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Complex behavior requires a flexible system that maintains task performance in the context of specific goals, evaluating behavioral progress, adjusting behavior as needed, and adapting to changing contingencies. Generically referred to as *performance monitoring*, a key component concerns the identification and correction of differences between an intended and an executed response (i.e., an error). Brain mapping experiments have now identified the temporal and spatial components of a putative error-processing system in the large-scale networks of the human brain. Most of this work has focused on the medial frontal cortex and an associated electrophysiological component known as the error-related negativity (or error negativity). Although the precise role, or roles, of this region still remain unknown, investigations of error processing have identified a cluster of modules in the medial frontal cortex involved in monitoring/maintaining ongoing behavior and motivating task sets. Other regions include bilateral anterior insula/inferior operculum and lateral prefrontal cortex. Recent work has begun to uncover how individual differences might affect the modules recruited for a task, in addition to the identification of associations between pathological states and aberrant error signals, leading to insights about possible mechanisms of neuropsychiatric illness. NEUROSCIENTIST 13(2):160–172, 2007. DOI:10.1177/1073858406298184

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Systems for Error Detection

Electrophysiological Evidence: The Error-Related Negativity

Seminal work by Rabbitt in the mid-1960s first raised the importance of a system that detected errors and adjusted performance (Rabbitt 1966). This system has many subcomponents, possibly resetting the brain or refocusing attention to the task at hand, leading to slower responses in trials following the error and often accompanied by an emotional reaction of frustration. Evidence for a neural system to process errors first appeared in the early 1990s. Two groups, working independently, noted that a negative electrical potential occurs in the medial frontal region of the brain, approximately 50 to 100 ms after making an error (see Figure 1*A*; Falkenstein and others 1991; Gehring and others 1993). This potential was dubbed the *error-related negativity* (ERN) or the *error negativity* (Ne). It begins in adolescence and increases in early adulthood, commensurate with the development of other capacities of cognitive control (Davies and others 2004; Hogan and others 2005). As one of the key components of the brain that monitors and adjusts flexible, goal-directed behavior, studies of the ERN have proceeded with great interest in the past decade.

Several important characteristics of the ERN have been noted. Studies typically use speeded, performance-demanding tasks, and investigators noted that emphasizing speed, at the expense of accuracy, diminished the amplitude of the ERN (Falkenstein and others 2000; Gehring and others 1993). Initial work suggested that the ERN reflected a mechanism of error detection and not an inhibitory or immediate corrective signal (Falkenstein and others 1999, 2000) because it occurred after the onset of an incorrect response (Scheffers and others 1996). As a part of an error detection system, one would expect to find a relationship between adjustments made after an error, such as the small but slight increase in reaction time seen in trials following an error (Rabbitt 1966). Accordingly, trial-by-trial estimates of the ERN have related the ERN magnitude to the amount of post-error slowing (Debener and others 2005; Gehring and others 1993). This relationship was also observed in group-averaged data for fMRI (Kerns and others 2004), although it has not been consistently found (Gehring and Fencsik 2001; Luu and others 2000b). The lack of a consistent relationship may reflect the fact that post-error slowing is not always observed and may not be a robust index of error processing (Ullsperger 2006), or it may reflect some of the many questions that remain about the actual functional role of the ERN.

One of the interesting findings about the ERN is the degree to which it reflects the importance that subjects place on avoiding mistakes or, alternatively, making a correct response. As mentioned above, when the experimenter emphasizes accuracy, the ERN increases (Falkenstein and others 2000; Gehring and others 1993). Hajcak and colleagues found larger ERNs for incorrect trials associated with higher point values, as well as trials in which subjects believed that the experimenter was evaluating their performance online (Hajcak and others 2005). Support for an evaluative role of the ERN has come from studies of similar electrophysiological components. For

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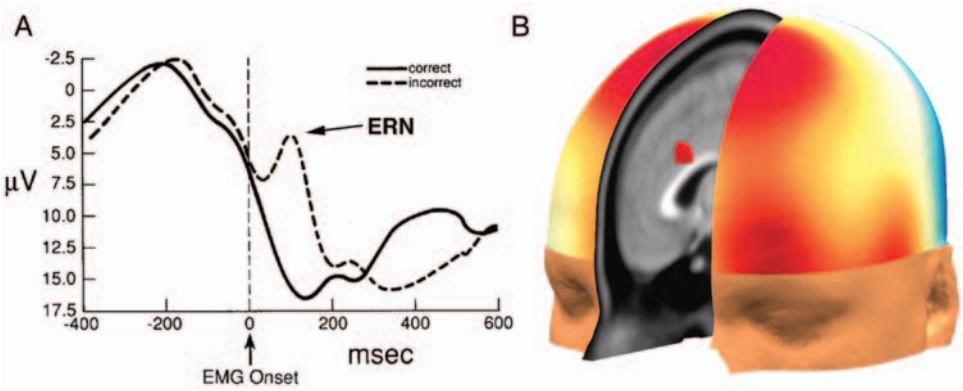

Fig. 1. The error-related negativity (ERN). (*A*) An event-related potential (ERP) waveform response-locked by the onset of electromyogram (EMG) activity shows the ERN occurring as a negative, upward deflection, approximately 100 msec after the incorrect response button was pushed (adapted with permission from Gehring and others 1993). (*B*) The map across the scalp surface shows the voltage distribution of a typical ERN waveform, taken at the peak of the ERN, 62 ms following the erroneous response. The focus of red at the fronto-central scalp sites indicates the maximum ERN amplitude. The diamond shape on the medial surface of the frontal cortex indicates the anterior cingulate cortex location of the best-fitting dipole model of the generator of the ERN.

instance, investigators have identified a medial frontal feedback negativity, which occurs approximately 250 ms after feedback and, like the ERN, has a similar localization (Gehring and Willoughby 2002; Holroyd and Coles 2002). In a simple, two-choice gambling paradigm, Gehring and Willoughby (2002) found that the feedback negativity reflected a choice that led to losing money more than it reflected the optimal choice in the gambling paradigm. They suggested that this feedback task isolated a separate component for evaluating task utility, apart from the detection of an error. Nieuwenhuis and colleagues showed that the feedback negativity responded to the first available information, indicating a "worse than expected" outcome, irrespective of whether it happened to be error or utility information (Nieuwenhuis and others 2004). Other work with medial frontal negativities linked to feedback have confirmed that this event-related potential (ERP) component is sensitive to the relative value of the outcome of task performance (Hajcak and others 2006; Holroyd and others 2004a). Questions remain as to how this evaluative function is implemented, and there is still debate as to whether the feedback negativity and the ERN reflect similar neural processes (for a discussion, see Gehring and Willoughby 2004). However, this class of ERP component clearly taps critical aspects of performance monitoring that evaluates ongoing behavior in response to a broader context of plans and goals.

