Behavioral/Systems/Cognitive

Posterior Medial Frontal Cortex Activity Predicts Post-Error Adaptations in Task-Related Visual and Motor Areas

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As Seneca the Younger put it, “To err is human, but to persist is diabolical.” To prevent repetition of errors, human performance monitoring often triggers adaptations such as general slowing and/or attentional focusing. The posterior medial frontal cortex (pMFC) is assumed to monitor performance problems and to interact with other brain areas that implement the necessary adaptations. Whereas previous research showed interactions between pMFC and lateral-prefrontal regions, here we demonstrate that upon the occurrence of errors the pMFC selectively interacts with perceptual and motor regions and thereby drives attentional focusing toward task-relevant information and induces motor adaptation observed as post-error slowing. Functional magnetic resonance imaging data from an interference task reveal that error-related pMFC activity predicts the following: (1) subsequent activity enhancement in perceptual areas encoding task-relevant stimulus features; (2) activity suppression in perceptual areas encoding distracting stimulus features; and (3) post-error slowing-related activity decrease in the motor system. Additionally, diffusion-weighted imaging revealed a correlation of individual post-error slowing and white matter integrity beneath pMFC regions that are connected to the motor inhibition system, encompassing right inferior frontal gyrus and subthalamic nucleus. Thus, disturbances in task performance are remedied by functional interactions of the pMFC with multiple task-related brain regions beyond prefrontal cortex that result in a broad repertoire of adaptive processes at perceptual as well as motor levels.

Introduction

When errors are committed, it is important that adaptive processes take effect immediately to generate adequate behavioral adjustments and prevent further errors. Behavioral adjustments in post-error trials occur at motor and attentional levels. Post-error slowing (PES) (Rabbitt, 1966) is a general adjustment thought to “buy” time to enable more controlled responding (Ridderinkhof et al., 2004a). The prefrontal cortex has been implicated in top-down control on other brain areas to guide behavior (Fuster, 2000; Miller and Cohen, 2001; Miller and D’Esposito, 2005). More specifically, monitoring for errors and signaling the need for adjustments has been associated with the posterior medial frontal cortex (pMFC) (Botvinick et al., 2001; Ridderinkhof et al., 2004b). However, how performance-related signals from the pMFC modulate sensory representations is still unclear. Current theories suggest that the pMFC interacts with the lateral prefrontal cortex (LPFC), which in turn is assumed to implement the necessary top-down control (Kerns et al., 2004; Carter and van Veen, 2007). Here, we investigate whether error-related activity in the pMFC directly predicts post-error adaptations in motor and perceptual systems in an interference task.

Recent studies suggest that successful implementation of control upon conflict is reflected in visual areas that are crucial for solving the task at hand (Egner and Hirsch, 2005; Wylie et al., 2006). In a task-switching paradigm, Wylie et al. (2006) found activity enhancement in the task-relevant visual brain area but no indicators for suppressed activity in task-irrelevant areas. However, suppression of neuronal activity due to attentional mechanisms has been observed in striate and extrastriate visual areas in monkeys (Ferrera and Lisberger, 1997; Vanduffel et al., 2000; Treue, 2001) and humans (Müller and Kleinschmidt, 2004; Baier et al., 2006). We hypothesized that error-related pMFC activity predicts both subsequent signal increases in perceptual areas encoding task-relevant stimulus features and signal decreases in perceptual areas encoding distracting stimulus features. Additionally, we expected PES to be related to preceding error-related pMFC activity (Garavan et al., 2002; Kerns et al., 2004; Debener et al., 2005) and to activity changes in the motor system. Since structural correlates of PES are yet unknown, we calculated correlations between diffusion-weighted imaging (DWI) and PES values. PES has been suggested to result from an increased motor threshold (Botvinick et al., 2001) that might be implemented by general motor inhibition. Therefore, we expected the structural analysis to reveal a network connecting brain regions implicated in motor inhibition, in particular right-hemispheric pre-supplementary area, in-
terior frontal cortex, and subthalamic nucleus (STN) (Aron et al., 2007).

Miller and D’Esposito (2005) have pointed out that the temper-
oral overlap of the hemodynamic response in successive trials
renders it difficult to investigate spatiotemporal dynamics inher-
ent in top-down processes with standard functional magnetic
resonance imaging (fMRI) analysis. This is especially problematic
when two trials of interest, e.g., error and post-error trials, occur
always in the same order by definition. Therefore, a group-level
spatial independent component analysis (ICA) (Calhoun et al.,
2001) was used to decompose the data into separate independent
components (ICs), followed by deconvolution to extract the trial-
by-trial dynamics of sequential effects. To study error-driven ad-
justments in cognitive control, we investigated ICs showing
significant activity changes in error and post-error trials.

Materials and Methods

Participants
Twenty-one neurologically and psychiatrically healthy participants took
part in this study. One male participant had to be excluded from data
analysis because he did not complete the task. Thus, the final sample
consisted of 11 female and 9 male participants (mean age: 24.1 years;
range: 21–35 years of age). Participants were all right handed and showed
no signs of color vision deficiencies. Before fMRI measurements, partic-
ipants provided written informed consent. The study was performed
according to the Declaration of Helsinki.

