can be drawn through the consequences of errors and other performance problems. In the 1960s, Rabbitt (429, 430) described typical behavioral changes after errors in speeded choice reaction time tasks: immediate error corrections by a second key press and response slowing after errors. Sometimes performance was also found to improve on trials after errors (316, 317), and error signaling (pressing a specific button whenever an error was encountered) was introduced to study conscious error detection (427, 431, 432).

Also in the 1960s, the first physiological evidence for a performance monitoring system in the human brain was reported by Bechtereva and colleagues (27–30), who by means of depth electrodes found increased neuronal activity in caudate and putamen specifically after errors but not after correct responses in psychological tests, which they interpreted as activity of "error detectors" of the brain.

1. Invasive electrophysiology

Single-unit recordings in the anterior cingulate cortex (ACC) of monkeys revealed that a subset of neurons specifically increased firing rate after errors and after omission of reinforcement on correct trials (380) (for anatomical details and nomenclatures used in this review, see **FIGURES 2** and **3**). A study on motor learning identified transcortical field potential changes in macaques' ACC area 24 at the ventral bank of the cingulate sulcus that were associated with erroneous and unrewarded movements (201). More recent experiments using a saccade countermanding task in which monkeys had to withhold prepotent prosaccades to a visual target upon occurrence of a rare stop signal extended these findings (271, 459, 500). This task allows the study of error-related activity on incorrectly executed saccades (errors of commission) and activity related to response conflict, which arises by competition between the impending prosaccade and the intention to withhold it. This response conflict (see sect. III*B* for a detailed discussion of this concept) was reflected by simultaneous activation of movement and fixation neurons in the frontal eye fields and superior colliculus. It was shown that neurons in the dorsal bank of the anterior cingulate sulcus (in the rostral cingulate motor area, CMAr) responded to errors (271). Half of these neurons were also responsive to omission of re-

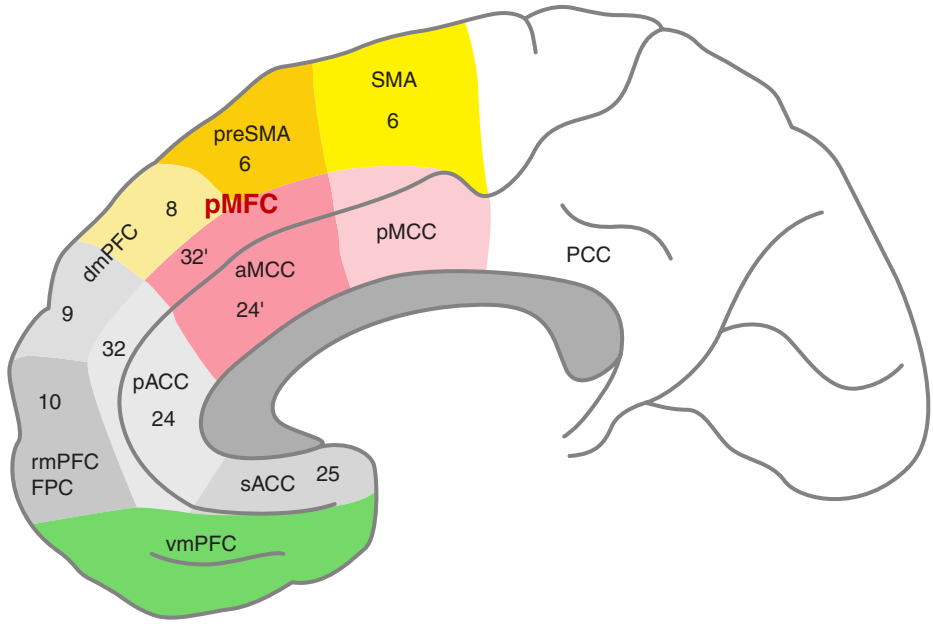

FIGURE 2. Subregions of the medial frontal wall. Based on cytoarchitectonical and functional criteria, the medial frontal cortex can be divided into cingulate and isocortical areas. The cingulate cortex has been divided into anterior, middle, and posterior portions, which are further subdivided into the subcallosal and pregenual anterior cingulate cortices (sACC and pACC, respectively), the anterior and posterior midcingulate cortices (aMCC and pMCC, respectively), and the posterior cingulate cortex (PCC) (556). Another terminology of the regions around the dorsal section of the cingulate sulcus has been suggested in an early meta-analysis attempting to link human cortical areas to their monkey's homologs (412, 413): the anterior and posterior parts of the rostral cingulate zone (RCZ), largely overlapping with the aMCC, are assumed to be the homolog of the monkey's rostral and ventral cingulate motor areas (CMAr, CMAv), respectively; and the caudal cingulate zone (CCZ) might correspond to the monkey's dorsal cingulate motor area (CMAd). The isocortical regions can be divided into ventromedial, rostromedial, and dorsomedial prefrontal cortex (vmPFC, rmPFC, dmPFC, respectively) and the presupplementary and supplementary motor areas (preSMA and SMA, respectively) (160). Hemodynamic signals in neuroimaging experiments often coactivate several neighboring regions such that the descriptive term posterior medial frontal cortex (pMFC) has been used to commonly refer to pre-SMA and aMCC, as well as adjacent SMA, posterior dmPFC, and pMCC (439). The numbers refer to cytoarchitectonic areas. FPC, frontopolar cortex.