Anterior Cingulate Cortex/Posterior Medial Frontal Cortex: Source of the ERN?

The obvious question to ask of electrophysiological studies that identify a component such as the ERN is the following: what neural structures generate it? Among the many dozens of ERP components, some of the best data on localization exist for the ERN. Source localization—using the topographic distribution of scalp electrical potentials to infer the location of neural generators, which requires solving the "inverse problem"—indicated an ERN source in the frontal midline cortex, specifically the anterior cingulate cortex (ACC; Dehaene and others 1994), an observation since confirmed by several groups (see Fig. 1*B*; Herrmann and others 2004; Mathewson and others 2005; van Veen and Carter 2002). Although source localization algorithms, particularly with low-density scalp recordings, have a precision on the order of centimeters, an estimated ACC location was supported by single-unit recordings of error-associated unit activity in the ACC of nonhuman primates (Niki and Watanabe 1979). Since the initial source localization with ERP, neuroimaging studies have refined and extended these estimates.

Carter and colleagues (Carter and others 1998) first suggested that the dorsal ACC (dACC) processes errors, as a part of a general "conflict/interference" detection system (see discussion below on conflict theory). As Table 1 indicates, the posterior medial frontal cortex, which includes the dACC, is the most consistently activated region of the brain in response to errors. However, examination of the individual studies, listed in Table 1, demonstrates significant variability in localization—as much as 6 cm, including the ACC proper (Brodmann areas 24 and 32), and the overlying prefrontal zones such as Brodmann areas 8 and 6 (see Ridderinkhof and others 2004). Many studies find error-related activations in the rostral extent of the ACC, sometimes in a large focus that covers both the anterior and posterior regions of the medial frontal cortex (MFC) (see Figure 2; Garavan and others 2003; Hester and others 2005; Kiehl and others 2000; Matthews and others 2005; Menon and others 2001; Polli and others 2005; Rubia and others 2003). Other areas activated, with less consistency than the dACC/posterior medial frontal cortex (pMFC), include the bilateral anterior insulae, extending into the inferior frontal operculum; the dorsolateral prefrontal cortex (dlPFC); the ventrolateral PFC (vlPFC); and lateral

Table 1. Selective Listing of fMRI Studies of Error-Related Processing

Author/Year	Task	Comparison	dACC/ pMFC	rACC/ aMFC	Anterior Insula/ Operculum	Ventrolateral PFC	Dorsolateral PFC	Lateral Parietal
Braver and others (2001)	Go/no go, oddball detection	Errors—corrects for all tasks	+					
Carter and others (1998)	A-X Continuous Performance Test (AX-CPT)	Errors—corrects	+			+	+	
Critchley and others (2005)	Physical and numerical Stroop	Errors—corrects	+		+	+		
Debener and others (2005)	Flanker	Incompatible errors—incompatible corrects	+		+		+	
Fiehler and others (2004)	Flanker	Errors—corrects	+					
Garavan and others (2002)	Go/no go	Errors—correct rejects	+				+	+
Garavan and others (2003)	Go/no go	Errors—correct rejects	+	+				
Hester and others (2005)	Error awareness task (EAT)	Aware or unaware errors—go trials	+	+		+	+	+
Kiehl and others (2000)	Go/no go	Errors—correct rejects	+	+				
Mathalon and others (2003a, 2003b)	Go/no go	Errors—hits Errors-correct rejects	+	+	+	+	+	+
Matthews and others (2005)	Stop-signal task	Errors (hard)—successful stops Errors (easy)—successful stops	+	+	+	+	+	+
Menon and others (2001)	Go/no go	Errors—correct rejects	+	+	+			
Polli and others (2005)	Saccade task	Errors—corrects	+	+	+	+		
Ramautar and others (2006)	Stop-signal task	Errors—go trials	+		+		+	+
Rubia and others (2003)	Tracking stop task	Errors—go trials	+	+				+
Ullsperger and von Cramon (2001)	Flanker task	Errors—corrects	+		+	+		+

dACC, dorsal anterior cingulate cortex; rACC, rostral anterior cingulate cortex; pMFC, posterior medial frontal cortex; aMFC, anterior medial frontal cortex; PFC, prefrontal cortex.

