation that alternates with oscillations over lateral sensorimotor cortex. Electrical source analyses were used to determine the brain sources involved in the generation of these oscillations.

**Results:** The results show that the midline and lateral oscillations have a period of about 200 ms (theta), and they are present for both correct and error responses. When an error is made, the midline error oscillation is recruited strongly, and it becomes correlated with the motor oscillation. Source analyses localized the midline error oscillation to centromedial frontal cortex and the lateral oscillation to sensorimotor cortices.

**Conclusions:** Because of the similarity between the midline oscillation observed in the present study and frontal midline theta, the nature of the Ne/ERN may be clarified by the frontal midline theta literature. The correlation between the midline and sensorimotor oscillations suggests a possible mechanism for how midline frontal evaluative and monitoring networks contribute to action regulation. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

**Keywords:** Anterior cingulate cortex; Supplementary motor area; Error-related negativity; Motor potentials; Event-related potentials; Theta; Oscillations

## 1. Introduction

When subjects must rapidly discriminate good from bad targets in a video game, statistical contrasts of brain electrical activity point to a region of midline frontal cortex that appears to index this decision within 300–400 ms of the target appearing on the screen (Tucker et al., 1994, 1999). This evaluative response appears similar to negative event-related potential (ERP) components observed after errors in response-locked averages. The error-related negativity (ERN), or error negativity (Ne), is an electrical wave that appears approximately 80–100 ms after subjects make an error (Falkenstein et al., 1991; Gehring et al., 1993). The similarity of this effect to the evaluative discrimination of good from bad targets is shown by the response to a feed-

back stimulus that signals whether the response was right or wrong. A negative deflection over midline frontal cortex is observed in response to an error feedback stimulus that appears similar to the ERN (Miltner et al., 1997; Badgaiyan and Posner, 1998).

Electrical source analysis of the Ne/ERN with dense-sensor arrays has suggested that the effect is localized to medial prefrontal cortex, including the anterior cingulate gyrus and supplementary motor area (SMA) (Dehaene et al., 1994; Holroyd et al., 1998; Luu et al., 2000a). This localization is consistent with error-related activity recorded from the anterior cingulate cortex (ACC) and the supplementary eye fields in animal studies (Niki and Watanabe, 1979; Gemba et al., 1986; Stuphorn et al., 2000). In monkeys, an Ne/ERN does not appear during early learning trials when the animal appears unable to discriminate errors from correct trials. This apparent requirement for a mental representation of the correct response is consistent with suggestions that the Ne/ERN indexes error monitoring

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(Falkenstein et al., 1991, 2000; Gehring et al., 1993). Others, however, have argued that the Ne/ERN reflects response competition, i.e. between alternative responses (Carter et al., 1998).

Evidence that complicates the error monitoring view is that an Ne/ERN-like electrical component may occur on correct as well as error trials (Ford, 1999; Luu et al., 2000b; Vidal et al., 2000). Ford refers to the smaller negativity seen after correct responses as correct-related negativity (CRN). There are conflicting views about whether the CRN and Ne/ERN are indeed the same component. Ford showed that the CRN and Ne/ERN have different topographies whereas Luu et al. and Vidal et al. showed that they have similar topographies. Scheffers and Coles (2000) have shown that an Ne/ERN still appears in correct trials if subjects report that they believed the response was in error. They use this evidence to suggest that the negativity seen in correct responses could be due to subjects believing the correct response to be erroneous, suggesting that the CRN and Ne/ERN are the same component.

Luu et al. (2000b) hypothesized that the Ne/ERN reflects the role of the medial frontal lobe in subjective evaluation of the action plan. This hypothesis is consistent with the findings on rapid evaluative decisions, and with the evidence that motivation is essential to observe robust effects on medial prefrontal electrical activity during error monitoring (Gehring et al., 1993, 2000; Tucker et al., 1999; Dikman and Allen, 2000; Luu et al., 2000a). The subjective evaluation of action must occur for both correct and incorrect responses, but it appears particularly strong, and thus easily measured, when an error is detected.

Self-monitoring may be deficient in certain personality disorders, such as psychopathy, and it may be exaggerated in others, such as obsessive-compulsive disorder (OCD). Dikman and Allen (2000) found that subjects scoring low on trait socialization (a normal analog of psychopathy) exhibited smaller Ne/ERN amplitudes than control subjects when errors were penalized. However, when errors prevented acquisition of a reward, the low socialization subjects showed similar Ne/ERNs as controls. These frontal electrophysiological effects thus seem to parallel the learning biases (insensitivity to punishment but sensitivity to reward) of psychopaths. At the other end of the self-monitoring spectrum, Gehring et al. (2000) found that OCD patients had unusually large amplitude Ne/ERNs when they made errors. Moreover, the amplitude of the Ne/ERN correlated with OCD symptom severity.

These individual differences in frontal electrophysiology of self-monitoring are consistent with the changes in behavior after frontal lobe lesions. Patients with medial prefrontal lesions often appear unconcerned with the negative consequences of their actions (Rylander, 1947; Tow and Whitty, 1953; Tucker et al., 1995). These patients may continue to make mistakes that seem obviously detrimental to their goals and life plans (Eslinger and Damasio, 1985). Nauta (1971) interpreted many of the deficits of the frontal

lobe patient as ‘interoceptive agnosia’, the faulty knowledge of the internal feelings that should be an integral part of evaluating events and action plans. Nauta proposed that the frontal lobe’s primary contribution to behavior is the integration of motivation with the ongoing control of action. In his view, the limbic connections of the frontal lobe provide ‘set-points’ or ‘navigational markers’ for evaluating the outcomes of actions. As actions are planned, a corollary discharge from motor control networks not only prepares sensory networks for the anticipated change in input, but also limbic networks for the anticipated evaluative qualities of the plan’s outcomes.

