RESEARCH ARTICLE

Motor and non-motor error and the influence of error magnitude on brain activity

**Karin Graziella Nadig · Lutz Jäncke ·
Roger Lüchinger · Kai Lutz**

Abstract   It has been shown that frontal cortical areas increase their activity during error perception and error processing. However, it is not yet clear whether perception of motor errors is processed in the same frontal areas as perception of errors in cognitive tasks. It is also unclear whether brain activity level is influenced by the magnitude of error. For this purpose, we conducted a study in which subjects were confronted with motor and non-motor errors, and had them perform a sensorimotor transformation task in which they were likely to commit motor errors of different magnitudes (*internal errors*). In addition to the internally committed motor errors, non-motor errors (*external errors*) were added to the feedback in some trials. We found that activity in the anterior insula, inferior frontal gyrus (IFG), cerebellum, precuneus, and posterior medial frontal cortex (pMFC) correlated positively with the magnitude of *external errors*. The middle frontal gyrus (MFG) and the pMFC cortex correlated positively with the magnitude of the *total error* fed back to subjects (*internal plus external*). No significant positive correlation between *internal error* and brain activity could be detected. These results indicate that motor errors have a differential effect on brain activity compared with non-motor errors.

K. G. Nadig (✉) · L. Jäncke · K. Lutz
Department of Neuropsychology, University of Zurich,
Binzmühlestrasse 14/25, 8050 Zurich, Switzerland
e-mail: k.nadig@psychologie.uzh.ch

R. Lüchinger
Institute for Biomedical Engineering,
Swiss Federal Institute of Technology, ETH Zurich,
Rämistrasse 10, 8091 Zurich, Switzerland

Introduction

Imagine yourself playing tennis. You throw the ball into the air, hit the ball and observe where it hits the ground. Throwing the ball, hitting it and monitoring the consequences are typical components of sensorimotor transformation tasks. The ball may hit the ground exactly where you wanted it to, although other outcomes are also possible. The ball may hit the ground right next to the planned spot, or could hit the ground way off the mark. There are several possible causes for such misses. A failure in precision may be due to an inappropriate movement by the agent. Alternatively, the ball's flight trajectory may have been changed (e.g. by a squall) even though the executed movement may have been fully appropriate. In the first case, the cause of the failure lies with the agent (self caused error, from now on called "*internal error*"), while in the second case, the cause lies with the agent's environment (externally caused error, from now on called "*external error*"). In most real-world situations, however, the failure will be due to a mixture of both, say a suboptimal motor action plus an additional external distortion. In any case of an error, by definition the intended goal does not agree with the achieved state.

The capacity to detect errors, i.e. to compare intended with actual outcome has been termed *error* or *performance monitoring* (Botvinick et al. 2001), and its neural correlates have received great attention in cognitive neuroscience. Studies on error detection in cognitive tasks (e.g. flanker tasks) have consistently reported activation of prefrontal

areas, subcortical structures and parietal structures, with the anterior cingulate cortex and posterior medial frontal cortex (pMFC) playing the major role (Ridderinkhof et al. 2004; Nachev et al. 2007). The pMFC seems not only to be involved in monitoring of *internal* non-motor errors (Botvinick et al., 2001; Ullsperger and von Cramon 2001; Fiehler et al. 2004; Li et al. 2008) but also in tasks in which the errors have *external* causes (Holroyd et al. 2004; Ullsperger et al. 2007). In addition to this the pMFC is involved in signaling the need for behavioral adjustments (Kerns et al. 2004; Ullsperger and von Cramon 2004). Meanwhile, researchers investigating motor errors have focused on the cerebellum and the parietal cortex (Blakemore et al. 2001; Blakemore 2003; Imamizu et al. 2003; Imamizu et al. 2004) and have suggested the concept of internal models. These internal models consist of two parts: an inverse and a forward model. While the forward model makes predictions about the behavior of the motor system and its sensory consequences, the inverse model calculates the motor commands required to achieve a certain goal. Deviations from the predicted and the actual outcome are detected by the forward model and used to update motor commands (Wolpert et al. 1995; Wolpert and Kawato 1998; Imamizu et al. 2007; Kawato 1999).

In the present fMRI study, we investigated perception of errors caused by an agent's motor system and errors caused by environmental factors, thereby considering how error magnitude impacts brain activity. To investigate these factors, we arranged for subjects to perform a sensorimotor transformation task in which they were likely to commit motor errors of different magnitudes; in some trials they were given incorrect feedback about their performance. In view of the pertinent literature, we anticipate activation in the pMFC to correlate with magnitude of *internal* and *total error*, as these error types reflect a general mismatch between the intended and actual outcome. Specifically for *external error* we expect cerebellar and parietal activity to correlate with their magnitude, because these *external errors* cannot be predicted by the forward model, and, therefore, there is a mismatch between expected and actual outcome—the higher the mismatch the stronger the need to update the internal model.

Materials and methods

Participants

Seventeen healthy right-handed subjects (mean 24.5 years, SD 3.2, 10 males), whose handedness was assessed with the Annett Handedness-Questionnaire (Annett 1970), participated in this study. Subjects gave written informed consent and performed two scanning runs, which were

separated by a short break (1–2 min). They were naïve about the purpose of the experiment and received 30 CHF for participation (approximately 30 US Dollars). The study was approved by the local ethics committee and tasks and testing procedures were in accordance with institutional guidelines of the Helsinki Declaration.

Stimuli and apparatus

At the beginning of each trial, a yellow square (visual angle of approximately 0.1°) was presented above a horizontal line (visual angle of approximately 14°) as a target cue (Fig. 1a). Its left–right position indicated the strength to be applied to a hand dynamometer (see below). Before the experiment, the position of each target was randomly chosen from the full range of possible positions without repetitions. After the movement, a triangle (visual angle of approximately 0.1°) was presented below the line as feedback. Feedback cues were placed according to the subjects' action. In 35% of the trials, their left–right position was additionally displaced (Fig. 1b). The motor responses were recorded with an MRI-compatible isometric hand dynamometer (isometric Sensory-Motor Systems Laboratory, ETH Zurich and University of Zurich), which was set to measure isometric grip force with a frequency of 60 Hz from 0 to 40 N in 8-bit resolution.