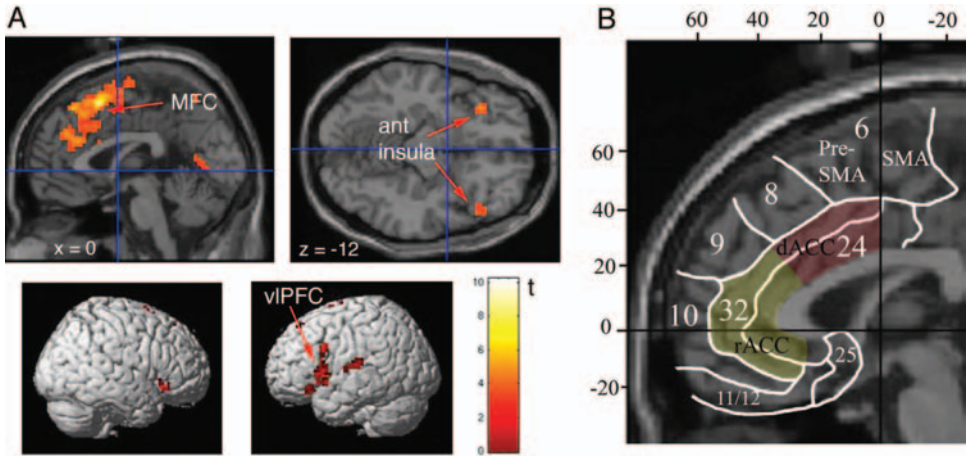

Fig. 2. (*A*) Error-related activity averaged from 21 healthy subjects performing an interference task gives robust activation of the medial frontal cortex (MFC). Subjects also exhibited activation in the anterior insula and the ventrolateral PFC (vlPFC). Data are displayed at an uncorrected $P < 0.005$ threshold, projected onto a reference brain atlas (SPM2). (*B*) Presumed Brodmann areas (BA) of the MFC are delineated, along with the reference coordinates of the Talairach and Tournoux (1988) system. The anterior cingulate cortex (ACC) is divided into rostral (rACC) and dorsal (dACC) sectors, corresponding to a rough segregation of emotional and cognitive functions, respectively (Steele and Lawrie 2004). SMA, supplementary motor area.

parietal cortex (typically Brodmann area 40). Thus, fMRI studies confirm that the ACC is involved in error processing, but they also implicate surrounding pMFC, rostral ACC (rACC), and other cortical areas.

In the effort to understand the function(s) of these regions and the role(s) they play in performance monitoring, the combination of ERP and fMRI has been useful. Measuring ERP and fMRI blood oxygenation level-dependent (BOLD) signals in separate sessions, Mathalon and colleagues found that dACC/pMFC BOLD signal was directly related to ERN magnitude in the dorsal and rostral ACC (Mathalon and others 2003b). Ullsperger and von Cramon (2001) also obtained ERP and fMRI data, separately, and found that the ACC focus from their fMRI data provided a good dipole fit for the ERN signal recorded in the same subjects. Debener and colleagues analyzed single-trial ERN data obtained inside the MR magnet, simultaneous with fMRI BOLD measurement, and found that the ERN magnitude correlated with the hemodynamic signal in the dACC but not in other error-related regions, such as the anterior insula and lateral prefrontal cortex (Debener and others 2005). Taken together, the fMRI and ERP studies provide good converging evidence that the dACC/pMFC is one of the principal generators of the ERN signal and a key part of an error-processing system.

Error Awareness and the Error Positivity

An error detection system might function completely within the realm of subjective awareness, implied in the idea of "detection," although it is not necessary that all components of such system be accessible to conscious awareness. There is some evidence that the ERN does not occur when subjects lack awareness of an error (Dehaene and others 1994; Luu and others 2000b), although no one would be surprised to find errors that completely escape detection by the brain. To more subtly parse the concept of awareness and error commission, Scheffers and Coles (2000) compared errors related to premature responding and errors related to stimulus uncertainty (degraded stimuli), and they found significantly larger ERNs when subjects made a premature response (i.e., confidence in the error appeared to increase the ERN). However, subjects making responses to degraded stimuli have lower expectations for a correct response and may correspondingly reduce the value they place on the trial. As mentioned above, when subjects reduce the personal investment they have in a correct trial, the ERN is reduced (Hajcak and others 2005). Evidence from ERP and fMRI has shown ERN/BOLD signals when subjects make errors of which they are not aware. During an antisaccade task, subjects are observed to make erroneous saccades, which are rapidly corrected below the level of awareness, usually within 200 ms of response initiation. Subjects are aware of corrections occurring with a longer latency, at 314 ms, but Nieuwenhuis and colleagues showed that the ERN for both types of error did not differ (Nieuwenhuis and others 2001). In an fMRI study, Hester and colleagues had subjects press a button to acknowledge their awareness of an error during a go/no-go task. The investigators found equivalent pMFC activation for aware and unaware errors, with larger lateral frontal and parietal activations for aware errors (Hester and others 2005). Thus, the data showing ERN and pMFC BOLD responses for errors outside of awareness provide evidence that subjective awareness is not a necessary concomitant of these medial frontal changes.

Some investigators have linked error awareness to another electrophysiological component, the *error positivity* (Pe; Davies and others 2001; Mathalon and others

2003a; Mathewson and others 2005; Nieuwenhuis and others 2001). The Pe frequently follows the ERN, around 200 to 300 ms after the response (Falkenstein and others 1991). Evidence for localization to specific brain areas is not as firm as the ERN, with some groups identifying the parietal cortex as a prominent generator (Davies and others 2001; Falkenstein and others 2000) and others pointing to a potential source in the anterior-rostral MFC/ACC (Herrmann and others 2004; Mathewson and others 2005; van Veen and Carter 2002). In the saccade task described above, in which the ERN occurred for aware and unaware errors, the Pe was attenuated for the saccade errors that occurred outside a subject's awareness (Nieuwenhuis and others 2001). Other work has shown a dissociation between the Pe (diminished) and ERN (preserved) in conditions associated with reduced overall awareness and arousal, such as prolonged wakefulness (Murphy and others 2006) and hypnosis (Kaiser and others 1997). Furthermore, the magnitude of the Pe has been correlated both with post-error slowing and with autonomic responses to errors (Hajcak and others 2003b). Because of topographic similarities with the P300 (P3), also associated with awareness for salient targets during a task, some authors have suggested that the Pe might reflect a P300-like component, in which the error is the salient stimulus that captures awareness (Davies and others 2001). Alternatively, Falkenstein and colleagues have suggested that it might reflect individual/emotional responses to an error, which might account for inconsistent findings in the published literature (Falkenstein and others 2000).