If Nauta is correct, then the midline frontal activity in error monitoring should be closely related to motor control. In examining individual subjects’ response-locked ERP averages, we observed that the motor potential over the cortex contralateral to the responding hand was easily observed if the slow wave (P300 in response to the stimulus) was eliminated with a high-pass filter. Remarkably, the Ne/ERN then appeared in this filtered data set as one of a series of midline oscillations at the theta (~6 Hz) frequency. These midline theta waves were apparent on correct as well as error trials. The present study was conducted to examine the midline frontal oscillations systematically, and to examine the hypothesis that they would show a significant correlation with the electrical activity over sensorimotor cortex.

## 2. Method

### 2.1. Subjects

The data from these subjects have been reported in other publications (Luu et al., 2000a,b) and are used in this study to analyze oscillatory activities. The study and use of human subjects were approved by the University of Oregon’s Institutional Review Board. Twenty-one subjects participated in the experiment. The subjects were recruited from the psychology department’s subject pool, and they participated to fulfill course requirement. The subjects were also offered the opportunity to earn a monetary reward, the amount of which was dependent upon their performance. All subjects had normal or corrected to normal vision and were fluent in English. They ranged in age from 18 to 26 years (mean 19.4 years, SD 1.9). Eight subjects were male and 19 subjects were right-handed. None of the subjects were currently taking prescription medications.

### 2.2. Task

The subjects performed the Eriksen flanker task (Eriksen and Eriksen, 1979). In this task subjects respond with a left or right hand response to a central target letter (e.g. H or S), flanked by letters requiring the same or conflicting response. Subjects were presented with a warning cue, an asterisk, at the center of a screen above a fixation mark, which was

present for the entire experiment. The warning cue was presented for 804 ms, after which it was replaced with one of the following string of target letters: HHHHH, SSHSS, SSSSS, HHS HH. The bottom of the letter strings was  $0.1^\circ$  above the fixation mark and each letter subtended  $0.5^\circ$ . The probability of each string of letters was 0.25. The target letter string was presented for 107 ms. The subject's task was to indicate as quickly and as accurately as possible which letter was in the center by pressing a key with one hand if the center letter of the target string was an H and another key with the opposite hand if the center letter was an S (keys were counterbalanced across subjects). The timing of the reaction time began with the presentation of the target. After the response interval, a feedback signal informing the subject of the status of the response was presented above the fixation mark (Luu et al., 2000a).

### 2.3. EEG acquisition

EEG was recorded from 128 scalp sites using the 128-channel Geodesic Sensor Net (Tucker, 1993). This device arrays EEG electrodes in a regular distribution across the head surface, with an approximately 3 cm inter-sensor distance. The impedance of all electrodes was between 10 and 40 k $\Omega$ . All recordings were initially referenced to Cz and subsequently re-referenced to the average reference prior to data analysis. EEG was recorded using a 0.1–50 Hz bandpass (3 dB attenuation). The signals were sampled at 125 samples per second and were digitized with a 12 bit A/D converter. The EEG was then averaged and aligned with the button press separately for correct and error responses according to the response hand. The EEG was then digitally filtered with a wide-band 4–12 Hz digital filter, which with these data has the primary effect of removing the large slow waves (e.g. contingent negative variation and late positive complex) which masked the oscillatory components seen in the present data. The digital filter that was used is a finite impulse response (FIR) filter with zero phase-shift.

### 2.4. Source analysis

The grand-averaged data were submitted to source analyses using both spatiotemporal equivalent dipole (MEGIS, 1999) and linear inverse (ANT, 2000) models. The spatiotemporal equivalent dipole analysis began with source locations indicated by the analysis of steady-state movement potentials by Gerloff et al. (1998a). First, two mirror dipoles were used and the search was constrained to the motor peak (MP) window ( $-48$  ms to response onset). This was accomplished separately for the left- and right-hand correct responses. The resulting model was used for the other movement-related potentials for both the correct and error responses.

The analysis of the Ne/ERN generator was also guided by the results of previous analyses (Dehaene et al., 1994; Holroyd et al., 1998; Luu et al., 2000a). A single dipole

was used to model the 48–152 ms window. Once the positions of the movement-related and Ne/ERN dipoles were obtained for each response hand, the positions were fixed (the orientations were free to vary). Examination of the residual variance (RV) then showed that an additional source was necessary to approximate the surface potentials for the window spanning 120 ms before to 160 ms after the response. Consistent with the focal frontal polar fields seen in the scalp voltage maps, this fourth dipole source was fit by the inverse modeling to orbital frontal cortex.

These 4 dipoles constitute the hypothesized number of generators, based upon surface topography. Moreover, their locations were hypothesized on the basis of previous results and known features of brain anatomy. The two dipoles used to model the movement-related potentials were expected to be located in regions adjacent to the central gyri. The dipole sources representing the vertex potentials (including the Ne/ERN) were expected to be located in the dorsomedial, prefrontal cortex. Finally, the scalp topography (focal gradients over the forehead) indicated that an additional source was probably located in the ventromedial, orbital frontal cortex. The utility of additional sources was evaluated based on the ability of the additional dipole(s) to account for additional variance, and upon the stability of the solutions. In each model, a final solution was considered to be adequate when the RV for both correct and error conditions of the same response hand was less than 20%.

For cross-validation of the equivalent dipole analysis, we submitted the data to a linear inverse analysis. This approach estimates the current density throughout the volume of the head, avoiding the need to restrict the number of active sources. Because the number of current sources that must be solved is typically much greater than the number of recording sensors, the problem is underdetermined. Assumptions are therefore made about what can be expected as the appropriate solution. A minimum norm method gives a solution based upon the assumption of minimal source moments. A weighted minimum norm, used here, balances the solution against the inherent bias to favor superficial sources, which explain the scalp data with less energy, i.e. a lower minimum norm, than deep sources (Knösche et al., 1996).