Task

The task consisted of a sensorimotor transformation. Sensorimotor transformations are usually characterized by a certain relationship between sensory stimuli and motor responses. The required association between a visual stimulus and a motor response was set up according to previous experiments (Toni et al. 2001a, b), with the difference that the motor response consisted of a quasi-continuously graded application of force on a hand dynamometer (Floyer-Lea and Matthews 2004, 2005; Keisker et al. 2009). In our experiment, subjects had to apply a force on a hand dynamometer as indicated by the target cue, and minimize the difference between the positions of feedback and target cues. The force applied by the subjects on each trial was transformed into a position on the horizontal line as follows: forces less than 10 N were coded by the leftmost position, whereas forces larger than 40 N were translated into the rightmost position on the line. Between 10 and 40 N, forces were transformed linearly into a corresponding position on the line.

In each trial, subjects were first shown the target position (indicated as a square). They were instructed to apply a force that matched the target position to the hand dynamometer immediately after target presentation. The force applied was translated into a position along the horizontal
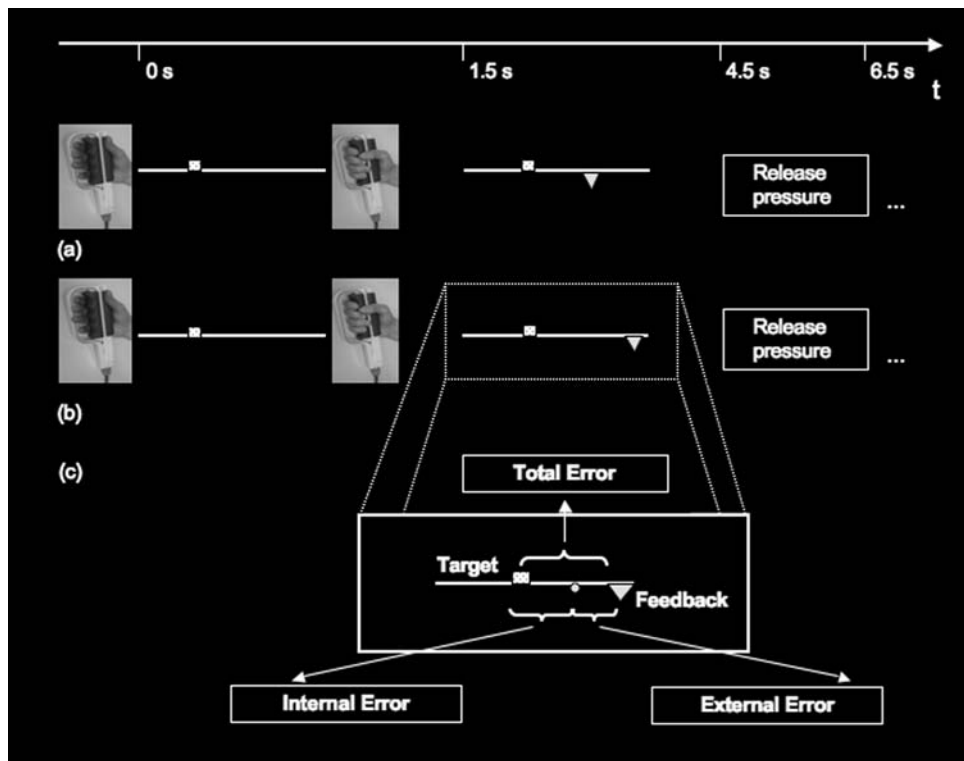
Fig. 1 Task setup. During the scanning session, participants had to associate a visual stimulus (position of a square above a line) with a motor response (application of force on the hand dynamometer) by trial and error. In each trial, a target square was presented above the line. After the target cue was presented, subjects had to manipulate the hand dynamometer in order to evoke a force that matched the target's position on the line. After 1.5 s they were given visual feedback about their performance. This took the form of a feedback triangle appearing at the location below the line, matching their applied force. The distance between the square and the triangle was regarded as the motor error; the closer, the better the subjects' motor performance. The fMRI experiment consisted of two sessions, each consisting of 140 trials, in which subjects were presented with incorrect feedback in 35% of the trials. **a** A correct feedback trial, i.e. a trial in which the discrepancy between the square and triangle reflects the subjects' performance error alone (internal error). **b** An incorrect feedback trial. Again, subjects were only presented with the triangle as feedback of their performance and they were left naïve about the additional error component which had been added to the feedback. Adding an external error always increased the incorrect trial feedback error in comparison with the subjects' real motor error. After presentation of the visual feedback, a further new trial was started. **c** The three measures that were subjected to a parametric analysis. The *gray circle* is inserted to illustrate the principle and reflects subjects' performance. "Internal error" refers to the errors caused by the subject, "External error" refers to the externally added error and "Total error" describes the error fed back to subjects. This "Total error" is either the result of internal errors only (65%) or internal and external errors together (35%)

line. Feedback stimuli (indicated as triangles in the above illustration) were always shown below the line. The spatial distance between the target and the feedback cue was regarded as the motor error (Fig. 1a). The motor response required manipulation of the hand dynamometer, and it was extremely unlikely that no *internal* motor errors would have been made, i.e. that the subject attained the desired position with a deviation of less than a pixel. After presentation of the feedback, a written instruction was presented to remove force from the dynamometer and a new trial subsequently began. Each trial lasted approximately 7 s, slightly varying due to the differing times it took for the subjects to release pressure from the hand dynamometer. The target cue was presented for 1.5 s, feedback presentation lasted for 3 s, and the request to release pressure was shown for 1.5 s. The whole experiment consisted of 280 trials, presented in two runs of 140 trials, adding up to a

total duration of approximately 35 min. The presentation times for cue and feedback were kept constant in both the correct and incorrect feedback conditions, and no measures were taken to delay motor response with respect to stimulus presentation. This approach was chosen because we were not interested in disentangling the discrete steps, but focused instead on the processing of errors. Regarding the trial as a whole allowed us to increase the number of trials in favor of statistical power, to compare trials with respect to presence or absence of *external errors* and to parametrically analyze the impact of error magnitude.