Lesion Studies and the Functional Role of the dACC/pMFC

The association of electrophysiological and BOLD-related signals with errors only provides the starting point for understanding the significance and functional role of these processes in detecting errors. Questions about the necessity of these processes for carrying out the behavior require investigations of patients with lesions, either accidental or induced. After applying transcranial magnetic stimulation over the medial frontal cortex, which induces temporary interruption of regional function, Rollnik and colleagues found a significant attenuation of the ERN, along with a reduction in error-corrective behavior (Rollnik and others 2004). Studies of the rare patients with lesions of the pMFC generally indicate that damage to this area of the brain affects the ERN, whereas effects on performance monitoring functions are not consistent, possibly reflecting compensatory mechanisms occurring after the initial brain damage. Stemmer and colleagues studied a series of 5 patients with ruptured anterior cerebral arteries, damaging the anterior extent of the MFC, including the ACC. These investigators found significant reductions in the ERN. Interestingly, some of the patients gave clear signs of being aware of error commission and did exhibit preservation of post-error slowing (Stemmer and others 2004). In a group of four patients with pMFC lesions, Fellows and Farah (2005) showed sparing of post-error slowing and sensitivity to conflict manipulations, challenging the idea that the ACC is necessary for cognitive control. Similarly, important data for any theory of dACC in performance monitoring come from studies of patients who undergo cingulotomy for refractory psychiatric disorders. Studies of these patients before and after ablation have turned up some evidence for impaired executive function and increased susceptibility to cognitive interference shortly after surgery (Cohen and others 1999a; Ochsner and others 2001). After several months of recovery, the patients show remarkable intactness of monitoring and executive functions, possibly due to significant compensatory changes (Cohen and others 1999b; Jung and others 2006).

The issue of compensatory changes also arises in studies of patients with lateral prefrontal cortex (PFC) lesions. Studies of these patients have revealed the absence of an ERN, as well as some failure to exhibit error-corrective behavior (Gehring and Knight 2000; Ullsperger and von Cramon 2006; Ullsperger and others 2002), whereas lesions of the frontal/orbitofrontal cortex or the temporal cortex did not affect the ERN in one cohort (Ullsperger and others 2002). Reviewing this literature, Ullsperger (2006) concluded that smaller lesions of key nodes of the performance monitoring network, such as the lateral PFC and the MFC, disrupt or "scatter" the signature of the ERN, whereas compensatory processing spares performance and permits relatively normal error detection and correction, unless the lesions are sufficiently large to permanently disable the system.

Abnormal Error Processing in Neuropsychiatric Populations

Hyperactive Error-Processing Signals in Obsessive-Compulsive Disorder and Depression

Since the discovery of the ERN and related performance monitoring work, the application of these paradigms to the study of neuropsychiatric illness has provided important insights about potential mechanisms of psychiatric illness and, in turn, new information about error processing. A fruitful area of investigation has been obsessive-compulsive disorder (OCD). Patients with OCD experience intrusive, repetitive obsessions that certain behaviors are "not right" or that their failure to do something will lead to bad outcomes. The obsessions lead to checking rituals, such as returning to the house dozens of times to ensure that the gas on the stove is turned off, or compulsive hand washing to remove perceived contamination. Pitman (1987) first suggested that OCD consists of defects in error monitoring systems, and Gehring and colleagues (2000) subsequently confirmed larger ERNs in OCD patients, even in tasks not related to OCD symptoms. These investigators also found a correlation between ERN magnitude and OCD symptoms. This work has since been replicated with ERP (Johannes and others 2001) and with BOLD fMRI (Fitzgerald and others 2005; Maltby and others 2005; Ursu and others 2003). The neuroimaging results are interesting because the finding of excessive task-related activity in the ACC corresponds to studies of OCD patients that have found increased ACC activity in a passive, resting state (Graybiel and Rauch 2000).

There is evidence that the abnormality in performance monitoring may be a trait phenomenon that establishes a vulnerability for OCD. Undergraduates scoring high on a questionnaire of obsessive-compulsive behaviors, not necessarily with full OCD, exhibited excessive ERNs compared to those scoring low on this questionnaire (Hajcak and Simons 2002). Also, patients with Tourette's syndrome, which has some genetic overlap with OCD, have exhibited increased ERNs (Johannes and others 2002). One group failed to find an excessive ERN in patients with OCD (Nieuwenhuis and others 2005a). Although alternative interpretations of the results are still possible, taken as a whole, the data strongly point to performance monitoring problems in OCD. Questions for further investigation have focused on whether the abnormality represents a "cognitive" deficit in a hypothetical comparator function that detects a mismatch between intended and actual responses, or whether the abnormality reflects an excessive affective response to an error in patients who are predisposed to excessive worry and perfectionism.

There is evidence that hyperactive error signals may not be unique to OCD. Like patients with OCD, patients with depression have exhibited greater ERN and feedback negativity (Kalayam and Alexopoulos 2003; Steele and others 2004; Tucker and others 2003). However, Ruchsow and colleagues reported no difference or reduced ERNs following erroneous trials for depressed patients (Ruchsow and others 2006). Although these inconsistencies need to be explained, there is additional evidence that negative affect, such as one finds in depression and OCD, may also be associated with elevated ERNs. A sample of healthy undergraduates with high scores on a worry questionnaire (Hajcak and others 2003a) and persons high in negative affect (Hajcak and others 2004; Luu and others 2000a) have also exhibited increased ERNs. Similar findings in depression and OCD should not be surprising, given the fact that both disorders respond to treatment with selective serotonin reuptake inhibitors (Graybiel and Rauch 2000). Taken together, the findings of increased error signals in OCD, depression, and personality types associated with these disorders suggest an endogenous trait, which may reflect a more generic mechanism of normal temperament and psychopathology. Along these lines, Fallgatter and colleagues reported a robust association between ERN magnitude and the short form of the polymorphism of the transcriptional control region of the serotonin transporter (Fallgatter and others 2004). This genotype has been associated with neuroticism (Sen and others 2004) and the interaction between early life stress and the development of depression in adulthood (Caspi and others 2003). Thus, the ERN, as well as the associated pMFC BOLD signal associated with errors, may turn out to have significant value in psychiatric research as an endophenotypic marker of liability for psychiatric illness.