Whereas the equivalent dipole model (BESA) was based on a spherical head model, the weighted minimum norm analysis was based on a boundary element head model (BEM). This model was derived from a typical subject brain that has been transformed into Talairach space (available from the Montreal Neurological Institute). The solution was constrained to the cortical surface, allowing for the source moments to be normal to the cortical surface. Because the medial surface of the brain is not assessable in our boundary element model, cortical sources in the medial hemisphere can not be modeled accurately. Therefore, the equivalent dipole model is required to identify deep medial sources.

### 2.5. Identifying the electrical components

Because of the similarity in wave shape between the electrical components seen in the present analyses, the precise spatiotemporal information gained from the dense-array electrical field animations (head surface potential map movies) was crucial for the definition of each component. We relied on the descriptions of motor potentials by Gerloff et al. (1998a,b) to identify the components of the averaged ERPs associated with motor areas. The pre-response motor peak (pre-MP) was defined as an average of the negative deflections occurring between  $-110$  and  $-50$  ms prior to response onset ( $0$  ms in the average) at vertex (Cz) and Fz sites. The MP potential was defined as the average of the potentials over 4 contralateral central channels (one of which was either C3 or C4, depending on the response hand, and the other 3 were 3 cm caudal to these channels) whose maximal latency was between  $-48$  ms and response onset. Using the same set of channels, the post-motor peak (post-MPI) was defined as the average of the potentials between 24 and 72 ms after response onset. The topography of the Ne/ERN is similar to that of the pre-MP, but its latency is approximately 80–100 ms after the button press. Therefore, the Ne/ERN was defined as an average of the potentials occurring in the same channels as the pre-MP, but occurring within a window 48–152 ms post-response. A second post-motor peak (post-MPII) can be observed in all conditions. The post-MPII was defined, using the same channels used for the MP, as the average negative peaks between 88 and 160 ms after response onset. Finally, the first negative peak of the orbital frontal potential was defined as an average of the peaks at two recording sites 3 cm rostral to Fp1 and Fp2, whose latencies were between response onset and 80 ms post-response.

The latency for each component was determined by using the latency, averaged over channels, of the peaks identified in the amplitude analysis. The time of response onset was used as the reference point for latency measures.

## 3. Results

### 3.1. Separating oscillations from slow waves

When an Ne/ERN-like deflection is observed in correct trials, it is most prominent at mediofrontal recording sites (e.g. Fcz). At midfrontal sites, negative deflections in the ERP can be observed prior to the button press and after the Ne/ERN for both correct and error responses (see Figs. 1 and 2). The sequence of these negative deflections appears to be periodic, but it is swamped by the large slow waves of the ERP. As can be seen in Fig. 1, once the effect of the slow wave is removed with the 4–12 Hz bandpass digital filter, the Ne/ERN appears to emerge from an oscillatory process that begins prior to response onset. The multiple negative deflections at approximately 200 ms intervals suggest that

the Ne/ERN may be part of an ongoing oscillatory process that occurs both before and after the response.

### 3.2. General topography of the oscillations

Fig. 2 shows the scalp topographies that were associated with the major oscillations in the waveforms. The midline oscillations from Fig. 2 can be seen for the error condition with a negative peak at  $-80$  ms, a positive peak at 8 ms, a negative peak at 88 ms (the Ne/ERN), and a positive peak at 168 ms (i.e. a period of 160–180 ms). For the correct condition, similar but attenuated waves are seen, i.e. negative at  $-64$  ms, positive at 16 ms, negative at 88 ms, and positive at 168 ms. Alternating with these midline waves is a stereotyped sequence of activity over contralateral sensorimotor ( $-32$  and 136 ms) and orbital frontal (32 and 224 ms) areas.

### 3.3. Identification of motor potentials

Alternating with the midline oscillation are electrical effects over the central regions of the hemisphere contralateral to the responding hand, i.e. the sensorimotor cortex. These are complex and include activations in both motor cortex and somatosensory cortex which superpose to create

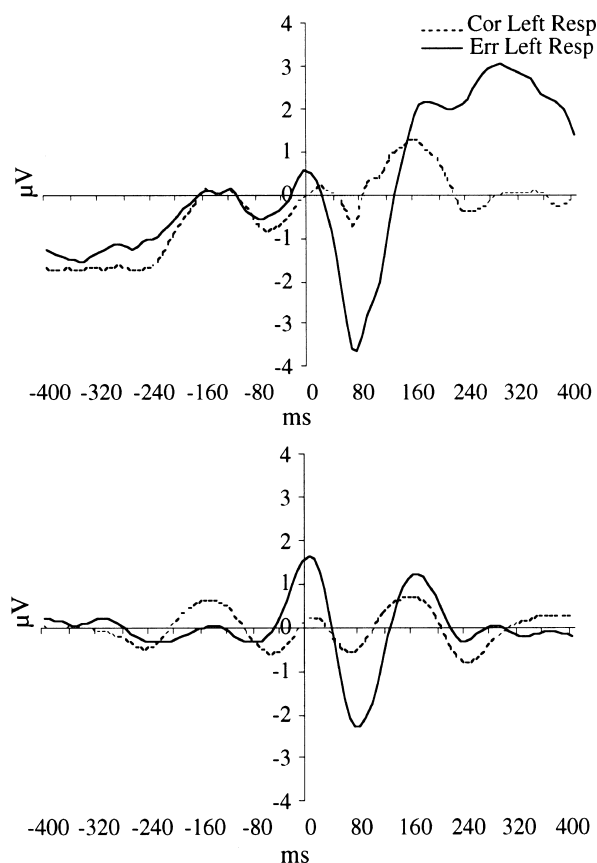


Fig. 1. Grand-average waveform plots of response-locked ERP for correct and incorrect trials (left-hand responses only). The data is from Fcz with a 0 ms marking response onset. The top graph is of unfiltered ERP data and the bottom graph shows the same data after filtering with a 4–12 Hz high-pass digital filter.