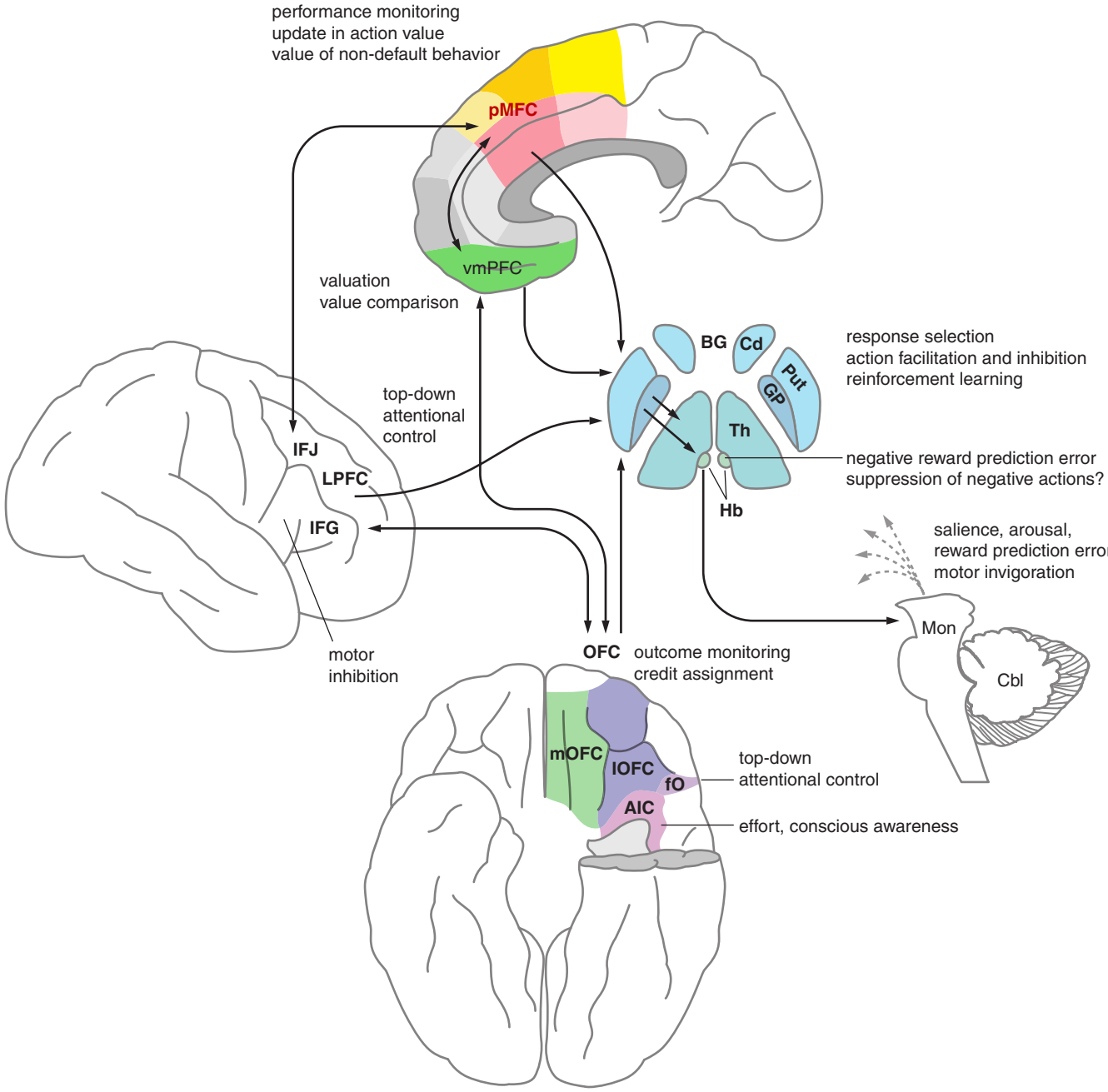

FIGURE 3. Important brain structures involved in performance monitoring and adaptive behavior, their function, and interaction. pMFC, posterior medial frontal cortex (see **FIGURE 2** for details); vmPFC, ventromedial prefrontal cortex; LPFC, lateral prefrontal cortex; IFJ, inferior frontal junction; IFG, inferior frontal gyrus; OFC, orbitofrontal cortex; m/lOFC, medial/lateral OFC; AIC, anterior insular cortex; fO, frontal operculum; BG, basal ganglia; Cd, caudate nucleus; Put, putamen; GP, globus pallidus; Th, thalamus; Hb, habenula; Mon, mesencephalic and pontine monoaminergic nuclei; Cbl, cerebellum.

wards. A different subset of ACC neurons specifically responded to earned and unexpected reward. Whereas none of the recorded ACC units showed activity related to response conflict, the supplementary eye fields contained distinct neuronal populations that were responsive to errors, reinforcement, or response conflict, respectively (500). In contrast, studies in humans undergoing cingulotomy for medically intractable psychiatric disorders reported neurons sensitive to response conflict in the anterior midcingulate cortex (aMCC), the putative homolog of the monkey's CMAr (127, 482).

A combined single-unit recording and inactivation study showed that the monkey's CMAr does not only respond to undesired action outcomes but is also involved in subsequent adaptive changes in action selection (485). In a modified response reversal task, the reward magnitude was gradually decreased on correct actions until the monkey

switched to the alternative action, which then became the rewarded response. Interestingly, 37% of CMAr neurons specifically increased firing *1*) after the reward was reduced and only *2*) before the monkey selected an alternative response on the subsequent trial. When the CMAr was reversibly inactivated by the injection of the $GABA_A$ agonist muscimol, the monkeys showed perseverance even when the reward was considerably reduced and spontaneous response switches in trial series with constant maximal reward. Nearly identical results were found in intraoperative single-unit from recordings the aMCC in humans undergoing surgical cingulotomy (580). Thus aMCC activity seems to translate changes in action outcomes into the need for adaptive behavior. This view is supported by findings that CMAr neurons encode action sequences and multiple feedbacks during exploration (423, 424). This activity ended as soon as enough information was accumulated to adapt behavior and exploit the gained knowledge. Action outcomes are informative with respect to the necessity of adaptation when they deviate from expectation, which can be expressed formally as reward prediction error (RPE). Several studies have demonstrated that CMAr neurons code RPEs (7, 288, 346, 455). Other variables needed for action valuation and assessing the need for ongoing and future adjustments also appear to be coded by anterior cingulate neurons, for example, reward expectancy and reward proximity (342, 484) as well as effort (111, 243, 244), often in an action-specific fashion. In addition to CMA, adjacent supplementary motor area (SMA) and pre-SMA also contain neurons that code evaluative signals such as expected outcome, actual outcome, RPE, and surprise (458).