Behavioral task
Participants performed a moving-dots interference task similar to a Si-
mon task (Simon, 1969) in the scanner. On each trial, a cloud of colored
moving dots (coherently moving leftward or rightward and extending
across 4.3° of visual angle) was presented centrally on a computer screen.
Speed of the moving dots was 10.2 degrees of visual angle per second.
Participants were asked to indicate the color of the dots (relevant feature)
by pressing a button with their left or right index finger while ignoring the
motion direction (irrelevant feature). Four isoluminant colors were cho-
sen from the Teufel colors (Teufel and Wehrhahn, 2000). The colors light
blue and beige required a left button press, while turquoise and light pink
required a right button press. Motion direction could either be congru-
et or incongruent with the required response side. The proportion of
congruent and incongruent trials was 50% each. The trial sequence was
pseudo-randomized to avoid direct repetitions of the same color in two
consecutive trials and to counterbalance the transitions of congruent
and incongruent trials. Trial duration was 5 s on average. To improve tem-
poral sampling of the hemodynamic response (HR), trials were “jittered”
with onset delays of 0, 330, 660, 1000, 1330, or 1660 ms, resulting in
an oversampling of the actual image acquisition time of 2 s by a factor of 6.
After this variable onset delay, during which a central fixation cross
was displayed on the screen, colored moving dots were presented until a
response was given, but maximally for 1500 ms. Finally, a fixation cross
appeared on the screen until the total trial duration reached 5 s. The
experiment consisted of 336 experimental trials and 40 null-events
pseudo-randomly interspersed in the experimental trials to affect all
transition types equally. Performance feedback was presented before ev-
every other null event for a duration of 2 s. Participants were informed
about the amount of correct and erroneous responses since the last feed-
back. If the participant’s response was slower than an individually adapt-
ing response deadline on more than three trials since the last feedback,
the feedback showed an additional “too slow” message. The response
deadline for the calculation of slow responses was initially set to 1000 ms
and subsequently adapted according to the subject’s average error rate in
incompatible trials.

Functional localizer
In addition to the task described above, we ran two functional localizer
tasks after acquisition of the Simon task to identify the color and motion
processing visual areas in each participant. The order of color and mo-
tion localizer was counterbalanced across participants.

The color localizer consisted of 12 blocks where (stationary) colored
dots were presented in the center of the screen and 13 blocks with gray
dots. Colored and gray dots were approximately isoluminant. Each im-
age was shown for 700 ms, followed by 300 ms of blank screen. Each block
consisted of 15 images, and thus one block lasted for 15 s. In colored
images, two colors were combined in one image: 50% of the dots were
presented in one color and 50% in another color. Colors were the same as
in the Simon task. In rare catch trials, all dots were presented in the same
color. Participants had to indicate this with a button press. Catch trials
were introduced to keep participants focused on the colors. They oc-
curred only six times, pseudo-randomly spread across the experiment.

The motion localizer also consisted of 12 stimulation blocks and 13
rest blocks. In stimulation blocks, 15 trials of gray moving dots were
depicted. In each trial, dots were presented for 500 ms followed by a
fixation cross, which was also presented for 500 ms. Speed of the moving
dots was 9° of visual angle per second. In rare catch trials, dots moved
noticeably faster with 24° per second. To keep participants focused on the
motion, they had to indicate the presence of a catch trial with a button
press. Six catch trials were presented in the course of this experiment.
During rest blocks, stationary gray dots were presented for 15 s.

Image acquisition: fMRI and anatomical data
Data acquisition was performed on a 3T Siemens Trio scanner. Thirty
slices (3 mm thickness, 3 × 3 × 3 mm voxel size, 0.3 mm interslice gap)
were obtained in an interleaved fashion parallel to the anterior commis-
sure–posterior commissure line using a single-shot gradient echo-planar
imaging (EPI) sequence [repetition time (TR): 2000 ms; echo time (TE):
30 ms; bandwidth: 116 kHz; flip angle: 90°; 64 × 64 pixel matrix; field of
view: 192 mm]. Before functional scanning, a high resolution (1 × 1 × 1.25 mm)
anatomical brain image was recorded from each participant in a separate
session using a modified driven equilibrium Fourier transform
sequence (TR: 1930 ms; TE: 5.8 ms).

Image acquisition: diffusion-weighted data
Diffusion-weighted images were acquired in a separate scanning session
using a twice-refocused spin-echo-planar imaging (TR: 12 s; TE:
100 ms; 72 axial slices; resolution: 1.72 × 1.72 × 1.7 mm). We used a
GRAPPA (generalized autocalibrating partially parallel acquisition)
technique (reduction factor: 2.0) for parallel imaging. Diffusion weight-
ing was isotropically distributed along 60 directions with a b value of 1000
s/mm². The high angular resolution of the diffusion weighting directions
improves the robustness of probability density estimation by increasing the
signal-to-noise ratio and reducing directional bias. Additionally, seven datasets with no diffusion weighting (b0) and a b value of 500
s/mm² were acquired initially and interleaved after each block of 10
diffusion-weighted images: Here the b0 images serve as anatomical re-
ference for motion correction, and the b500 images serve to suppress
pseudo-diffusion and cope with the CSF contamination effect. To fur-
ther increase signal to noise, we acquired three consecutive scans that
were subsequently averaged together. The entire data acquisition proto-
col lasted ~45 min.