In 35% of all trials the feedback was distorted. This involved the addition of a variable extra displacement (*external error*) to the feedback position. Importantly, in order to prevent *internal* and *external errors* from canceling each other out, we ensured that the *external error* always moved the feedback further away from the target.

Thus, if the *internal error* was caused by the application of too little force (feedback triangle left of the cue), a further displacement to the left was added. If the *internal error* was caused by too much force (feedback triangle right of the cue), the *external error* was added to the right side.

The magnitude of the additional external displacement errors were randomly taken from the pool of the ten *internal errors* previously committed by the same subject. This ensured that the size of the *external errors* was adjusted to the individual performance level, and thus *external* and *internal errors* were comparable in magnitude. The occurrence of an *external error* could not be predicted, and the magnitude of the added *external errors* did not correlate with the magnitude of the *internal errors*. Subjects had not been informed about the existence of incorrect feedback trials and were naïve with regard to this experimental manipulation. Prior to the fMRI scanning session, the participants performed a training session including 50 trials, during which no *external errors* were added to the feedback. This permitted them to become familiar with the task and with the use of the hand dynamometer, and served to stabilize performance. More importantly, this allowed an internal model to build up, which enabled the subjects to predict the position where the feedback triangle was to be expected according to their dynamometer manipulation.

Experimental setup

Throughout both scanning runs, participants lay supine in the scanner. Head movement was minimized using an adjustable vacuum cushion. Visual stimuli were projected onto a mirror above the participants' heads. The hand dynamometer was placed in their right hand. Stimulus presentation and response collection were controlled by *Presentation 11.2* software (Neurobehavioral Systems, Inc, Albany, USA). After the experiment, subjects were asked to complete a questionnaire in which they answered questions concerning their thoughts and emotions during the experiment and if they had noticed anything peculiar.

FMRI data acquisition

Functional magnetic resonance imaging was performed at the University Hospital of Zurich on a Philips Achieva 3-T whole-body MRI system (Philips Medical Systems, Best, The Netherlands). Three-dimensional anatomical images of the entire brain were obtained by using a T1-weighted three-dimensional spoiled gradient echo pulse sequence (180 slices, TR = 20 ms, TE = 2.3 ms, flip angle = 20°, FOV = 220 mm × 220 mm × 135 mm, matrix size = 224 × 187, voxel size = 0.98 mm × 1.18 mm × 0.75 mm, re-sliced to 0.86 mm × 0.86 mm × 0.75 mm). Functional data were obtained in 400 scans per run using 33 transverse slices covering the whole brain in oblique orientation. Slices were acquired in interleaved order, using a sensitivity encoded (SENSE, factor 2.0), single-shot echo planar imaging technique (TR = 2.5 s; TE = 35 ms; FOV = 220 mm × 220 mm × 132 mm; flip angle = 78°; matrix size = 80 × 80; voxel size = 2.75 mm × 2.75 mm × 4 mm, re-sliced to 1.72 mm × 1.72 mm × 4 mm). Three dummy scans were acquired at the beginning of each run and discarded in order to establish a steady state in T1 relaxation for all functional scans.

FMRI data analysis

Data analysis was performed using MATLAB 7.4.0 (Mathworks Inc., Natiek, MA, USA) and SPM5 (http://fil.ion.ucl.ac.uk/spm). All images were realigned to the first recorded volume, normalized into standard stereotactical space (using the EPI-template provided by the Montreal Neurological Institute, MNI brain), re-sliced to 2 mm × 2 mm × 2 mm voxel size and smoothed using a 6-mm full-width-at-half-maximum (FWHM) Gaussian kernel.

The general linear model (GLM) contained 11 regressors: four for the correct feedback trials, five regressors for the incorrect feedback trials, and two additional regressors common to both feedback conditions. The first regressor for correct feedback trials was motor preparation, which was modeled as an epoch starting from target stimulus onset and lasting until the onset of the movement. Thus, the duration of this epoch was variable from trial to trial. A second regressor was an event at the onset of the motor response. The third regressor was a 1.5-s epoch starting at the onset of feedback presentation. The fourth regressor was a parametric modulation of the feedback regressor by the magnitude of *internal error* (Buchel and Friston 1998; Buchel et al. 1998). The incorrect feedback trials had the same four regressors plus an additional regressor consisting of a parametric modulation of the feedback by *external error*. In the following, the term *internal errors* will refer to the results of a parametric analysis of the magnitude of internally caused errors in trials, where no additional external distortion was added. The term *external errors* labels the results of the parametric analysis of the magnitude of externally added errors in trials with additional external distortion, while the term *total error* describes the sum of responses (parameter estimates) to *internal* and *external* errors in trials with both *internal* and *external* error (Fig. 2c). Finally, we used two additional regressors: The first was a regressor applied to both correct and incorrect feedback trials for the instruction to release force of grip that consisted of a 1.5-s epoch beginning with the onset of the instruction. The second was an epoch of 7 s that modeled the missed trials.
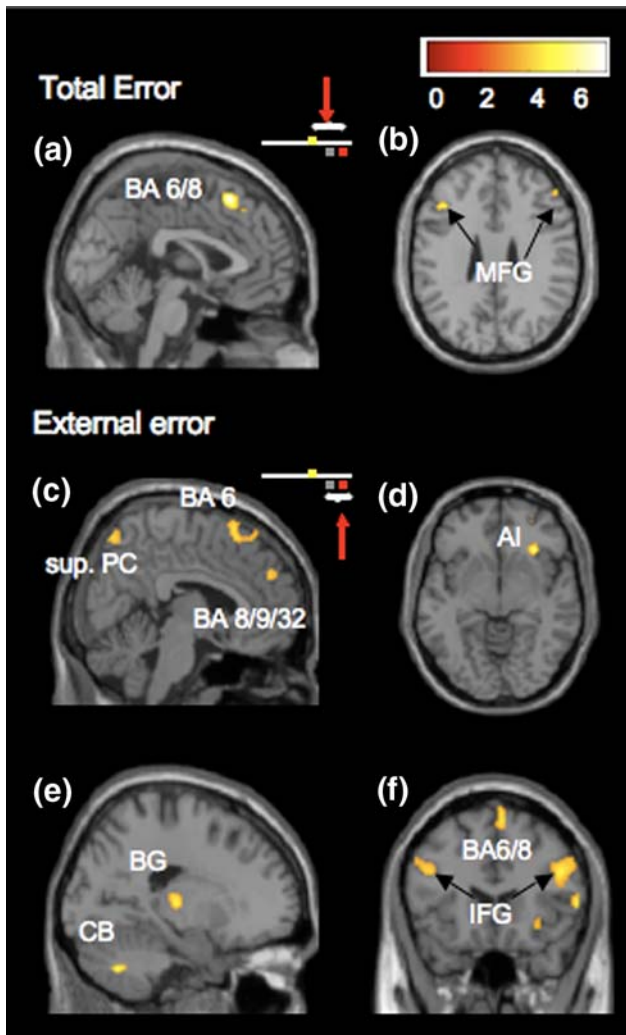
Fig. 2 Imaging Data. Anatomical location SPM(t) of the parametric analysis activations (**a-e**) detailed in Tables 1 and 2, overlaid on an MNI standard brain, together with parameter estimates (±90% CI). **a**, **b** Foci in which a BOLD response is correlated with the size of total error. One area is located in the pMFC, while the two others are located bilaterally in the MFG. In contrast, **c**–**f** show the areas in which a BOLD signal is correlated with the size of external error. **c** Activity in the pMFC and sup-PC, **d** the ventral anterior insula (AI), **e** the BG and the CB, **f** bilateral IFG and pMFC activity. *pMFC* posterior medial frontal cortex; *MFG* middle frontal gyrus; *sup-PC* superior parietal cortex; *AI* anterior insula; *BG* basal ganglia; *CB* cerebellum