While single-unit recordings in humans are performed rather rarely, more evidence on anatomical structures involved in performance monitoring has been collected using intracranial local field potentials (LFPs) reflecting postsynaptic activity. Error-related LFPs were reported in the ACC, aMCC, lateral frontal and mesial temporal cortices, and the amygdala of epilepsy patients (55, 56, 421) and in the dorsal ACC and supplementary eye fields of monkeys (154, 155). This suggests that performance monitoring signals are available throughout a distributed network rather than a single "error detector" region, but the electrophysiological responses to performance problems have been reported most consistently in the aMCC. A study using arrays of microelectrodes (566) in the human aMCC showed larger source currents with inhibited firing (in superficial layers) for errors compared with correct responses and for negative compared with positive feedback. Interestingly, source currents were also increased for novel stimuli and with increasing task difficulty. The authors suggest active inhibition in superficial cingulate layers based on these findings. The neuronal activity from deep layers where the efferents of the ACC arise was not recorded, however.

2. Event-related potentials

In the 1990s, performance monitoring research was significantly boosted by the discovery of error-related event-related brain potentials (ERPs) in the scalp-recorded EEG making the monitoring process observable by noninvasive techniques **(FIGURE 4)**. The error-related negativity (ERN) or error negativity (Ne) was discovered in response-locked ERPs on errors in speeded choice reaction time tasks (165, 198). It is a frontocentrally distributed negative deflection starting around the time of the response and reaching its peak between 50 and 100 ms later. When referenced to averaged mastoids, ERN amplitudes can reach up to 15 μV at the electrodes FCz and Cz. It is preceded by a positive deflection peaking 50 to 0 ms prior to the response and followed by another positive deflection which peaks 100–250 ms after the response. This sequence of frontocentral positive and negative deflections has raised the notion of an oscillation time-locked to the erroneous response in the theta band (5–7 Hz). This theta power increase is larger on errors than on correct trials and has been observed in averaged and single-trial data (79, 136, 328, 330, 379, 599, 600). The question whether the ERN might result from a power increase and/or phase-locking of theta oscillations is still under debate (592). The frontocentral positive deflection directly following the ERN (also called early error positivity, see below) is somewhat broader than the ERN which is in line with findings of an error-specific increase in delta power (1.5–3.5 Hz; Ref. 599). The ERN is independent of stimulus and effector modality, i.e., independent of whether visual, auditory, or tactile stimuli are presented (166, 213) and independent of whether manual, foot, eye-movement, or vocal responses are given (193, 194, 250, 340, 376, 539, 574). Electrical source analyses consistently suggest the ERN and its magnetoencephalography (MEG) equivalent to be generated in the posterior mesial frontal cortex (pMFC), specifically in the aMCC (137, 213, 250, 287, 355, 536). A recent MEG study (1) suggested additional involvement of the posterior cingulate cortex (PCC). In a study with simultaneous EEG and functional magnetic resonance imaging (fMRI), we found a trial-by-trial correlation of the ERN amplitude with the hemodynamic response in the aMCC (136). Moreover, studies in monkeys suggest a close link between error-related LFPs in the anterior cingulate cortex and the scalp-recorded ERN (154, 204). Taken together, source localization findings and invasive recordings in humans and monkeys provide overwhelming evidence that the ERN is generated in the pMFC with a focus in the aMCC. Further research is needed to elucidate the significance of the recently reported additional activity in PCC (1, 83). Various functional interpretations of the ERN will be discussed in section III.

Whereas in young healthy participants correct responses only sometimes elicit a clear response-locked negativity in the raw ERPs, a negativity similar to the ERN, usually of smaller amplitude, is often seen in older subjects and pa-