Image processing and analysis: localizer tasks
Analysis of fMRI data of the functional localizer tasks was carried out
using the Oxford Centre for Functional MRI of the Brain (FMRIB) Soft-
ware Library (FSL), version 4.0.3 (http://www.fmrib.ox.ac.uk/fsl/) (Smith
et al., 2004). Non-brain data were removed from functional and anatom-
ical datasets using the Brain Extraction Tool (BET) (Smith, 2002). Func-
tional data were motion corrected using rigid body registration to the
central volume (Jenkinson et al., 2002). and corrected for saccade onset
time differences using sinc interpolation. Low-frequency signals were
removed using a 1/30 Hz highpass filter. Spatial smoothing was applied
using a Gaussian filter with 5 mm full width at half maximum (FWHM).
Registration of the EPI images with the high resolution brain images and
normalization into standard [Montreal Neurological Institute (MINI)]
space was carried out using affine registration (Jenkinson and Smith,
2001). A general linear model was fitted into prewhitened data space to
account for local autocorrelations (Woolrich et al., 2001).
FMRI image processing and analysis of interference task

Preprocessing. All images were realigned to the first image in the time series to correct for head movement and then normalized to the MNI reference space using SPM5 statistical parametric mapping (http://www.fil.ion.ucl.ac.uk/spm). Normalized data were resliced to a cubic voxel size of 3 mm³ and smoothed with a Gaussian kernel with 8 mm FWHM.

Independent component analysis. As pointed out above, it is difficult to analyze the temporal dynamics of successive trials with standard fMRI analysis procedures. Therefore, here we employed a group-level ICA followed by deconvolution of the HR as described by Eichele et al. (2008).

In brief, the ICA analysis was followed by estimation of subject- and IC-specific HRs. The HRs were deconvolved from the time courses of the ICs to recover empirical HRs (Aguirre et al., 1998; Handwerker et al., 2004). These were used subsequently for estimation of the amplitude of the event-related response to each trial (Eichele et al., 2008). For an overview of the ICA and subsequent statistical analyses, see the flow chart in supplemental Figure 1 (available at www.jneurosci.org as supplemental material).

Error monitoring and the various subsequent adaptations are likely implemented by different brain networks (pMFC, motor system, visual perceptual areas), such that we expected these networks to be reflected in separate ICs. We first decomposed the data using the group spatial ICA rationale proposed by Calhoun et al. (2001), which is implemented in GIFT (Group ICA of fMRI Toolbox; http://www.albany.edu/projects/gift/index.php), running in MATLAB. For each individual separately, the preprocessed fMRI data were whitened and reduced via temporal principal component analysis (PCA) to 100 components. Then, group-level aggregate data were generated by concatenating and reducing individual principal components in a second PCA step. Infomax ICA was performed in this set with a high model order of 100 components (Kiviniemi et al., 2009). To estimate robust components, the decomposition was performed 100 times with random initial conditions and identified centroids with a canonical correlation-based clustering (ICASSO; Himberg et al., 2004). All components that we interpret in this dataset have a robustness index of higher than 0.9. Individual IC maps and time courses were back-constructed by multiplying the corresponding data with the respective portions of the estimated demixing matrix. The group average maps were inspected to identify and discard those ICs primarily associated with artifacts representing signal from large vessels, ventricles, motion, and susceptibility. From the remaining ICs, only those with significant random effects t statistics of their maps set at a threshold of t(199) > 5 (uncorrected p = 4 · 10⁻⁵; this uncorrected t threshold being equal or exceeding the threshold estimated for a false discovery rate (FDR) corrected p < 0.05 in any of the maps, since FDR varies across maps as a function of the distribution of the p values) and cluster extent of at least one other voxel were selected for further analysis. To account for issues related to crossing fibers and produces more reliable results compared with a single-fiber model. The result is a brain image in which all voxels have a value that represents the connectivity (number of fibers from the probabilistic analysis) between that voxel and the voxels in the seed region. One advantage of the probabilistic tractography is that it accounts for uncertainty inherent in local fiber directions and thus estimates a spatial probability distribution of connectivity from the seed regions. Those WM regions showing significant correlations between FA values and PES were taken as seed regions for tractography. All tractography was done in each participant’s native space (un-normalized) data, and the resulting maps were warped into standard space (using the MNI 1 mm isotropic brain as reference) for cross-subject averaging and comparison.

Results

Behavioral data

Total error rate was 5.18% (SEM: 0.8%). Error rates did not differ between congruent and incongruent trials (p = 0.62). Probability for committing errors was significantly reduced on post-error
trials compared with post-correct trials (2.78% vs 5.25%; \(t_{(19)} = 2.7, p = 0.014\)), demonstrating improved accuracy as a result of post-error adjustments.