Functional data were analyzed using a GLM involving the abovementioned 11 regressors and a high-pass filter with a cut-off period of 128 s. The GLM was computed for each subject and then subjected to a second-level analysis. First-level linear contrasts (against global mean) were employed to test for specific condition effects for each voxel and each subject and condition (Friston et al. 1995). This results in one statistical parametric map for each subject and each contrast (three contrasts): (1) parametric modulation by *internal error* in correct feedback trials; (2) parametric modulation by *external error* in incorrect

feedback trials; (3) parametric modulation by *total error* in incorrect feedback trials. These contrast images were smoothed using an 8-mm FWHM Gaussian kernel, leading to an overall smoothing by 10-mm FWHM $(6^2 + 8^2)^{(1/2)}$. This was undertaken to account for inter-individual differences in localization of activated brain regions and to further increase statistical sensitivity by reducing the effective number of independent observations. In order to permit population-level inferences to be made, maps of contrast coefficients were collectively submitted to one-sample t tests against the null hypothesis of no activation for each of the first level contrasts while controlling for random effects. Activation differences were tested on a cluster level corrected for multiple comparisons using a statistical threshold of $P < 0.05$ and were reported using a cluster size of >25.

Behavioral results

Every subject performed 280 trials. Two participants were excluded from the analyses due to more than 15% missed trials, which made them outliers with respect to task processing. The final sample comprised 15 participants (mean age 24.5 years, SD 3.2, 10 males). On average, these subjects missed 12.3 trials (SD 4.68, range 5–20) where no action on the hand dynamometer took place. The average *internally generated error* magnitude was 78.84 pixels (SD 15.0, range 1–480) and the average *externally added error* was 78.33 pixels (SD 13.97, range 1–435). A two-tailed paired t test revealed no significant difference in magnitude of motor error [$t(14) = 0.20$; $P = 0.85$)] for the correct and incorrect feedback trials. To identify whether subjects' performance changed over time, *internal error* magnitude was compared in the first and second half of the experiment using a paired t test. This revealed no significant difference between the first and second run ($t = 0.941$, $df = 134$, $P = 0.35$).

To check for post-error-adjustment, we calculated the correlation coefficient between the errors and the following force production per subject in four different ways: (C1) correlation of the magnitude of *internal error* with the magnitude of *internal error* of the following trial; (C2) correlation of *total error* magnitude (*internal* plus *external*) with *internal error magnitude* of the following trial; (C3) correlation of *externally added error* with the *internal error* of the following trial; (C4) in order to assess any potential effect of time on this correlation, we computed a correlation between *external error* and the *internal error* of the next trial (equivalent to C3) only for the first half of the dataset. No significant correlations were found between the error magnitude and the correction in the subsequent trials, suggesting that no post-error adjustment took place during the experiment.

Data from the post-experimental questionnaire revealed that 14 of 15 subjects had gained the impression that the hand dynamometer was sometimes not acting in the way they had intended.

Imaging results

First, we looked for regional brain activity that correlated linearly with the *total error* fed back to the subject (combined *internal* and *external*), taking all trials into account (Fig. 2a, b; Table 1). We found activity at the upper border of the rostral cingulate zone expanding into the pre-SMA, as well as activity in the right and left medial frontal gyrus (MFG), to positively correlate with the *total error* magnitude. Next, we investigated whether activity in any region displayed a linear parametric modulation with the magnitude of *internal errors*. No region could be identified showing this relationship. Last, we looked for regions in which activity increased linearly with the size of the *externally added error*. This analysis revealed nine clusters that showed such a relationship (Fig. 2c–f; Table 2). One of these clusters contained several local maxima. The strongest local maximum was found to be located in the right inferior frontal sulcus, the second in the right inferior frontal gyrus (IFG) and the third in the

right ventral anterior insula. Left IFG/sulcus activity was also revealed. In addition, significant activation was also found in the pMFC, the left inferior semilunar lobule of the cerebellum, the MFG, the basal ganglia and in the right precuneus.

Discussion

The aim of this study was to establish a relationship between neural activity and the magnitude of three types of errors: (1) motor errors committed by the agent (*internal errors*) (2) non-motor errors induced by environmental factors (*external errors*), and (3) the sum of these (*total errors*). For this purpose, a sensorimotor transformation task was chosen in which participants committed motor errors of different magnitudes (*internal errors*) in which incorrect feedback was given (*external errors*) during some trials.