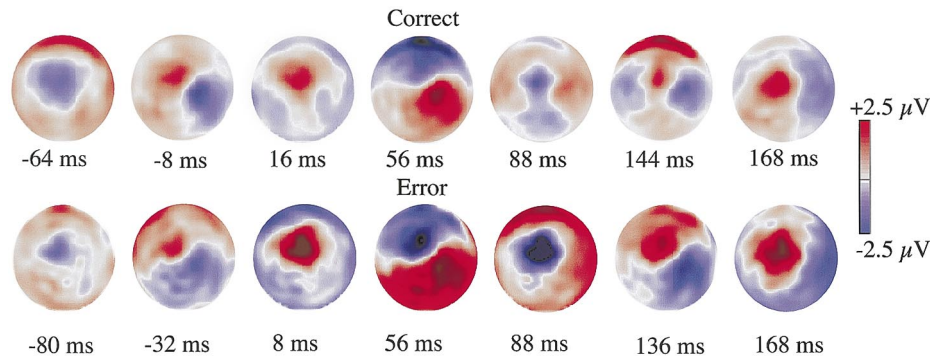


Fig. 2. Polar topographies of the oscillatory potentials. The view is down on the head with the nose at the top. The top row is the correct responses, and the bottom row is the error responses, both shown only for the left hand.

the scalp electrical fields. To identify these from the scalp maps, we will refer to the component nomenclature used by Gerloff et al. (1998a).

Gerloff et al. (1998a) observed a centroparietal negativity prior to EMG onset and referred to this component as the pre-MP. This appears similar in latency, and in some topographic features, with the initial midline negativity (−80 and −64 ms for the left hand in Fig. 2). The second component is a negative deflection of the scalp potential over central and parietal regions contralateral to the response hand, peaking between −32 and −8 ms. This appears to be the motor peak or MP reported by Gerloff et al. (1998a).

Roughly coincident with the parietal negativity of the MP is a positivity over the vertex. This positivity gives the MP the look of a tangentially-oriented, dipolar, potential field (see the −8 and −32 ms maps). However, inspection of the scalp electrical field animations indicates that the positivity is most probably a separate electrical event from the MP. When the electrical topographies are animated in sequence, the time course (onset, peak, and offset) of the negativity is dissociated from the time course of the positivity; if they reflected a single dipolar source they would be exactly coincident. The positivity seen at −8 and −32 ms continues to develop until it takes the form of the midline positivity peaking between 8 and 16 ms after the button press.

The next major event is seen over orbital frontal regions. This negative peak begins as the vertex positivity fades,

such that its onset can be seen in the 8 ms map (Fig. 2) for the error condition. The orbital frontal negativity is well-developed by 56 ms (for both conditions). At this time, it overlaps with a positivity over contralateral motor cortex. This positivity was described as the post-MPI by Gerloff et al. (1998a).

For the error responses, the Ne/ERN emerges during the peak of the post-MPI and then reaches a maximum approximately 80–100 ms after the button press. For the correct responses, an attenuated but similar component is seen at 88 ms.

The next component has a similar topography as the MP but its latency is between 136 and 144 ms after the button press. We refer to this second negative post-motor component as the post-MPII. In the present data, the post-MPII is different from the MP in that there is a smaller negative deflection over the ipsilateral parietal regions for the correct conditions than for the error condition. As with the MP, this feature is also associated with a vertex positivity that peaks slightly later (i.e. at 168 ms). After this point, there is a suggestion that the midline oscillations continue briefly, but there are no clear repetitions of the previous topographic sequences.

#### 3.4. Linear inverse estimation of cortical current density

Fig. 3 presents the results from the weighted minimum

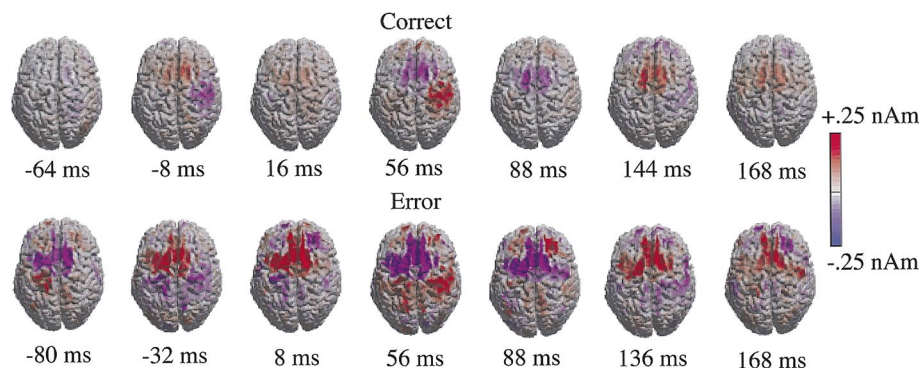


Fig. 3. Source solutions derived from the weighted minimum norm method. Displayed solutions are for left-hand responses.

norm analysis for the left- and right-hand responses. These cortical maps generally parallel the scalp surface maps in Fig. 2, but with some important differences. Similar to the surface midline oscillations, these analyses continue to show the alternation of the current density sources and sinks along the midline of the prefrontal cortex.

As with the scalp maps, the oscillation of the midline current density can be observed for both correct and error responses regardless of the response hand, but it is much larger for the error responses. At approximately 88 ms after response onset, the current sink is observed as the Ne/ERN. In these source estimations, the biggest region of current density is medial and just anterior to the central sulci of both hemispheres, but there is also additional activity along the rostral banks of the medial surface of the hemispheres. This pattern is more revealing than the Ne/ERN seen in the scalp maps.

The pre-MP appears to be modeled primarily by the current density along the midline of the prefrontal lobe. Because of the inaccessibility of the medial surface in the BEM of the cortex, the actual distribution of the active cortex is likely to be along the medial surface, perhaps in the region of the ACC or SMA as identified by the dipole source analyses below.