Reaction times for compatible and incompatible trials in general were similar (mean RT in congruent trials: 613 ms; RT in incongruent trials: 614 ms), but a conflict adaptation effect was found (interaction “current trial congruency” × “previous trial congruency”: \(F_{(1,19)} = 8.21; p = 0.01\), indicating an influence of previous congruency on the current RT. For further analyses trials were categorized into pre-error, error, post-error, and post-correct trials (only correct trials preceded by at least two and followed by at least one other correct trial). A repeated-measures ANOVA showed a significant effect of trial type in RTs, \(F_{(3,17)} = 4.86, p = 0.013\) (Fig. 1). The comparison of post-error RTs with post-correct RTs revealed post-error slowing (mean RT in error trials \(t_{(1,19)} = 2.68, p = 0.015\)). Furthermore, IC 02 covering the cuneus showed increased activity during errors (mean RT in error trials \(t_{(1,19)} = 2.21, p = 0.040\)), and IC 03, covering the right inferior occipital cortex and cerebellum, showed an activation decrease (mean RT in error trials \(t_{(1,19)} = -2.18, p = 0.042\)).

ICs showing activity modulations in both error and post-error trials

IC 04, located in the task-relevant color-encoding visual area, and IC 05, covering the task-irrelevant motion-encoding visual area (encoding the distracting stimulus dimension), were modulated in error and post-error trials. Both ICs showed a clear overlap with activations in the color and motion localization, respectively (Fig. 2A). In the task-relevant area, activity decreased already in pre-error trials (mean RT in error trials \(t_{(1,19)} = -2.22, p = 0.039\)) and was further decreased in error trials (mean RT in error trials \(t_{(1,19)} = -4.35, p < 0.001\)). In post-error trials, activity of IC 04 increased again compared with error trials but was still below baseline (mean RT in error trials \(t_{(1,19)} = -4.49, p = 0.001\) and returned to baseline within two trials following the error (Fig. 2A, see mean component activation time course across pre-error, error, and post-error trials).

In line with the assumption that at least some errors result from increased processing of task-irrelevant visual features, there was a trend for pre-error activity enhancement in the motion-processing IC 05 (mean RT in error trials \(t_{(1,19)} = 1.64, p = 0.059\) in trial 2 before the error, and mean RT in error trials \(t_{(1,19)} = 1.37, p = 0.093\) in trial 1 before the error, both one-tailed). Activity in this component then decreased in error trials (mean RT in error trials \(t_{(1,19)} = -2.73, p = 0.013\)), potentially reflecting the onset of adaptive processes that are continued in post-error trials. The trial immediately following an error showed further decreased activity (mean RT in error trials \(t_{(1,19)} = -3.17, p = 0.005\) in these motion-processing areas, and activity was also still below baseline (mean RT in error trials \(t_{(1,19)} = -2.53, p = 0.021\) in trial 2 after the error).

ICs showing activity modulations only in post-error trials

IC 06, located in frontopolar cortex and anterior dorsolateral prefrontal cortex (DLPFC) areas (Fig. 2B), selectively showed increased amplitudes in activity in post-error trials (mean RT in error trials \(t_{(1,19)} = 2.69, p = 0.015\)). Besides the peak activation in DLPFC, this component also comprised activity in the rostral cingulate zone.

A decrease in activity was observed in two ICs showing activations in the left and right hemispheric motor system (IC 07 and IC 08, respectively). Although only the dominant left-sided IC 07 was significantly different from baseline in post-error trials (mean RT in error trials \(t_{(1,19)} = -2.74, p = 0.013\)), IC 08 showed a similar decrease in post-error trials as that of IC 07, and activated brain areas in IC 08 mirrored the activations of IC 07 in the other hemisphere. To take both left and right hemispheric motor activations into account in the following correlational analysis, we therefore averaged amplitudes from IC 07 and IC 08. This averaged motor IC shows a significant decrease in post-error trials compared with error trials (mean RT in error trials \(t_{(1,19)} = -2.40, p = 0.027\).

Correlations between frontal and visual components

Two ICs were located in frontal cortical areas that, according to current theories (Botvinick et al., 2004; Kerns et al., 2004; Carter and van Veen, 2007), could be the source of top-down modulations in visual areas: the monitoring-related pMFC-centered IC 01, modulated in error trials, and the DLPFC/frontopolar IC 06, modulated in post-error trials. To investigate whether the pMFC component is related to performance monitoring and initiates an increase in activity in the lateral prefrontal cortex that then in turn regulates top-down modulations, or whether the pMFC shows a direct functional link to modulations in visual areas, we conducted correlations between both IC 01 and IC 06 on the one hand and activation changes in color-encoding areas (IC 04, en-
Coding relevant stimulus dimension) and motion-encoding areas (IC 05, encoding distracting stimulus dimension) on the other hand. Adaptation effects in IC 04 were quantified as the slope of activity between error and post-error trials (Fig. 2). As indicated by the mean activation plot of this component, activity in color-encoding areas was lowest in the error trial and increased again in the following trials, presumably reflecting adaptive mechanisms. In contrast, in motion-related areas activity is already reduced in error trials (compared with pre-error) and further decreases in post-error trials. This seems to indicate that adaptive mechanisms in motion-processing areas occur earlier than in color-processing areas and affect the activation level in the error trial already. Therefore, adaptive effects in motion areas were quantified as the slope of activity between pre-error and post-error trials.