We found that the activity of the MFG and the pMFC was enhanced with the magnitude of the *total error* fed back to the subject, while the parametric analysis of the magnitude of *internal errors* alone revealed no significant correlation with activity in any brain region. Anterior insular and lateral prefrontal areas as well as cerebellar, parietal

Table 1 MNI coordinates of significant clusters ($P > 0.005$, corrected for multiple comparisons, minimum cluster size = 25 voxels), number of voxels and P value per cluster, as well as MNI coordinates and t values of the maximally activated voxel in each cluster yielded by the parametric analysis of the magnitude of the *total errors* (*external plus internal errors*)

Side	Brain region	Cluster size (# voxel)	P value	x	y	z	t value
Parametric analysis of total error: positive correlation
R/L	Posterior medial frontal cortex BA 6, 8	212	<0.001	0	22	54	7.07
L	Middle frontal gyrus	62	<0.001	−42	26	32	6.28
R	Middle frontal gyrus	48	0.001	52	34	34	5.33

Table 2 Anatomical specification, MNI coordinates of significant clusters ($P < 0.05$, corrected for multiple comparisons, minimum cluster size = 25 voxels), number of voxels per cluster, P and t values of clusters yielded by the parametric analysis of the magnitude of the *external errors*

Side	Brain region	Cluster size (# voxel)	P value	x	y	z	t value
Parametric analysis of external errors: positive correlation
R	Inferior frontal sulcus	1,562	<0.001	40	32	16	6.28
R	Inferior frontal sulcus/gyrus		<0.001	50	32	12	6.26
R	Anterior insula		<0.001	32	26	−6	5.08
R	Middle frontal gyrus	130	<0.001	32	54	2	3.62
R	Posterior medial frontal cortex	117	<0.001	6	24	58	3.84
	BA 6/8			6	36	58	3.20
R	Posterior medial frontal cortex BA 8/9/32	120	<0.001	0	50	32	3.93
R	Superior parietal lobe	78	0.003	4	−72	56	3.07
L	Precuneus BA 7	56	0.031	−22	−56	46	3.63
L	Inferior frontal sulcus/gyrus	334	<0.001	−48	30	30	3.14
L	Basal ganglia	57	0.027	−18	−20	6	4.28
L	Cerebellum	52	0.027	−18	−64	−38	4.87

and pMFC (BA 6/8) activity were found to correlate positively with the magnitude of *external errors*.

The task used in this experiment differed from classical non-motor error paradigms (reviewed e.g. by Ridderinkhof et al. 2004). First, this task was not composed of a two or three-alternative forced-choice task in which the answer was either correct or incorrect and was therefore not limited to a dichotomous right or wrong feedback. This novel task extended beyond a qualitative analysis of the feedback to a quantitative analysis of error magnitude. Second, the required motor responses did not depend on a pure cognitive evaluation of a stimulus (e.g. stimulus A present or not) but on a transformation of visual input into a graded motor response.

Total error

One aim of this study was to determine the areas in which activity correlates positively with the magnitude of *total error* fed back to the subjects. The pMFC and the MFG/sulcus were positively correlated with *total error* magnitude. The source of this *total error* could either be of an *internal* nature only or a combination of *internal* and *external errors*. The confrontation with large error feedback is likely to induce several processes. Besides signaling an error, it may lead higher neural efforts for the correct planning, programming, execution as well as updating of the associated motor response.

The fact that we found activity modulation within the pMFC (BA 6/8) for errors is consistent with the results from error monitoring in cognitive tasks (e.g. Botvinick et al. 2001; Ullsperger and von Cramon 2001; Holroyd et al. 2004; Ullsperger et al. 2007; Li et al. 2008). When subjects are confronted with large errors, this may activate a process that calls for improvement of the motor response. Optimization of a motor response calls for new planning, which has been shown to trigger activity in the pre-SMA (Tanji 1994; Picard and Strick 2001). Furthermore, the pMFC has also been linked to signal the need to adjust behavior (Ullsperger et al. 2004), and it has also been shown that the intensity of pMFC activity allows predictions to be made about the strength of future adjustments (Kerns et al. 2004; Debener et al. 2005). Importantly, however, our behavioral findings reveal no such error adjustment. Thus, the interpretation that pMFC activity leads to future adjustments does not match our data. The activity we report here might instead reflect the signaling of a discrepancy between intended and actual outcome and thus the potential need to adjust performance. The lack of post-error adjustment might be due to the fact that our subjects had practiced the task ahead of scanning and were already stably performing at their optimum therefore no update would be implemented, which is different to previously described

studies in the cognitive domain where learning was involved.

In addition to pMFC activity, bilateral MFG/sulcus activity was found to correlate positively with the magnitude of the feedback discrepancy. Since the medial and the dorsolateral prefrontal cortex are tightly linked anatomically (Luppino et al. 1993) and also a strong functional connectivity between these areas has been shown (Chaminade and Fonlupt 2003), the dorsolateral prefrontal activity we find may be considered a pMFC co-activation. It has been suggested that the pMFC acts as a monitor, while the dorsolateral cortex as a controller (Ridderinkhof et al. 2004; Fletcher et al. 2001) or as a conflict solver (Casey et al. 2000), which interacts in the regulation of goal directed behavior. We might interpret the present activity of dorsal middle frontal cortex and anterior MFG in accordance to these studies as signaling the need to adjust behavior.

The total error corresponds to a mixture of *internal* and *external errors*. For a cognitive system it is important to be able to locate the source of error so that appropriate actions can be undertaken to prevent errors. For this reason, in the following we separately investigate the specific contribution of the *internal* and *external errors* to these brain signals.