Error-Processing Abnormalities in Other Disorders

Studies of error processing in schizophrenia have provided an interesting contrast to the work in OCD and depression. In general, almost all studies have found that schizophrenic patients show smaller ERNs and diminished MFC BOLD signals in response to errors (Alain and others 2002; Bates and others 2004; Kim and others 2006; Laurens and others 2003; Mathalon and others 2002). Although most of the patients in these studies were taking antipsychotic medication, Bates and colleagues (2004) studied patients in the acute stages of a psychotic episode (some of whom had gone off medication) and found reduced ERNs. The ERN amplitude increased after several weeks of treatment, but it remained smaller than the control group (Bates and others 2004). Using fMRI, Laurens and coworkers identified the rACC, and not the dACC, as the source of a smaller BOLD signal in a go/no-go task (Laurens and others 2003). These authors interpret the findings as a reflection of a motivational deficit, referred to in schizophrenia as *negative symptoms*, interacting with performance monitoring. At least one group has reported an inverse correlation between the magnitude of the ERN and the severity of negative symptoms (Bates and others 2002). Thus, an examination of the error-processing literature in schizophrenia raises interesting questions about the relationship between the psychopathology of negative symptoms and motivation deficits.

Affect and the Anterior MFC

Several lines of evidence lead to a consideration of the role of affect in error processing. When a person makes an error, emotions of frustration and disappointment can occur, and these reactions can be amplified in psychiatric conditions or in persons prone to more negative affects, as described above. Investigators of the ERN have suggested that the emotional response to an error formed an important part of the measured scalp potential (Gehring and others 1993; Luu and others 2003) and that the rACC might process the emotional component of the error signal (Luu and others 2003; van Veen and Carter 2002). Table 1 indicates that some, but not all, neuroimaging studies activated the rACC in the anterior MFC. Relative to the caudal/posterior section of the ACC/MFC, the rACC exchanges more projections with limbic brain regions such as the amygdala (Kunishio and Haber 1994; Vogt and Pandya 1987). Based on a review of the primate and lesion literature, Devinsky and colleagues designated it the "affective division" (Devinsky and others 1995). More recent meta-analytic reviews of human functional neuroimaging studies have confirmed a functional segregation between cognitive activity in the dACC/pMFC and emotional activity in the rACC/anterior medial frontal cortex (aMFC; Bush and others 2000; Steele and Lawrie 2004).

Testing the notion that the rACC reflects an emotional response to an error, Taylor and colleagues used a response interference task with a monetary incentive, in which errors led to either losing money or failing to gain money on some trials. They reasoned that an affective response to a stimulus would reflect the salience and value that an individual attaches to a stimulus. As predicted, they found that when subjects made errors leading to a monetary loss, rACC activity was greater, compared to error trials in which no money was lost or

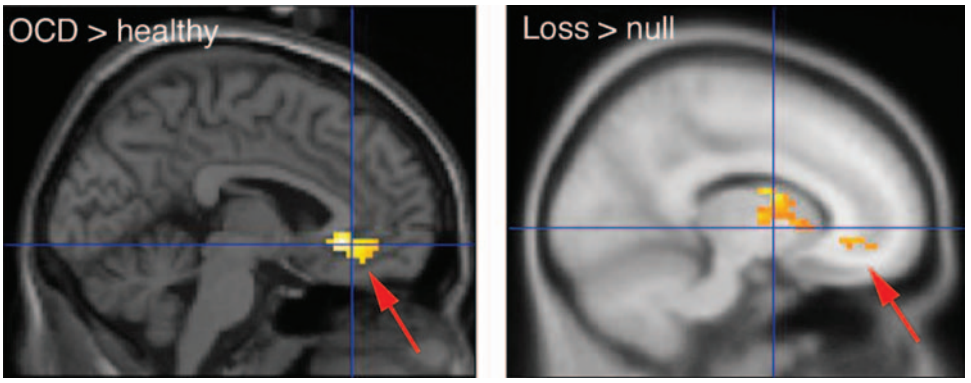

Fig. 3. Error-related activations in the rACC are associated with an emotional disorder and with a more negative outcome for healthy individuals. During error commission, the rACC is activated for patients with obsessive-compulsive disorder (OCD) greater than healthy subjects (figure modified with permission from Fitzgerald and others 2005) and in healthy subjects for loss-related errors, relative to errors without associated financial loss (figure modified with permission from Taylor and others 2006).

gained (Taylor and others 2006). This rACC/subgenu ACC focus was in the same region as hyperactive error-related activity for OCD subjects on a flanker task (see Fig. 3; Fitzgerald and others 2005). One interpretation of these results is that the greater value that OCD subjects placed on performing correctly was driving the excessive error-related activity in the rACC.

Making Sense of the Data: Theoretical and Integrative Accounts

Several theories have arisen to explain the role of the electrophysiological and neuroanatomical components associated with errors. Most accounts have focused on medial frontal negativities (ERN and feedback negativity) and medial frontal hemodynamic changes. Two fairly detailed theories based on computational models, conflict theory (Botvinick and others 2001; Carter and others 1998) and reinforcement learning theory (Holroyd and Coles 2002), have suggested that the medial frontal error signal presents either a specific occurrence of conflict monitoring or an evaluative function signifying "worse than expected events," respectively. In this section, we briefly review these theoretical accounts, as well as some more general attempts to integrate the existing findings.

Conflict Theory: Errors as a Special Case of High Conflict

One of the most successful and influential approaches to performance monitoring and cognitive control has been conflict theory (Botvinick and others 2001; Carter and others 1998). In addition to accounting for several experimental findings involving the dACC and dlPFC, error-related signals have been explained as a special occurrence of cognitive conflict. Cognitive conflict (also known as interference) occurs when a strong response tendency competes with, and must be overcome by, the intended response (e.g., saying the font color of a word, which itself depicts a different color, such as "RED" printed in green letters—the so-called Stroop effect). Slower reaction times invariably occur when subjects name the color of a font incongruent with the color word, compared to the case where the color font and color word match (Stroop 1935). According to conflict theory, the dACC monitors for the presence of cognitive conflict and passes a signal to the lateral PFC to increase cognitive control (e.g., "attend to color font") when conflict is high (Botvinick and others 2001; Carter and others 1998; Kerns and others 2004; Yeung and others 2004). Errors generate high conflict when the stronger, but undesired, response tendency reaches a sufficient threshold to command an actual response. During successful trials, the less potent channel (boosted by increased control) "wins out" over the more potent channel—leading to a reduction in conflict. But during an incorrect trial, the two channels compete for longer, leading to more response conflict that persists after the response (e.g., the ERN; for a detailed computational account, see Yeung and others 2004).