Greater error-related activity in the pMFC-centered IC 01 predicted a stronger post-error signal increase in color-encoding areas ($r = 0.59$, $p = 0.006$, Cook’s distance of all values $< 1$) (Fig. 3). Moreover, error-related IC 01 activity was negatively correlated with the activity change in motion-processing areas ($r = -0.56$, $p = 0.011$; Cook’s distance of all values $< 1$): The more pMFC activity in the error trial, the stronger the decrease in motion areas from pre-error to post-error trials. This suggests that pMFC activity triggers both enhancement in the visual area relevant for encoding the stimulus (color) and inhibition of the area responsible for encoding the distracting dimension (motion).

In contrast, the enhanced post-error DLPFC activity (IC 06) was neither correlated with the activation increase in color areas ($p = 0.28$) nor with the activation decrease in motion areas ($p > 0.34$). Furthermore, in contrast to what would have been predicted according to Kerns et al. (2004), pMFC activity in error trials did not correlate with DLPFC activity in post-error trials ($p = 0.16$). Neither the pMFC component (in the error trial) nor the dorsolateral/frontopolar component (post-error) were correlated with the post-error activation change in the right lateralized inferior occipital component (IC 03, both $p > 0.18$).

**Correlations between frontal and motor components**

Adaptive processes in the mean motor IC were quantified as slope of decreasing activity between error and post-error trials. Strength of activity in pMFC (IC 01) predicted the amount of activation decrease in the mean motor IC ($r = -0.74$, $p < 0.001$; Cook’s distance of all values $< 1$). The larger pMFC activity in error trials, the stronger the activation decrease in motor areas in post-error trials.

Furthermore, the level of motor activation in the post-error trial was negatively correlated with the behavioral measure of post-error slowing ($r = -0.46$, $p = 0.043$; for one value Cook’s distance was 1.013; after removing this case the correlation remained significant, $r = -0.54$, $p = 0.017$). Lower post-error activity in the motor ICs was associated with greater post-error slowing.

**Diffusion imaging results**

Correlations between fractional anisotropy values and participants’ post-error slowing measures were computed, to identify those white matter regions where individual differences in FA contribute to different behavioral outcomes. Note, that at least parts of the correlating WM tracts might serve inhibitory functions. This assumption is due to the fact that the FA values of interest correlate with prolonged reaction times, i.e., PES. FA in two medial frontal WM regions correlated with PES (Fig. 4a; Table 3): the left anterior midcingulate region and the right presupplementary motor area (pre-SMA).

These two WM areas were taken as seed points for probabilistic tractographies to reveal those brain regions that are connected by the PES-related fiber tracts. The tractography from the pre-SMA seed region showed a network that has previously been described as an inhibitory network related to the slowing or stopping of motor responses (Aron et al., 2007). This tract comprises the pre-SMA, posterior inferior frontolateral areas, and the STN of the right hemisphere (Fig. 4b). Parts of this tractography reached the left-hemispheric pMFC, but overall the network was mainly located within the right hemisphere.

WM tracts, running through the anterior midcingulate seed region, connect frontal dorsolateral and frontopolar areas with the medial frontal cortex. Moreover, there seem to be connec-

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**Figure 2.** Independent components showing activity modulations around error trials. **A,** IC 01, covering the pMFC and other areas related to error processing, showed an activation increase on the error trial. IC 04 was located in task-relevant color encoding areas (red, IC 04; green, activations from the color localizer task; yellow, overlap of color localizer and IC) and showed increasing activity from the error to the post-error trial. IC 05, covering the distractor-encoding motion processing areas, showed decreasing activity between the pre-error and the post-error trial. **B,** Dorsolateral prefrontal and frontopolar areas (IC 06) were increased in activity in the post-error trial, whereas two ICs covering the left and right motor system (IC 07 and IC 08, respectively) showed reduced activity in post-error trials.
Table 2. MNI coordinates, maximum t value, and volume of activated areas of independent components showing significant modulations in error and/or post-error trials