Internal errors

Another aspect of this study was to determine the areas where activity increases with the magnitude of the *internal motor errors*. Interestingly, we found no significant pMFC activity to correlate with the magnitude of *internal error*. This is somewhat surprising, since one would expect some analogies with the error monitoring previously investigated in the cognitive domain. These earlier studies consistently show pMFC activity to be triggered by error perception (e.g. Carter et al. 1998; Botvinick et al. 2001; van Veen et al. 2004; Ullsperger et al. 2007). One reason why no relation was found between error size and pMFC activity may be provided by the internal model theory (Kawato and Wolpert 1998; Wolpert and Kawato 1998). These internal models enable the agent to form a prediction about the sensory consequences of a motor action and to compare the predicted outcome with the actual outcome. At the same time research into error monitoring and perception in cognitive tasks has pointed out that pMFC is only activated when a deviation from an expected target is detected (Knutson and Cooper 2005; Bubic et al. 2009). Since the prediction of the sensory consequence of the motor command has already been made by the forward model, a deviation between target and feedback cue is not unexpected, and may therefore not trigger pMFC activity. Evidence for this line of argument may be seen in the fact that pMFC activity was only detected in trials in which *external errors* had

been added in addition to the *internal errors*—a component that could not have been predicted by the forward model. Another hypothesis could be that correct feedback trials are the ones with the best possible outcome and that the need for adjustment could have been perceived as low. However, one should interpret these null-findings with caution. The absence of an effect may be due to experimental factors such as the sample size or any non-linearities in the BOLD response that are not accounted for in the regression model.

External errors

The third aim of this study was to assess the activity of brain areas positively correlating with the magnitude of the *externally* added error alone. To start with, we would like to comment on the fact that in trials including an *external error*, the size of explicitly fed back error is on average larger than in the remaining trials. However, please note, it is the size of the *external error* component alone, rather than the (explicitly available) *total error*, which shows a significant correlation between activation size in several additional brain regions. Thus, this *external error* component elicits significant reactions in the brain, which are discussed below.

Similar to the *total error*, the *external error* was also correlated with activity in the pMFC (BA 6/8), which conforms with results obtained from error monitoring in cognitive tasks (Botvinick et al. 2001; Ullsperger and von Cramon 2001; Fiehler et al. 2004; Holroyd et al. 2004; Ullsperger et al. 2007). In the incorrect feedback condition, feedback is distorted, and the outcome could therefore not be predicted correctly. We argue that the unexpected outcome triggered pMFC activity, which, in turn, may have signaled the need to change behavior for outcome optimization. The same line of argumentation may also hold for the internal models, and we have indeed found cerebellar and parietal activity, as would have been predicted according to the work of several authors (Blakemore et al. 2001; Blakemore and Sirigu 2003; Imamizu et al. 2003; Imamizu et al. 2004; Imamizu and Kawato 2009).

Besides regions of the error network, we additionally found brain regions known to be involved in *affective* processes, such as anterior insula and lateral prefrontal cortex. Our analysis revealed IFG and anterior insular activity to increase with *external error* magnitude. The IFG is part of the lateral prefrontal cortex that supports the cognitive regulation of feelings and thoughts (Hariri et al. 2000; Kuchinke et al. 2005; Koelsch et al. 2006; Levesque et al. 2003; Ochsner et al. 2004; Baumgartner et al. 2006; Chiu et al. 2008). Furthermore, it has been proposed that the insula, which is part of the ventral emotional system, is important for the identification of the emotional significance of the stimuli, the production of affective state

responses and (as the IFG) involved in autonomic regulation of emotional responses (Lane et al. 1997; Buchel et al. 1999; Phelps et al. 2001; Phan et al. 2002; Phillips et al. 2003; Jabbi et al. 2008). Several studies dealing with negative emotions such as omission of social reward (Siegrist et al. 2005), unfairness (Sanfey et al. 2003) or frustration (Abler et al. 2005) report insular as well as IFG activity as observed in the current study. The magnitude of *external errors* in our study reflects the degree to which the individual performance has been distorted by external influences. This external feedback may be perceived as *unfair feedback*, e.g. in the study of Abler et al. (2005) participants were promised money when performing a task correctly, but the reward was omitted in some trials. In their study as well as in ours, subjects were presented with a worse outcome than would be expected from performance. They interpreted insular and IFG activation as being due to frustration and the need to regulate or inhibit pain distress and negative emotion.

In light of the abovementioned studies, a tentative explanation could be that adding *external errors* to the performance feedback results in emotional disturbance—the more so, the bigger the *external error* is. The question, however, arises whether such emotional consequences of distorted performance feedback depend on the subjects' conscious perception of a faulty feedback, or may be triggered by a feeling of uncertainty regarding performance outcome. Subjects were not always conscious of an external manipulation, but it is obvious from the statements gathered in the post experiment questionnaire that being confronted with error induced negative emotions in the subjects. Answers to the question "what was your reaction to an error?" ranged from "I tell myself to do better in the next trial", "the device must be out of whack", "frowning", "being annoyed", "upset", "irritated" to "frustrated". This is comparable to a tennis player who gets emotionally agitated after missing a ball and might either attribute the failure to environmental causes or to his skills. From our verbal reports alone, it is difficult to specify the attributional style, or locus of error, subjects have assumed in each trial. We abstained from asking subjects about their reactions after every trial, since that would undoubtedly have introduced bias in the subject's manner of dealing with errors, and the focus of this study was to investigate whether the brain reacts differently to errors from different sources. Thus, in our study subjects might have occasionally felt that they were unable to influence the result and to adjust their behavior in order to avoid these errors. However, this will have only been true for a small subset of trials because external errors ranged from very small and unnoticeable to very large and clearly noticeable.

In a task with unpredictable and infrequent events, such as *external errors,* these may be perceived as deviants.

Taking this into account, we would like to shortly discuss common aspects of oddball paradigms and the present experiment. At unpredictable times, subjects are confronted with unexpected stimuli, which in oddball settings have been shown to consistently activate a large network including parietal, medial and lateral frontal areas (Kiehl and Liddle 2001; Huettel and McCarthy 2004; Brazdil et al. 2007). Being confronted with unexpected stimulation may have induced an attentional modulation in our experiment comparable with oddball experiments. This activity pattern classical to oddball paradigms is largely consistent with ours. However, our task differs in several aspects from oddball paradigms. First, the successful manipulation relies on an active sensorimotor integration of visual stimuli into a motor response, which induced a sense of agency not common to oddball paradigms. Second, in order to optimize behavior, the output has to be monitored and in case of a mismatch between expected and actual outcome, the source of such a mismatch has to be located. Additionally, in the present study, reactions to unexpected stimuli evoke emotional responses going beyond classical oddball tasks. Therefore, despite common aspects, our task interpretation cannot be equaled to one of oddball paradigms.