Support for the contention that errors represent conflict first came from functional neuroimaging work. In the first fMRI study to examine error-related activity, Carter and colleagues showed that dACC activity was elevated both for trials with high conflict and for trials in which errors occurred (Carter and others 1998). In subsequent work, this group also showed that dACC activity predicted dlPFC activity in a subsequent trial (the signal to increase control), and adjustments following an error—the post-error slowing—were also predicted by dACC activity in the prior trial (Kerns and others 2004). The theory makes strong predictions that the same dACC region will process conflict-related activity and error-related activity. ERP data in support of this prediction have found that the N2, a stimulus-locked electrophysiological index of conflict (increased in conditions of Stroop incongruent, relative to congruent, words), has identical source localization as the ERN—both in the dACC (van Veen and Carter 2002). In addition to significant support from the published literature, conflict theory also rests upon an explicit, well-characterized computational model (Botvinick and others 2001) that has been used to model ERN waveforms

(Yeung and others 2004). Overall, the theory has explained many findings in the error-processing literature, and it has generated testable predictions. How well it has held up to some of these tests is a matter of ongoing debate.

An interesting aspect of conflict theory is that it does not posit an error detection mechanism, per se. Error-related signals occur in the process of perceiving stimuli and translating the percept into the task-appropriate response. Therefore, one should also find a medial negativity for correct-responses trials with high conflict. Indeed, investigators have identified a correct-related negativity (CRN) with a similar scalp distribution and time course as the ERN (Vidal and others 2000, 2003). However, Coles and colleagues have suggested that the CRN may reflect error processing on correct trials or a contamination by stimulus-associated negativities (Coles and others 2001), and other groups have not found reliable CRNs (e.g., Gehring and others 1993). Bartholow and coworkers did find CRNs during a flanker task, and they manipulated the expectancy for trials of low and high conflict. Contrary to predictions of conflict theory, they found that the CRN was more sensitive to low-probability trials, regardless of the level of conflict in the stimulus (Bartholow and others 2005). Thus, although supporting the notion that a CRN does occur, they suggest that strategic expectations about an upcoming trial also influence the degree of conflict in the performance monitoring networks.

Several lines of research from ERP, neuroimaging, and animal electrophysiology studies have challenged the contention of conflict theory that error signals reflect the same processes and neural systems as response conflict. ERP data have demonstrated that the N2 and ERN components dissociate in groups of subjects and across modalities, such that the ERN remains relatively constant, whereas the N2 varies (Davies and others 2001; Falkenstein and others 1999). Examining correlations between the N2 and fMRI BOLD signal, Mathalon found that whereas the ERN (after removing correlations with N2) correlated with rACC and dACC, the N2 correlated only with dACC (Mathalon and others 2003b). Functional imaging studies attempting to separate conflict processing and error processing have not replicated the work of Carter and colleagues (Carter and others 1998). Instead, this work has noted a consistent tendency toward locating conflict-related foci in Brodmann areas 6/8 (presupplementary motor area, or pre-SMA) and error-related foci in Brodmann areas 24/32 (dACC), in addition to areas of overlap (see Fig. 4; Braver and others 2001; Garavan and others 2003; Kiehl and others 2000; Ullsperger and von Cramon 2001, 2003). Single-unit recordings from the dACC of nonhuman primates have recorded activity sensitive to errors (and to the absence of reward) in a saccade task but no cells responsive to the high-conflict situation of having to countermand a reflexive saccade (Ito and others 2003).

How are we to explain different findings with respect to conflict and error processing in the neuroimaging literature? At least some of the contradictory findings may stem from the potential hazards inherent in the interpretation of group-averaged data, particularly because group averages

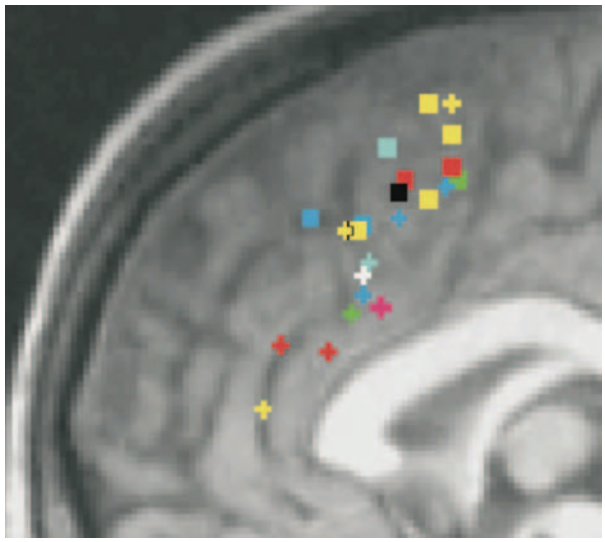

Fig. 4. The figure plots medial frontal cortex (MFC) foci from fMRI blood oxygenation level-dependent (BOLD) studies, which separated interference/conflict-related (squares) and error-related (crosses) activations, demonstrating a tendency for error-related activity to fall in the rostral anterior cingulate cortex (rACC) and dorsal ACC (dACC) and conflict-related foci to fall in the dACC and presupplementary motor area (pre-SMA). Colors represent the following: green (Braver and others 2001), red (Garavan and others 2003), yellow (Kiehl and others 2000), blue (Ullsperger and von Cramon 2001), and light blue (Ullsperger and von Cramon 2003). Figure modified from Hester and colleagues (Hester and others 2004), with permission.

conflate the magnitude and spatial location of individual signals. This is illustrated in Figure 5, from a study by Taylor and colleagues that distinguished conflict-related activation in a response interference task from error-related activation (Taylor and others 2006). Although the group-averaged error signal was actually in the pre-SMA, in contradiction to data summarized in Figure 4, the individual activation peaks for errors covered a wide expanse of the aMFC and pMFC. Whether the individual subjects shown in Figure 5 used different neural systems to accomplish a similar task or whether the same system maps to different anatomy across individuals remains to be determined. Whatever the case, the implication for conflict theory and error processing is that attention to individual differences may be critical to advance our understanding.