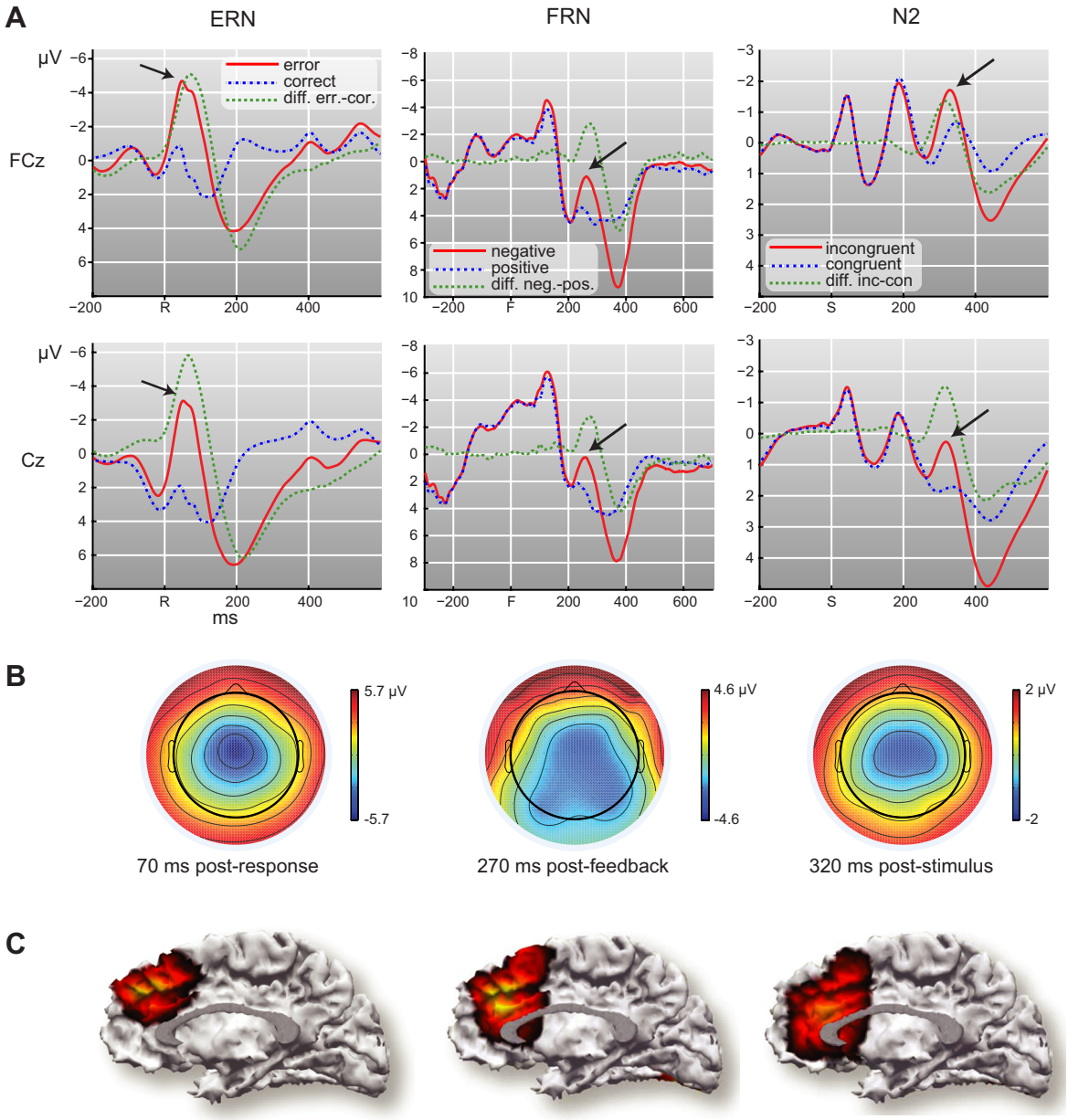

FIGURE 4. Event-related potentials associated with performance monitoring. *A*: prototypical ERPs in response to errors (ERN, response-locked), negative feedback (FRN, feedback-locked), or preresponse conflict (N2, stimulus-locked) at midline electrodes FCz and Cz. *B*: corresponding topographies of difference waves from *A*. *C*: source localizations ERN, FRN, and N2. R, response; F, feedback; S, stimulus. [From Gruendler et al. (213).]

tients, the so-called correct-related negativity (CRN) (181, 199, 538). In young participants it can be revealed by Laplacian transforms of the EEG data (553, 554) which filter out low spatial frequencies masking the focal CRN activity. Recent studies using blind source separation by temporal independent component analysis (ICA; Refs. 335, 336) strongly suggest that ERN and CRN stem from the same or largely overlapping generator structures (202, 441, 573). A temporospatial principal component analysis (PCA) revealed two temporospatial factors contributing to both ERN and CRN (156). In agreement with the ICA findings, a central factor was found that was sensitive to response correctness and task difficulty. A more frontal negative factor was present for all responses and was not modulated by accuracy and difficulty. It has been suggested that the CRN reflects partial error processing on correct trials with high uncertainty about the action outcome, for example, due to stimulus ambiguity (101, 401, 460). Notably, partial error execution observable by isometric muscular activity of the incorrect response hand is not a necessary prerequisite for the CRN (553). Rather, the amplitude of the response-related negativities CRN and ERN seems to reflect the objectively accumulated evidence in favor or against having made an error (574). It has been suggested

that both, ERN and CRN, signal the need for adjustments (22). This is consistent with the finding that the CRN amplitude is smaller on trials preceding errors and the resulting notion that it is involved in keeping up resources (effort) allocated to the task at hand (5, 219, 437). The above-mentioned finding that the CRN is larger and easier to detect in older subjects and some patient groups has not been explained unambiguously, yet. Perhaps several factors such as higher motivation (and thus higher effort invested in the task), higher uncertainty, as well as delay and increased jitter of other onging EEG activity with the potential to mask CRN activity contribute to this effect.

As shown in **FIGURE 4**, the ERN is followed by positive deflections specific to error trials, collectively referred to as error positivity (Pe) (165, 166). The frontocentral positive deflection following the ERN is sometimes called "early Pe"; a positive slow wave at parietal electrodes sustained from 300 to 500 ms post response is the classical Pe, sometimes called "late Pe" (546). Dipole localization studies suggest the early Pe to be generated by the same generators as the ERN, whereas parietal cortex and rostral ACC seem to contribute to the late Pe (232, 546). However, these results have to be interpreted with caution due to methodological limitations such as low electrode number and localization based on grand mean average activity. The functional significance of the Pe is still rather unclear. It appears to reflect the accumulated subjective evidence for an error associated with conscious perception of the error (398, 497, 526, 574). Furthermore, it seems to share features with the P300 observed on infrequent target stimuli in oddball tasks (12, 126, 438).

The ERN occurs in speeded reaction time tasks, in which stimuli usually convey the necessary information to unequivocally determine the correct response (given enough processing time). Therefore, errors can be detected without external feedback. In many situations, however, we select our actions under significant uncertainty. In such underdetermined situations, errors can only be detected based on external information about the action outcome provided by the sensory systems. Negative feedback provides evidence to the performance monitoring system that the action was not successful. In a time estimation task, in which participants had to press a button within a small, adaptive time window around 1 s after an imperative stimulus, only feedback can provide sufficient information whether the response was given at the correct time or not. Such time estimation tasks reliably elicit a negative ERP deflection with a frontocentral scalp distribution similar to the ERN (213, 252, 356), the feedback-related negativity (FRN; also called feedback-ERN or feedback negativity). This negative deflection is usually greater on negative than on positive feedback, occurs independently of feedback modality, and peaks approximately between 200 and 300 ms after the feedback. It was also found in gambling tasks and reinforcement learning tasks (200, 249). The FRN amplitude is higher on more unexpected outcomes and was suggested to scale with the RPE, i.e., the difference between predicted and obtained action outcome (84, 96, 249, 252, 255, 375). In contrast, other studies suggest that the FRN amplitude is only influenced by the valence of the outcome in a quasi-binary fashion and that the magnitude of the violation of outcome expectancy is reflected in the amplitude of the subsequent feedback-related P300 deflection (216, 251, 411, 598). Moreover, the FRN is modulated by task context such as the range of possible outcomes (254) and whether attention is directed to the utilitarian (gain/loss) or performance information (error/correct) contained in complex feedback (377). Interestingly, the FRN is also elicited when an unfavorable action outcome requiring behavioral adjustments cannot be attributed to the actor but results from external factors, e.g., technical malfunction (202). Interpreting FRN results requires attention to several caveats. Studies differ substantially in FRN quantification (e.g., difference waves vs. single-condition ERPs, theta-band filtering), baseline correction, and how they deal with the overlap with the subsequent P300 deflection. Moreover, the FRN occurs in the time range of the N2 family of ERPs (180) and may therefore be masked by other factors influencing the N2 (248). A recent systematic review of FRN studies synthesizes the above-mentioned findings and concludes that the FRN represents quantitative RPE, is elicited by outcomes as well as outcome-predicting stimuli, changes (along with behavior) with learning of stimulus-outcome contingencies, and is maximally engaged by volitional actions (563). A recent study comparing EEG activity elicited by real outcomes (reward/punishment) and by fictive outcomes (based on feedback indicating what would have happened had one decided differently) revealed a double dissociation (177). Real outcomes elicited a frontocentral FRN reflecting an RPE and a subsequent frontocentral P3a. In contrast, no FRN or P3a was found in the fictive condition; instead, an earlier occipitoparietal outcome correlate was found. About 400 ms after feedback, brain activity for both conditions converged into a common adaptive pathway, reflected in parietal P3b-like activity that was predictive of future choice behavior. The absence of the FRN for fictive feedback is surprising as even the observation of mistakes made by others elicits similar EEG activity (see further below). It may result from the fact that fictive feedback was given, when participants decided not to actively select a stimulus, which is in line with the notion that the FRN is maximal for volitional motor actions (563).