The motor-related surface potentials can also be observed in the cortical current density estimations. In Fig. 3, the MP (−8 and −32 ms) is seen as inward current flows (sinks) in cortical areas adjacent to the central sulcus of the contralateral hemisphere for all the responses, although, interestingly, it is more bilateral for the errors made with the left hand. Outward current flows (sources) over the same cortical regions are observed for the post-MPI. During the post-MPII interval, there is inward current flow around the region of the central gyrus. Finally, the orbital frontal negativity is modeled by the linear inverse estimation as inward current flow in orbital frontal and anterior temporal cortices (not displayed by the views shown in Fig. 3).

### 3.5. Dipole source estimation of cortical activity

A converging perspective of the neural sources of the scalp fields is provided by dipole source analysis. The mirror dipoles (sources 1 and 2, see Fig. 4) situated anterior to the central sulci are located slightly more medial in the right-hand condition than in the left-hand condition. Source 3 is located in midline prefrontal cortex (around the region of the ACC and/or SMA). It is located slightly left of midline in the right-hand condition. Source 4 is located in the ventromedial orbital frontal region. Its location is quite similar between the two responses. This is a deep source, and the dipole model may be trying to account for bilateral temporal pole activity as well as orbital frontal activity. Fig. 4 illustrates the locations of the 4 dipoles for correct and error responses made with the left hand. The 4 dipole model serves as an adequate model for the entire epoch (left-hand

error RV = 10%, left-hand correct RV = 14%, right-hand error RV = 13%, and right-hand correct RV = 10%).

Fig. 5 shows the relative contribution of each source to the recorded scalp potential for the left- and right-hand conditions. Unlike the report by Gerloff et al. (1998a), the bilateral dipoles located adjacent to the central sulci were unable to account for a significant proportion of variance in the pre-MP interval. Instead, the pre-MP is better modeled by sources 4 (for the right-hand correct response) and 3 (for the left-hand correct and error responses). This is expected given the difference between the nature of the responses in the Gerloff et al. report (fast steady-state movements) and the present study (slower planned responses). In the present study, it is likely that response preparation involves the medial pre-motor areas (e.g. SMA). During the MP interval, the bilateral sources adjacent to the central sulci contribute substantially to the MP. The source on the contralateral side is larger and reaches its peak as the correct button press approaches. For the left-hand error response, there is bilateral activity during the interval leading up to the button press (similar to the linear inverse solution), but the contralateral source is more sustained and larger.

At the time of the button press, the contralateral source adjacent to the central sulcus begins to wane, and source 3 begins to peak positively in all conditions. Consistent with the oscillations seen in the scalp topographies, the orientation of source 3 during this time is in the opposite direction (i.e. positive) from that during the pre-MP interval and is clearly larger for error than for correct responses. Next, as

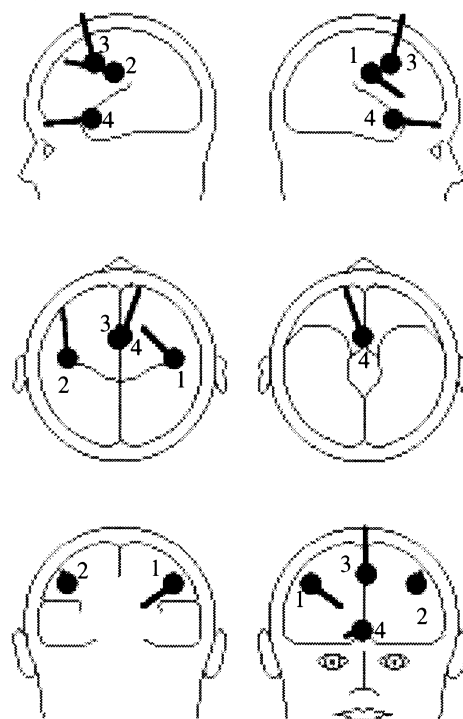


Fig. 4. Intracranial locations of the equivalent dipole electrical sources for correct and error responses made with the left hand.