Reinforcement Learning: Errors as a Worse-Than-Expected Outcome

Errors represent negative, undesirable events, and they can provide feedback that helps a subject adjust behavior (i.e., people can "learn from mistakes"). This colloquial notion is embedded in another important computational account of error processing, first suggested by Holroyd and colleagues (Holroyd and Coles 2002; Holroyd and others 2005). The authors built upon

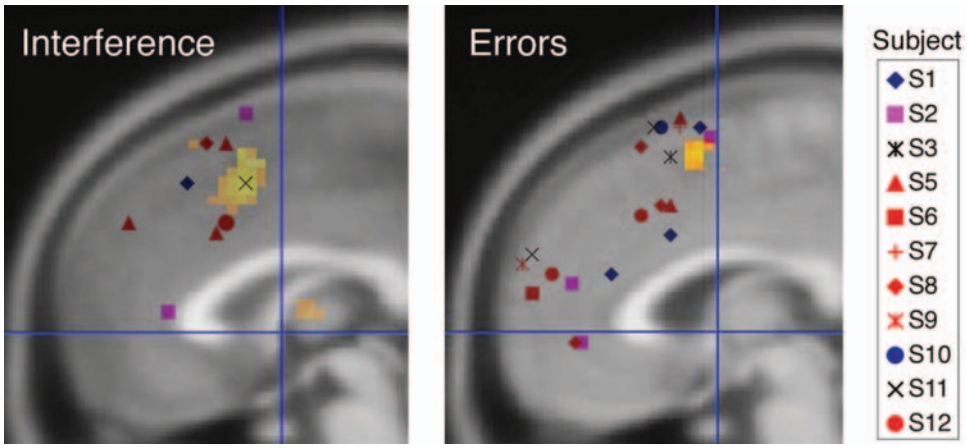

Fig. 5. Although group-averaged data show relatively discrete foci, the individual data that contribute to a group focus often have considerable anatomic spread. This figure demonstrates that for 12 subjects, foci from each subject (colored markers) had a more rostral distribution for error-related activity compared to interference/conflict-related activity. However, the group-averaged foci (yellow shading) yielded dorsal activations for errors and interference. Individual foci indicate only the point of maximum significance ($P < 0.05$, corrected for the search region in the medial frontal cortex), and the extent of activation has been omitted for clarity. Figure modified, with permission, from Taylor and colleagues (Taylor and others 2006).

studies of feedback negativities, first described by Miltner and colleagues for a task in which subjects had to estimate the duration of one second (Miltner and others 1997). A feedback stimulus of 600 ms after the response indicated whether the subject correctly estimated the elapsed time. The ERP component exhibited a negative deflection, which Miltner and coworkers related to the ERN. Because the feedback follows the response, the feedback negativity cannot be explained as an effect of conflict originating in the generation of the response. As an alternative theoretical framework, Holroyd and colleagues invoked concepts borrowed from reinforcement learning (RL) theory.

They posited that error processing in the pMFC represents a signal, reflecting activity in midbrain dopamine neurons, that an expected, positive event (correct response) has not occurred (i.e., the event is negatively evaluated as "worse than expected"). This theory builds upon work done by Schultz and colleagues, who have demonstrated that these dopamine neurons respond to stimuli that predict a reward and reduce activity when an expected reward does not occur (Schultz 2000). The reduction in dopaminergic activity in the absence of an expected reward is hypothesized to disinhibit pMFC activity, specifically in the dACC. Support for the hypothesis that error-related activity in the pMFC activity reflects a negative evaluation comes from several different lines of study. Single-unit recordings of pMFC neurons in monkeys (Ito and others 2003; Shima and Tanji 1998) and humans (Williams and others 2004), as well as an fMRI study in humans (Bush and others 2002), have demonstrated increased neuronal activity in the pMFC in response to the decrease or absence of an expected reward. Rushworth suggests that the dACC plays a key role in linking actions to consequences (Rushworth and others 2004), and RL theory has attempted to build upon this work to explain the specific processes involved in performance monitoring and error detection.

Significant experimental support for the RL account of performance monitoring has accumulated, in addition to data not in accord with the theory. The feedback negativity has been shown to occur following monetary loss (Gehring and Willoughby 2002; Holroyd and others 2004a) and the unexpected absence of reward (Holroyd and others 2003). However, recent work has found that the feedback negativity occurs for passive tasks with negative outcomes (Yeung and others 2005), showing that if it is a learning signal, the learning occurs in the context of expectations, not just actions. Donkers and colleagues studied subjects in a passive "slot machine" paradigm, which could yield a payoff or loss, and found a feedback negativity in response to trials that differed from a previous trial, irrespective of gain or loss (Donkers and others 2005). They found that the amplitude of that feedback negativity magnitude correlated with time estimation feedback negativity but not with an ERN recorded in a flanker interference task. A similar dissociation has been reported between feedback-related findings and performance-related error signals in the pMFC. Some groups have found pMFC activity in response to an error and negative feedback (Holroyd and others 2004b; Ullsperger and von Cramon 2003), but others have not found this congruence (Nieuwenhuis and others 2005b; van Veen and others 2004). Despite these failures to fully explain the data, RL theory has provided an important contribution by focusing the field on the several types of medial frontal negativities that monitor performance and may index separate, though related, functions of evaluating outcomes.