<table>
<thead>
<tr>
<th>IC</th>
<th>Region</th>
<th>Volume (mm³)</th>
<th>Maximum t value</th>
<th>x</th>
<th>y</th>
<th>z</th>
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<tbody>
<tr>
<td>IC 01 (modulation in error trials)</td>
<td>Posterior medial frontal cortex</td>
<td>36,999</td>
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<td></td>
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<td></td>
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<td>2</td>
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<td></td>
<td>Right operculum/insula</td>
<td>6790</td>
<td>11.20</td>
<td>53</td>
<td>8</td>
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<td></td>
<td>Left posterior insula</td>
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<td>Left premotor cortex</td>
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<td>Left posterior SFS</td>
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<td>Posterior MTG</td>
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<td></td>
<td>Left inferior parietal lobule</td>
<td>237</td>
<td>5.99</td>
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<tr>
<td></td>
<td>Left hypothalamus</td>
<td>451</td>
<td>8.78</td>
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<td>IC 02 (modulation in error trials)</td>
<td>Cuneus</td>
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<td>11.83</td>
<td>26</td>
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<td></td>
<td></td>
<td>9.76</td>
<td>47</td>
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<td>−11</td>
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<tr>
<td></td>
<td>Left posterior SFG</td>
<td>439</td>
<td>7.40</td>
<td>−26</td>
<td>1</td>
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<tr>
<td>IC 04 (modulation in error and post-error trials)</td>
<td>Left color-encoding area</td>
<td>29,710</td>
<td>23.72</td>
<td>−25</td>
<td>−86</td>
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<td></td>
<td>15.64</td>
<td>33</td>
<td>−94</td>
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<tr>
<td></td>
<td></td>
<td>13.43</td>
<td>28</td>
<td>−85</td>
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<td></td>
<td>Left parahippocampal gyrus</td>
<td>444</td>
<td>9.14</td>
<td>−17</td>
<td>−26</td>
<td>−11</td>
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<tr>
<td>IC 05 (modulation in error and post-error trials)</td>
<td>Right motion-encoding area (and surrounding areas)</td>
<td>73,682</td>
<td>27.12</td>
<td>53</td>
<td>−70</td>
<td>−1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22.13</td>
<td>47</td>
<td>−61</td>
<td>−12</td>
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<td></td>
<td></td>
<td>19.40</td>
<td>53</td>
<td>−74</td>
<td>−1</td>
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<td></td>
<td></td>
<td>19.07</td>
<td>44</td>
<td>−70</td>
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<tr>
<td></td>
<td></td>
<td>13.60</td>
<td>30</td>
<td>−79</td>
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<tr>
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<td>Left motion-encoding area</td>
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<tr>
<td></td>
<td></td>
<td>14.61</td>
<td>−42</td>
<td>−68</td>
<td>−2</td>
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<td></td>
<td></td>
<td>12.12</td>
<td>−46</td>
<td>−65</td>
<td>2</td>
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<tr>
<td></td>
<td>Caudate nucleus</td>
<td>177</td>
<td>5.66</td>
<td>19</td>
<td>16</td>
<td>9</td>
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<tr>
<td>IC 06 (modulation in post-error trials)</td>
<td>Frontopolar cortex/anterior dorsolateral cortex</td>
<td>49,272</td>
<td>25.37</td>
<td>38</td>
<td>53</td>
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<td>23</td>
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<td></td>
<td>16.23</td>
<td>−22</td>
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<td>Rostral cingulate zone</td>
<td>15.39</td>
<td>5</td>
<td>64</td>
<td>29</td>
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<td></td>
<td>Collateral sulcus</td>
<td>2646</td>
<td>7.69</td>
<td>−4</td>
<td>31</td>
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<tr>
<td></td>
<td>Left cerebellium</td>
<td>258</td>
<td>6.48</td>
<td>26</td>
<td>−8</td>
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<tr>
<td></td>
<td></td>
<td>458</td>
<td>7.06</td>
<td>−38</td>
<td>−59</td>
<td>−34</td>
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<tr>
<td>IC 07 (modulation in post-error trials)</td>
<td>Left motor cortex</td>
<td>31,145</td>
<td>35.96</td>
<td>−36</td>
<td>−29</td>
<td>53</td>
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<tr>
<td></td>
<td></td>
<td>23.69</td>
<td>−43</td>
<td>−25</td>
<td>46</td>
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<td></td>
<td></td>
<td>16.25</td>
<td>−27</td>
<td>−44</td>
<td>59</td>
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<tr>
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<td>Left posterior insula</td>
<td>5876</td>
<td>12.98</td>
<td>−46</td>
<td>−14</td>
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<td>SMA</td>
<td>3558</td>
<td>9.56</td>
<td>−3</td>
<td>−16</td>
<td>43</td>
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<td>Left thalamus</td>
<td>592</td>
<td>9.60</td>
<td>−13</td>
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<td>Right cerebellium</td>
<td>5562</td>
<td>14.66</td>
<td>23</td>
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<td>−29</td>
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<td>IC 08 (modulation in post-error trials)</td>
<td>Right motor cortex</td>
<td>35,271</td>
<td>44.91</td>
<td>48</td>
<td>−22</td>
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<td>57</td>
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<td></td>
<td></td>
<td>24.36</td>
<td>45</td>
<td>−32</td>
<td>50</td>
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<td></td>
<td></td>
<td>17.16</td>
<td>53</td>
<td>−11</td>
<td>53</td>
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<tr>
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<td>Right posterior insula</td>
<td>6674</td>
<td>13.81</td>
<td>44</td>
<td>−16</td>
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<tr>
<td></td>
<td>SMA</td>
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<td>12.97</td>
<td>10</td>
<td>−19</td>
<td>45</td>
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<td>Left postcentral gyrus</td>
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<td>7.33</td>
<td>−33</td>
<td>32</td>
<td>55</td>
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<td></td>
<td>Right thalamus</td>
<td>328</td>
<td>8.58</td>
<td>17</td>
<td>−19</td>
<td>−1</td>
</tr>
<tr>
<td></td>
<td>Left central sulcus</td>
<td>201</td>
<td>6.67</td>
<td>−48</td>
<td>−26</td>
<td>44</td>
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<tr>
<td></td>
<td>Left cerebellium</td>
<td>5236</td>
<td>12.61</td>
<td>−11</td>
<td>50</td>
<td>−30</td>
</tr>
</tbody>
</table>