The initial assumption that ERN and FRN are functionally equivalent (249, 356) has found strong support by electrical source localization (213) and blind source separation using ICA (202), suggesting that the ERN and FRN stem from the same or at least highly overlapping generator structures in the pMFC.

In addition to own, self-generated errors, humans can also detect when other persons make mistakes, adjust their own behavior accordingly, and learn to avoid similar mistakes. The observation of mistakes committed by others elicits a frontocentrally distributed negative ERP deflection similar to the FRN to visual feedback (134, 302, 354, 544). Source localization of this observed-error-related negativity (oERN) again hints at the pMFC. It appears, however, that the observed error must entail a consequence to the observer along a reward-punishment axis to elicit the oERN, because the mere counting of errors in everyday behavior did not evoke ERN-like activity (130). A recent study in macaques revealed that neurons in the pre-SMA and cingulate sulcus increased activity on observed errors associated with omission of the reward delivery to both the observing and acting monkeys (601). Whereas a subset of these neurons did also respond to unexpected reward delivery when the monkey was acting, the overlap with pMFC neurons responding to own errors was negligible. Activity of neurons responsive to observed errors in the cingulate sulcus appeared furthermore to be associated with subsequent behavioral adjustments of the observing monkey.

The stimulus-locked N2 deflection comprises a family of ERP responses which, in part, are related to performance monitoring and cognitive control (180). Simultaneous activation of competing response tendencies is associated with increased frontocentral N2 amplitudes (306, 546). Particularly in the framework of the response conflict monitoring theory discussed further below, a functional equivalence of the stimulus-locked N2 on correct high-conflict actions and the response-locked ERN has been suggested (125, 593, 595). Frontocentral N2 modulations are also found during inhibition of preactivated motor responses in GoNogo and stop signal tasks (180). It has been argued that the N2 increase in GoNogo tasks can be explained by a conflict between executing and inhibiting a response (146, 158, 378). A comparison of scalp distribution and results of source localization suggested a large overlap between N2, FRN, and ERN (213). In addition to a pMFC source found for all three ERPs, an additional N2 source was found in the right inferior frontal cortex, which is in line with other findings suggesting an involvement of this area in motor inhibition (14, 15). Intracranial recordings also showed conflict-related theta-band activity coupled with frontocentral surface N2-like EEG activity (97).

Salient and surprising events such as novel stimuli are also associated with modulations of the stimulus-locked N2-P300 complex (110, 180, 420, 492). Recently, it has been shown that ERN sources estimated with ICA can explain a substantial part of novelty N2 activity, suggesting overlapping sources of brain activity related to errors and valence-free surprising action outcomes (573). In a number of studies the FRN appears to be more driven by unexpectedness of an outcome than by its valence (145, 173, 248), also suggesting that this ERP wave is to some extent susceptible to valence-free expectancy violation (i.e., surprise). This is in line with recordings from the aMCC homolog in monkeys showing neuronal activity coding valence-independent prediction errors (227, 346) and novelty of stimuli (347).

In sum, invasive recordings in rodents and primates have consistently demonstrated pMFC responses coding various pieces of information needed for action valuation and evaluation such as reward expectation, reward proximity, reward delivery, errors, surprise, effort, and observed errors. Thus pMFC neuronal activity appears to integrate multiple decision parameters using a common valuation currency (288). These information contents appear to also modulate scalp-recorded ERPs related to performance monitoring such as the ERN, FRN, oERN, N2, Pe, and P3. It appears, however, that a one-to-one matching of type of information and ERP is not possible, although these ERPs are modulated differentially.

B. Functional Neuroimaging

As a result of its high spatial resolution, functional neuroimaging has been particularly influential in performance monitoring research. In line with the electrophysiological findings, fMRI signal increases related to various evaluative signals have been found in the pMFC with great consistency (for reviews and meta-analyses, see Refs. 296, 374, 439, 534). For example, hemodynamic signals related to errors in speeded forced choice task (76, 196, 256, 290, 292, 536); to conflict between competing response tendencies (44, 76, 195, 291, 352, 536, 545); to decision uncertainty, outcome predictability, and volatility of the environment (33, 406, 407, 558, 559); to feedback and punishment (256, 297, 339, 361, 532, 565); to reward, reward anticipation, and reward prediction errors (282, 300, 301, 397); to the observation of errors committed by others (131, 478); to externally induced failure to achieve action goals (528); and to valence-free surprising action outcomes (573) have been reported. Furthermore, pMFC activity has been shown to correlate positively with effort and negatively with the subjective action value discounted by effort (121, 422). This fits with the finding that in two-choice decisions an inverse value difference signal was found in aMCC. The hemodynamic signal increases when the difference between the values of the choice options decreases, i.e., when value comparison becomes more difficult and time-consuming (24, 224).

Furthermore, appreciation and expression of negative emotions and acute pain, observation of others experiencing pain, and social exclusion are associated with signal increases in this region, too (152, 160, 318, 475, 555). These latter situations have in common with the performance monitoring signals that they are evaluative and may trigger adaptive actions (530). This notion has been addressed and

elaborated in a recent review demonstrating overlapping activation in aMCC to pain, negative effect, and cognitive control resulting in the adaptive control hypothesis (475). Briefly, this hypothesis suggests that the aMCC "represents a hub, where information about pain, and other, more abstract kinds of punishment and negative feedback could be linked to motor centers responsible for expressing emotion on the face (a communicative means of adaptation; note from the authors) and coordinating aversively motivated instrumental behaviours" (p. 156; Ref. 475). We will return to this hypothesis and reconcile it with other theories in section IV.