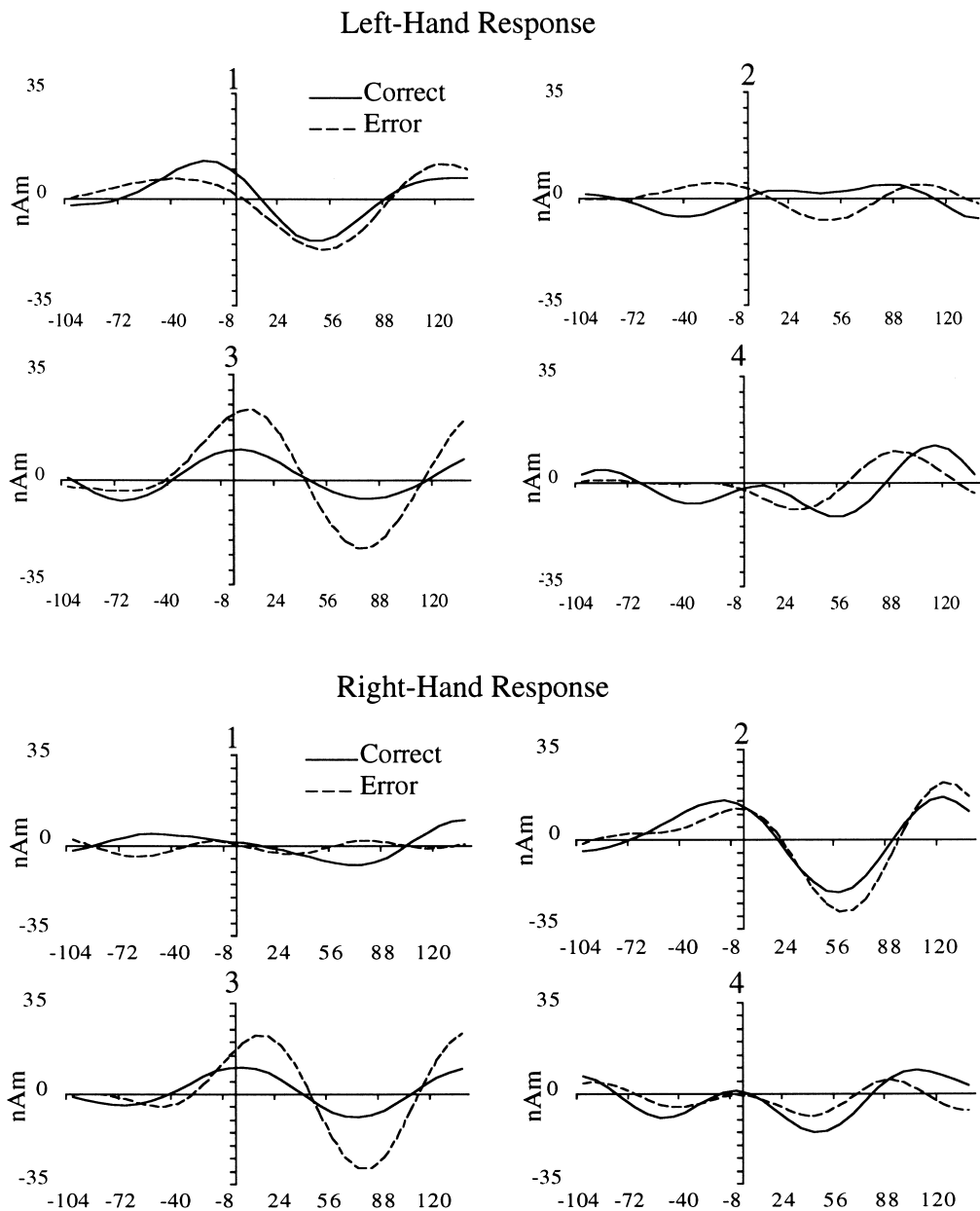


Fig. 5. Waveforms illustrating the time course of each source for correct and error responses made with the left and right hand.

source 3 begins to fade, source 4 becomes active. This activation of source 4 accounts for the appearance of the orbital frontal negativity. As this source weakens, the contralateral movement-related source becomes active again, but its activity is in the opposite direction as it accounts for the post-MPI. Source 3 becomes active during the time of the post-MPI and peaks shortly thereafter. As can be seen in Fig. 5, it is overwhelmingly larger for error conditions; this is the standard Ne/ERN effect. The post-MPII is then modeled by the activity of the contralateral, movement-related source and is followed by source 3 peaking to account for the vertex positivity.

In summary, the two source estimation approaches, with differing assumptions and methods, converge to provide

similar views of brain activity. However, each approach also gave a unique perspective on the data. For example, the weighted minimum norm solution made the spatial oscillations much more apparent and showed that the Ne/ERN is made up of a distributed source along the midline (suggesting that there may be two distinct regions of active cortex). On the other hand, the equivalent dipole approach was able to model activity on the medial surface of the prefrontal lobe that could not be modeled using the current BEM of the cortical surface.

### 3.6. Statistical analyses of midline and motor oscillations

To examine the stability of the amplitude differences

Table 1  
Paired *t* tests of amplitude differences

|                          | Correct mean<br>( $\mu$ V) | Error mean<br>( $\mu$ V) | <i>t</i> value | <i>P</i> value |
|--------------------------|----------------------------|--------------------------|----------------|----------------|
| Pre-MP                   | −2.2                       | −2.4                     | 0.5            | NS             |
| MP                       | −1.8                       | −1.5                     | 2.1            | <0.05          |
| Orbitofrontal negativity | −2.7                       | −3.2                     | 0.8            | NS             |
| Post-MPI                 | 0.4                        | 0.6                      | −2.5           | <0.03          |
| Ne/ERN                   | 1.3                        | −3.8                     | 5.2            | <0.001         |
| Post-MPII                | −1.0                       | −1.9                     | 4.5            | <0.001         |

between the correct and error responses for each of the components, paired *t* tests were conducted. Table 1 presents the results of the paired *t* test for each component. Only the pre-MP and orbital frontal negativity amplitudes failed to show significant differences between the correct and error conditions. It should be noted that several components are highly consistent across subjects, such that even small differences were statistically significant. Overall, the components are amplified for the error condition, with the exception of the MP, which was attenuated.

Paired *t* tests were performed to assess differences in peak latency between correct and error responses for each component. Table 2 presents the results of the latency analysis. Prior to the response, the pre-MP and the MP reach their peaks substantially earlier for the error responses than the correct responses. After the response, the peak of the post-MPII is substantially earlier for the error condition.

Next, analyses were completed to investigate the relation of the Ne/ERN to the other oscillatory components. Table 3 presents the correlations between the Ne/ERN amplitude and the other 5 peak events. It can be seen that for correct responses there are no relations between the Ne/ERN and any other component. For error responses, the Ne/ERN was correlated most strongly with the pre-MP, MP, and post-MPII. It was only weakly related to the orbital frontal negativity.