In summary, we can postulate that anterior insular and IFG activity reflects the emotion induced by the *external errors*, that the pMFC results from exposure to an unexpected event and, finally, that cerebellar-parietal activity may reflect adjustments of the internal model. To explicitly address the issue of awareness of the source of error, a future study is planned.

Conclusion

Our experiment yields three major conclusions: (1) pMFC (BA 6/8) and bilateral MFG activity correlates positively with the magnitude of *total errors*. The larger the errors subjects were confronted with the higher the perceived need to adjust behavior or an internal model relating action to expected outcome. (2) Activity in pMFC (BA 6/8), anterior insula, cerebellum, precuneus and IFG correlates with the magnitude of *external errors*. Presumably, these regions reflect a negative emotional response evoked while facing unexpected and potentially unfair feedback. (3) pMFC activity does not significantly correlate with the size of *internal errors*. The fact that pMFC correlates with *external errors* and with *total errors* but not with *internal errors* leads us to assume that *internal motor errors* are processed differently from non-motor errors. One explanation for this may be given by the framework of internal models. These internal models enable the sensory consequences of motor commands to be predicted, and these errors are therefore not unexpected. Detection of motor and non-motor errors apparently relies on different neural networks.

References

Abler B, Walter H, Erk S (2005) Neural correlates of frustration. Neuroreport 16:669–672

Annett M (1970) A classification of hand preference by association analysis. Br J Psychol 61:303–321

Baumgartner T, Lutz K, Schmidt CF, Jancke L (2006) The emotional power of music: how music enhances the feeling of affective pictures. Brain Res 1075:151–164

Blakemore SJ (2003) Deluding the motor system. Conscious Cogn 12:647–655

Blakemore SJ, Sirigu A (2003) Action prediction in the cerebellum and in the parietal lobe. Exp Brain Res 153:239–245

Blakemore SJ, Frith CD, Wolpert DM (2001) The cerebellum is involved in predicting the sensory consequences of action. Neuroreport 12:1879–1884

Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD (2001) Conflict monitoring and cognitive control. Psychol Rev 108:624–652

Brazdil M, Mikl M, Marecek R, Krupa P, Rektor I (2007) Effective connectivity in target stimulus processing: a dynamic causal modeling study of visual oddball task. Neuroimage 35:827–835

Bubic A, von Cramon DY, Jacobsen T, Schroger E, Schubotz RI (2009) Violation of expectation: neural correlates reflect bases of prediction. J Cogn Neurosci 21:155–168

Buchel C, Friston KJ (1998) Dynamic changes in effective connectivity characterized by variable parameter regression and Kalman filtering. Hum Brain Mapp 6:403–408

Buchel C, Holmes AP, Rees G, Friston KJ (1998) Characterizing stimulus-response functions using nonlinear regressors in parametric fMRI experiments. Neuroimage 8:140–148

Buchel C, Dolan RJ, Armony JL, Friston KJ (1999) Amygdala-hippocampal involvement in human aversive trace conditioning revealed through event-related functional magnetic resonance imaging. J Neurosci 19:10869–10876

Carter CS, Braver TS, Barch DM, Botvinick MM, Noll D, Cohen JD (1998) Anterior cingulate cortex, error detection, and the online monitoring of performance. Science 280:747–749

Casey BJ, Thomas KM, Welsh TF, Badgaiyan RD, Eccard CH, Jennings JR, Crone EA (2000) Dissociation of response conflict, attentional selection, and expectancy with functional magnetic resonance imaging. Proc Natl Acad Sci USA 97:8728–8733

Chaminade T, Fonlupt P (2003) Changes of effective connectivity between the lateral and medial parts of the prefrontal cortex during a visual task. Eur J Neurosci 18:675–679

Chiu PH, Holmes AJ, Pizzagalli DA (2008) Dissociable recruitment of rostral anterior cingulate and inferior frontal cortex in emotional response inhibition. Neuroimage 42:988–997

Debener S, Ullsperger M, Siegel M, Fiehler K, von Cramon DY, Engel AK (2005) Trial-by-trial coupling of concurrent electroencephalogram and functional magnetic resonance imaging identifies the dynamics of performance monitoring. J Neurosci 25:11730–11737

Fiehler K, Ullsperger M, von Cramon DY (2004) Neural correlates of error detection and error correction: is there a common neuroanatomical substrate? Eur J Neurosci 19:3081–3087

Fletcher PC, Anderson JM, Shanks DR, Honey R, Carpenter TA, Donovan T, Papadakis N, Bullmore ET (2001) Responses of

human frontal cortex to surprising events are predicted by formal associative learning theory. Nat Neurosci 4:1043–1048

Floyer-Lea A, Matthews PM (2004) Changing brain networks for visuomotor control with increased movement automaticity. J Neurophysiol 92:2405–2412

Floyer-Lea A, Matthews PM (2005) Distinguishable brain activation networks for short- and long-term motor skill learning. J Neurophysiol 94:512–518

Friston KJ, Frith CD, Turner R, Frackowiak RS (1995) Characterizing evoked hemodynamics with fMRI. Neuroimage 2:157–165

Hariri AR, Bookheimer SY, Mazziotta JC (2000) Modulating emotional responses: effects of a neocortical network on the limbic system. Neuroreport 11:43–48

Holroyd CB, Nieuwenhuis S, Yeung N, Nystrom L, Mars RB, Coles MG, Cohen JD (2004) Dorsal anterior cingulate cortex shows fMRI response to internal and external error signals. Nat Neurosci 7:497–498

Huettel SA, McCarthy G (2004) What is odd in the oddball task? Prefrontal cortex is activated by dynamic changes in response strategy. Neuropsychologia 42:379–386

Imamizu H, Kawato M (2009) Brain mechanisms for predictive control by switching internal models: implications for higher-order cognitive functions. Psychol Res 73(4):527–544

Imamizu H, Kuroda T, Miyauchi S, Yoshioka T, Kawato M (2003) Modular organization of internal models of tools in the human cerebellum. Proc Natl Acad Sci USA 100:5461–5466