Cyto- and receptor architecture as well as connectivity data suggest that the pMFC is subdivided into different regions (31, 284, 404, 405, 556). It is conceivable that these different anatomical subregions, although often coactivated during performance monitoring, serve at least partly dissociable functions. On the basis of electrophysiological data, functional subregions differing with respect to the motor effects of stimulation have been identified in the pMFC of monkeys (413). In humans too, several studies have suggested that the different evaluative signals found in the pMFC are coded in distinct subregions, which has caused an ongoing debate. Although a somatotopy for motor actions has been described for the anterior and posterior rostral cingulate zone (413), the distribution of conflict-related fMRI signals appears to be unaffected by effector modality (19). Some studies, however, showed that response errors predominantly elicited aMCC responses, whereas response conflict on correct trials was more associated with increased activity in the more dorsal mesial area 8 and pre-SMA (53, 195, 534, 536) or, more generally, that pre-response performance problems are coded more dorsally than post-response performance problems (439). In contrast, a more recent analysis showed a somewhat different distribution along an anterior-posterior and inferior-superior axis (374). Other studies found localization differences of response conflict (more anterior) and degrees of freedom in choice of a volitional action (more posterior) within the pMFC (370) (see also Refs. 182, 565). Moreover, it has been suggested that the different subregions of the pMFC might play different roles in the initiated adaptations. Increased arousal and autonomic responses (115, 118, 408) as well as reactive, general cognitive adjustments appear associated with aMCC activity (294, 527). In contrast, proactive, task-specific adjustments may be associated with pre-SMA activity increases (242, 294, 527). Most of the above-mentioned studies were not designed to reveal subtle regional differences and suffered from spatial smoothing and the fact that group analyses ignore individual anatomical variations. Thus, at this point, we have to state that evidence for the suggested subregional dissociations is still too sparse and equivocal to extract a clear functional distribution within pMFC. Therefore, future research aiming at a functional parcellation of the pMFC needs to better take into account individual anatomy, use high-resolution imaging, and combine functional data with structural, e.g., tractographic data. Recent reports suggest that individual patterns of pMFC gyrification influence performance monitoring functions as well as their ERP and fMRI correlates (8, 267).

During performance monitoring, numerous other brain regions are usually coactivated with the pMFC. Most consistently, the anterior insula, parietal cortex, lateral prefrontal cortex, and subcortical regions such as the basal ganglia, thalamus, and midbrain are reported (296). Reward and reward prediction error-related signals are also found in many cortical and subcortical areas, as will be discussed further below.

With the use of separate and simultaneous EEG/fMRI recordings, correlations between the hemodynamic response in the aMCC and scalp-recorded ERN and FRN amplitude, respectively, have been found within and across participants (1, 73, 136, 266, 341). More negative single-trial ERN amplitudes were associated with stronger aMCC responses and increased reaction times on subsequent trials (136).

III. THE PERFORMANCE MONITORING NETWORK: CAUSAL EVIDENCE

Based on the above-discussed electrophysiological and imaging findings and anatomical studies on the connectivity of the pMFC, a basic network of brain structures typically involved in performance monitoring can be derived **(FIGURE 3)**. The causal involvement of the nodes in this performance monitoring network can be addressed in lesion studies in animals and in patients with circumscribed lesions resulting from stroke, tumor excision, traumatic brain injury, etc. Furthermore, stimulation of the network constituents using transcranial magnetic stimulation (TMS) or in patients undergoing deep brain stimulation (DBS) can reveal functional interactions.

A. Cortical Regions

As discussed above, correlative evidence suggests that the pMFC is essential for performance monitoring. Focal lesions of the pMFC, in particular of the aMCC, are rare, and resulting impairments may be transient and can disappear in chronic stages (99). The small number of patients and studies, the uncontrollable size of lesions often extending far beyond pMFC, and the limited amount of behavioral and neurophysiological variables that could be obtained from these patients render the results hard to interpret. Despite these difficulties, a series of studies in patients with unilateral focal lesions of the aMCC demonstrated impairments in post-error and conflict-driven adaptations, accom-

panied by reduced ERN amplitudes (142, 504–506). In contrast, in another patient group with large pMFC lesions, no impairments in error- and conflict-induced performance adjustments were found (171), except for slowed error corrections in a flanker task (360). This suggests that pMFC lesions interfere with the solution of response conflict, because fast error corrections result from concomitant activation and sequential execution of the incorrect and correct responses (496, 533). In line with this, TMS of the pre-supplementary motor area (pre-SMA) affects processing of competing response tendencies (512) and intracranial stimulation of the pre-SMA in monkeys replaced automatic incorrect responses by slower correct responses (270). Moreover, patients with pMFC lesions showed increased false alarm rates in a two-back task associated with higher subjective confidence in action selection (518). This seems to be in line with findings that macaques with sulcal anterior cingulate lesions show increased impulsivity and reduced impact of reinforcement history in choice behavior (289). In sum, the pMFC appears involved in and necessary for rapid online adjustments, evaluation of confidence with choice, and between-trial adjustments. Lesions of the pregenual and subcallosal ACC have been shown to result in strongly reduced ERN amplitudes (499) and difficulties in conflict-induced trial-by-trial adjustments (142). These conflict-driven sequential adaptations seem particularly impaired when stimuli had an emotional component such as face expression (333).

Different subregions of the lateral prefrontal cortex (LPFC) have been implicated in maintaining and updating task representation, goals, and contextual information (51, 139, 551), and in exerting top-down control in mutual interaction with the pMFC (291, 331). Its necessity for performance monitoring is strongly suggested by the fact that ERN generation is impaired in patients with LPFC lesions comprising the middle and inferior frontal gyri, anterior insula, and underlying white matter: the amplitudes of ERN and CRN did not differ from each other (199, 535, 538). Whereas post-error slowing appeared unaffected, in some patients error corrections were diminished (199), particularly when white matter tracts connecting LPFC, pMFC, and the striatum were affected (535). The importance of the fiber connections at the base of the middle and inferior frontal gyri is also reflected in a reduced ERN in patients with isolated lesions in that area (245).