#### 4. Discussion

In the response-locked averages of dense-array recordings, oscillatory-like dips and peaks often can be observed at medial frontal recording sites. When an error is made, the Ne/ERN becomes a prominent dip. Because most reaction times fall within the stimulus-locked P300 window (300–

Table 3  
Ne/ERN correlation with movement-related and orbitofrontal components sorted by response type

| Variable                 | Correct        |                | Errors         |                |
|--------------------------|----------------|----------------|----------------|----------------|
|                          | <i>r</i> value | <i>P</i> value | <i>r</i> value | <i>P</i> value |
| Pre-MP                   | 0.12           | NS             | 0.53           | <0.02          |
| MP                       | −0.32          | NS             | 0.52           | <0.02          |
| Orbitofrontal negativity | −0.04          | NS             | 0.39           | <0.09          |
| Post-MPI                 | 0.01           | NS             | −0.28          | NS             |
| Post-MPII                | 0.30           | NS             | 0.49           | <0.05          |

500 ms post-stimulus), response-related events are superimposed on the P300. The Ne/ERN is readily apparent in response-locked averages because of its large amplitude. However, because other response-related events are comparatively smaller, they are either not visible because of the superimposed P300, or they are only observed at recording sites (e.g. frontal) where the P300 is minimal. By removing the large amplitude of the P300 and other slow potentials with a 4–12 Hz filter, we were able to observe the oscillatory components of the ERP that reflect both activity in lateral motor cortex and activity in midline frontal and orbital frontal cortices.

##### 4.1. The Ne/ERN and midline oscillations

Statistical analyses revealed that the amplitude of the Ne/ERN component, the negative deflection about 80 ms post-response, was greater following errors. The analysis also demonstrated that there were no latency differences between the Ne/ERN associated with correct or error responses. These findings replicate previous reports showing that the Ne/ERN is present in both types of responses but is largest when errors are committed (Luu et al., 2000b; Vidal et al., 2000).

The finding that the Ne/ERN is present in both correct and error responses has raised some questions about the nature of the process(es) indexed by the Ne/ERN. To account for this finding, some researchers have suggested the Ne/ERN may reflect the response checking process rather than the error detection process (Falkenstein et al., 2000; Vidal et al., 2000). Others have argued that the Ne/ERN does indeed reflect an error detection process, and that the Ne/ERN associated with correct responses could be due to the fact that correct trials can contain trials that subjects believe were

Table 2  
Paired *t* tests of latency differences

|                          | Correct mean (ms) | Error mean (ms) | <i>t</i> value | <i>P</i> value |
|--------------------------|-------------------|-----------------|----------------|----------------|
| Pre-MP                   | −42.0             | −93.0           | 7.01           | <0.001         |
| MP                       | −25.0             | −32.0           | 2.1            | <0.05          |
| Orbitofrontal negativity | 47.0              | 42.0            | 1.46           | NS             |
| Post-MPI                 | 60.0              | 60.0            | 0.11           | NS             |
| Ne/ERN                   | 86.0              | 90.0            | 0.88           | NS             |
| Post-MPII                | 127.0             | 119.0           | 2.2            | <0.05          |

erroneous even when the trials were indeed correct (Scheffers and Coles, 2000). Another hypothesis put forth by Falkenstein et al. is that the Ne/ERN seen after correct trials reflects response comparison processes and that the Ne/ERN observed after error responses reflects the response comparison plus an overlaid error signal. This latter hypothesis relies on the assumption that response checking and the error signaling processes temporally and spatially overlap, because no differences in topography nor latency were observed between the Ne/ERNs associated with correct or error responses in the present study, which is consistent with the reports of Vidal et al. (2000) and Luu et al. (2000b). It should be noted, however, that Ford (1999) did find a different topography for correct responses.

Although the midline oscillation observed in the present study is only a few cycles, it shows the periodicity (150–200 ms) of the frontal midline theta that has been described in the ongoing EEG during mental effort (Schacter, 1977; Mizuki et al., 1980; Sasaki et al., 1996). Moreover, the functional nature of the frontal midline theta may be relevant to functional interpretations of the Ne/ERN. In tasks in which difficulty is increased by inducing time pressures or increasing demands on working memory, increases in frontal midline theta are often observed (Gevins et al., 1997; Slobounov et al., 2000). In a maze task in which subjects have to navigate a ball through a maze while making sure that the ball does not touch the walls of the maze, Slobounov et al. (2000) found that successful trials were associated with larger theta amplitudes than failed trials.

Frontal midline theta increases in infants have been shown to be associated with emotion-related experience such as tickling, kissing, and suckling (Maulsby, 1971). More recent research with 2–11 month old infants has also shown theta increases under similar conditions (Futagi et al., 1998). However, Futagi et al. found theta distribution to vary with each condition. In comparison to suckling and crying, theta increases were largest over frontal midline sites when infants handled an object. An increase in frontal midline in infants has also been reported under conditions that solicit emotional reactions and in which internal attentional control is required (Stroganova et al., 1998). In adults, decreased frontal midline theta is associated with increased anxiety (Suetsugi et al., 1998). Suetsugi et al. found that administration of anxiolytic drugs increases frontal midline theta in anxious patients.

In the present study, the source of the centromedial oscillation (including the Ne/ERN) was localized by both dipole and cortically-constrained linear inverse analyses to the ACC and/or SMA, which is consistent with findings reported in previous EEG studies (Dehaene et al., 1994; Miltner et al., 1997; Holroyd et al., 1998; Luu et al., 2000a). In more recent analysis of both grand-averaged and single subject data, we found the source of the Ne/ERN to be consistent with an SMA location (Luu et al., 2001). Given the scalp distribution of the frontal midline theta, a source in the ACC would be expected. Using dense-

array EEG, Gevins et al. (1997) found that a source within the ACC can generate the frontal midline theta. More recent source analysis results identified an additional source in the region of the SMA (Asada et al., 1999). Asada et al. showed that two sources, one in the ACC and the other in the region of the SMA, were required to account for the frontal midline theta activity. These sources were alternately activated approximately 40–120° out of phase for one theta cycle.