IC 01 shows an extended activation in the posterior medial frontal cortex. IC 02 shows a large activation in the cuneus, and the activation of IC 03 is mainly located in the right inferior occipital cortex, extending into the cerebellum. Activations in IC 04 correspond to color-processing visual areas, and activations in IC 05 correspond to motion-processing visual areas. IC 06 shows a post-error activation increase predominantly in frontopolar and anterior dorsolateral prefrontal areas. IC 07 and IC 08 reflect activations in the left and right motor system, respectively. All listed activations have a minimum volume size of 135 mm³ (five contiguous voxels). SFG, Superior frontal gyrus; SFS, superior frontal sulcus; MTG, middle temporal gyrus; SMA, supplementary motor area.
tions between medial frontal cortex and posterior running tracts, with the latter probably representing parts of the inferior fronto-occipital fascicle. There were also projections toward inferior thalamic nuclei and toward anterior cingulate regions in the contralateral hemisphere. However, these tracts were mainly located within the left hemisphere. Tracts from both pre-SMA and anterior midcingulate seed regions extended to WM regions beneath the pMFC component (IC 01), suggesting a link between cortical and WM areas associated with PES.

**Discussion**

The present experiment was set up to investigate the behavioral and neuronal level of post-error adaptations on a trial-to-trial basis, as well as the structural connections supporting these functions. It is assumed that post-error adaptations are triggered by the performance monitoring system and serve to improve future performance, i.e., avoid further errors. Participants indeed showed improved accuracy and prolonged reaction times in post-error trials (PES).

Seven ICs showed activity modulations in error and post-error trials. The IC showing selectively enhanced activity during error trials comprised regions usually implicated in performance monitoring (Ullsperger and von Cramon, 2001; Ridderinkhof et al., 2004b): the peak activity of this monitoring IC was located in the pMFC; smaller coactivations were located in the anterior insula bilaterally. The monitoring IC showed the most relevant result to our inquiry, since its level of activity in error trials predicted the strength of peri-error and post-error adjustments in task-related visual ICs and in the motor system. As the time course is equal for all parts of an IC, it is possible that, in addition to pMFC, anterior insula activity contributes to driving these adaptive changes.

Activity in task-relevant color-encoding areas was low in error trials but showed an increase in post-error trials, whereas the task-irrelevant, motion-processing IC (encoding distractors) decreased after errors. This decrease already started during the error trial and continued in the post-error phase. Both color area increase and motion area decrease were correlated with the preceding level of error-related pMFC activity. These changes in post-error activity may help to prevent further errors by enhancing activity in relevant brain areas and inhibiting distracting information at the same time. The result corroborates the suggestion that the pMFC both detects performance problems and acts to change behavior (Ridderinkhof et al., 2004b; Kennerley et al., 2006). Previously, only links between pMFC function and motor-related adaptations (PES, response selection) have been shown (Debener et al., 2005). Our data not only support those previous findings but provide evidence for an important extension of pMFC function: it appears to act on task-related visual areas as well. Sarter et al. (2006) hypothesized that anterior cingulate cholinergic activity contributes (presumably via the basal forebrain) to the recruitment of top-down control mainly to attenuate effects of distracting input, but they speculated that evidence for suppression of task-irrelevant cortical regions has remained scarce due to methodological reasons. However, suppression of striate and extrastriate neuronal activity has been observed before in macaques (Ferrera and Lisberger, 1997; Vanduffel et al., 2000; Treue, 2001). Thus, inhibitory effects in motion areas seem to be plausible in the present task, where motion direction is the distracting stimulus dimension.

Egner and Hirsch (2005) dissociated activity changes in the fusiform face area (FFA) when it was task relevant from changes in the same area when it was task irrelevant. By using a name–face interference task, they demonstrated that the activation in FFA can be modulated by an interaction of cognitive control and conflict. While they found a modulation when FFA was the task-relevant visual area, they did not find any modulation when FFA was the irrelevant visual area. These FFA modulations were observed in correct trials that were influenced differentially by conflict. They did not report a functional relationship between pMFC areas and adaptations in FFA, but instead suggested that the LPFC drives the changes in FFA.

Based on previous studies, one might expect a close interaction between the pMFC and DLFPC, which has been associated with the implementation of cognitive control (Garavan et al., 2002; Botvinick et al., 2004; Kerns et al., 2004; Cavanagh et al., 2009). Although we did find a DLFPC component showing post-error activation enhancement, this IC did not correlate with either the pMFC or the color and motion ICs. This corresponds with results by Hyafil et al. (2009) and Kouneiher et al. (2009) that also did not show any cognitive control-specific correlation between pMFC and DLFPC activity. Thus, at least in some tasks pMFC seems to be more directly linked to adjustment processes in stimulus-encoding areas than DLFPC. It has been suggested that lateral prefrontal areas maintain task-representations...
The individual post-error slowing measure (within average WM skeleton).

Table 3. White matter regions where fractional anisotropy values correlated with hemisphere.

Table 3. White matter regions where fractional anisotropy values correlated with the individual post-error slowing measure (within average WM skeleton).