Whereas patients with lesions of the posterior orbitofrontal cortex (OFC) extending into the subgenual ACC and the ventromedial prefrontal cortex (vmPFC) showed severe attenuation of the ERN and error corrections (520), more anterior OFC and frontopolar lesions did not interfere with performance and ERN generation in a flanker task (538). Nevertheless, vmPFC and OFC play a major role in motivated and adaptive behavior, particularly with respect to establishing stimulus-outcome associations, credit assignment, task and reinforcement history, and value-guided choice. These aspects will be discussed in section V*D* on monitoring-based learning processes.

B. Subcortical Circuitry

Cortico-striato-thalamic circuits are highly important for action selection and learning. They can thus be expected to be an essential part of the performance monitoring network. The basal ganglia are closely connected to the cortical areas involved in performance monitoring and adaptive behavior, such as pMFC, LPFC, vmPFC, and OFC. Particularly, spiraling connections from the striatum to the dopaminergic midbrain and back, as well as nonreciprocal cortico-thalamic projections appear important in connecting the different basal ganglia loops (215). Thus the subcortical circuitry discussed below is involved in performance monitoring by receiving and sending information about outcome predictions, aversive and appetitive outcomes, prediction errors, and adaptive signals from and to the relevant cortical areas.

The necessity of the basal ganglia in performance monitoring is demonstrated by the finding that focal and isolated damage in the striatum disrupts the generation of the ERN (535). Performance monitoring is also impaired in degenerative diseases of the basal ganglia. Parkinson's disease (PD) is characterized by a gradual loss of dopaminergic neurons that progressively affects dorsal and later ventral striatal function. PD patients quite consistently display reduced ERN amplitudes (162, 498, 579; but see Ref. 257), but no significant effects of medication on the ERN have been observed. Less is known about the FRN in PD, although behavioral studies show an imbalance of preference versus avoidance learning depending on whether the patients are medicated or not (187, 188). Generally, the FRN might be affected later in the course of disease progression than the ERN because the ventral striatum, relevant for reward processing, seems to be affected by dopamine depletion only at more severe stages of PD (104, 105).

Huntington's disease (HD) is an autosomal dominant neurogenetic disorder characterized by striatal degeneration. In HD patients, a consistent reduction of the ERN was found that was related to the genetic mutation and the reduction of gray matter volume in pMFC (37, 38).

Therapeutic high-frequency deep brain stimulation (DBS) opens up the opportunity to investigate the effect of stimulating subcortical brain regions. In a patient treated for intractable alcohol dependence, bilateral DBS in the nucleus accumbens over 12 mo reduced clinical symptoms significantly reflected in subpathological clinical scores at the end of the observation period. In addition, DBS nearly doubled the ERN amplitude in a flanker task (315). This effect was reversible when stimulation was temporarily turned off and

replicable over several measurements. Notably, behavioral performance remained unaffected. It suggests fast functional interactions of the ventral striatum and the medial frontal ERN generators.

Studies in non-human primates suggest that the aMCC receives inputs from the basal ganglia circuitry mostly via the ventral anterior (VA) and ventrolateral anterior (VLa) nuclei of the thalamus (226, 543), a region which also integrates cerebellar circuitries assumed to be involved in motor control (262). In addition to the VA/VLa nuclei the mediodorsal (MD) thalamus sends fibers to the pMFC (483, 557). Compared with healthy controls, patients with thalamic lesions show impaired conscious error detection, post-error slowing, post-error accuracy improvement, and smaller error-related ERPs (410, 471). A detailed analysis revealed a double dissociation within the thalamus: lesions affecting VA and VLa abolish the ERN while leaving the Pe nearly intact. In contrast lesions encompassing MD only slightly decrease the ERN amplitude and completely wipe out the Pe (299, 471). This suggests a differential involvement of thalamic nuclei in different stages of performance monitoring.

The subthalamic nucleus (STN) is an important modulatory part of the cortico-striato-thalamocortical circuits. It has been suggested to modulate cognitive control and decision making by providing a general NoGo signal unspecifically inhibiting motor response tendencies under situations of high response conflict and uncertainty (14, 183). Indeed, high-frequency DBS in the STN for PD results in more impulsive decisions (reflected in shorter reaction times in high-conflict conditions) in decision making and more errors of commission in simple motor Go/NoGo tasks, respectively (17, 80, 187). It has been suggested that evaluative signals stem from pMFC via a hyperdirect pathway and that STN then implements motor inhibition to slow down reactions on conflict-laden decisions (183), thereby allowing to accumulate additional information useful for more specific adaptation. This might also apply to errors; in section VC we present evidence for involvement of the STN in post-error slowing. However, DBS in STN seems to yield paradoxical effects dependent on the stage of decision making and response selection: fast impulsive errors appear disinhibited, but slow selective inhibition of incorrect responses is improved at later stages (590). The effect of DBS on impulsivity appears to also depend on the subtype of PD (591). In any event, the STN appears to use performance-monitoring signals to on-line modulate motor behavior. In line with this notion, depth recordings from STN revealed conflict- (80) and action-outcome-related signals that were related to motor adjustments on subsequent trials (62) and modulated by motivation (313).

The habenular complex (Hb) is another key subcortical structure for performance monitoring and adaptive behavior. It is part of a major top-down pathway from forebrain to midbrain modulating the activity of dopaminergic and serotonergic brain stem nuclei (230, 231, 241, 324). Neuroimaging in humans and invasive recording in animals showed that the Hb codes negative prediction errors (59, 259, 344, 454, 532). In animals, electrical stimulation of the lateral Hb strongly inhibits firing of dopaminergic neurons in the ventral tegmental area (VTA) and substantia nigra pars compacta (SNc) (88, 277, 344) and of serotonergic raphé neurons (567). Conversely, Hb lesions result in increased striatal and prefrontal DA turnover (327, 381). Thus the Hb seems to influence approach-avoidance decisions, impulsivity, and acute pain- and error-induced remedial actions; in particular, it has been suggested to regulate motor suppression induced by these diverse situations (241). Support for this hypothesis comes from the finding that electrical stimulation of the lateral habenula after rewarding saccades can delay subsequent saccadic eye movements (343). Similarly, in gerbils, stimulation of the lateral habenula and VTA, respectively, had opposite effects on the acquisition of avoidance behavior (487).