Error Processing in the Context of Action Regulation and Motivating Contexts

When a person commits an error—a deviation from intended behavior—the error may require a very small behavioral adjustment, or it may entail the reassessment of an entire behavioral plan. An efficient error-monitoring system should be able to evaluate the significance of an error, in addition to detecting that an error has occurred. Some errors, such as rapidly corrected saccades, may not even rise to the level of awareness (Nieuwenhuis and others 2001). Other errors may challenge a person's sense of self-worth. Although most laboratory experiments are unlikely to make people feel badly about themselves, we have reviewed data showing that emotional disorders, such as OCD and depression, exhibit a hyperactive error signal. Furthermore, dozens of laboratory studies have now demonstrated that ERNs, feedback negativities, and MFC BOLD signals are increased when subjects place more value on correct responses. One conclusion to draw from a review of the neural systems of error processing is that multiple motivating frameworks establish contexts in which action is monitored and regulated.

This idea is depicted in Figure 6, in which a hierarchy of cortical modules influences and monitors stimulus-response translation and action selection. At the most elementary level, lateral PFC, along with dACC, establishes the immediate task context. In the case of a Stroop task, this context is as follows: "Read color font." In superordinate relationship to the task, higher level contextual representations monitor and influence, representing motivating contexts such as "Correct response is good," "Accuracy makes me a good person, or "I will show the experimenter how quick I am." Each one of these representations probably uses different cortical modules, which cluster in the aMFC and parts of the pMFC. In this hierarchy, superordinate modules in the anterior/rostral medial cortex, such as rACC and dorsal medial PFC (dmPFC; generally not activated in most error studies, although evident in a few individuals in Fig. 5), evaluate outcomes, both positive and negative (Coricelli and others 2005; Elliott and others 2000), and assess self-relevance (Ochsner and others 2004). One explanation for the individual differences depicted in Figure 5 may be the tendency of each individual to recruit different motivating contexts, subserving different overarching goals, in the performance of a task. Support for this hypothesis comes from studies that have used differences in individual temperament and personality style to explain variance in ERP (Hajcak and others 2003a, 2004; Luu and others 2000a) and neuroimaging studies (Hester and others 2004) of error processing.

Once an error is detected, a compensatory adjustment occurs, which several investigators have formulated as processes for resetting or remotivating the cortical modules engaged in the task. Luu and colleagues have suggested that the ERN reflects theta activity that entrains multiple corticolimbic circuits (Luu and others 2003). Critchley and colleagues have posited that the ACC mediates the integration of arousal with cognitive, emotional, and motivational information (Critchley and others 2003). They have shown that during error commission, an index of sympathetic autonomic arousal occurring with the error (pupil dilation) correlates with the BOLD signal in the rACC. From these data, they infer that this region integrates motivation/arousal with the ongoing task (Critchley and others 2005). Interestingly, these investigators also found correlations of the autonomic index with bilateral anterior insula—a commonly activated and poorly understood region found in error processing. In a recent meta-analysis of 10 diverse tasks—including verbal generation, visual matching, semantic judgment, visual search, and motor timing—Dosenbach and colleagues found that the dACC/pMFC and bilateral anterior insula/inferior operculum were consistently activated across the 10 tasks. Activity in these regions was associated with task initiation, maintenance, and error processing. They suggest that, together, these regions form a part of a core "task-set" system (Dosenbach and others 2006). Although details of implementation remain vague (e.g., How much of this activity is conflict related? Do these regions select and monitor?), the association between error processing and core task-set activities provides an important starting point for understanding performance monitoring.

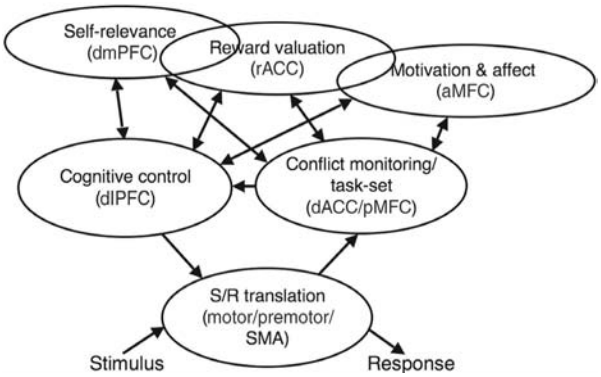

Fig. 6. A proposed hierarchy of cortical modules that influence and monitor stimulus-response translation and action selection. At the middle level, the dlPFC provides control that influences task selection at the first level, in conjunction with a conflict monitoring/task set region (dACC/pMFC). These levels and their unidirectional interrelationships are modified from conflict theory (Botvinick and others 2001; Yeung and others 2004). Superordinate modules are invoked to provide motivational contexts that provide overarching goals, which vary with the individual. Functional mappings are tentative, as are the interrelationships, and some functional overlap may occur within anatomical regions (e.g., dACC may also process motivational information; Rushworth and others 2004). dlPFC, dorsolateral prefrontal cortex; dmPFC, dorsal medial prefrontal cortex; dACC, dorsal anterior cingulate cortex; rACC, rostral anterior cingulate cortex; pMFC, posterior medial frontal cortex; aMFC, anterior medial frontal cortex; SMA, supplementary motor area.

Conclusion: The Emerging Neurobiological Basis of Performance Monitoring

The past 15 years of research into the neural mechanisms of performance monitoring and error detection have yielded a rich, rapidly growing field of converging studies. Findings point convincingly to the ERN, with a primary contribution from the dACC/pMFC, as one of the key nodes in this process, along with lateral PFC and rACC. However, outside of these regions, comparatively little research exists on the role of bilateral anterior insula or the parietal regions frequently activated in some, but not all, studies. Other medial frontal negativities besides the ERN are implicated by the evaluative process of performance monitoring, although more work remains to clarify the roles and interrelationships of these ERP components. More recent attention has begun to focus on individual differences, including specific genotypes, as a source of functional variance in these neurobiological measures. Examining the data, particularly from patients with lesions, leads to the conclusion that the system is very plastic and adaptable and may even function with the benefit of parallel systems that allow functional redundancy. Many questions will likely yield to studies of the next 15 years, including a better understanding of the pathological conditions that manifest in aberrant monitoring behavior.

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