Although previous reports have not identified two medial sources for the generation of Ne/ERN, the finding that in some studies the source of the Ne/ERN is located in the SMA while in others it is in the ACC, coupled with the findings reported by Asada et al. (1999), raises an interesting possibility that two sources may be active during the time of the Ne/ERN. Indeed, results from the cortically-constrained linear inverse analysis in this study suggest the involvement of a broader region in the generation of the Ne/ERN that is more consistent with two sources than one. In dipole models, an average of the two sources would result in a single-source solution located half-way between the two sources, as suggested by Asada et al. (1999). This possibility has theoretical implications for the hypothesis put forth by Falkenstein et al. (2000). It may be that response checking processes are indexed by the activity of one source and error output by the other. Additional experiments will be required to investigate this possibility.

#### 4.2. Alternating sensorimotor activations

In the present research, we observed that the sensorimotor cortex activations associated with the response alternated with the midline theta activity (Figs. 2 and 3). Although there were several differences between the potentials in the dense-array recording from earlier sparse-array studies (Nagamine et al., 1994; Kristeva-Feige et al., 1997; Gerloff et al., 1998b), such as for the pre-MP or pre-motor peak, there was good agreement for the MP and post-MPI over contralateral motor cortex just prior to the response.

The MP is thought to reflect motor cortex activation associated with response execution (Nagamine et al., 1994; Kristeva-Feige et al., 1997; Gerloff et al., 1998b). After this the post-MPI or post-motor field (pMFI – from magnetoencephalography (MEG)) is observed, which is thought to reflect sensory afferents to somatosensory cortices or secondary movements (Kristeva-Feige et al., 1997). In the MEG literature, there is another component referred to as the pMFII. In the present results, this component (the post-MPII) appeared to reflect an additional activation of motor cortex, about 140 ms after the response (see Figs. 3 and 4).

Results from the latency analysis suggest that the pre-MP and MP occur much earlier relative to the button press in the error condition than in the correct condition. In other words, the response itself appears to be delayed in relation to both the pre-MP and the MP for the error condition. The amplitude analysis demonstrated that the amplitude of the MP is smaller in the error condition than in the correct condition.

Taken together, these findings suggest that corrective mechanisms may have already been initiated prior to the button press and the appearance of the Ne/ERN in error conditions. This finding is consistent with the findings that during error responses corrective EMG activations are initiated prior to the button press and when the error response is made the response force is significantly weaker (Gehring et al., 1993; Gehring and Fencsik, 1999).

#### 4.3. Orbitofrontal activation

Previous studies have found a stimulus-locked frontal polar potential that is related to motor responses. Makeig et al. (1999) identified a frontal polar component that is related to response production. These researchers found that this component's peak latency was nearly simultaneous with subcortical motor commands in fast responders. Potts and Tucker (2001) also observed a similar frontal polar component that is correlated with reaction time. However, this component is not necessarily dependent upon overt responses. In a task in which subjects are required to respond yes or no to the self-relevancy of trait descriptive words, we have found that a frontal polar component predicted whether a subject was going to endorse or reject a trait word (Tucker et al., 2001). It should be noted that in these studies the frontal polar components were observed in stimulus-locked averages. In contrast, the frontal polar component observed in the present study is synchronized with the response. To investigate if the latency of the orbital frontal component is related to reaction time, we conducted a correlational analysis. The correlation with reaction time was not significant. This is not surprising given the fact that the component peaks after response onset. However, as shown by Potts and Tucker (2001) and Tucker et al. (2001) the stimulus-locked frontal polar component is not critically dependent upon the immediate response. Our analysis did not reveal any amplitude or latency differences between correct and error conditions for this component, nor was it significantly related to the Ne/ERN.

In a recent fMRI study, Menon et al. (2001) reported bilateral activation in the anterior insula lateral orbital frontal regions when subjects make an erroneous response. These authors speculated that these regions may be involved in articulation of action. It is likely that the orbital frontal activation observed in the present study is a result of bilateral orbital frontal or temporal/insula activities, as suggested by the linear inverse solution. The functional significance of the orbital frontal component observed in this study and its relation to medial frontal responses in action evaluation remain to be clarified with additional experiments.

#### 4.4. Coupling of midline and motor activity

Statistical analyses revealed a number of significant relations between the midline and sensorimotor oscillations when an error was made. The correlation of component

peak latency revealed that the amplitudes of the movement-related oscillations, such as the MP and post-MPII, are significantly correlated with the midline oscillations (i.e. the Ne/ERN) only when errors are committed. It is possible that the lack of correlation between the Ne/ERN and sensorimotor oscillations for correct responses is due to a poorer signal-to-noise ratio caused by smaller amplitudes of the Ne/ERN, post-MP, and post-MPII in the correct condition. However, for the pre-MP and orbital frontal negativity, there were no amplitude differences. Moreover, the MP amplitude is actually larger for correct responses. Nevertheless, correlation analyses provide compelling evidence for action regulation by means of interactions between medial frontal limbic and sensorimotor areas.

Studies of hippocampal projections to the cingulate gyrus in rabbits have suggested that as the animal prepares to make a learned response, unit activity in the hippocampal-cingulate projections becomes increasingly synchronized in theta bursts (Gabriel et al., 1986; Gabriel, 1990). Although the role of the cingulate gyrus in regulating response learning appears to be a complex one, depending on the animal's evaluation of the behavioral context (Gabriel et al., 1986; Freeman et al., 1996), the result appears to be a direct modulation of the outflow to the corticostriatal motor control circuits (Gabriel et al., 1986; Gabriel, 1990).

Each of the major sites of the response-locked oscillation in the present data is a target of one of the corticostriatal loops linking specific regions of the striatum and thalamus with specific regions of frontal and motor cortex (Alexander et al., 1986; Alexander, 1994; Groenewegen and Berendse, 1994; Groenewegen et al., 1997). Of the identified corticostriatal loops, the anterior cingulate, the lateral orbital, and the motor corticostriatal circuits (Alexander, 1994) are most relevant to the present findings, given the source locations of the observed oscillations. It remains for future studies to investigate how and under what conditions do midline frontal structures interact with and regulate premotor and sensorimotor cortices to produce learning and adaptive behavior.

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