IV. PSYCHOLOGICAL AND NEUROBIOLOGICALLY INFORMED MODELS

A. Mismatch Theory

Early evidence on nearly immediate error corrections, post-error slowing, and post-error improvements in accuracy suggested a genuine error detection mechanism (10, 11, 428–430). The discovery of the ERN triggered the proposal of the mismatch theory of error detection. It assumes a comparator detecting a discrepancy (i.e., mismatch) between the representations of the executed and the correct actions, which then is reflected in the ERN and error-related aMCC activity (101, 165, 166, 198, 536). On the basis of behavioral observations, the early onset of the ERN which sometimes even precedes the erroneous motor response, and a single-case study showing a normal ERN in a patient with sensory deafferentation (6), it has been argued that the representation of the executed response cannot be derived from proprioceptive feedback but rather from a central efference copy of the motor program. The representation of the correct action directly results from ongoing, even after response elicitation continued perceptual processing and stimulus-response mapping according to the task rules. In line with this view, the ERN is often seen on premature erroneous responses executed before completion of stimulus-response mapping. Factors that affect the representations of either executed or correct action reduce the amplitude difference between ERN and CRN, reflecting disturbance of the comparison process (101, 460). On the basis of continuous flow of information accounts of stimulus-response mapping (208), it has been assumed that the action comparator issues its signal when the motor efference copy

arrives and uses whatever information about the correct response is available at this stage (101). The mismatch theory has been extended to explain the FRN occurring when external feedback information is available (356). Here, the mismatch between representations of the intended outcome, derived from reward prediction, reinforcement learning, and forward modeling, and the actually achieved outcome gives rise to the error signal driving the pMFC activity. Limitations of the mismatch theory are that it is, at least in its original form, not mathematically formalized and that it cannot explain pMFC activity and N2 modulations on correct actions involving response competition and/or higher effort.

B. Response Conflict Monitoring

A broader perspective on cognitive control suggests that not only erroneous actions but also difficulties during ongoing actions can initiate adjustments. This has been formalized in the response conflict monitoring theory (46), which suggests that the performance monitoring system monitors for response conflicts between concomitantly evolving response tendencies rather than for errors per se. Response conflict arises when action implementation simultaneously activates two or more incompatible response tendencies. This may occur when distractors or apparent regularities of the stimuli prime a prepotent but incorrect response. A strong correct response tendency may override incorrect response tendencies. In these cases, the highest overlap of the competing response tendencies occurs before the (correct) response, thus yielding preresponse conflict. If, however, a strong and prematurely executed incorrect response tendency results in an error, response conflict reaches its maximum after the response. Continuously incoming information from stimulus processing is translated into a rising correct(ive) response tendency which conflicts with the executed error. Thus errors in reaction time tasks are typically associated with postresponse conflict.

Computational models have allowed simulations and predictions for numerous task situations which have been compared with empirical evidence (46, 47, 595). Briefly, response conflict signals are assumed to recruit cognitive control processes and to initiate appropriate adjustments. Connectionist parallel distributed processing models of various stimulus-response compatibility tasks (159, 488, 489) form the basis of the response conflict monitoring theory. The models usually comprise three layers of units: an input layer with units representing stimulus features, a response layer consisting of a unit for each response, and an attentional layer with units corresponding to each feature of the stimulus set. The information flow is realized by bidirectional excitatory weights between layers. Competition is elicited by within-layer inhibitory links between the units. The measured response conflict depends on the relative activation levels of the competing response units and is computed by a multiplicative measure, the Hopfield energy (46, 260). A conflict monitoring feedback loop is assumed to reflect the contribution of the pMFC to performance monitoring and initiating adjustments of control. When a stimulus pattern is fed to the input units, activations flow via their connections to the response units. If a response unit crosses an arbitrary response threshold, the corresponding response will be produced by the model, allowing to predict reaction times. When one response unit is active and the others are inhibited, conflict is low or zero. When two or more response units are active, however, the response conflict is large. Adaptation is brought about by feeding back the conflict signal to the attentional layer where it drives attentional refocusing on task-relevant features and/or to the response unit where it modulates response threshold (46, 595). The response conflict model quite accurately predicts behavioral effects of conflict on current and subsequent trials (46, 125, 495, 496).

Numerous neuroimaging studies have demonstrated that the pMFC is engaged when response conflict occurs (20, 44, 53, 76, 77, 291, 348, 353, 439, 536, 545, 570, 604). Also ERP findings, such as the modulation of the stimulus-locked N2, ERN and lateralized readiness potentials by differential stimulus conditions, attentional and pathological states can be explained by conflict monitoring models for the according tasks (125, 495, 593, 595, 597). The N2 is assumed to be modulated by pre-response conflict, whereas the ERN reflects mostly post-response conflict. Strong post-response conflict signals may serve as a reliable basis for internal error detection, rendering a specialized error detection mechanism unnecessary (595). It was furthermore shown that conflict-related pMFC activity varies with the amount of conflict at the response level but not with conflicts at other levels such as stimulus identification (148, 353, 547).

The response conflict monitoring theory has repeatedly been challenged and is still under debate (63, 64, 72, 210, 211, 496, 594). Moreover, the theory cannot account for feedback-related activity in the pMFC that occurs in the absence of motor response activation.

It is noteworthy that invasive studies in monkeys did not find any neurons whose firing patterns coded response conflict (271, 373, but see Ref. 482 for single unit activity in human aMCC associated with response conflict). Perhaps the discrepancy between the ease at which conflict-related signals in pMFC can be measured at the mesoscopic (multicellular) level using EEG and fMRI and the difficulty to find single neurons coding response conflict could be explained by biophysical cortical network attractor models that have been applied successfully to sensory and value-based decision making in parietal and ventromedial prefrontal cortices (265, 278, 585, 586). A substantial number of pMFC neurons show activity specific to a particular action or action sequence from the available action set (423,