Imamizu H, Kuroda T, Yoshioka T, Kawato M (2004) Functional magnetic resonance imaging examination of two modular architectures for switching multiple internal models. J Neurosci 24:1173–1181

Imamizu H, Higuchi S, Toda A, Kawato M (2007) Reorganization of brain activity for multiple internal models after short but intensive training. Cortex 43:338–349

Jabbi M, Bastiaansen J, Keysers C (2008) A common anterior insula representation of disgust observation, experience and imagination shows divergent functional connectivity pathways. PLoS One 3:e2939

Kawato M (1999) Internal models for motor control and trajectory planning. Curr Opin Neurobiol 9:718–727

Kawato M, Wolpert D (1998) Internal models for motor control. Novartis Found Symp 218:291–304 discussion 304–307

Keisker B, Hepp-Reymond MC, Blickenstorfer A, Meyer M, Kollias SS (2009) Differential force scaling of fine-graded power grip force in the sensorimotor network. Hum Brain Mapp 30(8):2453–2465

Kerns JG, Cohen JD, AWr MacDonald, Cho RY, Stenger VA, Carter CS (2004) Anterior cingulate conflict monitoring and adjustments in control. Science 303:1023–1026

Kiehl KA, Liddle PF (2001) An event-related functional magnetic resonance imaging study of an auditory oddball task in schizophrenia. Schizophr Res 48:159–171

Knutson B, Cooper JC (2005) Functional magnetic resonance imaging of reward prediction. Curr Opin Neurol 18:411–417

Koelsch S, Fritz T, von Cramon DY, Muller K, Friederici AD (2006) Investigating emotion with music: an fMRI study. Hum Brain Mapp 27:239–250

Kuchinke L, Jacobs AM, Grubich C, Vo ML, Conrad M, Herrmann M (2005) Incidental effects of emotional valence in single word processing: an fMRI study. Neuroimage 28:1022–1032

Lane RD, Reiman EM, Ahern GL, Schwartz GE, Davidson RJ (1997) Neuroanatomical correlates of happiness, sadness, and disgust. Am J Psychiatry 154:926–933

Levesque J, Joanette Y, Mensour B, Beaudoin G, Leroux JM, Bourgouin P, Beauregard M (2003) Neural correlates of sad feelings in healthy girls. Neuroscience 121:545–551

Li CS, Yan P, Chao HH, Sinha R, Paliwal P, Constable RT, Zhang S, Lee TW (2008) Error-specific medial cortical and subcortical activity during the stop signal task: a functional magnetic resonance imaging study. Neuroscience 155:1142–1151

Luppino G, Matelli M, Camarda R, Rizzolatti G (1993) Corticocortical connections of area F3 (SMA-proper) and area F6 (pre-SMA) in the macaque monkey. J Comp Neurol 338:114–140

Nachev P, Wydell H, O'neill K, Husain M, Kennard C (2007) The role of the pre-supplementary motor area in the control of action. Neuroimage 36(Suppl 2):T155–T163

Ochsner KN, Ray RD, Cooper JC, Robertson ER, Chopra S, Gabrieli JD, Gross JJ (2004) For better or for worse: neural systems supporting the cognitive down- and up-regulation of negative emotion. Neuroimage 23:483–499

Phan KL, Wager T, Taylor SF, Liberzon I (2002) Functional neuroanatomy of emotion: a meta-analysis of emotion activation studies in PET and fMRI. Neuroimage 16:331–348

Phelps EA, O'Connor KJ, Gatenby JC, Gore JC, Grillon C, Davis M (2001) Activation of the left amygdala to a cognitive representation of fear. Nat Neurosci 4:437–441

Phillips ML, Drevets WC, Rauch SL, Lane R (2003) Neurobiology of emotion perception. I: The neural basis of normal emotion perception. Biol Psychiatry 54:504–514

Picard N, Strick PL (2001) Imaging the premotor areas. Curr Opin Neurobiol 11:663–672

Ridderinkhof KR, Ullsperger M, Crone EA, Nieuwenhuis S (2004) The role of the medial frontal cortex in cognitive control. Science 306:443–447

Sanfey AG, Rilling JK, Aronson JA, Nystrom LE, Cohen JD (2003) The neural basis of economic decision-making in the Ultimatum Game. Science 300:1755–1758

Siegrist J, Menrath I, Stocker T, Klein M, Kellermann T, Shah NJ, Zilles K, Schneider F (2005) Differential brain activation according to chronic social reward frustration. Neuroreport 16:1899–1903

Tanji J (1994) The supplementary motor area in the cerebral cortex. Neurosci Res 19:251–268

Toni I, Ramnani N, Josephs O, Ashburner J, Passingham RE (2001a) Learning arbitrary visuomotor associations: temporal dynamic of brain activity. Neuroimage 14:1048–1057

Toni I, Rushworth MF, Passingham RE (2001b) Neural correlates of visuomotor associations. Spatial rules compared with arbitrary rules. Exp Brain Res 141:359–369

Ullsperger M, von Cramon DY (2001) Subprocesses of performance monitoring: a dissociation of error processing and response competition revealed by event-related fMRI and ERPs. Neuroimage 14:1387–1401

Ullsperger M, von Cramon DY (2004) Neuroimaging of performance monitoring: error detection and beyond. Cortex 40:593–604

Ullsperger M, Volz KG, von Cramon DY (2004) A common neural system signaling the need for behavioral changes. Trends Cogn Sci 8:445–446 author reply 446–447

Ullsperger M, Nittono H, von Cramon DY (2007) When goals are missed: dealing with self-generated and externally induced failure. Neuroimage 35:1356–1364

van Veen V, Holroyd CB, Cohen JD, Stenger VA, Carter CS (2004) Errors without conflict: implications for performance monitoring theories of anterior cingulate cortex. Brain Cogn 56:267–276

Wolpert DM, Kawato M (1998) Multiple paired forward and inverse models for motor control. Neural Netw 11:1317–1329

Wolpert DM, Ghahramani Z, Jordan MI (1995) An internal model for sensorimotor integration. Science 269:1880–1882