<table>
<thead>
<tr>
<th>Region</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>Volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WM beneath left anterior midcingulate cortex</td>
<td>-20</td>
<td>36</td>
<td>25</td>
<td>47</td>
</tr>
<tr>
<td>WM beneath right pre-SMA</td>
<td>15</td>
<td>26</td>
<td>43</td>
<td>43</td>
</tr>
</tbody>
</table>

Activation cluster with a threshold of p < 0.001 and more than 40 contiguous activated voxels are listed.

(gehring and Knight, 2000; Ullsperger et al., 2002; Ullsperger and von Cramon, 2006) that are strengthened after conflict or errors (Botvinick et al., 2001). Although pMFC and DLPFC activations occur in close temporal proximity, there might be several intermediate neuronal steps between monitoring in pMFC and the updating of task-representations in DLPFC. Therefore, DLPFC activations do not need to be linearly correlated with pMFC activity.

This experiment showed that error-related pMFC activity predicts a subsequent activation decrease in the motor system, which in turn is correlated with the behavioral PES effect. It is thought that PES reflects more controlled responding (Ridderinkhof et al., 2004a). Thus, following errors, it might be a useful strategy that the pMFC not only modulates task-relevant visual areas to enable better performance but also triggers the slowing of the next motor response, which may provide more time for task-focused visual encoding processes. However, activity decreases in motor areas (King et al., 2010) and PES (Notebaert et al., 2009) might be a very general post-error effect that could be functionally independent from activity modulations in visual areas.

Our finding is in line with data from the linear ballistic accumulator model, a mathematical model for exploring speed-accuracy trade-off mechanisms, suggesting that more accurate (post-error) responses occur when response thresholds are higher; according to this model, the accumulation of decision-relevant information takes time, and thus high response thresholds lead to slower but more accurate responses while low response thresholds lead to faster but more error-prone decisions (Forstmann et al., 2008). In case of post-error trials, lower motor cortex activations might reflect the higher response threshold. Whereas previous evidence for a relationship between pMFC activity and PES (Gehring et al., 1993; Garavan et al., 2002; Kerns et al., 2004; Debener et al., 2005; di Pellegrino et al., 2007) did not speak to the specific role of the motor system in this adjustment, our finding of reduced post-error motor activity is in line with recent evidence (Marco-Pallares et al., 2008; King et al., 2010) suggesting motor inhibition as a mechanism underlying PES. Consistent with this, transcranial magnetic stimulation (TMS) studies have recently demonstrated that the pre-SMA can modulate M1 activity in conflicting situations and thus influence corticospinal excitability (Mars et al., 2009; Neubert et al., 2010). This corroborates our result showing that pMFC activity predicts the strengths of motor activity following errors, i.e., stronger pMFC activity leads to less motor activity in the post-error trial. Furthermore, a disruption of medial frontal activity by TMS leads to stronger activations of the incorrect response in the motor system in an interference task (Taylor et al., 2007).

To explore whether the PES underlying anatomical structures is consistent with the motor inhibition account, correlations were calculated between PES values and FA values. Several neurobiological factors influence FA values; higher FA values can be a sign of a higher degree of myelination, higher fiber density, bigger axon diameters, or fewer crossing fibers (Beaulieu, 2009; Scholz et al., 2009). Our data revealed that FA values beneath the pMFC, i.e., WM tracts in the vicinity of the right pre-SMA and the left anterior midcingulate cortex, correlated with PES. Tractographies from these seed regions showed that the area beneath the pre-SMA belongs to fiber tracts connecting right-hemispheric pre-SMA, inferior frontal cortex, and the subthalamic nucleus. This network has been associated with stopping and slowing of motor responses (Aron et al., 2007). Consistent with the motor inhibition account of PES, WM integrity of the inhibition network appears to modulate the decrease in motor areas in post-error trials and, therefore PES.

The PES-related left anterior midcingulate area belongs to fiber tracts connecting medial frontal cortical areas with frontopolar and dorsolateral prefrontal cortices. Frontopolar areas have been associated with attentional dimension weighting (Weidner et al., 2002; Pollmann et al., 2006), i.e., these areas are active when subjects have to shift their attention from one visual feature to another. In the present task, this might reflect an attentional shift away from the motion feature toward the color feature following errors.

In conclusion, by employing combined single-trial fMRI analysis and DWI, this study revealed that error-related pMFC activity drives adaptive processes in visual areas, i.e., a post-error increase in the task-relevant visual area and a peri-error decrease in the task-irrelevant (distractor encoding) visual area. This strongly suggests a top-down regulated attentional shift away from task-irrelevant and toward task-relevant stimulus features. Furthermore, pMFC activity was also related to PES and corresponding adaptations in the motor system. Individual differences in PES were reflected in FA values in WM tracts beneath the pMFC. Motor slowing following errors seems to be triggered by pMFC activity and communicated via an inhibitory network connecting pre-SMA, inferior frontal cortex, and STN. While
References


previous work suggested that pMFC activity may be driven in a bottom-up fashion by conflict between task-relevant and disrupting inputs (Liston et al., 2006), here we show a top-down influence of pMFC activity biasing motor and visual cortex function in the service of adaptive control.

age analysis and implementation as FSL. Neuroimage 23 [Suppl 1]:S208–S219.


